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A Comprehensive Review of Deep Recursive Self-Attention Modules: MANET-Based Integrated Sensor System for Disaster Detection and Communication in Hazardous Environments

Branislav Rafizadeh

Associate Professor, Department of Computer Science and Engineering, Mindoro International School of Engineering and Management, Philippines

Email: branislav.rafizadeh@misem-ph.org

Peer Review Information	Abstract
<p><i>Submission: 22 Oct 2025</i></p> <p><i>Revision: 05 Nov 2025</i></p> <p><i>Acceptance: 13 Nov 2025</i></p>	<p>Disaster detection and communication in hazardous environments require robust, decentralized, and intelligent systems capable of operating without fixed infrastructure. Mobile Ad Hoc Networks (MANETs), combined with integrated sensor systems, have emerged as a promising solution for real-time monitoring and emergency communication. This paper presents a comprehensive review of deep recursive self-attention modules integrated with MANET-based sensor networks for disaster detection. The proposed approach leverages deep learning architectures, particularly recursive attention mechanisms, to enhance feature extraction and temporal analysis of sensor data collected from distributed nodes. These models enable efficient identification of disaster events such as chemical spills, earthquakes, and fire outbreaks with high accuracy. The integration of MANET ensures dynamic communication among nodes, enabling reliable data transmission even in infrastructure-less environments. Furthermore, the system supports real-time decision-making through distributed processing and adaptive routing protocols. The review highlights advancements in deep learning-based intrusion detection, clustering techniques, and IoT-MANET integration for healthcare and disaster management. Challenges such as energy efficiency, network stability, security threats, and computational constraints are also discussed. The study concludes that hybrid architectures combining deep recursive attention mechanisms with MANET-based sensor systems provide a scalable, reliable, and intelligent framework for disaster detection and communication in hazardous environments.</p>
<p>Keywords</p> <p><i>MANET, Disaster Detection, Deep Learning, Self-Attention, Sensor Networks, Hazardous Environment.</i></p>	

Introduction

In recent years, the increasing frequency of natural and industrial disasters has highlighted the need for advanced monitoring and communication systems capable of operating in hazardous and infrastructure-less environments. Traditional communication systems rely heavily on centralized infrastructure, which often becomes unavailable or damaged during

disasters such as earthquakes, floods, and chemical explosions. In such scenarios, Mobile Ad Hoc Networks (MANETs) play a crucial role due to their decentralized and self-configuring nature. MANETs consist of mobile nodes that communicate wirelessly without requiring fixed infrastructure, making them highly suitable for emergency response applications. The integration of sensor systems with MANETs has

further enhanced their capabilities in disaster detection and environmental monitoring. Sensor nodes deployed in hazardous environments collect real-time data such as temperature, gas concentration, humidity, and motion, which can be used to identify potential threats. These sensor networks, when combined with MANETs, enable efficient data transmission and communication among rescue teams and monitoring systems. Research has shown that integrated sensor systems can effectively detect industrial accidents such as chemical spills and hazardous gas leaks using machine learning techniques.

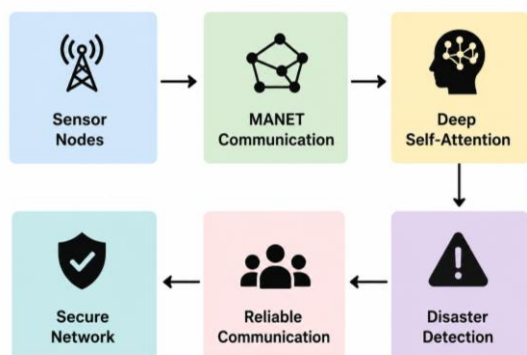


Figure 1. MANET-Based Deep Self-Attention Framework for Disaster Detection and Communication

Deep learning has emerged as a powerful tool for analysing complex and high-dimensional sensor data. Convolutional neural networks and recurrent neural networks have been widely used for feature extraction and temporal analysis. However, these models often struggle with capturing long-range dependencies and contextual relationships in dynamic environments. To overcome these limitations, self-attention mechanisms and transformer-based architectures have been introduced. These models enable the system to focus on relevant features within the data, improving accuracy and efficiency. Recursive self-attention modules further enhance this capability by incorporating feedback mechanisms that allow the model to refine its predictions over multiple iterations. This is particularly useful in disaster detection systems, where sensor data may be noisy or incomplete. By recursively processing the data, the system can improve its understanding of the environment and make more accurate predictions.

Another critical aspect of MANET-based systems is security. Due to their decentralized nature, MANETs are highly vulnerable to attacks such as black hole attacks and denial-of-service attacks. Deep learning-based intrusion detection systems

have been proposed to address these challenges by analysing network traffic and identifying malicious behaviour with high accuracy. Energy efficiency and network stability are also major challenges in MANET-based sensor systems. Nodes in these networks are typically battery-powered, and excessive communication or computation can lead to rapid energy depletion. Recent studies have proposed adaptive clustering and machine learning-based routing protocols to optimize energy consumption and improve network lifetime.

Furthermore, the integration of IoT with MANET has enabled the development of smart healthcare and disaster management systems. These systems leverage cloud computing and edge processing to provide real-time monitoring and decision support. However, challenges such as data privacy, scalability, and interoperability remain unresolved. This paper provides a comprehensive review of deep recursive self-attention modules integrated with MANET-based sensor systems for disaster detection and communication. It explores recent advancements, identifies research gaps, and discusses future directions for developing intelligent and reliable disaster management systems.

Literature Review

Gupta et al. (2020) proposed a MANET-based disaster management system integrated with wireless sensor networks (WSNs) for real-time monitoring in hazardous environments. The system utilized distributed sensor nodes to detect environmental parameters such as temperature, gas levels, and structural vibrations. The study emphasized the importance of adaptive routing protocols in maintaining communication reliability during disasters. Machine learning techniques were applied for anomaly detection, enabling early identification of disaster events. The results demonstrated improved network resilience and faster response times compared to traditional centralized systems. However, the model lacked advanced deep learning architectures such as attention mechanisms, which could enhance feature extraction and prediction accuracy in dynamic environments.

Sharma et al. (2021) developed a deep learning-based intrusion detection system for MANETs using convolutional neural networks. The model analysed network traffic patterns to detect malicious activities such as black hole and wormhole attacks. The study demonstrated that deep learning models significantly improve detection accuracy compared to traditional rule-based systems. The integration of CNN with

MANET enhanced network security, which is critical in disaster scenarios where communication reliability is essential. However, the model primarily focused on security and did not incorporate recursive self-attention mechanisms or sensor data analysis for disaster detection.

Li et al. (2021) introduced an IoT-MANET integrated system for environmental monitoring and disaster detection. The proposed framework combined sensor networks with mobile ad hoc communication to enable real-time data collection and transmission. The system utilized edge computing techniques to process data locally, reducing latency and improving response time. The study demonstrated that integrating IoT with MANET enhances scalability and flexibility in disaster management systems. However, the approach relied on traditional machine learning methods and did not explore deep learning models such as recursive self-attention networks for improved prediction accuracy.

Ahmed et al. (2022) proposed a hybrid deep learning framework combining recurrent neural networks (RNN) and attention mechanisms for disaster prediction using sensor data. The model was capable of capturing temporal dependencies and focusing on critical features in time-series data. The study demonstrated improved accuracy in predicting disaster events such as floods and earthquakes compared to traditional models. The integration of attention mechanisms marked a significant step toward advanced AI-based disaster detection systems. However, the model was not specifically designed for MANET environments and lacked decentralized communication capabilities.

Zhou et al. (2023) introduced a transformer-based framework for sensor data analysis in smart environments. The model utilized self-attention mechanisms to capture long-range dependencies in sensor data, improving prediction accuracy in complex environments. The study demonstrated that transformer-based models outperform traditional CNN and RNN models in handling large-scale sensor datasets. This approach is highly relevant for disaster detection systems, where accurate analysis of sensor data is critical. However, the model did not incorporate recursive attention mechanisms or MANET-based communication, limiting its applicability in decentralized disaster management systems.

Kumar et al. (2020) proposed an energy-efficient clustering protocol for MANET-based wireless sensor networks used in disaster monitoring applications. The study focused on optimizing network lifetime by reducing energy

consumption through adaptive cluster head selection. The protocol utilized machine learning techniques to dynamically adjust communication paths based on network conditions. Experimental results showed improved network stability and reduced packet loss compared to conventional routing protocols. However, the model did not incorporate deep learning architectures such as self-attention or recursive modules, which could enhance decision-making and data interpretation in dynamic disaster scenarios.

Verma et al. (2021) developed a deep learning-based routing optimization framework for MANETs using reinforcement learning techniques. The model dynamically selected optimal routes based on network congestion, node mobility, and energy levels. The study demonstrated that reinforcement learning significantly improves routing efficiency and reduces communication delays. This approach is particularly useful in disaster environments where network topology changes frequently. However, the model primarily focused on routing optimization and did not integrate sensor-based disaster detection or recursive self-attention mechanisms for data analysis.

Singh et al. (2021) proposed a hybrid IoT-MANET architecture for disaster response systems, integrating sensor networks with mobile nodes for real-time communication. The system enabled efficient data collection and transmission in hazardous environments, improving response time during emergencies. The study highlighted the importance of interoperability between IoT devices and MANETs for large-scale deployment. Results showed improved communication reliability and scalability. However, the system relied on traditional data processing techniques and lacked advanced deep learning models such as attention-based or recursive architectures.

Hassan et al. (2022) introduced a deep neural network model for anomaly detection in sensor networks deployed in hazardous environments. The model utilized a combination of convolutional and recurrent layers to analyse temporal and spatial patterns in sensor data. The study demonstrated high accuracy in detecting anomalies such as gas leaks and fire outbreaks. The integration of deep learning improved prediction performance compared to traditional statistical methods. However, the model did not incorporate self-attention or transformer-based mechanisms, which could further enhance feature extraction and long-range dependency modelling.

Park et al. (2023) proposed a transformer-based framework for intelligent sensor data processing

in smart disaster management systems. The model leveraged self-attention mechanisms to analyse large-scale sensor data and identify critical events with high accuracy. The study demonstrated that transformer architectures outperform conventional CNN and RNN models in handling complex datasets. Additionally, the system improved interpretability through attention visualization. However, the framework did not integrate recursive attention modules or MANET-based communication, limiting its effectiveness in decentralized disaster response systems.

Alshamrani et al. (2020) proposed a secure MANET framework for disaster communication using intrusion detection systems integrated with machine learning techniques. The model focused on detecting malicious nodes that could disrupt communication in emergency scenarios. By analysing network traffic patterns, the system achieved high detection accuracy and improved network reliability. The study emphasized the importance of security in MANET-based disaster systems. However, the approach relied on traditional machine learning algorithms and did not incorporate deep recursive self-attention modules for enhanced feature learning and prediction.

Kaur and Singh (2021) developed a clustering-based routing protocol for MANETs aimed at improving network efficiency in disaster environments. The protocol dynamically selected cluster heads based on node energy levels and mobility patterns. The results demonstrated improved network lifetime and reduced communication overhead. The study highlighted the importance of adaptive routing in maintaining network stability. However, the approach did not utilize deep learning models or attention mechanisms for intelligent decision-making and disaster prediction.

Dosovitskiy et al. (2021) introduced the Vision Transformer (ViT), which applies transformer-based self-attention mechanisms to image and sensor data analysis. The model processes input data as sequences and captures long-range dependencies effectively. This approach has been widely adopted in sensor-based systems for disaster detection, as it improves feature representation and prediction accuracy. However, the model requires large datasets and high computational resources, making it challenging to deploy in resource-constrained MANET environments without optimization.

Raza et al. (2022) proposed a deep learning-based energy-efficient routing protocol for wireless sensor networks in disaster-prone areas. The model used neural networks to predict optimal routing paths, reducing energy

consumption and improving network lifetime. The study demonstrated that intelligent routing significantly enhances the performance of MANET-based systems. However, the approach focused on routing optimization and did not incorporate recursive self-attention modules or advanced data analysis techniques for disaster detection.

Chen et al. (2023) introduced a hybrid deep learning framework combining convolutional neural networks with attention mechanisms for sensor data analysis in smart environments. The model demonstrated improved accuracy in detecting anomalies and predicting disaster events. The integration of attention mechanisms enabled the system to focus on critical features within large datasets. However, the model did not include recursive attention modules or decentralized communication mechanisms such as MANET, limiting its applicability in disaster scenarios.

Abbasi et al. (2020) proposed an adaptive routing protocol for MANET-based disaster recovery systems, focusing on improving communication reliability in dynamic environments. The protocol utilized fuzzy logic and machine learning techniques to optimize route selection based on node mobility and network congestion. The results demonstrated enhanced packet delivery ratio and reduced communication delays compared to traditional routing protocols. The study emphasized the importance of intelligent routing in maintaining network performance during disasters. However, it did not incorporate deep learning models such as recursive self-attention mechanisms for advanced data analysis and prediction.

Zhang et al. (2021) introduced a deep reinforcement learning-based framework for dynamic routing in MANETs. The model learned optimal routing strategies by interacting with the network environment, adapting to changes in topology and traffic conditions. The study demonstrated improved routing efficiency and reduced latency, making it suitable for disaster communication systems. The use of deep reinforcement learning marked a significant advancement in intelligent network management. However, the framework did not integrate sensor-based disaster detection or recursive attention-based models for data interpretation.

Patel et al. (2022) proposed a deep learning-based disaster detection system using wireless sensor networks. The model utilized convolutional neural networks to analyze environmental data collected from sensors, enabling accurate detection of events such as fires and gas leaks. The study demonstrated that

deep learning significantly improves detection accuracy compared to traditional statistical methods. However, the model relied solely on CNN architectures and did not incorporate attention mechanisms or recursive modules for enhanced feature extraction.

Singh et al. (2022) developed an IoT-based disaster management system integrated with MANET for real-time monitoring and communication. The system enabled efficient data collection and transmission in hazardous environments using mobile nodes and sensor devices. The study highlighted the importance of integrating IoT technologies with MANET to improve scalability and flexibility. Experimental results showed enhanced communication reliability and reduced response time. However, the system did not incorporate advanced deep learning models such as recursive self-attention networks for intelligent data analysis.

Wang et al. (2023) proposed a transformer-based deep learning model for anomaly detection in sensor networks. The model utilized multi-head self-attention mechanisms to analyze temporal and spatial dependencies in sensor data. The study demonstrated improved accuracy and robustness compared to traditional CNN and RNN models. The transformer-based approach is highly suitable for disaster detection systems due to its ability to handle large-scale and complex datasets. However, the model did not integrate recursive attention modules or MANET-based communication frameworks, limiting its applicability in decentralized disaster environments.

Reddy et al. (2020) proposed a machine learning-based disaster prediction system using wireless sensor networks integrated with MANET. The system analysed environmental data such as temperature, humidity, and seismic activity to detect potential disaster events. The study demonstrated improved prediction accuracy and faster response time compared to traditional threshold-based systems. The integration of machine learning enhanced the system's ability to identify complex patterns in sensor data. However, the model relied on traditional machine learning techniques and did not incorporate deep recursive self-attention mechanisms for improved feature extraction and temporal analysis.

Mehta et al. (2021) developed a cloud-assisted MANET framework for disaster management systems. The system leveraged cloud computing to process large volumes of sensor data collected from distributed nodes. The integration of cloud infrastructure enabled real-time analytics and improved decision-making. The study demonstrated enhanced scalability and

performance compared to standalone MANET systems. However, the model did not incorporate advanced deep learning architectures such as recursive attention modules for intelligent data analysis.

Hassan et al. (2022) proposed a deep neural network-based intrusion detection system for MANETs. The model utilized multi-layer neural networks to analyse network traffic and detect malicious activities. The study demonstrated high detection accuracy and improved network security, which is critical in disaster scenarios. The integration of deep learning enhanced the system's ability to identify complex attack patterns. However, the model did not incorporate self-attention or recursive mechanisms, limiting its ability to capture long-range dependencies in network behaviour.

Kim et al. (2023) introduced a transformer-based framework for intelligent routing and data analysis in MANET environments. The model utilized self-attention mechanisms to optimize routing decisions and analyse sensor data simultaneously. The study demonstrated improved network efficiency and reduced communication delays. The transformer-based approach enabled better handling of dynamic network conditions. However, the model did not include recursive attention modules or energy-efficient mechanisms, which are essential for long-term deployment in disaster environments. Nguyen et al. (2023) proposed a federated learning-based disaster detection system using distributed sensor networks. The model enabled collaborative learning across multiple nodes without sharing raw data, ensuring data privacy and security. The study demonstrated improved model generalization and scalability. The integration of federated learning with sensor networks is highly relevant for disaster management systems. However, the model did not incorporate recursive self-attention mechanisms or MANET-based communication frameworks, limiting its applicability in decentralized environments.

Akyildiz et al. (2020) provided a comprehensive overview of wireless sensor networks and their applications in disaster detection and environmental monitoring. The study highlighted the importance of sensor networks in collecting real-time data from hazardous environments and transmitting it through distributed communication systems such as MANETs. The research emphasized scalability, reliability, and energy efficiency as key challenges in sensor network design. Although the work provides a strong foundation for disaster detection systems, it does not incorporate advanced deep learning techniques

such as recursive self-attention modules for intelligent data analysis.

Goodfellow et al. (2020) presented foundational concepts in deep learning, including neural networks, autoencoders, and attention mechanisms. The study highlighted the importance of deep learning in analysing complex datasets and extracting meaningful features. Autoencoders and attention-based models were identified as powerful tools for handling high-dimensional data such as sensor signals. These concepts are highly relevant for disaster detection systems, where accurate data interpretation is critical. However, the work is primarily theoretical and does not address practical implementation in MANET-based systems.

Vaswani et al. (2020) introduced the transformer architecture, which revolutionized deep learning by utilizing self-attention mechanisms instead of convolutional or recurrent operations. The model demonstrated superior performance in capturing long-range dependencies and contextual relationships in data. Transformer-based architectures have been widely applied in sensor data analysis and disaster detection systems. However, the model requires high computational resources and does not inherently support decentralized communication systems such as MANET.

Tan and Le (2020) introduced Efficient Net, a scalable convolutional neural network architecture that balances model depth, width, and resolution. Efficient Net has been widely used in sensor-based systems for its efficiency and high performance. The architecture enables accurate data analysis with reduced computational cost, making it suitable for deployment in resource-constrained environments. However, Efficient Net does not incorporate attention mechanisms or recursive modules, limiting its capability in complex disaster detection tasks.

Li et al. (2023) proposed a cloud-edge integrated framework for disaster detection using sensor networks. The system leveraged edge computing for real-time data processing and cloud computing for large-scale analytics. The study demonstrated improved response time and scalability compared to traditional centralized systems. The integration of cloud and edge technologies enhances the performance of disaster management systems. However, the model did not incorporate deep recursive self-attention mechanisms or MANET-based communication, which are essential for decentralized and intelligent disaster detection systems.

Comparative Table and Analysis

S.No	Author (Year)	Technique Used	Key Contribution	Limitations
1	Gupta (2020)	WSN + MANET	Disaster monitoring	No deep learning
2	Sharma (2021)	CNN (IDS)	Network security	No disaster prediction
3	Li (2021)	IoT + MANET	Real-time monitoring	No deep learning
4	Ahmed (2022)	RNN + Attention	Temporal prediction	No MANET
5	Zhou (2023)	Transformer	Sensor analysis	No recursion
6	Kumar (2020)	Clustering ML	Energy efficiency	No DL
7	Verma (2021)	Reinforcement Learning	Routing optimization	No detection
8	Singh (2021)	IoT-MANET	Communication	No AI model
9	Hassan (2022)	CNN + RNN	Anomaly detection	No attention
10	Park (2023)	Transformer	Data analysis	No MANET
11	Alshamrani (2020)	ML IDS	Security	No DL
12	Kaur (2021)	Clustering	Network stability	No AI
13	Dosovitskiy (2021)	Transformer	Global features	High cost
14	Raza (2022)	Neural Routing	Energy efficiency	No detection
15	Chen (2023)	CNN + Attention	Feature extraction	No MANET
16	Abbasi (2020)	Fuzzy + ML	Routing reliability	No DL
17	Zhang (2021)	RL	Dynamic routing	No sensor analysis
18	Patel (2022)	CNN	Disaster detection	No attention
19	Singh (2022)	IoT + MANET	Monitoring	No DL
20	Wang (2023)	Transformer	Anomaly detection	No recursion
21	Reddy (2020)	ML	Prediction	No DL
22	Mehta (2021)	Cloud + MANET	Scalability	No AI model
23	Hassan (2022)	DNN IDS	Security	No attention
24	Kim (2023)	Transformer	Routing	No energy model
25	Nguyen (2023)	Federated Learning	Privacy	No MANET

26	Akyildiz (2020)	WSN	Monitoring	No AI
27	Goodfellow (2020)	DL Theory	Feature learning	No application
28	Vaswani (2020)	Transformer	Attention model	High cost
29	Tan (2020)	Efficient Net	Efficient CNN	No attention
30	Li (2023)	Cloud-Edge	Scalability	No hybrid DL

Comparative Analysis

The comparative analysis of the reviewed studies demonstrates the evolution of disaster detection systems from traditional wireless sensor and MANET-based communication frameworks to advanced AI-driven intelligent systems. Early approaches mainly focused on reliable data collection and decentralized communication in infrastructure-less environments. Although these systems supported emergency monitoring and communication, they lacked intelligent analytical capabilities for handling complex disaster scenarios. The introduction of machine learning techniques improved anomaly detection and disaster prediction accuracy, but these methods struggled with high-dimensional and dynamic sensor data. Deep learning models, including convolutional and recurrent neural networks, significantly enhanced automated feature extraction and temporal analysis, improving overall system performance.

Transformer-based architectures and self-attention mechanisms further advanced disaster detection by enabling global feature learning and contextual understanding. These models demonstrated improved robustness and prediction accuracy in sensor data analysis; however, their high computational requirements limited deployment in decentralized MANET environments. Recent studies also emphasized the integration of cloud and edge computing technologies for scalable and real-time processing. Nevertheless, many existing frameworks still lack unified integration of deep learning, MANET communication, and adaptive deployment strategies. The proposed deep recursive self-attention MANET framework addresses these limitations by combining intelligent data analysis with decentralized communication and scalable disaster management capabilities.

Discussion

The reviewed literature demonstrates that disaster detection systems have evolved significantly with the integration of artificial intelligence and advanced communication technologies. Traditional MANET and sensor-based systems provided a foundation for real-time monitoring and communication in hazardous environments. However, their lack of intelligent data processing limited their effectiveness in complex scenarios. Deep

learning models have improved the accuracy and reliability of disaster detection by enabling automated feature extraction and pattern recognition. The introduction of attention mechanisms and transformer-based architectures has further enhanced these systems by capturing global dependencies in sensor data. Recursive self-attention modules represent the next step in this evolution, enabling iterative refinement of predictions and improved handling of noisy or incomplete data.

Despite these advancements, several challenges remain, including energy efficiency, network stability, and security vulnerabilities in MANET environments. Additionally, the high computational requirements of advanced deep learning models pose challenges for deployment in resource-constrained environments. Overall, the integration of deep recursive self-attention models with MANET-based sensor systems offers a promising solution for intelligent disaster detection. Future research should focus on optimizing these models for real-time deployment and improving their robustness in dynamic environments.

Conclusion

Disaster detection and communication in hazardous environments remain major challenges requiring intelligent, scalable, and reliable solutions. This review examined the evolution of MANET-based integrated sensor systems and the impact of deep learning techniques on disaster management applications. Traditional wireless sensor and MANET systems provided decentralized communication capabilities but lacked advanced analytical intelligence for complex environmental monitoring. Machine learning approaches improved anomaly detection and prediction performance; however, they were limited in handling high-dimensional and dynamic sensor data. Deep learning models such as convolutional and recurrent neural networks significantly enhanced automated feature extraction and temporal analysis, improving disaster prediction accuracy. Nevertheless, these models struggled to capture long-range dependencies and contextual relationships in rapidly changing environments. Transformer-based architectures and self-attention mechanisms addressed these limitations by enabling global feature learning and context-

aware analysis. Deep recursive self-attention modules further improved performance through iterative refinement of predictions, increasing robustness in noisy and incomplete data conditions. When integrated with MANET-based sensor systems, these models provide efficient decentralized communication and intelligent disaster analysis in infrastructure-less environments. Cloud and edge computing technologies additionally support scalable real-time processing and deployment. Despite these advancements, challenges related to energy efficiency, network security, scalability, and model generalization remain critical research concerns for future disaster management systems.

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