Hindawi
International Journal of Distributed Sensor Networks
Volume 2024, Article ID 6656884, 27 pages
https://doi.org/10.1155/2024/6656884

Review Article

Survey of Connectivity Restoration in 3D Wireless Ad Hoc/Sensor Networks

Hongsheng Chen, Chunhui Wu, Mou Wu, Bin Xu, and Ping Fan

School of Computer Science and Technology, Hubei University of Science and Technology, Xianning 437100, China

Correspondence should be addressed to Hongsheng Chen; chenhs1981@163.com

Received 10 March 2023; Revised 18 March 2024; Accepted 22 March 2024; Published 9 April 2024

Academic Editor: Luca Reggiani

Wireless ad hoc/sensor networks (WASN) have seen increased application in three-dimensional (3D) environments, such as underwater and aerial scenarios. However, WASN may be fragmented or unable to connect continuously due to the harsh surrounding environment or high mobility. Therefore, restoring the network connectivity and transmit data in real time is very important. This paper focuses on the critical task of restoring network connectivity in 3D WASN, a complex issue given that existing connectivity restoration algorithms for two-dimensional environments are not directly applicable or become overly complicated in 3D contexts. We present a comprehensive analysis of the current research landscape, summarizing key findings related to various aspects of 3D WASN connectivity restoration. These aspects include the application environment (underwater, in the sky, and recovery disaster), opportunities for restoration (active, passive, and active/passive), implementation strategies (clustering and sleep scheduling), and resource constraints (node deployment and movement control). Our study also proposes a classification of connectivity restoration solutions for 3D WASN, identifying existing gaps and suggesting potential future research directions. By providing specific insights and a structured overview of the field, we aim to contribute to the ongoing development of robust and resilient 3D WASN.

1. Introduction

WASN have been applied more and more widely and have gradually extended from the original two-dimensional plane to three-dimensional space applications. Such as the emerging underwater wireless sensor networks (UWSNs) and airborne ad hoc networks (AANETs), which are typical applications in 3D environments. However, in the underwater environment, due to the limitation of the sensor's own resources and the influence of the harsh environment, the nodes are easily damaged, and the network is disrupted. The aircraft in the air environment can not be connected continuously because of its fast moving speed. Therefore, it is particularly important to restore network connectivity in time and transmit data effectively in real time when the network is disconnected. At the same time, in the case of large-scale damage to the whole network after experiencing large-scale disasters (such as earthquakes, typhoons, and floods), it is also very important to establish a fast communication ad hoc network using the remaining devices such as handheld devices (mobile phones and tablets) and aircraft (such as UAVs).

There are many traditional connectivity recovery methods in the two-dimensional plane. Previously, we reviewed the connectivity recovery algorithms in WSN in the two-dimensional plane [1], mainly including deploying nodes at appropriate locations to achieve network connectivity recovery and waking up mobile nodes to move to corresponding locations to achieve connectivity recovery. Generally, the number of relay nodes deployed and the distance of node movement are two important factors to consider in connectivity recovery. However, how to find the minimum relay nodes and move the shortest distance has been proven to be NP problems. Therefore, heuristic algorithms are widely used to solve it. However, heuristic algorithm designed for a 2D environment may not perform effectively in a 3D environment, and the algorithm will become more complex. Therefore, connectivity restoration in 3D WASN is still a challenging problem. Liu and Jin [2] summarized and analyzed the basic problems of the three-dimensional sensor network from the aspects of coverage, connectivity, extreme attribute, topology control, and deployment. Shah and Kim [3] reviewed several key issues such as network model, location technology, topology design, and routing protocol. Vihman et al. [4] have reviewed the fault-tolerant technology of underwater sensor networks. Dagdeviren et al. [5] reviewed the problem of k-connectivity in WSN and pointed the future research directions. In this paper, the author categorizes K-connected problems into three categories, namely, detection, deployment, and restoration, and provided a detailed overview and analysis. Dagdeviren and Akram [6] also discussed the Connectivity Estimation Approaches for Internet of Things-Enabled WSN. In this study, they categorize the studied algorithms into two divisions as 1-connectivity estimation algorithms and k-connectivity estimation algorithms. Within the scope of 1-connectivity estimation algorithms, they dissect the exact algorithms for bridge and cut vertex detection. They investigate various algorithmic ideas for k-connectivity estimation approaches by illustrating their operations on sample networks. They also discuss possible future studies related to the connectivity estimation problem in IoT. Temene et al. [7] proposed a comprehensive review and categorization of algorithms that incorporate mobility into WSNs. Given that WSNs can be seen as both a subset and a precursor to IoT, they argue that existing mobility solutions for WSNs can be adapted for IoT applications. They also conclude by discussing open issues and future research directions, including wireless power transfer, network fault detection, and real-world or testbed evaluation of algorithms. The article [8] reviews the application of artificial intelligence (AI) techniques to address coverage, deployment, and localization challenges in wireless sensor networks (WSNs). The paper provides a comprehensive analysis of recent studies (from 2010 to 2021) that have utilized various AI methods to enhance WSNs. It is aimed at guiding readers towards understanding the latest applications of AI methods in tackling different WSN challenges. Aiming to postdisaster communications, Matracia et al. [9] provide a comprehensive review of the state-of-the-art literature on postdisaster wireless communication networks, offering insights for future network establishment, particularly in the context of 6G. The paper covers topics such as channel modeling, coverage and capacity, radio resource management, localization, and energy efficiency. It also discusses integrated space-air-ground architectures, routing, delay-tolerant/software-defined networks, and edge computing.

However, as far as we know, few researchers have reviewed the connectivity restoration of WASN in 3D environments. Therefore, this paper reviews the recent literature on the connectivity restoration of WASN in 3D environments, especially underwater wireless sensor networks (UWSNs) and airborne ad hoc networks (AANETs). The aim of our research work is to provide a comprehensive review and analysis of the current methods and strategies used for restoring connectivity in 3D wireless ad hoc/sensor networks (WASN), understand the unique challenges and issues faced in maintaining and restoring connectivity in 3D WASN, especially in dynamic and harsh environments, and identify the gaps in current research and suggest potential future research directions. The ultimate goal is to contribute to the development of a more robust and resilient 3D WASN by providing a structured overview of the field and highlighting areas for further exploration and improvement.

The main contributions of this study are as follows:

(1) We analyze the latest literature on WASN from the application environment, opportunity, recovery implementation, and insufficient resources

(2) We summarize the recovery method, contribution, and limitation of the latest literature in UWSNs, AANETs, and disaster environment

(3) We summarize and point out some important open research issues and proposed some effective methodological guidance

The rest of this paper is organized as follows: In section 2, we summarize the existing solutions of connectivity restoration in three-dimensional WASN. Section 3 describes the connectivity restoration methods in different application environments, such as in UWSNs and AANETs. Section 4 describes the latest recovery method in a two-dimensional environment. Section 5 points the deficiency and future research direction. Finally, section 6 concludes the paper.

2. The Existing Solutions of Connectivity Restoration in 3D WASN

At present, there are many researches on connectivity restoration, but there are few researches on connectivity restoration in three-dimensional WASN. Some traditional restoration algorithms in the two-dimensional environment are not effective in the three-dimensional environment, so researchers continue to put forward some new restoration strategies. Of course, some scholars have improved the restoration algorithms in the two-dimensional environment and achieved good results. Overviewing the recent literature on connectivity recovery in 3D environments at home and abroad, the application scenarios of 3D wireless ad hoc/sensors mainly include underwater, aerial, and postdisaster recovery. Most of the connectivity recovery in underwater environments adopts active recovery strategies. Connectivity recovery is performed by moving and clustering of controlled nodes. In the sky environment, passive strategies are mainly used, because the sky is mainly composed of UAVs and other flight equipment, and many of them use mobile clustering for data transmission and connectivity recovery. In the postdisaster environment, most of them adopt passive strategies, mainly through the deployment of UAVs and other flight equipment or handheld devices and the remaining limited equipment for communication recovery. Some of the recovery algorithms in a three-dimensional environment use sleep scheduling and power adjustment to achieve connectivity recovery. At the same time, this paper also summarizes other 3D restoration-related methods and some recent restoration methods in 2D environment. Table 1 is

Table 1: Comparison of the use of various methods in various literature.

Literature	Application environment			Opportunity			Recovery implementation		Insufficient resources		Other conditions	
	Underwater	In the sky	Disaster recovery	Active	Passive	Active/passive	Cluster	Sleep scheduling	Controlled movement	Node deployment	3D other recovery-related methods	2D latest recovery method
[1]												√
[2]											√	
[3]											√	
[4]	√										√	
[10]	√			√					√	√		
[11]	√			√			√	√	√			
[12]	√			√			√		√			
[13]	√			√			√					
[14]	√			√			√	√	√			
[15]	√			√			√		√			
[16]	√			√			√		√			
[17]	√			√			√		√			
[18]	√			√			√		√			
[19]	√			√			√		√			
[20]		√			√		√					
[21]		√			√		√					
[22]		√			√		√					
[23]		√	√		√		√					
[24]		√	√		√							
[25]		√	√		√							
[26]		√										
[27]		√										
[28]			√			√			√			
[29]			√		√				√			
[30]			√	√								
[31]			√		√				√			
[32]			√		√			√	√			
[33]			√		√			√	√			
[34]											√	
[35]											√	
[36]											√	
[37]					√		√		√			√
[38]						√			√			√
[39]					√		√		√			√

Table 1: Continued.

Literature	Application environment			Opportunity			Recovery implementation		Insufficient resources		Other conditions	
	Underwater	In the sky	Disaster recovery	Active	Passive	Active/passive	Cluster	Sleep scheduling	Controlled movement	Node deployment	3D other recovery-related methods	2D latest recovery method
[40]						√	√		√			√
[41]					√		√	√		√		√
[42]												√
[43]												√
[44]				√			√					√
[45]				√								√
[46]				√			√		√			√
[5]						√			√			
[6]						√			√			
[7]											√	
[47]		√									√	
[48]				√								√
[49]					√		√	√				√
[50]	√			√				√		√		
[51]											√	
[52]				√			√		√			√
[8]												√
[53]	√			√				√	√			
[54]		√			√					√		
[9]			√									
[55]		√			√					√		
[56]					√			√	√			√
[57]				√								√
[58]	√			√						√		
[59]		√			√		√		√			
[60]					√					√		√
[61]				√					√			√
[62]					√			√				√
[63]											√	

summarized according to some methods mentioned in the current literature for comparison.

3. Connectivity Recovery Methods in Different Application Environments

3.1. Connectivity Recovery in UWSNs. At present, UWSNs are more and more widely used, including marine graphic data collection, scientific marine sampling, pollution and environmental monitoring, border patrol, searching and destroying objects, observing different networks, acting as relays for ad hoc networks, marine climate records, marine commercial operations, oil exploration, disaster prevention, auxiliary navigation, and weather management. From the perspective of research, these applications can be roughly divided into three categories, namely, scientific applications, industrial applications, and national defense applications.

As shown in Figure 1 [4], UWSNs are composed of different types of static and mobile sensor nodes, which jointly perform monitoring tasks in 3D space. In UWSNs, sensor nodes communicate with each other through unique acoustic signals, so they will encounter large propagation delay, high error rate, and multipath effect. At the same time, sensor nodes deployed underwater are prone to failure. On the one hand, due to limited energy, some nodes will die due to energy depletion. On the other hand, due to the harsh underwater environment, some harmful objects, such as jellyfish, sharks, angry fish, big stone heads, unpredictable weather, and similar marine objects, may lead to node failure. Therefore, the connectivity of the network is restored, and real time and effective data transmission is particularly important. Among them, the authors in [10–19, 50, 53, 58] have all done relevant research on the connectivity recovery of underwater wireless sensor networks, adopting the recovery method of active clustering, and achieved good results. Table 2 summarizes the recovery method, contribution, and limitation of some literature in UWSNs.

Due to the harsh underwater environment, the authors in [10–19, 50, 53, 58] adopt the active recovery strategy of fault detection or vulnerability detection and then fault recovery. The article [10] proposes an underwater event coverage vulnerability (UECH) repair algorithm based on multiautonomous underwater vehicles (multi-AUVs) in multiconstraint 3D underwater wireless sensor networks. This paper realizes the underwater event coverage vulnerability algorithm for the first time and realizes the multiconstraint problem of underwater event coverage (including spatial constraints and resource constraints). At the same time, it designs an algorithm to use multiautonomous underwater vehicles to realize event coverage vulnerability recovery (MECHR). This algorithm symmetrically completes subtasks through information exchange and interaction with other agents. Different from existing repair strategies, MECHR algorithm can effectively repair a large number of UECHs caused by changes in underwater monitoring scenarios and requirements. MECHR algorithm can adapt to a wide range of harsh scenes and multiconstrained 3D underwater environment.

The article [11] also proposes a coverage vulnerability repair algorithm based on clustering and sleep scheduling in underwater wireless sensor networks. This algorithm uses a cubic unit cell model and defines fault nodes, coverage vulnerabilities, coverage matrices, key locations, and supplementary nodes, as shown in Figure 2. The coverage matrix and vulnerability edge nodes are used to determine whether the coverage vulnerabilities need to be recovered. If there are vulnerabilities that need to be recovered, redundant nodes that can work normally are identified first, their priorities are set, and nodes are awakened in order of priority until the vulnerabilities are recovered. If the repair is not completed, find a suitable redundant node in the vertical direction of the partition unit to wake up and move to the corresponding position to complete the repair. This algorithm is more efficient and effective than other similar algorithms in terms of network coverage, number of wake-up nodes, and average utilization of wake-up nodes.

The article [14] proposes a clustered multiautonomous underwater vehicle (multi-AUVs) vulnerability prediction and repair method (RevoHPR) in UWSNs. This algorithm is a global solution, which combines clustering method and multiple autonomous underwater vehicles. First, stable cluster heads are selected through entropy-based qualification ranking to form the same cluster. Then, the dynamic Kalman filter method is used to determine whether the node is sleeping or active according to the current state of the node, so as to achieve sleep scheduling. Finally, the vulnerabilities are detected and repaired by the double criteria mayfly optimization algorithm (BICMO). The specific algorithm model is shown in Figure 3. Compared with similar algorithms in terms of average energy consumption, delay, packet delivery rate, and throughput rate, this algorithm better avoids and alleviates the generation of vulnerabilities. However, this algorithm does not consider the security of data transmission, especially how to ensure low energy consumption and high quality of service under various attacks.

The above two methods are combined with cluster and sleep scheduling to achieve vulnerability detection and recovery of underwater sensor networks. The authors in [12] proposed a cat group optimization-based autonomous recovery (CSO) for heterogeneous underwater wireless sensor networks. This algorithm makes a prediction before network segmentation and moves the node closest to the key node (AP) to the AP location in advance to avoid network segmentation. First, use the depth-first algorithm (DFS) to detect the key nodes, and then, use the cat optimization algorithm to restore network connectivity, The specific recovery algorithm is shown in Figure 4. In Figure 4, AMS represents aerial mobile sink nodes, and CH represents the static cluster head nodes. If any AP is predicted, it updates this information to the CH. CH in turn informs all the cat nodes of the region of the predicted AP. Each cat then evaluates its fitness function, while still in seeking mode. The fitness function is a minimization function. The cat which is having minimum distance from the AP is considered the best cat. The best cat then changes its mode to tracing mode. It then moves towards the AP in order to avoid the network from getting disconnected. As shown in Figure 4, C1 and C2

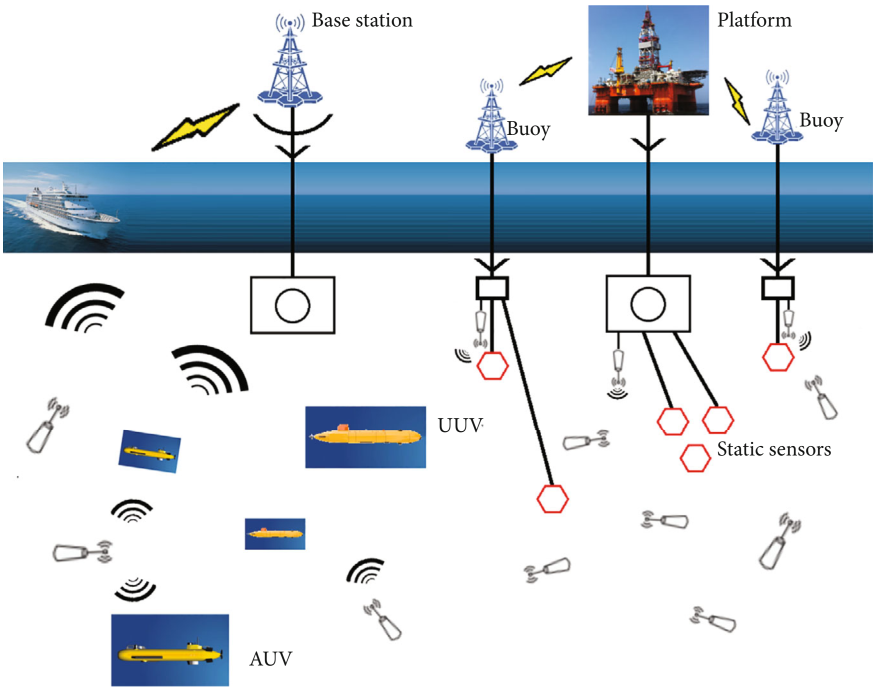


Figure 1: Underwater wireless sensor network.

are the AP. This algorithm improves the network performance in terms of delay and threshold, thus obtaining higher reliability.

The article [15] proposed a strategy for energy-saving fault detection and recovery management (EFRM) in underwater wireless sensor networks. This strategy proposed a hidden Poisson Markov model and applied it to node fault detection and recovery algorithm. This method uses forwarding algorithm for each node through Poisson's distribution to identify damaged regions, which provides accurate region-based fault detection for the network. Once the damaged node is identified, the analytical network process model is used to select the best recovery node in the damaged area, and this selection can be performed based on multiple parameters. At the same time, this optimal selection also reduces the network recovery time. Experiments show that the algorithm has high detection accuracy, and even when the failure probability is 40%, the detection accuracy of the proposed EFRM exceeds 99%. However, this strategy does not address the error control mechanism during packet transmission.

The article [16] also proposed a fault prediction, detection, and recovery algorithm based on tree network topology using the Markov chain Monte Carlo (MCMC) process. The algorithm uses the error pattern of the delayed message to identify the failed node, and the threshold limit is based on the time probability distribution function. In the process of fault detection, threshold limit and residual energy are used to detect the fault sensor nodes. In the recovery algorithm, the faulty sensor node is replaced by the nearest neighboring sensor node with high energy remaining. Theoretical analysis and experimental simulation results show that this algorithm has achieved good results in coverage, fault prediction, network life, recovery strategy, and other performance indicators, thus greatly improving the coverage and connectivity of underwater wireless sensor networks. As shown in Figure 5, which is a tree-based network topology, the data is transmitted to the base station through the CH nodes. If any of the nodes are found to be fault state or failure state, the failure nodes will be identified with the help of failure prediction algorithm and then recovered with the nearest neighbor node which has the highest energy power consumption to replace it, such as the red nodes in Figure 5 are the faulty nodes.

The articles [18, 19] are cluster-based recovery algorithms, and both of use cluster head and candidate cluster head methods for recovery. The article [18] proposed a new fault detection and recovery technology (FDRT) for underwater wireless sensor networks based on clusters. It mainly uses fuzzy logic technology to select backup cluster heads (BCH) based on node density, residual energy, load, distance, link quality, and other parameters when selecting cluster heads (CH). Then, detect the failures of CH, BCH, and cluster members (CM). If a fault is detected under the CH, the BCH will start to execute the failed CH task. Meanwhile, when BCH fails, any other CM will be selected as BCH. If any CM is not executed, CH will detect a communication failure and request BCH to convert data from the failed CM to CH, as shown in Figure 6. By comparing the end-to-end delay, energy consumption, and data transmission success rate based on data packets with other existing algorithms, the simulation results show that FDRT algorithm reduces the data transmission delay and energy consumption, improves the data transmission success rate, and thus extends the network life.

The article [19] also proposed a new method to better restore cluster head nodes in underwater sensor networks. This paper also adopted the method of primary cluster head

Table 2: Summarization of the recovery method, contribution, and limitation of some literature in UWSNs.

Literature	Recovery method	Contribution	Limitation
[10]	Active fault detection, multi-AUV recovery	The proposed algorithm MECHR can adapt to a wide range of harsh scenes and multiconstrained 3D underwater environment.	Not applicable for large-scale damaged networks.
[11]	Active fault detection, node movement recovery based on clustering and sleep scheduling	The failure node, coverage vulnerability, coverage matrix, key position, and supplementary node are all considered in the proposed algorithm.	It requires the deployment of a large number of nodes in advance, leading to resource wastage.
[12]	Active fault detection, node movement recovery based on cat group optimization	The proposed algorithm CSO can predict a possible articulation point in the network, and it can search both locally and globally.	This method is only suitable for data collection and does not ensure permanent network connectivity.
[13]	Active fault detection reduces the destruction of sensors modifying the routing path	The proposed algorithm can prevent the unwanted loss of the data and decrease the damage of sensors.	This method does not detect vulnerabilities and connectivity restoration but only reduces the destruction of sensors by changing the route.
[14]	Active fault detection, multi-AUV recovery based on clustering and sleep scheduling	The proposed ReVOHPR algorithm can minimize the energy consumption and void hole avoidance.	This algorithm does not consider the security of data transmission, especially how to ensure low energy consumption and high quality of service under various attacks.
[15]	Active fault detection, node movement recovery based on clustering using hidden Poisson Markov model	The proposed HPM model provides an accurate region-based fault detection in the network, and the ANNP model for optimal node selection reduces the recovery time of the network.	This strategy does not address the error control mechanism during packet transmission.
[16]	Active fault detection, node movement recovery based on clustering using the Markov chain Monte Carlo process	The proposed 3D UWSN mechanism enhances coverage, connectivity, reliability, and network lifetime through static and mobile sensor deployment.	Not applicable for large-scale damaged networks.
[17]	Using node sinking for recovery based on the three-dimensional sphere packaging mode	The algorithm demonstrates superior coverage, network connectivity, and reduced time complexity compared to exhaustive search and peer-to-peer algorithms.	It requires the deployment of many nodes in advance, leading to resource wastage.
[18, 19]	Active fault detection, node movement recovery based on clustering using cluster head and candidate cluster head methods	Their algorithms all reduce the energy consumption and extend the network life.	The two algorithms are recovery responses to the failure of a single node.
[53]	Active fault detection, node movement recovery based on group nodes using multiobjective emperor penguin optimization	The DHD-MEPO algorithm utilizes group nodes for information management and uses a multiobjective optimization method for selecting repair node.	This method is not considered in real scenarios, and the sensing range of the sensor node is also affected by environmental changes and multiple obstacle obstructions, as well as the fact that its sensing range is variable over time in complex scenarios.
[58]	AUV deployment using an improved nondominated sorting genetic algorithm-II	This paper utilizes an NSGA-II metaheuristic approach with multipoint crossover and adaptive mutation for AUV deployment to achieve k-coverage and m-connectivity in UWSNs.	This method is not suitable for heterogeneous underwater cognitive sensor network where AUVs do not also have various sensing and communication capabilities.

(CH) and standby cluster head (BCH) and realized this through two main programs, namely, detection failure and recovery program. First is to detect any fault in the network and then report this information to the relevant nodes to start recovery. The recovery process determines who and when to trigger the recovery function according to the cause of the failure of the CH node. The failure cause may be the energy depletion of the CH battery or software/hardware failure. The specific algorithm process is shown in Figure 7. However, the above two algorithms are recovery responses

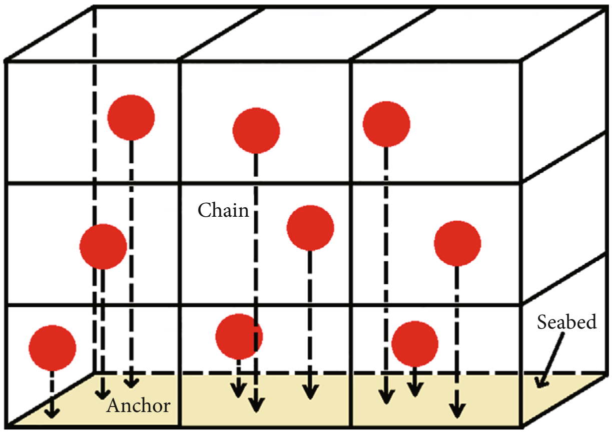


Figure 2: Schematic diagram of node layout.

to the failure of a single node. When multiple nodes fail at the same time, how to make a quick response and ensure the success rate of data transmission is very important.

The article [13] proposed an anomaly detection method for underwater sensor networks. This algorithm mainly represents the routing protocol by using the detection algorithm and modifying the routing path in the underwater wireless sensor networks, so as to reduce the number of damaged sensors. It mainly includes two steps: first, in the anomaly detection process, the transmission path (route) is recovered when harmful objects are detected; the second is routing protocol processing, which uses RIP protocol to change routing. Experiments show that this algorithm can greatly reduce the number of destroyed sensors. However, this method does not detect vulnerabilities and connectivity restoration but only reduces the destruction of sensors by changing the route.

The article [17] proposed a node-sinking algorithm for 3D coverage and connectivity of underwater sensor networks. This algorithm includes three stages: first, based on the three-dimensional sphere packaging mode, select the first batch of sinking nodes on the surface to sink to the ideal placement location, which uses the minimum cost perfect matching of weighted complete bipartite graph to minimize the total deviation distance. Then, the connectivity of the sink node is checked. If it is not connected, the proposed two algorithms are used to restore network connectivity. Finally, the remaining surface nodes (if any) are further sunk to repair the coverage vulnerability of those nodes that have sunk, while ensuring the connectivity of the network. The algorithm demonstrates superior coverage, network connectivity, and reduced time complexity compared to exhaustive search and peer-to-peer algorithms.

The article [50] proposed a priority-based coverage hole restoration and m-connection approach using a whale optimization scheme. This scheme is aimed at restoring coverage holes and extract relevant information for the construction of undersea oilfield reservoirs, minerals, and mines. The proposed scheme identifies k-coverage holes and directs autonomous underwater vehicles (AUVs) to place additional mobile nodes in the appropriate coverage holes. A novel multiobjective function is formulated to determine the optimal path for AUVs. Additionally, the scheme checks node connectivity while restoring coverage holes and coordinates sleep scheduling among neighboring nodes to maintain energy efficiency. Performance evaluation shows that the proposed scheme outperforms existing schemes under various network scenarios, providing maximum coverage and connectivity, reduced energy consumption, and a high convergence rate.

The article [53] presents a novel distributed hole detection and multiobjective optimization emperor penguin repair algorithm (DHD-MEPO) to address the issue of coverage holes in three-dimensional hybrid wireless sensor networks. In the detection phase of DHD-MEPO, the monitoring region is divided into units based on the number of nodes and the sensing range. Static nodes use the sum-of-weight method to campaign for group nodes on their terms, and coverage holes are located by calculating the coverage of each cell. In the repair phase, the set of repair nodes is determined by calculating the mobile node coverage redundancy. Regions with high hole levels are prioritized, and the residual energy homogeneity of nodes is considered when designing multiobjective functions. A lens-imaging mapping learning strategy is introduced to perturb the location of repair nodes for the optimization of the emperor penguin algorithm. However, in real scenarios, the sensing range of the sensor node is also affected by environmental changes and multiple obstacle obstructions, as well as the fact that its sensing range is variable over time in complex scenarios.

The authors in [58] proposed a coverage and connectivity aware deployment scheme for optimal placement of autonomous underwater vehicles (AUVs) within underwater wireless sensor networks (UWSNs). The authors propose a scheme using an improved nondominated sorting genetic algorithm-II-based metaheuristic technique with a novel fitness function. This function includes three parameters: coverage quality, connected cost, and network lifetime. The proposed scheme also applies an effective encoding scheme for population representation and devises a novel fitness function for improving the quantity and location of the AUVs. Simulation results confirm that the proposed approach improves the network's coverage. However, this method is not suitable for heterogeneous underwater cognitive sensor network where AUVs do not also have various sensing and communication capabilities.

The above contributions review the connectivity restoration in UWSNs. Almost all literature adopt active clustering and mobility to restore and have two processes: fault detection and connectivity recovery. Some literature combine sleep scheduling and power adjustment to achieve network connectivity. There are few ways to recover by deploying new nodes, because it is difficult to redeploy new nodes in the underwater environment. Most of them adopt the method of underwater vehicle movement to collect data and restore network connectivity.

3.2. Connectivity Recovery in AANETs.

AANETs are decentralized multihop wireless ad hoc networks comprising highly mobile aircraft nodes linked via remote data

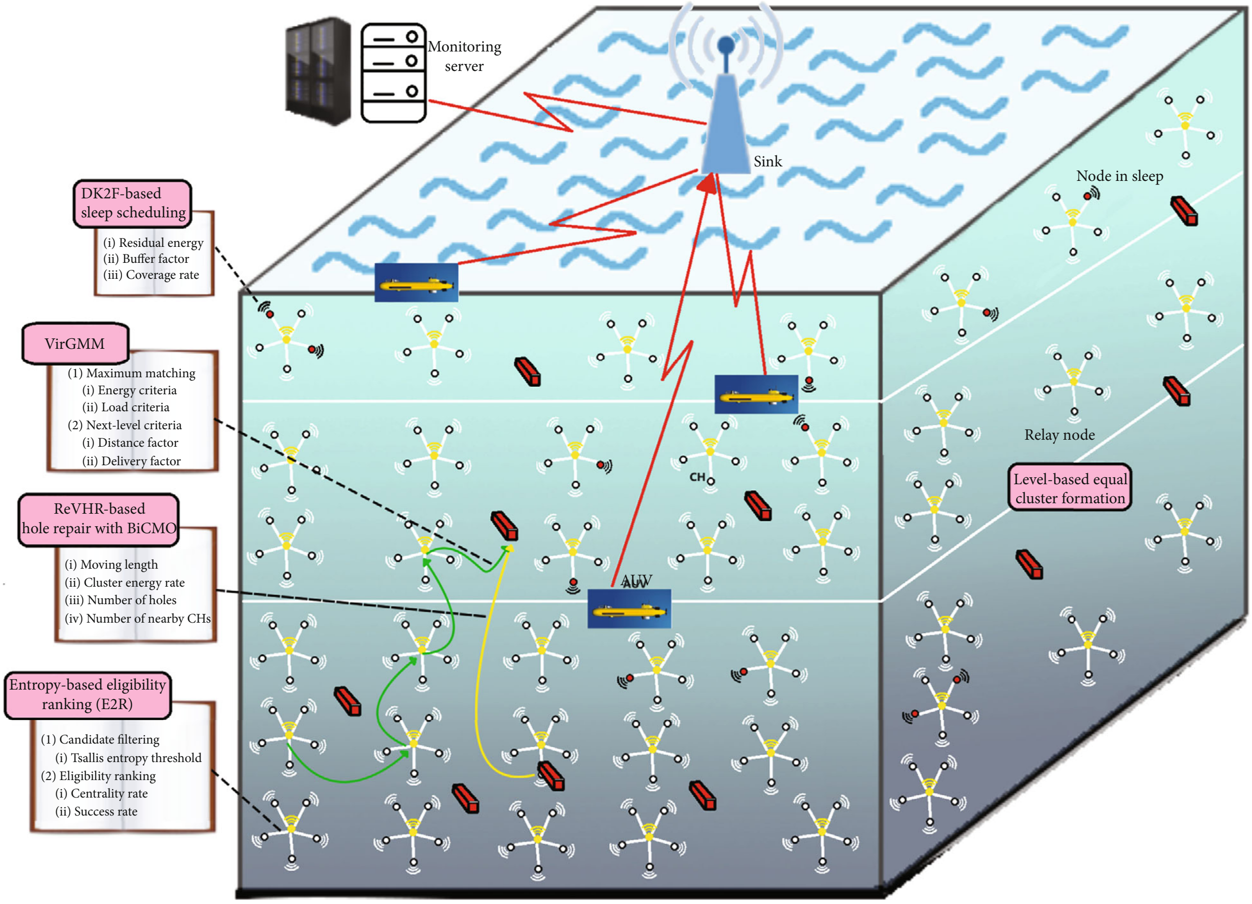


FIGURE 3: RevoHPR algorithm model.

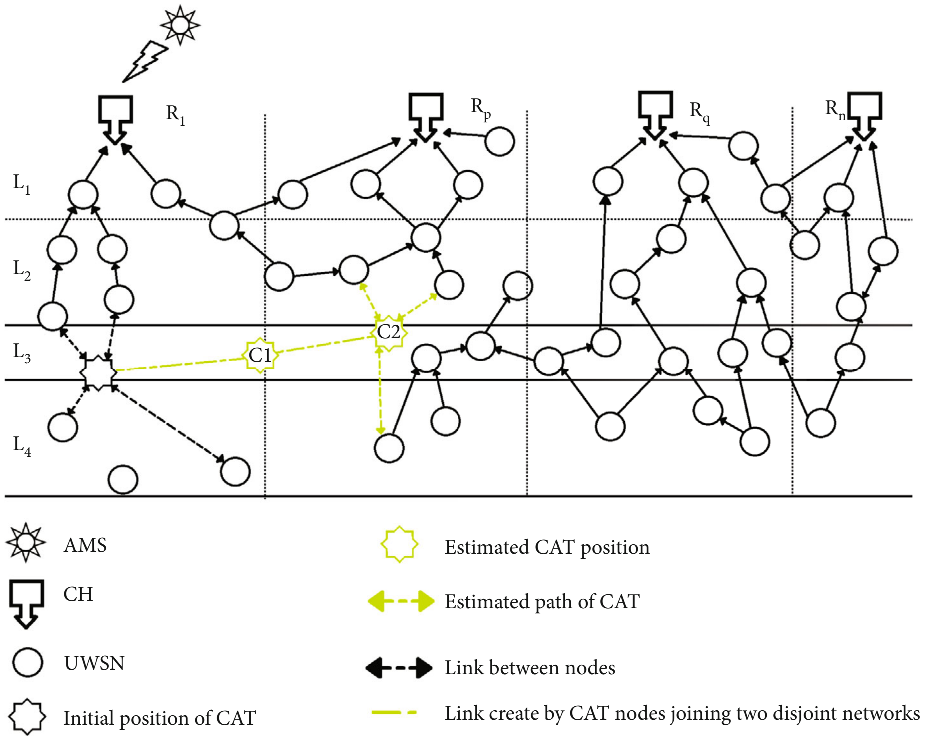


FIGURE 4: CSO algorithm diagram.

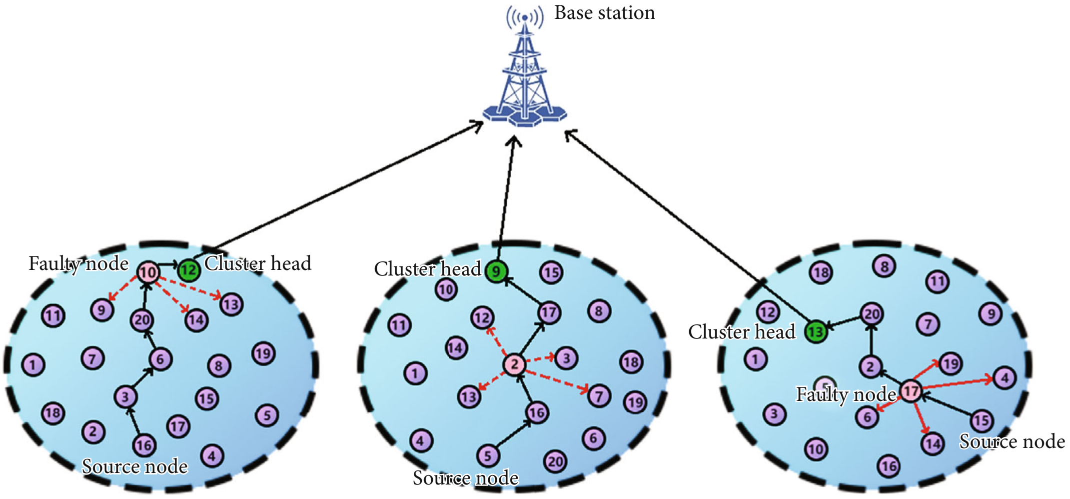
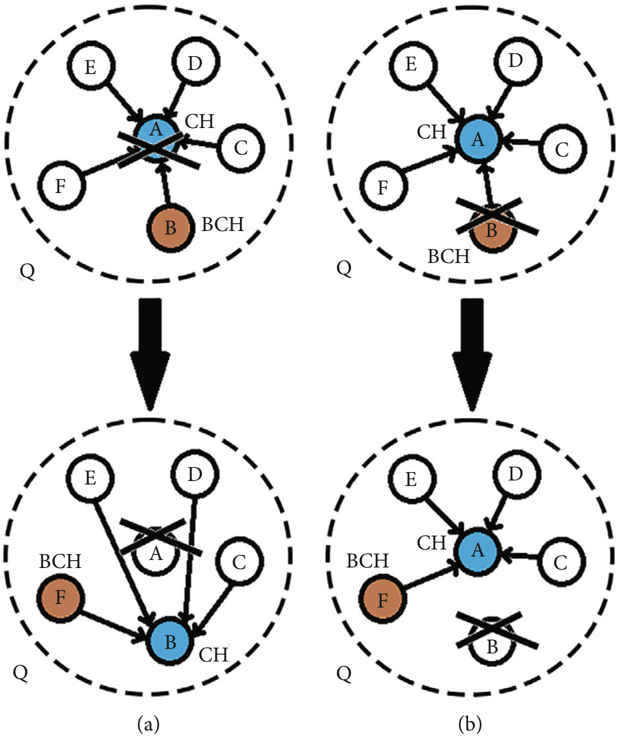


FIGURE 5: Algorithm diagram.



(a)

(b)

FIGURE 6: (a) In cluster Q, when CH_A gets failed, then BCH_B will take its place until the failure is rectified. (b) In cluster Q, when BCH_B gets failed, then another CM_F will take its place until the failure is rectified.

connections. They offer the potential to significantly decrease reliance on ground infrastructure and costly satellites. AANETs represent a novel form of ad hoc network, encompassing aircraft, UAVs, and fighters, and are distinguished by their self-organized communication and potential applications in civil, commercial, and scientific domains. They also serve a crucial role in aeronautical communication, navigation, and surveillance and are particularly valuable for enterprises, private Internet users, and government institutions, including military applications. Furthermore, AANETs can be integrated with underwater wireless sensor networks and disaster recovery efforts [3], as depicted in Figure 8.

However, due to AANETs, nodes operate in a highly dynamic environment, and the topology changes every second; thus, it is particularly important to effectively transmit the data in real time. Among them, [20–26, 47, 54, 55, 59] have studied connectivity recovery under AANETs to ensure real time and effective data transmission. Most of them use

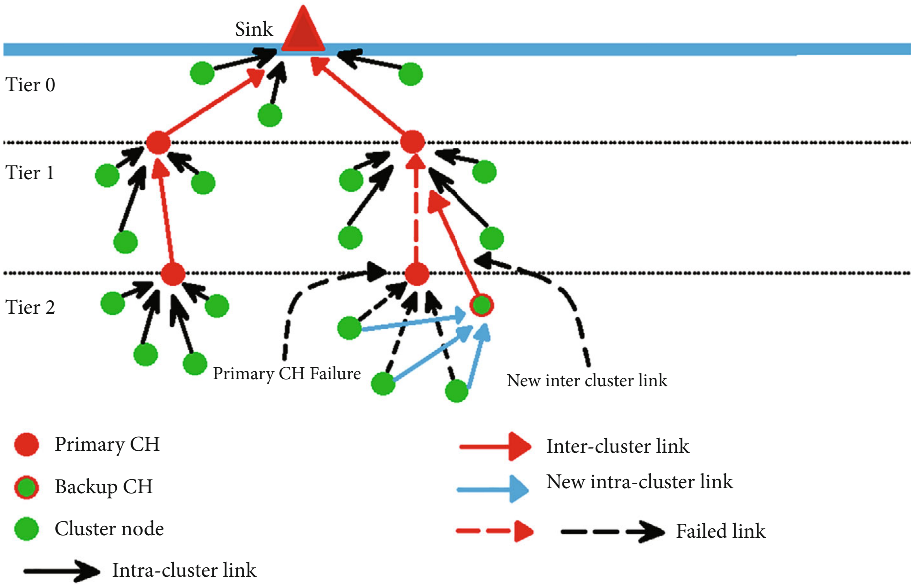


Figure 7: Algorithm diagram.

passive clustering to achieve real time and effective data transmission. Table 3 summarizes the recovery method, contribution, and limitation of some literature in AANETs.

Bacanli et al. and Bacanli and Turgut proposed the deployment method of charging station and UAV scanning method in the UAV opportunity network environment, respectively, in [20, 22]. The authors in [20] defined the UAV application scenario in the opportunity network and simulated it using real-world data sets (including human mobility traces from North Carolina State University). In view of this definition scenario, an unmanned charging station solution based on spiral scanning technology is proposed. The proposed direct routing strategy between UAV and ground nodes minimizes information exchange and does not need to exchange location information and encounter history, thus creating a more lightweight communication architecture. At the same time, this strategy can also add additional UAVs without changing the data processing framework. The experimental results show that the K-means algorithm with three clusters is superior to the other two methods in terms of success rate and message delay.

Bacanli and Turgut [22] proposed an energy-saving UAV scanning method of node clustering in the opportunity network. This method is based on the state campus routing (SCR), with density-based noise application spatial clustering (DBSCAN), which is a meander, random, and random spiral scanning method, and simulated on two actual data sets (the real data sets of nodes moving around Orlando and the Korean Academy of Science and Technology (KAIST)), as shown in Figure 9. Figure 9 shows the SCR with DBSCAN clustering approach with framing.

The UAV sets the maximum and minimum points based on n_1 and n_3 after scanning the entire map. Subsequently, it performs a spiral scan around the n_2 node, with the spiral's radius being half of the maximum distance between the two points in the cluster. Upon completion of the spiral scan, all points in the cluster are revisited, provided that their positions remain within the same cluster group. The proposed method achieves good results in terms of message delay and success rate through the state-based campus routing control node. Similarly, the UAV does not need any excessive information exchange between nodes, because the UAV has location tracking information such as GPS, and the minimum information use makes this method reduce communication overhead and make the system more suitable for large-scale networks. However, the above two methods have fewer nodes and do not consider the impact on message delay and success rate when UAV speed increases or decreases.

Poudel and Moh proposed the unequal size clustering method of unmanned aerial vehicle-assisted wireless sensor networks and the hybrid path planning method for efficient data collection for emergency applications in [21, 23], respectively. The authors in [21] propose a clustering algorithm with unequal size for unmanned aerial vehicle-assisted sensor to UAV communication. The cluster size is determined according to the residual energy of sensor nodes. This algorithm is superior to traditional methods in terms of network life and data transmission rate. The authors in [23] proposed a hybrid path planning (HPP) algorithm for efficient data collection to ensure the shortest anticollision path for UAVs in emergency environments. The shortest path map and optimized artificial ant colony (ABC) algorithm are designed through probabilistic route map (PRM) algorithm to improve different path constraints in three-dimensional environments. This algorithm has the following advantages:

(1) The UAV uses directional antennas, including two wireless receivers that operate simultaneously, to ensure that the UAV can communicate with cluster heads in a timely and low-power manner

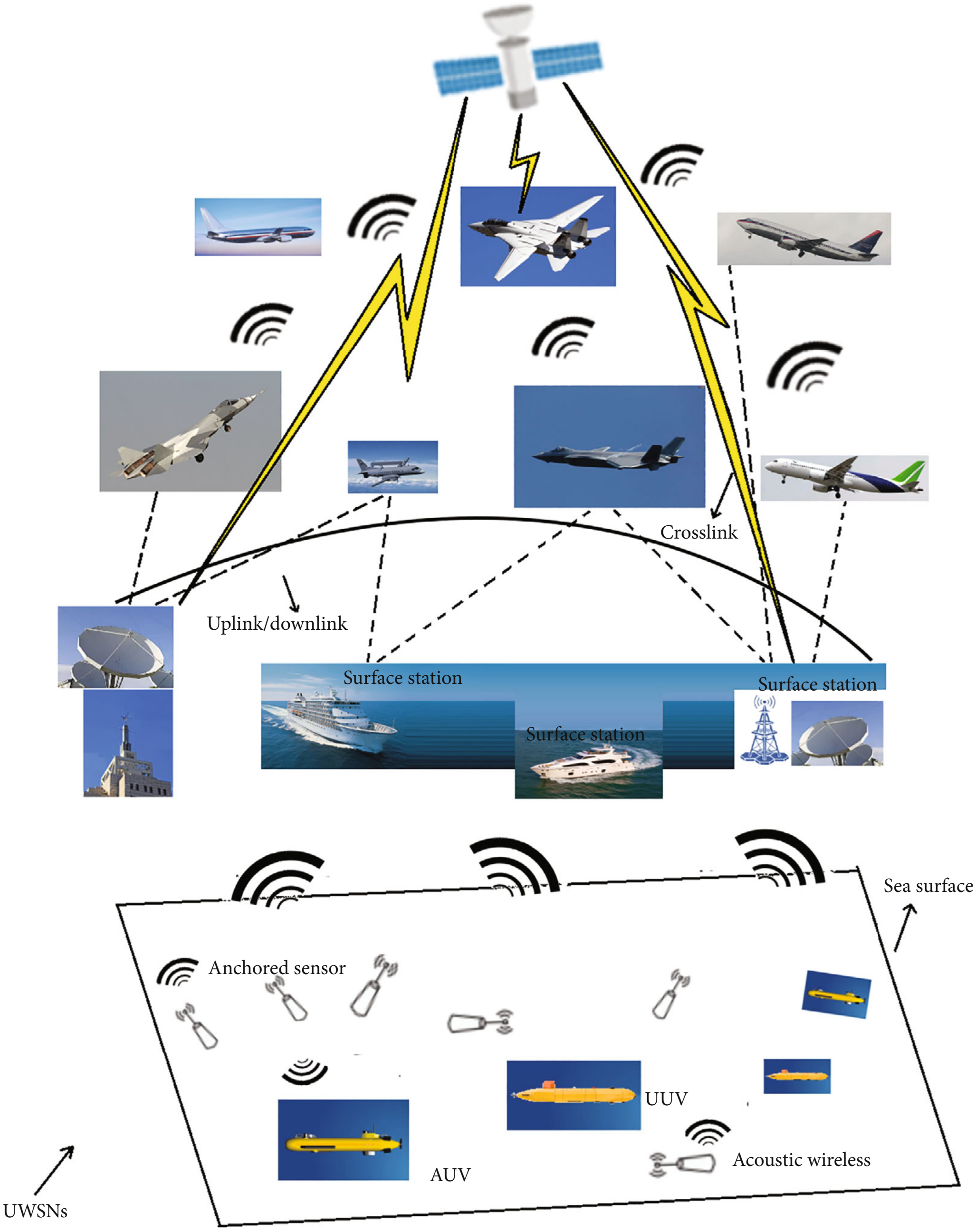


Figure 8: Schematic diagram of AANETs combined with UWSN cooperative communication.

(2) The model uses energy-saving clustering technology, which reduces the delay and energy consumption

(3) The proposed hybrid path planning algorithm can dynamically find the location coordinates when there are some threats or obstacles in the flight process

(4) The proposed HPP algorithm enhances the cluster head wake-up schedule in the target WSN through UAV path planning to minimize the energy consumption of the cluster head and ensure that the ground sensors collect data fairly and efficiently

Shortcoming:

(1) The experiments in different size, speed, and dynamic obstacle scenes are not considered

(2) How to ensure accurate synchronization of sleep and wake-up with UAV arrival time in practice

The article [47] proposed the use of a bioinspired ant colony optimization (ACO) algorithm, “Ant-Hocnet,” enhanced with optimized fuzzy logic, to improve routing in FANETs. Fuzzy logic is employed to analyze wireless link status

Table 3: Summarization of the recovery method, contribution, and limitation of some literature in AANETs.

Literature	Recovery method	Contribution	Limitation
[23]	Data collection by hybrid path planning using probabilistic roadmap and artificial bee colony algorithm	The proposed UAV system employs directional antennas, energy-saving clustering, and a hybrid path-planning algorithm to optimize communication, energy efficiency, and obstacle avoidance in UAV-aided WSNs.	The experiments in different size, speed, and dynamic obstacle scenes are not considered. How to ensure accurate synchronization of sleep and wake-up with UAV arrival time in practice is not considered.
[24]	Restore emergency communication using a new routing protocol, connectivity modules for UAVs, and a tested navigation system.	The proposed emergency communication system, comprising three subsystems, was evaluated using simulation and real flight data, demonstrating its practicality and effectiveness in postdisaster scenarios.	The inadequacy of this research is that only one helicopter is used for simulation. Therefore, how to use a group of autonomous helicopters to conduct field tests to verify the success of the proposed communication system in many performance parameters, including jitter, throughput, availability, range, and packet loss, is a certain challenge.
[25]	Recover the communication link in a natural disaster in multi environments.	The work utilizing UAV-IoFT communications to provide alternative coverage services through UAV deployment, considering dual-slope propagation models and user device distance for improved connectivity and energy efficiency in postdisaster scenarios.	The ray signals between the UAV and the ground user device by the diffracted or reflected represent indirect links due to obstacles' interaction.

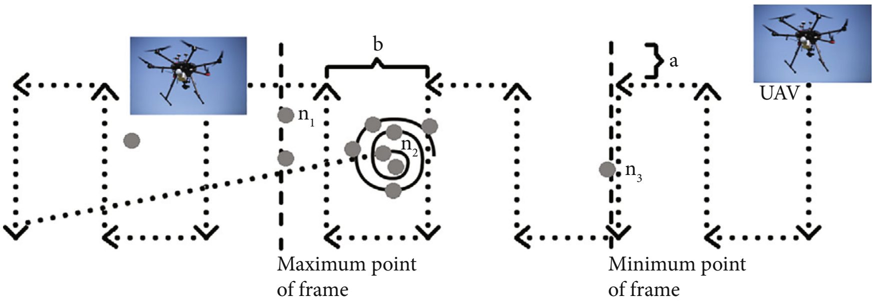


Figure 9: DBSCAN algorithm diagram.

information, such as available bandwidth, node mobility, and link quality, and to determine the optimal wireless links without the need for a mathematical model. This design was implemented in the MATLAB simulator for evaluation and comparison. The results indicate that this approach improves throughput and reduces end-to-end delays, thereby enhancing the reliability and efficiency of FANETs.

The article [54] addresses the issue of reconnecting disconnected sensor networks by deploying unmanned aerial vehicles (UAVs) as relay nodes. Unlike previous works that treat disconnected nodes as independent data sources, this paper proposes a cooperative approach where sensors form subnets to facilitate data transmission. The problem is formulated to maximize the number of nodes that can find a route to the sink, given a limited number of relay UAVs. The paper proves that the problem is NP-hard and proposes a two-step heuristic algorithm for the relay placement problem. The algorithm's polynomial runtime and approximation ratio are analyzed.

The article [59] proposed three types of UAV swarm modes and designs of UAV swarm-assisted connectivity enhancement algorithms (UsCE). A UAV swarm, with its high degree of freedom and flexibility, offers a new solution to the connectivity problem in IoT. The goal is to find an optimal solution that minimizes the number of UAVs in the swarm and maximizes the connection time of MISN. The paper divides the working modes of a UAV swarm into hovering and flying. First, ground sink nodes are classified by a MISN's sink node classification algorithm to generate hovering points for the UAV swarm. Then, the results are optimized and adjusted by a minimum UAV swarm hovering connection algorithm to obtain an optimal solution under the hovering mode. Finally, optimal connectivity is achieved when the UAV swarm works in flying mode through the UAV swarm flight connectivity algorithm. Simulation results show that the proposed algorithms have low complexity, significantly increase the connection time of MISN, and require a small number of UAVs.

At the same time, AANETs, especially UAVs, also play a very important role in postdisaster network recovery. The authors in [24, 25, 55] all realize postdisaster communication recovery with the help of UAVs. Literature [24] proposes the solution of using UAV teams to achieve postdisaster recovery, which can be used anytime, anywhere. Each UAV in the team has an airborne computer, which runs three main subsystems and is responsible for end-to-end communication, formation control, and autonomous navigation. The airborne computer and the low-level controller of the UAV cooperate to achieve the goal of providing local communication infrastructure. At the same time, the subsystems running on each UAV are evaluated through simulation research and field tests using autonomous helicopters. The accuracy of the navigation subsystem is evaluated through field tests, and the proposed system can be successfully used to establish an emergency communication system in the event of disasters. However, the inadequacy of this research is that only one helicopter is used for simulation. Therefore, how to use a group of autonomous helicopters to conduct field tests to verify the success of the proposed communication system in many performance parameters, including jitter, throughput, availability, range, and packet loss, is a certain challenge.

The article [25] proposed a disaster recovery based on multiple environments of the flight Internet of Things, which provides coverage services for ground user equipment in disaster events by using wireless coverage on UAVs and recovers communication links in natural disasters in multiple environments. At the same time, in a multi environment system, the elevation and distance of user equipment will affect the coverage probability and path loss, so this paper also studies the optimal user equipment distance and elevation of user location to improve the coverage probability, which is particularly useful for UAV deployment design. The specific scene is shown in Figure 10. Figure 10 illustrates three types of ray signals received by ground user devices: direct, reflected, and diffracted. Direct rays denote unobstructed signal transmission between the UAV and ground user devices, while diffracted or reflected rays represent indirect links resulting from obstacles' interaction.

The article [55] proposed a novel approach for deploying unmanned aerial vehicle-mounted base stations (UmBS) in disaster-stricken areas, addressing challenges such as unknown user equipment (UE) positions, UmBS transmit power optimization, and UE-UmBS association. The proposed approach, localization of ground UEs and their association with the UmBS (LUAU), ensures the localization of ground UEs and energy-efficient deployment of UmBSs. Unlike existing studies that rely on known UE positional information, this paper first proposes a three-dimensional range-based localization approach (3D-RBL) to estimate the position information of the ground UEs. An optimization problem is then formulated to maximize the UE's mean data rate by optimizing the UmBS transmit power and deployment locations, considering interference from surrounding UmBSs. The Q-learning framework is utilized to achieve the goal of the optimization problem, leveraging its exploration and exploitation abilities. Simulation results demonstrate that the proposed approach outperforms two benchmark schemes in terms of the UE's mean data rate and outage percentage, highlighting its potential for restoring wireless services in disaster-affected areas.

The authors in [26, 27] proposed the method of satellite scheduling, in which article [26] proposed a community-driven distributed reception paradigm for LEO satellite signals, and the signals received on many small handheld receivers (not necessarily deployed on the roof, but also deployed indoors) are coherently combined to recover the required signals. This is achieved by using new synchronization and receiver orientation techniques to study satellite trajectories and utilize the presence of other environmental signals. The experimental results show that this method (deployed indoors) saves a lot of costs compared with large commercial receivers deployed on the roof, as shown in Figure 11.

The article [27] proposed a geographically distributed ground station design L2D2, which uses low-cost commodity hardware to provide low latency and robust downlink. L2D2 is the first system to use a hybrid ground station model, in which only some ground stations have uplink functions, as shown in Figure 12. This paper designs a new algorithm for scheduling and rate adaptation, which can achieve low delay and high robustness despite the limitation of only receiving ground stations. The L2D2 was evaluated through track-driven simulation and real world satellite ground station measurements. The results show that the geographically distributed design of L2D2 can reduce the data downlink delay from 90 minutes to 21 minutes.

The above contributions review the connectivity restoration in the airborne ad hoc network environment except for [27], which focus on the reduction of the data downlink delay. In addition to [26, 27], almost all other literature uses passive clustering for recovery, and most of them are simulated in actual application scenarios or real UAV scenarios, which have strong practicability.

3.3. Ad Hoc Network Connectivity Recovery after Disaster.

Natural disasters such as earthquakes, typhoons, and floods will cause heavy losses to life and property. According to the data of the Disaster Epidemiology Research Center, since 1900, natural disasters have affected an average of 218 million people every year. Moreover, in recent years, the number of large-scale natural disasters that last for days or even weeks has increased. Examples abound around the world, including the earthquake in Nepal (2015), Hurricane Maria in Puerto Rico, Hurricane Harvey in Houston (2017), and the recent Hurricane Farni in India and devastating floods in Southeast Asia (2019).

In such an event, it is difficult for first aiders to quickly find people trapped in debris. Therefore, some form of instant communication between the victim and the first aider is critical to ensure successful rescue and life-saving. At the same time, many of these disaster scenarios are dynamically evolving, usually in unexpected ways. Therefore, situational awareness of its evolution is also crucial for providing appropriate emergency response services in rescue and evacuation, medical care, shelter, food, medicine, and other rescue operations.

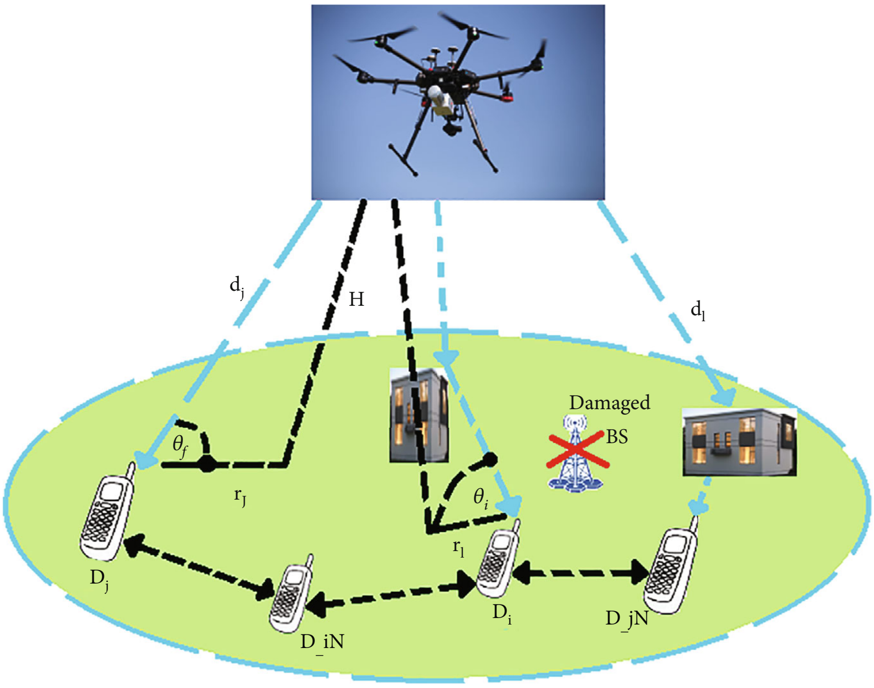


Figure 10: Schematic diagram of disaster recovery based on multi environment of flight Internet of Things.

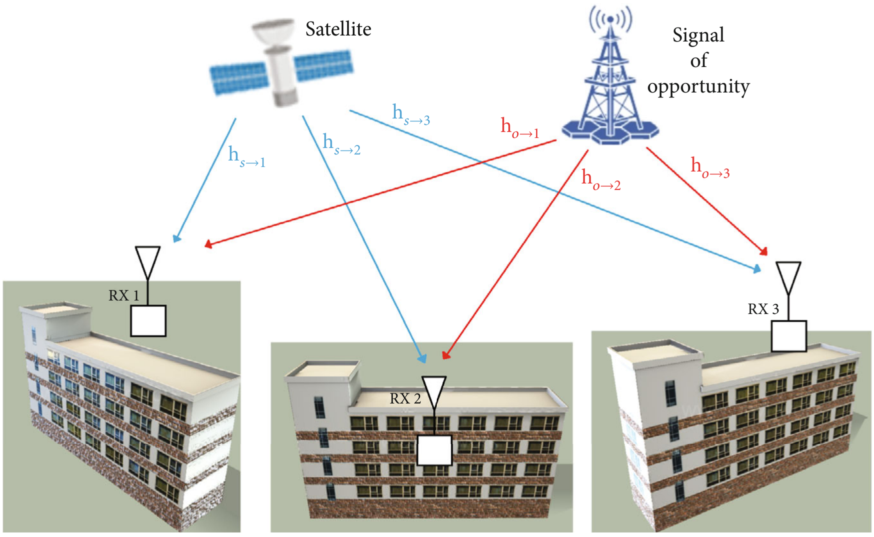


Figure 11: Schematic diagram of receiver receiving information deployed indoors and on the roof.

However, due to the network infrastructure that is generally partially or completely damaged in natural disasters, it is almost impossible to use the original equipment for communication. Therefore, one method is to search and collect information by UAV. For example, the above articles [24, 25] are used for postdisaster recovery communication. However, with the widespread use of smart phone technology, smart phones are increasingly becoming the lifeline of communication, personnel tracking, and demand assessment, especially during and after disasters. At the same time, given that smart phones carry a large number of sensors (for example, cameras, microphones, kinetic energy/vibration sensors, and GPS), the data that they capture has very valuable value for better evaluating the damage and demand of disaster-affected areas. In other words, in addition to typical manual use (such as voice calls, publishing text/photos or videos to social media), smart phones can also provide great added value through (semi) automated data collection, analysis, and decision-making processes. Therefore, it is very important for rescue to use intelligent handheld devices to establish rapid communication in a self-organized way after a disaster, to achieve connectivity recovery, and to send

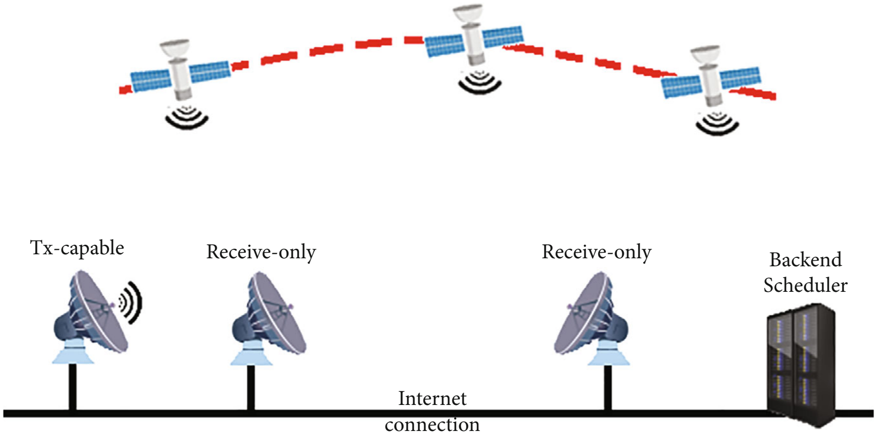


Figure 12: L2D2 model diagram.

messages in a timely manner, as shown in Figure 13. Table 4 summarizes the recovery method, contribution, and limitation of some literature in disaster.

The authors in [28–33] have carried out relevant research on connectivity recovery in postdisaster ad hoc networks to ensure real-time and effective data transmission. Most of them use the combination of passive and controlled mobility to achieve rapid communication recovery. The authors in [32, 33] have studied how to establish a network through self-organization of smart handheld devices, such as smart phones, and effectively transmit data in real time.

The article [28] proposed a four-tiered plan hybrid architecture disaster recovery system (as shown in Figure 14) and conducted an effectiveness study using data mules. At the same time, it also showed that this architecture design ensures the optimal utilization of resources under delay constraints, resulting in two NP optimization problems: graph clustering and multi site vehicle routing. Experiments show that this method has greatly improved the delivery probability and delay.

In Figure 14, when the underlying cannot handle this situation, the lower range and cheaper devices can be used at the bottom to build the next higher level device with a higher range and more expensive devices. It has a fixed main control station (MCS), which is used to control the centralized rescue/rescue operations in the disaster area (AA) composed of many shelters (SPs). Rescue workers in each SP carry smart phones to form DTN (first layer) to exchange information and regularly transmit data packets to the nearest DropBox (DB) (second layer) in each SP. For sparse DTN and remote DB, it is recommended that the vehicles used by rescue/rescue teams be equipped with WiFi and VSAT (for emergency messages) and serve as data mules (DM) (mechanical return) (the third layer) to transmit information to MCS. Due to physical obstacles, the placed SP may become inaccessible to the DM. The wireless ad hoc network can solve this problem. If the AA diameter is large, it is not feasible to deploy a dedicated DM for each SP to meet the delay limit. Therefore, a DM needs to be shared among multiple SPs. Then, use an effective clustering algorithm to group SPs, and place a (NLOS/ear LOS) WiFi tower (WT) (the fourth layer) in the center of each group to accumulate data from a group of non overlapping DBs.

The article [29] proposed a coordinated repair routing problem for disaster recovery of interdependent infrastructure networks. This paper focuses on the postdisaster repair operations of multiple interdependent lifeline networks, including functional dependencies. Thus, a postdisaster coordination infrastructure maintenance route problem is introduced, and a mixed integer programming model is proposed, which allocates maintenance teams to sites and constructs routes for each team to minimize the total recovery time of all network components. A heuristic simulated annealing algorithm is also developed to solve the proposed coordinated routing problem. The performance of the proposed solution algorithm is tested on a set of examples developed based on two interdependent lifeline networks (such as electricity and natural gas). The results show that this heuristic algorithm can quickly find high-quality solutions, while coordinating maintenance operations can significantly improve the overall recovery time of the interdependent infrastructure network. This algorithm has some shortcomings. Although the proposed problem assumes that the maintenance teams are the same, in fact, the size and capability of the maintenance teams may be different, and factors such as the size and capability of the maintenance teams are not considered.

The article [30] proposed a base station selection strategy suitable for postdisaster rapid road network recovery in vulnerable urban areas. In this study, appropriate base station location selection was studied for postdisaster rapid road network recovery (RNR), and ant colony optimization-based task scheduling (SRNR) was used to determine the optimal base station location. The study was conducted in Laodaka, a large city in Bangladesh, as a case study, and achieved good results.

The article [31] proposed a performance model of a hybrid disaster recovery framework based on device-to-device (D2D) communication. This model is used for the public security network (PSN) framework using collaborative devices with long-term evolutionary (LTE) device-to-device (D2D) communication capabilities. Mobile stations beyond the coverage of cellular networks use D2D communication. Mobile stations

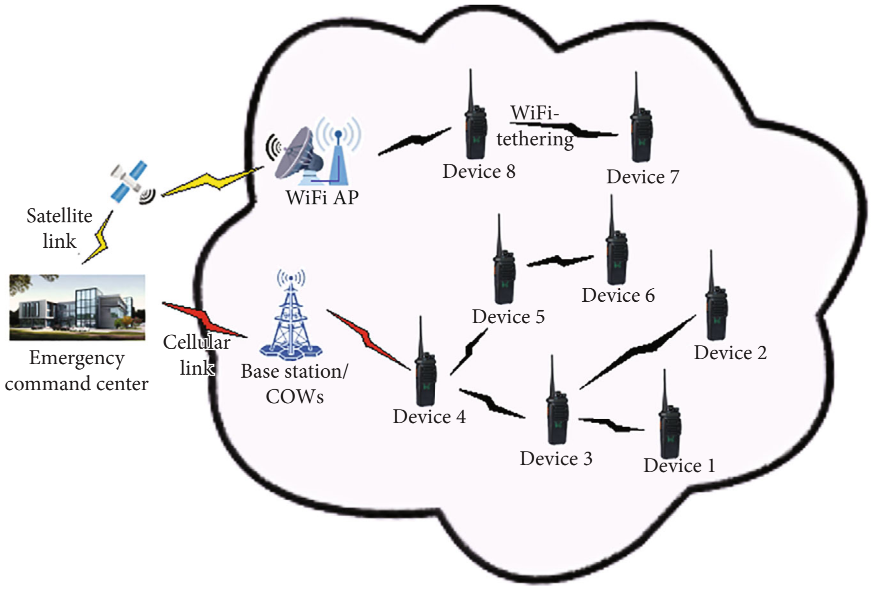


Figure 13: Cooperative communication between different devices with WiFi network sharing technology.

Table 4: Summarization of the recovery method, contribution, and limitation of some literature in disaster.

Literature	Recovery method	Contribution	Limitation
[29]	Repair the network using mathematical model and a practical simulated annealing heuristic to determine the order of repairs for each network component.	This study introduces a coordinated postdisaster repair routing problem considering infrastructure interdependencies, develops a mathematical model for prioritizing repairs, and presents an efficient simulated annealing metaheuristic to find high-quality solutions for realistic instances.	Although the proposed problem assumes that the maintenance teams are the same, in fact, the size and capability of the maintenance teams may be different, and factors such as the size and capability of the maintenance teams are not considered.
[32]	The proposed SmartDR method, utilizing smart phone-assisted disaster recovery with D2D communication in 5G networks for postdisaster communication.	SmartDR enables smart phones to self-detect disasters, switch to a disaster mode, and relay emergency messages using a multihop D2D approach. The method includes a rendezvous process, a path selection algorithm considering delay and energy, and a multichannel hopping protocol for victim localization and an energy-aware routing protocol to improve energy efficiency during rescue operations.	This method does not integrate the disaster detection (predisaster scenario) part with the postdisaster recovery methods, so as to design a complete end-to-end system for disaster detection and recovery.
[33]	Restore network communication through building ad hoc network using the smart devices.	This article's main contribution lies in determining optimal ad hoc network construction, efficient network building under mobility challenges, and scheduling data transfer effectively in disaster scenarios using WiFi tethering technology, offering a novel approach to data routing in such contexts.	The disadvantage is that mobile devices with more extensive features in terms of available sensors, network functions, and storage availability are not considered, and security issues and the trade-off between security and performance are also not considered.

in healthy areas can act as relay nodes to provide information about the location of potential victims to the central system. Since the relay node may become the bottleneck of a large-scale disaster, this study focuses on the interaction between the relay node and the base station. The analysis model and solution are suitable for evaluating the quality of service of PSNs with similar infrastructure. The results obtained from the analysis model are compared with the results obtained from the discrete event simulation for verification, and the maximum difference is less than 1.4%. In the confidence

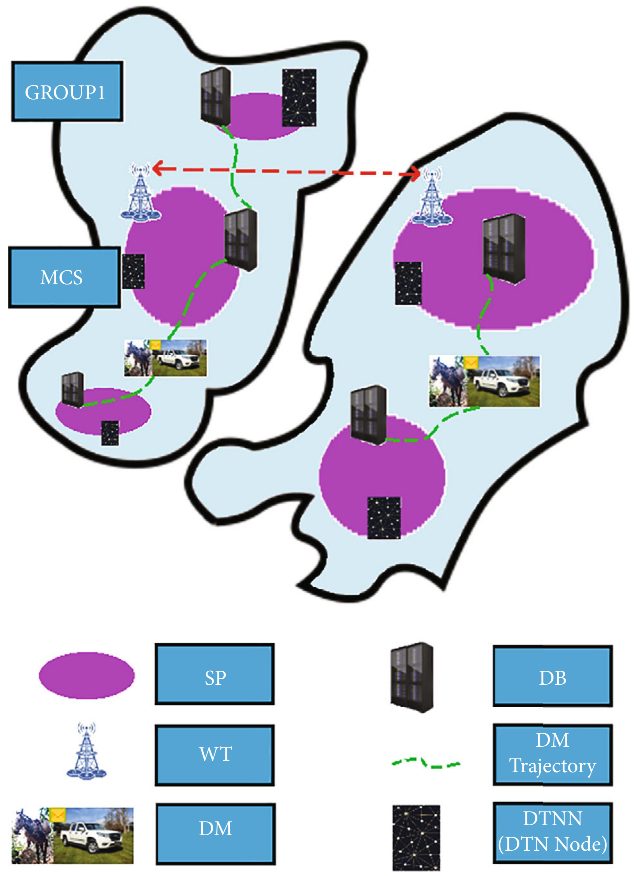


Figure 14: Postdisaster recovery system diagram of four-tiered hybrid architecture.

interval, it will be applied to large-scale models for trial in the future.

The article [32] also proposed a device-to-device communication strategy for disaster recovery, and this paper introduced a smart phone-assisted disaster recovery (SmartDR) method using smart phones for postdisaster communication. SmartDR makes use of the device-to-device (D2D) communication technology in the fifth generation (5G) network to realize direct communication between adjacent devices without relay through network infrastructure such as mobile access points or mobile base stations. At the same time, a multihop D2D communication scenario is also studied, in which the smart phones carried by the trapped victims and other people in the affected areas can self-detect the occurrence of disaster events by monitoring the radio environment and then can automatically switch to the disaster mode to transmit emergency help messages and their location coordinates to other nearby smart phones. In order to locate other smart phones running in disaster mode and the same channel nearby, each smart phone will run a convergence process, so the emergency message is relayed to the functional base station or rescue center. In order to promote the routing of emergency messages, this paper also proposes a path selection algorithm, which takes into account the delay and residual energy of devices (in this case, smart phones). Therefore, the SmartDR method includes (i) multichannel channel hopping convergence protocol to improve victim location or neighbor discovery and (ii) energy-aware multipath routing (energy-aware self-organized on-demand distance vector (E-AODV)) protocol to overcome the high energy consumption rate of devices related to a single shortest path. The SmartDR approach can guide search and rescue operations and increase the likelihood of saving lives immediately after a disaster event. Finally, a simulation-based performance study was conducted to evaluate the performance of the protocol in the postdisaster scenario. The simulation results show that significant performance gains can be achieved when the device uses channel information for the convergence process and residual energy for routing path selection. At the same time, when channel quality information is considered in the channel hope (CH) sequence design, peer discovery in multichannel D2D environments can be significantly improved. In addition, selecting a routing path according to the standard deviation of the residual energy of the device and the residual energy of the path can not only improve the network life but also reduce the chance of the network being divided. Figure 15 shows the postdisaster network scenario.

The article [33] also proposed a postdisaster operational network architecture based on smart phones using WiFi network sharing, as shown in Figure 13. This paper proposes to build temporary subnets of disconnected smart phones through WiFi network sharing technology and finally connect them to emergency communication devices deployed in disaster areas or other smart phones that still have network connectivity. The architecture proposed by the emergency control center (ECC) for such integrated and defined software-based control can collect key data through smart phone sensors. The solution developed supports the mobility of all smart phones, including those that lose direct cellular connectivity and those that do not have and are willing to act as gateways. At the same time, they also studied how the proposed scheme relates to the standardized wireless emergency alarm service, and how to effectively deal with mobile fault-tolerant device discovery and data transmission. This method implements prototype and large-scale simulation on the Android platform and analyzes the proposed solution through a set of comprehensive experiments. The disadvantage is that mobile devices with more extensive features in terms of available sensors, network functions, and storage availability are not considered, and security issues and the trade-off between security and performance are also not considered.

The above summarizes the connectivity recovery in the postdisaster self-organized network environment. Most of them use passive mobility to recover, some combine sleep scheduling to save energy consumption, and some literature use smart devices such as mobile phones to recover connectivity through D2D communication. Based on the above literature review, this paper believes that the postdisaster network recovery under large-scale damage can be solved as follows: First, find the optimal deployment location. You can broadcast the corresponding communication equipment to the corresponding location for network recovery by means of flight equipment broadcasting, or you can transport the personnel with handheld communication equipment to the

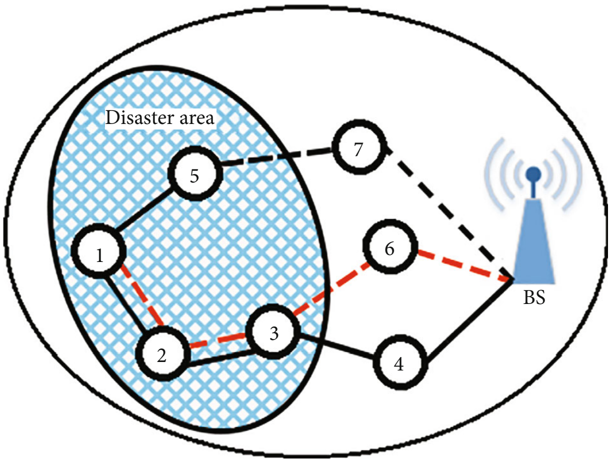


Figure 15: Postdisaster network scenario.

corresponding location by helicopter to achieve effective information transmission; then, the smart phones carried by the trapped victims and others in the disaster-stricken areas are used for self detection, automatic switching to the same frequency band for self-organized communication, and important information such as location information that is forwarded. Finally, using WiFi network sharing technology to build a temporary subnet of disconnected smart phones finally connects them to the emergency communication equipment deployed in the disaster area or the equipment and handheld device personnel broadcast, for fast communication, to ensure timely rescue of the victims, and the corresponding rescue, evacuation, medical care, shelter, food, medicine and other rescue operations are rapidly coordinated.

3.4. Other Connectivity Restoration Methods in 3D WASN. In addition to connectivity recovery mentioned in this paper, there are many other key issues in the 3D wireless ad hoc/sensor network environment, such as coverage, connectivity, positioning, and other key technologies.

The article [34] proposed a node optimization coverage method under the link model of the three-dimensional wireless sensor network passive monitoring system. This method abstracts the problem into the optimal coverage problem and solves it through improved genetic algorithm and particle swarm optimization algorithm. Finally, it achieves good results in improving network coverage, fast convergence, and reducing network energy consumption.

The article [35] proposed a low connection, full coverage three-dimensional wireless sensor network model, designed and proved the optimality of 1 and 2 connection models under any value of the ratio of communication range rc to sensing range rs in the conventional lattice deployment model, further proposed a group of models to implement 3 and 4 connection models, and studied the evolution between all proposed low connection models. Finally, the proposed model is studied under several practical settings.

The article [36] studied the space-filling curve of three-dimensional wireless sensor networks and its application and proposed a connectivity-based, distributed algorithm for constructing the three-dimensional space-filling curve. Its main idea is to divide the entire network into several layers and traverse them from inside to outside in order to ensure the coverage of the whole network and minimize the number of repeated visits of nodes. At the same time, the proposed space-filling curve is applied to the field of sensor mobile charging, and a charging plan based on the space-filling curve is proposed to improve the charging efficiency and optimize it. Experiments show that the proposed algorithm can quickly traverse all nodes in the network when the average coverage of nodes is less than twice.

The article [51] explores the use of jumping robot sensor nodes (JRSNs) for improving network performance in obstacle-dense environments. The study first simulates the impact of the 3D deployment of JRSNs on network connectivity and energy consumption. It then proposes a precise localization method for JRSNs during deployment, combining ultrawideband technology, an inertial navigation system, and a jumping error model. The paper also presents path planning and deployment algorithms that consider JRSNs' locomotion pattern and obstacles. Experimental results confirm the feasibility of the proposed approach, with JRSNs' deployment error less than 25 cm and a significant improvement in network connectivity by 57.70%. The findings suggest that JRSNs can autonomously deploy for various applications in environments rich in obstacles.

The article [63] proposed an efficient QoS-based MRP scheme for WBAN healthcare applications, enhancing energy efficiency, network throughput, and reliability. It categorizes available routes into best and alternate paths based on traffic priority, improving throughput significantly and minimizing average end-to-end delay for critical traffic.

4. The Latest Recovery Method in Two-Dimensional Environment

The connectivity recovery of WASN in a two-dimensional environment is still a hot topic of concern to many researchers. A large number of researchers are committed to the research in this area. The articles [37–46, 48, 49, 52, 56, 57, 60–62] are the latest research on connectivity recovery. From the perspective of timing, most of the literature still adopts active, passive, or active-passive combination for recovery. Most of the recovery methods use clustering and controlled mobility to achieve network connectivity. Table 5 summarizes the recovery method, contribution, and limitation of some literature in 2D WASN.

4.1. Preprocessed Active Recovery. This recovery method refers to all nodes in the network that make some pre preparation decisions before the failure node occurs, so as to minimize energy consumption and reduce the probability of node failure, so as to restore immediately in case of node failure or network disconnection. The authors in [44–46, 48, 52, 57, 61] adopt this method for fault tolerance recovery.

The article [44] proposed an adaptive and fault-tolerant routing algorithm for wireless sensor networks in microgrids. This algorithm uses particle swarm optimization to construct routing, including inter cluster structure and intra

Table 5: Summarization of the recovery method, contribution, and limitation of some literature in 2D WASN.

Literature	Recovery method	Contribution	Limitation
[37]	Passive, node movement recovery based on clustering and considering the secondary damage.	This proposed DBCE connectivity establishment scheme, which includes segment evaluation/selection approaches to reduce connectivity cost, enhance network robustness, and improve longevity by considering segment shapes and local network features.	This method cannot be fully applied in the 3D environment.
[38]	Active passive hybrid, node movement k-connectivity recovery based on noncritical nodes.	The proposed PINC algorithm efficiently restores movement-based k-connectivity by categorizing nodes into critical and noncritical groups, moving noncritical nodes to replace failed critical nodes with minimal movement cost, outperforming competitors in terms of speed and effectiveness based on real motes and robot testbed data.	This algorithm reduces coverage and cannot be fully applied in the 3D environment.
[39]	Passive, node movement recovery based on clustering and using machine learning.	The proposed CRrbf, a machine learning-based connectivity restoration strategy using RBFNN and UKF to optimize aggregation ratio, reduce energy cost, and outperform distance and terrain-based strategies in terms of aggregation ratio, network latency, throughput, and energy efficiency based on theoretical analysis and simulation results.	This method is not considered to restore the connectivity through a limited number of relay nodes and mobile data collectors. At the same time, it is not considered to use deep reinforcement learning (i.e., DDPG) for efficient path optimization of mobile data collectors.
[40]	Active passive hybrid, node movement k-connectivity recovery based on two-hop neighbor nodes and considering the locations, moving costs, and obstacles.	The proposed CMH algorithm for k-connectivity restoration in heterogeneous WSANs, where nodes determine local subgraphs and minimum moving costs, check failure impact on k using disjoint paths, and utilize actuators to restore connectivity.	It does not consider how to realize k-connectivity restoration in the 3D environment.
[41]	Passive, node deployment recovery based on clustering and sleep scheduling using the Steiner tree and convex polygons.	The proposed method utilizes the Steiner tree and convex polygons to enhance fault tolerance in wireless sensor networks by creating dual connectivity through relay nodes. By simplifying the network structure and reducing data communication delay, the approach minimizes relay node deployment and extends the network lifetime compared to existing algorithms.	There is no simulation experiment in the actual scene, and the security of data transmission is not considered. And it also cannot be fully applied in the 3D environment.
[46]	Active, node movement recovery based on clustering using irregular cellular automata.	The proposed irregular cellular automata (ICA) model in WSN for fault node identification through clustering and cluster-head selection, minimizing computational overhead and bandwidth usage. The system utilizes node data structures to select cluster heads based on specific rules within ICA.	The number of clusters is not optimal, and they also dot not consider the security, QoS, and load balancing. This method cannot be fully applied in the 3D environment.

Table 5: Continued.

Literature	Recovery method	Contribution	Limitation
[57]	Active, critical node (C-N) detection only using the neighbor's received signal strength indicator (RSSI) information.	The proposed ABCND algorithm for critical node detection in IWSN, consisting of a 2D critical node detection algorithm in phase I and a correlation-based reliable RSSI approach in phase II. The algorithm achieves efficient convergence and critical node detection with reduced energy consumption compared to state-of-the-art methods, demonstrating 90% to 95% accuracy in detecting critical nodes while consuming 50% less energy.	The ABCND algorithm is not simulated in the large-scale IWSN and on real hardware. Moreover, the algorithm has some false positivity when implemented in 3D topology.
[60]	Passive, node deployment recovery based on multiobjective evolutionary method using a hop count bound as a delay constraint.	The proposed GPrim algorithm to minimize relay nodes and maximize network lifetime with local heuristics aiding initialization, crossover, and mutations in wireless sensor networks. Extensive experiments demonstrate the method's effectiveness in improving network metrics with reasonable computational time tradeoff compared to standard encoding methods.	The model cannot cope with mobile sensors and is not suitable in heterogeneous wireless sensor networks.

cluster structure, taking into account distance, energy, and traffic. Cluster head nodes are adaptive and adjust their communication range according to network conditions and current load. In addition, the sensor can solve unexpected faults automatically and quickly and has the ability of self-repair. The stability and reliability of the network are improved by simulation evaluation algorithm. The authors in [45] proposed a multipath reliable transmission (BIM2RT) algorithm for fault tolerance mechanism of wireless sensor networks based on BWAs (Best Worst Ant System) immune mechanism. This algorithm includes BWA-based multipath establishment algorithm (BME) and immune-based multipath transmission algorithm (IMT). BME uses pheromone information generated by artificial ants as guidance to quickly establish all possible transmission paths from the source node to the destination node. These multipaths are inputs and form the initial mutation population of the next IMT, which performs mutation on the initial mutation antibody population. IMT establishes the optimal transmission path with good convergence and avoids obtaining local optimization due to the initial optimal solution of BME. The problem of multipath establishment is converted into multiobjective optimization, taking into account transmission delay, energy consumption, equal hop distance, and other factors, combined with load balancing mechanism, and the fault tolerance of multipath transmission is proved through redundant routing and transmission. The simulation results show the good performance of data transmission reliability and fault tolerance. Both of the above algorithms use heuristic algorithms to find the optimal solution.

The article [46] proposed an adaptive cellular automata scheme (CA-based FT) for fault tolerance diagnosis and connectivity maintenance in wireless sensor networks and proposed an irregular cellular automata (ICA) model based on clustering to identify faulty nodes, and cluster head selection will not consume a lot of computing overhead and bandwidth. Node data structures contain many parameters, such as node energy levels, neighbors, coverage, and connection variables. Based on a set of rules in ICA, this data structure helps to select cluster heads, so that when a cluster head fails, the original cluster head node will be replaced by a node with the best energy consumption and route. At the same time, this algorithm can run in a distributed manner. The simulation results show that this scheme has low energy consumption and low information transmission, thus delaying the life cycle of the network. The specific algorithm is shown in Figure 16.

The article [48] introduces a novel security approach, "Detection and Prevention of GHA" (DPGHA), designed to counteract both variants of GHA in Ad Hoc On-Demand Distance Vector- (AODV-) based VANETs. The approach generates dynamic threshold values of abnormal differences in received, forwarded, and generated control or data packets among nodes and their sequence numbers. Implemented and tested in NS-2 and SUMO simulators, DPGHA outperformed benchmark approaches, reducing routing overhead by 10.85% and end-to-end delay by 3.85%, increasing packet delivery ratio (PDR) by 4.67% and throughput by 6.58%, and achieving a maximum detection rate of 2.3%.

The article [52] addresses common disruptions in Internet of Things (IoT) networks and wireless sensor networks (WSNs), such as node faults, path disconnections, and security attacks. To ensure network functionality despite component failures, the paper proposes a decentralized fault-tolerant algorithm that leverages mobile nodes to manage network failures. The algorithm comprises two methods: detection and recovery. The detection method identifies the

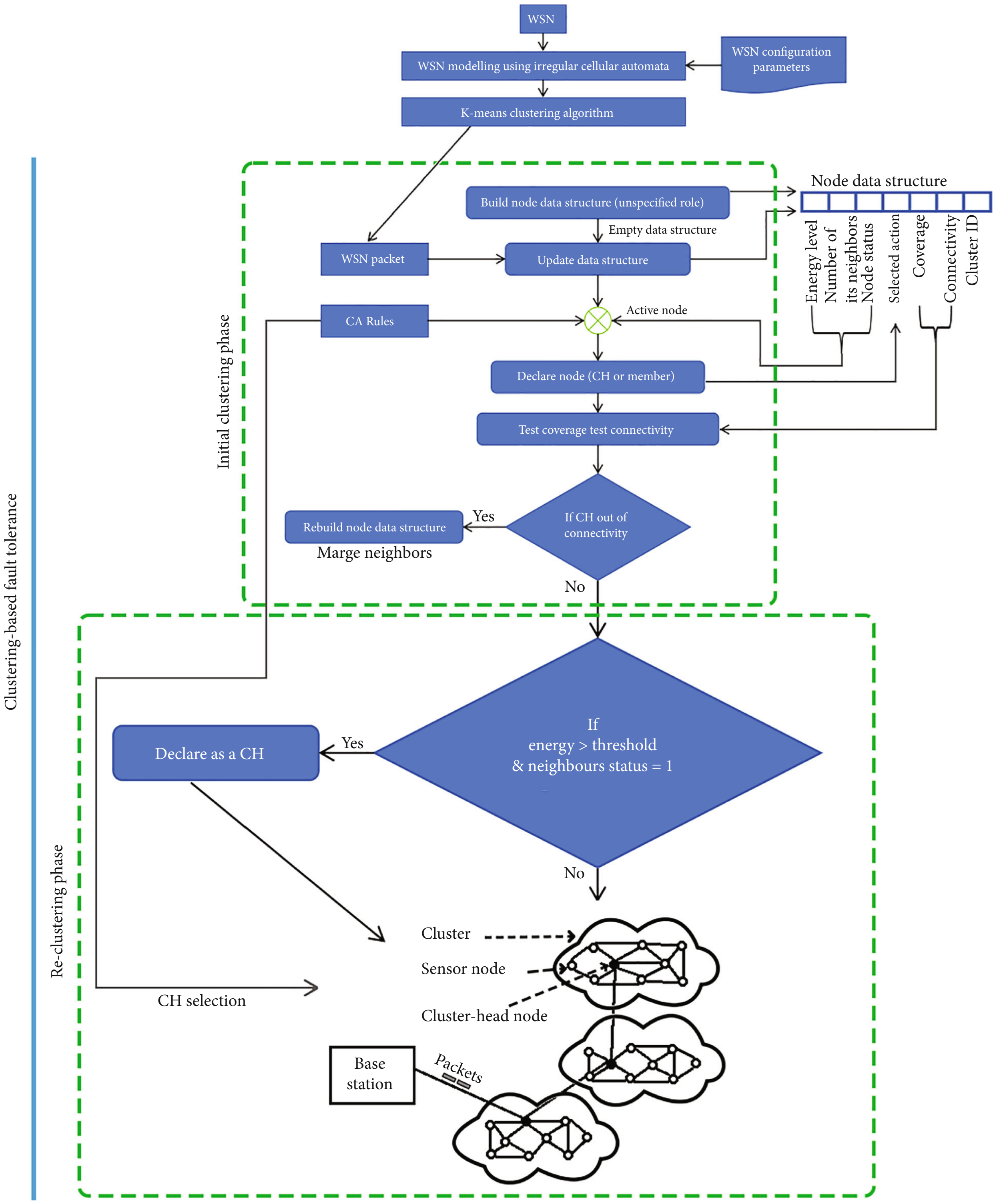


Figure 16: CA-based FT algorithm.

fault and assesses the affected area, while the recovery method deploys mobile nodes to reconnect the impacted areas. Simulation results indicate that the proposed algorithm significantly aids in detecting and recovering from faults in IoT and WSNs.

The article [57] presents a two-phase algorithm, Angle Based Critical Nodes Detection (ABCND), to address the problem of node failure in wireless sensor networks (WSNs). The first phase of ABCND proposes a 2D critical node (C-N) detection algorithm that uses only the neighbor's received signal strength indicator (RSSI) information. The second phase proposes a correlation-based reliable RSSI approach to increase node resilience against adversaries. This ABCND algorithm has a low time complexity, and simulation results show that ABCND consumes 50% less energy to detect C-N with 90% to 95% accuracy in identifying critical nodes. However, the ABCND algorithm is not simulated in the large-scale IWSN and on real hardware. Moreover, the algorithm has some false positivity when implemented in 3D topology.

The article [61] used a mobile sensor to efficiently cover blind regions, and present a 0-1 mixed integer programming model to find the shortest trajectory without mobility pattern assumptions. It demonstrated the NP-hardness of the problem and offered optimization-based heuristics and algorithms to efficiently find high-quality solutions in a short time, highlighting the impact of starting point and potential stops on the tour length.

4.2. Passive Recovery. Passive recovery refers to the corresponding processing and recovery when the node fails. In passive recovery, some methods have preprocessing, such as evaluating the area shape in advance, training, and learning several important parameters, and some methods do not save any information.

The article [37] proposed a method to ensure persistent connectivity (DBCE) in a severely damaged sensor network environment, which is mainly capable of coping with secondary damage. This method consists of three steps, namely, segment shape evaluation method, area different connection method, and data traffic transmission method. This method is the first attempt to study segment shape, and it has proved that it has a great impact on the robustness of the network. On the other hand, different from the existing network with unified connectivity rules, the network is divided into two parts, and different connectivity sequences and connectivity methods are designed according to different characteristics and requirements of the network. The article [39] proposed a connection recovery strategy (CRrbf) for the industrial Internet of Things based on machine learning. As far as we know, this is one of the few strategies to apply machine learning to connection recovery. This strategy uses a radial basis function neural network (RBFNN) and traceless Kalman filter (UKF) to maximize the polymerization rate and reduce energy costs. Theoretical analysis and simulation results show that CRrbf outperforms distance-based strategy and terrain-based strategy in terms of aggregation rate, network delay, and network throughput. And the energy cost of CRrbf is lower than that of distance-based strategy. However, it is not considered to restore the connectivity of IIoT through a limited number of relay nodes and mobile data collectors. At the same time, it is not considered to use deep reinforcement learning (i.e., DDPG) for efficient path optimization of mobile data collectors.

The article [41] proposed a WSN partition dual connectivity recovery algorithm based on the Steiner tree and convex polygon. This algorithm combines the quadrilateral Steiner tree and Graham convex shell algorithm to achieve dual connectivity and implements the sleep wake-up mechanism for nodes, thus ensuring the network connectivity after secondary damage. Experiments show that this algorithm reduces the number of inherited nodes in deployment and extends the network life. The disadvantage of this algorithm is that there is no simulation experiment in the actual scene, and the security of data transmission is not considered.

The article [49] introduces a novel "Energy-Efficient Dynamic and Adaptive State-based Scheduling" (EDASS) scheme for wireless sensor networks. The proposed method dynamically switches nodes between states and adapts to new states based on the contents of sensed data packets. It derives four distinct energy states from a combination of internal sensor modules. The typical operation sequence is altered, activating all sensors when a new event occurs. EDASS has demonstrated significant energy savings, reducing energy consumption by 29% in live nodes, message overhead by 41%, and the cluster head selection process by 33%. However, it also results in a slight increase in average delay, from 1.26 ms to 1.39 ms, due to control message overhead. This trade-off is a consideration for the implementation of the EDASS scheme.

The article [56] proposed an Enhanced Mobile Sink-based Coverage Optimization and Link-stability Estimation based Routing (EMSCOLER) protocol to address coverage and energy efficiency issues in wireless sensor networks (WSNs). The proposed EMSCOLER protocol optimally resolves the coverage restoration issue and prevents network transmission faults. The protocol consists of two phases: coverage restoration and Link Stability Estimation based Routing (LSER). Initially, a grid is constructed in the coverage area, and nodes are randomly deployed. The Grid-based Red Deer Simulated Annealing (GRDSA) model detects the coverage holes in the sensing field and moves redundant nodes to the hole area to solve the restoration problem. The LSER algorithm estimates link quality and selects relay nodes for data transmission to maximize network lifetime and provide energy-efficient routing.

The article [60] proposed a multiobjective evolutionary algorithm called GPrim to solve this problem. The algorithm is aimed at minimizing the number of used relay nodes and the maximum node energy consumption, thereby prolonging the network's lifetime while ensuring connectivity. A hop count bound is considered as a delay constraint to improve the network's reliability. GPrim combines edge-set encoding and the NSGA-II framework. It leverages problem-specific properties and introduces objective-oriented heuristics into initialization, crossover, and mutation operators to improve the algorithm's convergence. Simulation results on 3D datasets show that the proposed algorithm significantly outperforms existing algorithms on all measured metrics, demonstrating its effectiveness in optimizing relay node placement in wireless sensor networks. However, the model proposed in this paper cannot cope with mobile sensors and is not suitable in heterogeneous wireless sensor networks.

The article [62] proposed ToMaCAA, an energy-efficient adaptive topology-management system for sustaining network connectivity in resource-constrained WSNs. It consists of two phases: network initialization and maintenance to address connectivity failures while conserving network resources. Simulation results demonstrate that ToMaCAA outperforms existing schemes like DPV, ADPV, and PINC in terms of energy efficiency and fault tolerance.

4.3. Active Passive Hybrid Recovery. This kind of recovery refers to not only doing some preprocessing such as saving neighbor node information, but also processing when the node fails. The authors in [38, 40] adopt this active passive hybrid recovery method, and these two strategies are k-connected recovery algorithms, which have strong network robustness.

The article [38] proposed a k-connectivity recovery algorithm (PINC) based on picking up noncritical nodes in wireless sensor networks. This algorithm divides nodes into critical nodes and noncritical nodes. When a critical node fails, PINC will move the noncritical node to the location of the failed node at the minimum mobile cost to achieve k-connectivity recovery. The measurement results obtained from the real IRIS node scene and the Kobuki robot test bench, as well as extensive simulations, show that PINC can generate the best motion faster than other algorithms to recover the k-connectivity. However, this algorithm reduces coverage. The article [40] also proposed a distributed k-connectivity recovery algorithm for fault-tolerant wireless sensor and actuator networks, where nodes can be static or mobile. In this algorithm, each node identifies the mobile node in the network and its 2-hop local subgraph. After a node fails, if the failure decreases and causes non k-connectivity, the neighbor of the failed node will trigger a mobile node to the location of the failed node at the minimum mobile cost to achieve k-connectivity recovery. At the same time, the least cost mobile path between the neighbors of the failed node and the mobile node is constructed by considering the location, mobile cost, and obstacles of the node. Through the actual scene experiment and comprehensive simulation, it shows that the proposed distributed algorithm can recover k-connectivity with a lower cost of sending bytes and moving compared with existing algorithms. The disadvantage of this algorithm is that it does not consider how to realize k-connectivity restoration in the 3D environment. The authors in [42, 43] reviewed the key technologies such as connectivity, coverage, and deployment in wireless sensor networks and pointed out the main research directions in the future.

In a word, there are many connectivity recovery methods in 3D wireless self-organizing/sensor networks. The above analysis of the methods proposed in some current literature shows that any method has its advantages and disadvantages. The purpose is to achieve network recovery with the least resources and the shortest delay. However, it is not ideal to give consideration to coverage, and many of them adopt heuristic or distributed algorithms for preprocessing and recovery. It is very difficult to find the optimal algorithm, so researchers still disdain efforts for it.

5. Deficiencies and Future Research Directions

According to the current research, there are many challenging problems in restoring connectivity in 3D WASN:

(1) At present, most of the connectivity recovery methods in 3D WASN are based on vulnerability detection and then implementation of connectivity recovery. It does not consider how to find the optimal solution to redeploy new nodes or mobile neighbor nodes to corresponding locations when the network is damaged in a large scale. Of course, this problem is more complex in the 3D environment and has been proven to be a NP problem. Some literature also use heuristic algorithm to find placement, but this problem is still a challenging problem

(2) When restoring connectivity, many literature only consider how to restore connectivity but do not consider the quality of service, especially the coverage. At the same time, some literature do not consider security, scalability, energy efficiency, dynamic and changing environments, and cross-layer optimization or only consider one factor. Thus, combining the above factors to achieve connectivity recovery will also be one of the important challenges in the future

(3) In terms of connectivity recovery, the performance coordination of all aspects is also the future research direction, especially in the case of high-speed movement of nodes in the airborne ad hoc network, vulnerability of nodes to attacks in the underwater network environment, and rapid communication recovery in the disaster relief environment, and how to ensure its following characteristics:

    (a) Self-organization: for large-scale damage of postdisaster communication. It is very important to realize connectivity and fast communication through the self-organized network as soon as possible

    (b) Reliability: if network connectivity is achieved through mobile node mobility, the software and hardware fault tolerance design and intelligent mobile algorithm of mobile node are very important, and the accuracy of aircraft mobility in an airborne self-organized network is very important

    (c) Real time: in case of network disconnection or large-scale damage, such as in the postdisaster environment, it is particularly important to quickly and automatically realize communication recovery and network connectivity

(4) How to combine machine learning and deep learning with the above-mentioned performance factors to achieve connectivity recovery in 3D WASN will also be one of the important challenges in the future

(5) In connection and recovery of 3D WASN, how to combine with key technologies in 3D ad hoc networks such as deployment, location, topology design, routing design, and communication protocols to build a 3D wireless ad hoc/sensor network with stable performance is also one of the challenges in the future

6. Conclusion

In this paper, the main research results of connectivity recovery in 3D WASN and fast communication recovery in disaster relief environment are reviewed. At present, most of the research is still in the exploratory experimental research stage, especially in the aspects of collaborative performance such as security, reliability, real-time, and so on, which need further research by researchers. And there are few systems that are really used in practice. However, the research in this area is the current hot spot, because in the modern era of rapid development of the network, especially in the society with increasingly high degree of intelligence, 3D WASN will be more widely used. Thus, it is of great significance to study connectivity recovery and other performance indicators (such as coverage) under 3D WASN. Our research provides a comprehensive overview of the current state of the art, summarizing key findings and categorizing solutions. We have identified several areas where further research is needed, including the development of more efficient algorithms for connectivity restoration in 3D environments, strategies for dealing with resource constraints, and methods for handling high mobility scenarios. We believe that our work holds certain value for future research in this field, pointing out certain research directions for more robust and resilient 3D WASN.

Data Availability

All data generated or analyzed during this study are included in this published article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the Natural Science Foundation of Hubei Province under Grant Nos. 2021CFB388, 2016CFC721, 2019CFC881, and 2019ZYYD009; the outstanding young and middle-aged science and technology innovation team of universities in Hubei Province (grant number No. T2022032); the innovation team of Hubei University of Science and Technology (grant number No. 2022T04); the science and technology planning project of Xianning City (grant number No. 2022GXYF056); the Young Talent Project of Hubei Provincial Department of Education under Grant Nos. Q20162801 and B2021226; the Project of Hubei University of Science and Technology under Grant Nos. 2022XB018, ZJ0016, and BK202030; the Ministry of Education of Chinese Collaborative Education Project for Industry-Academia-Research Integration (grant number No. 230705211134832); and the collaborative innovation project of "Integration of Moss, digital intelligence" funded by the innovation fund of University production, learning and research of the science and technology development center of the Ministry of Education.

References

[1] C. Wu and H. Chen, "Survey of connectivity recovery in wireless sensor networks," *Computer Application Research*, vol. 35, no. 5, pp. 1302–1307, 2014.

[2] H. Liu and S. Jin, "Overview of 3D wireless sensor networks," *Computer Application*, vol. 27, no. B12, pp. 1–5, 2007.

[3] B. Shah and K. I. Kim, "A survey on three-dimensional wireless ad hoc and sensor networks," *International Journal of Distributed Sensor Networks*, vol. 10, no. 7, pp. 616014–616020, 2014.

[4] L. Vihman, M. Kruusmaa, and J. Raik, "Overview of fault tolerant techniques in underwater sensor networks," 2019, http://arxiv.org/abs/1910.00889.

[5] Z. A. Dagdeviren, V. K. Akram, O. Dagdeviren, B. Tavli, and H. Yanikomeroglu, "*k*-Connectivity in Wireless Sensor Networks: Overview and Future Research Directions," *IEEE Network*, vol. 37, no. 3, pp. 140–145, 2023.

[6] Z. A. Dagdeviren and V. Akram, "Connectivity estimation approaches for Internet of Things-enabled wireless sensor networks," in *Emerging Trends in IoT and Integration With Data Science, Cloud Computing, and Big Data Analytics*, IGI Global, 2022.

[7] N. Temene, C. Sergiou, C. Georgiou, and V. Vassiliou, "A survey on mobility in wireless sensor networks," *Ad Hoc Networks*, vol. 125, no. 102726, pp. 1–17, 2022.

[8] W. Osamy, A. M. Khedr, A. Salim, A. I. Alali, and A. A. Elsawy, "Coverage, deployment and localization challenges in wireless sensor networks based on artificial intelligence techniques: a review," *IEEE Access*, vol. 10, pp. 30232–30257, 2022.

[9] M. Matracia, N. Saeed, M. A. Kishk, and M. S. Alouini, "Post-disaster communications: enabling technologies, architectures, and open challenges," *IEEE Open Journal of the Communications Society*, vol. 3, pp. 1177–1205, 2022.

[10] Y. Zhuang, C. Wu, H. Wu et al., "Event coverage hole repair algorithm based on multi-AUVs in multi-constrained three-dimensional underwater wireless sensor networks," *Symmetry*, vol. 12, p. 1884, 2020.

[11] W. Zhang, G. Han, Y. Liu, and J. Wang, "A coverage vulnerability repair algorithm based on clustering in underwater wireless sensor networks," *Mobile Networks and Applications*, vol. 26, no. 3, pp. 1107–1121, 2021.

[12] M. Rao and N. K. Kamila, "Cat swarm optimization based autonomous recovery from network partitioning in heterogeneous underwater wireless sensor network," *International Journal of System Assurance Engineering and Management*, vol. 12, no. 3, pp. 480–494, 2021.

[13] F. Nasrin, A. Yasmin, and N. I. Ahmed, "Anomaly Detection Method for Sensor network in Under Water Environment," in *2021 International Conference on Information and Communication Technology for Sustainable Development (ICICT4SD)*, pp. 380–384, Dhaka, Bangladesh, 2021.

[14] A. Chaaf, M. Saleh Ali Muthanna, A. Muthanna et al., "Energy-efficient relay-based void hole prevention and repair in clustered multi-AUV underwater wireless sensor network," *Security and Communication Networks*, vol. 2021, Article ID 9969605, 20 pages, 2021.

[15] A. Prasanth, "Certain investigations on energy-efficient fault detection and recovery management in underwater wireless sensor networks," *Journal of Circuits, Systems and Computers*, vol. 30, no. 8, article 2150137, 2021.

[16] R. R. Priyadarshini and N. Sivakumar, "Failure prediction, detection & recovery algorithms using MCMC in tree-based network topology to improve coverage and connectivity in 3D-UW environment," *Applied Acoustics*, vol. 158, pp. 107053.1–107053.9, 2020.

[17] Z. Wang and B. Wang, "A novel node sinking algorithm for 3D coverage and connectivity in underwater sensor networks," *Ad Hoc Networks*, vol. 56, pp. 43–55, 2017.

[18] N. Goyal, M. Dave, and A. Verma, "A novel fault detection and recovery technique for cluster-based underwater wireless sensor networks," *International Journal of Communication Systems*, vol. 31, no. 4, pp. 1–14, 2018.

[19] K. Ovaliadis, N. Savage, and V. Tsiantos, "A new approach for a better recovery of cluster head nodes in underwater sensor networks," in *2014 International Conference on Telecommunications and Multimedia (TEMU)*, pp. 167–172, Heraklion, Greece, 2014.

[20] S. S. Bacanli, E. Elgeldawi, and D. Turgut, "Charging Station Placement in Unmanned Aerial Vehicle Aided Opportunistic Networks," in *ICC 2021 - IEEE International Conference on Communications*, pp. 1–5, Montreal, QC, Canada, 2021.

[21] S. Poudel and S. Moh, "Unequal-size clustering approach for unmanned aerial vehicle-aided wireless sensor networks," in *Proc. of 8th Int. Conf. on Smart Media and Applications*, Guam, USA, 2020.

[22] S. S. Bacanli and D. Turgut, "Energy-efficient unmanned aerial vehicle scanning approach with node clustering in opportunistic networks," *Computer Communications*, vol. 161, pp. 76–85, 2020.

[23] S. Poudel and S. Moh, "Hybrid path planning for efficient data collection in UAV-aided WSNs for emergency applications," *Sensors*, vol. 21, no. 8, p. 2839, 2021.

[24] G. Tunaa, B. Nefzi, and G. Conte, "Unmanned aerial vehicle-aided communications system for disaster recovery," *Journal of Network and Computer Applications*, vol. 41, pp. 27–36, 2014.

[25] A. Saif, K. B. Dimyati, K. A. B. Noordin et al., "Internet of fly things for post-disaster recovery based on multi-environment," pp. 1–5, 2021, http://arxiv.org/abs/2104.08892v2.

[26] V. Singh, A. Prabhakara, and Z. Diana, "A community-driven approach to democratize access to satellite ground stations," in *MobiCom '21: Proceedings of the 27th Annual International Conference on Mobile Computing and Networking*, pp. 1–14, New Orleans, LA, USA, 2021.

[27] D. Vasisht, J. Shenoy, and R. Chandra, "L2D2: low latency distributed downlink for low earth orbit satellite," in *SIGCOMM'21*, pp. 151–164, Virtual Event, USA, 2021.

[28] S. Sujoy, V. K. Shah, R. Mandal, and S. Nandi, "Is it worth taking a planned approach to design ad hoc infrastructure for post disaster communication," in *CHANTS '12: Proceedings of the seventh ACM international workshop on Challenged networks*, pp. 87–89, Istanbul, Turkey, 2012.

[29] E. Atsizl, B. Balcik, D. Gunnec, and B. U. Sevindik, "A coordinated repair routing problem for post-disaster recovery of interdependent infrastructure networks," *Annals of Operations Research*, vol. 319, no. 1, pp. 41–71, 2022.

[30] M. S. Hossain, A. Anjum, M. A. H. Akhand, and N. Siddique, "Suitable Base Station Selection for Post Disaster Quick Road Network Recovery in a Vulnerable Urban Area," in *2020 IEEE Region 10 Symposium (TENSYMP)*, pp. 1180–1184, Dhaka, Bangladesh, 2020.

[31] E. Evera, E. Gemikonaklib, H. X. Nguyenc, F. Al-Turjmand, and A. Yazicie, "Performance evaluation of hybrid disaster recovery framework with D2D communications," *Computer Communications*, vol. 152, pp. 81–92, 2020.

[32] M. A. Hossain, S. K. Ray, and J. Lota, "SmartDR: a device-to-device communication for post-disaster recovery," *Journal of Network and Computer Applications*, vol. 171, article 102813, 2020.

[33] A. Pal, M. Raj, K. Kant, and S. K. Das, "A smartphone-based network architecture for post-disaster operations using WiFi tethering," *ACM Transactions on Internet Technology*, vol. 20, no. 1, pp. 1–27, 2020.

[34] Z. Hao, Q. Nanjiang, X. Dang, and J. Hou, "Node optimization coverage method under link model in passive monitoring system of three-dimensional wireless sensor network," *International Journal of Distributed Sensor Networks*, vol. 15, no. 8, pp. 1–16, 2019.

[35] X. Bai, C. Zhang, D. Xuan, J. Teng, and W. Jia, "Low-connectivity and full-coverage three dimensional wireless sensor networks," in *MobiHoc '09: Proceedings of the tenth ACM international symposium on Mobile ad hoc networking and computing*, pp. 145–154, New Orleans, Louisiana, USA, 2009.

[36] W. Wei, *Research on Space Filling Curve and Its Application in 3D Wireless Sensor Networks*, Huazhong University of science and technology, 2016.

[37] X. Liu, A. Liu, T. Qiu, B. Dai, T. Wang, and L. Yang, "Restoring connectivity of damaged sensor networks for long-term survival in hostile environments," *IEEE Internet of Things Journal*, vol. 7, no. 2, pp. 1205–1215, 2020.

[38] V. K. Akram, Z. A. Dagdeviren, O. Dagdeviren, and M. Challenger, "PINC: pickup non-critical node based k-connectivity restoration in wireless sensor networks," *Sensors*, vol. 21, no. 19, p. 6418, 2021.

[39] J. Wang, H. Zhang, Z. Ruan, T. Wang, and X. Wang, "A Machine Learning Based Connectivity Restoration Strategy for Industrial IoTs," *IEEE Access*, vol. 8, pp. 71136–71145, 2020.

[40] V. K. Akram, O. Dagdeviren, and B. Tavli, "Distributed *k*-Connectivity Restoration for Fault Tolerant Wireless Sensor and Actuator Networks: Algorithm Design and Experimental Evaluations," *IEEE Transactions on Reliability*, vol. 70, no. 3, pp. 1112–1125, 2021.

[41] J. Zhang, X. Yu, and Y. Huang, "WSN partitioned double connected restoration of Steiner tree and convex polygon," *Control and Decision-Making*, vol. 34, no. 11, pp. 2351–2357, 2019.

[42] A. Boukerche and P. Sun, "Connectivity and coverage based protocols for wireless sensor networks," *Ad Hoc Networks*, vol. 80, pp. 54–69, 2018.

[43] S. Abdollahzadeh and N. J. Navimipour, "Deployment strategies in the wireless sensor network: a comprehensive review," *Computer Communications*, vol. 91–92, pp. 1–16, 2016.

[44] L. Rui, X. Wang, Y. Zhang, and X. Wang, "A self-adaptive and fault-tolerant routing algorithm for wireless sensor networks in microgrids," *Future Generation Computer Systems*, vol. 100, pp. 35–45, 2019.

[45] H. Li, Q. Chen, Y. Ran, X. Niu, L. Chen, and H. Qin, "BIM2RT: BWAS-immune mechanism based multipath reliable transmission with fault tolerance in wireless sensor networks," *Swarm and Evolutionary Computation*, vol. 47, pp. 44–55, 2019.

[46] S. Darwish, M. El-Dirini, and A. Abd El-Moghith, "An adaptive cellular automata scheme for diagnosis of fault tolerance

and connectivity preserving in wireless sensor networks," *Alexandria Engineering Journal*, vol. 57, no. 4, pp. 4267–4275, 2018.

[47] S. Khan, M. Z. Khan, P. Khan, G. Mehmood, A. Khan, and M. Fayaz, "An ant-hocnet routing protocol based on optimized fuzzy logic for swarm of UAVs in FANET," *Wireless Communications and Mobile Computing*, vol. 2022, Article ID 6783777, 12 pages, 2022.

[48] A. Malik, M. Z. Khan, S. M. Qaisar, M. Faisal, and G. Mehmood, "An efficient approach for the detection and prevention of gray-hole attacks in VANETs," *IEEE Access*, vol. 11, pp. 46691–46706, 2023.

[49] M. N. Khan, H. U. Rahman, M. Z. Khan et al., "Energy-efficient dynamic and adaptive state-based scheduling (EDASS) scheme for wireless sensor networks," *IEEE Sensors Journal*, vol. 22, no. 12, pp. 12386–12403, 2022.

[50] S. Kumari, P. K. Mishra, A. K. Sangaiah, and V. Anand, "Priority based k-coverage hole restoration and m-connectivity using whale optimization scheme for underwater wireless sensor networks," *International Journal of Intelligent Networks*, vol. 4, pp. 240–252, 2023.

[51] J. Zhang, B. Chen, Y. Zhang, C. Jiang, and A. Song, "3D self-deployment of jumping robot sensor nodes for improving network performance in obstacle dense environment," *Measurement*, vol. 207, article 112410, 2023.

[52] N. Temene, A. Naoum, C. Sergiou, C. Georgiou, and V. Vassiliou, "A Decentralized Node Placement Algorithm for WSNs and IoT Networks," in *2022 IEEE 8th World Forum on Internet of Things (WF-IoT)*, pp. 1–6, Yokohama, Japan, 2022.

[53] P. Gou, M. Guo, B. Guo, and S. Mao, "DHD-MEPO: a novel distributed coverage hole detection and repair method for three-dimensional hybrid wireless sensor networks," *Electronics*, vol. 12, no. 11, p. 2445, 2023.

[54] L. Lin, X. Zhu, J. Tang, and C. Dong, "Placement of UAVs to Reconnect Lost Subnetworks in Wireless Sensor Networks," in *2023 IFIP Networking Conference (IFIP Networking)*, pp. 1–9, Barcelona, Spain, 2023.

[55] D. Mandloi and R. Arya, "Q-learning-based UAV-mounted base station positioning in a disaster scenario for connectivity to the users located at unknown positions," *The Journal of Supercomputing*, vol. 79, no. 14, pp. 15643–15674, 2023.

[56] S. Juneja, K. Kaur, and H. Singh, "An intelligent coverage optimization and link-stability routing for energy efficient wireless sensor network," *Wireless Networks*, vol. 28, no. 2, pp. 705–719, 2022.

[57] S. Shukla, "Angle based critical nodes detection (ABCND) for reliable industrial wireless sensor networks," *Wireless Personal Communications*, vol. 130, no. 2, pp. 757–775, 2023.

[58] S. Kumari, P. K. Mishra, and V. Anand, "Coverage and connectivity aware deployment scheme for autonomous underwater vehicles in underwater wireless sensor networks," *Wireless Personal Communications*, vol. 132, no. 2, pp. 909–931, 2023.

[59] J. Pei, H. Chen, and C. K. Tse, "UAV Swarm for Connectivity Enhancement of Multiple Isolated Sensor Networks for Internet of Things Application," *IEEE Transactions on Vehicular Technology*, vol. 72, no. 3, pp. 3914–3929, 2023.

[60] B. H. Ngoc, N. T. Tam, H. T. T. Binh, and L. T. Vinh, "A phenotype-based multi-objective evolutionary algorithm for maximizing lifetime in wireless sensor networks with bounded hop," *Soft Computing*, pp. 1–19, 2023.

[61] C. Cav and A. Altın-Kayhan, "Coverage hole optimization with a mobile sensor in wireless sensor networks for smart grid," *Ad Hoc Networks*, vol. 140, article 103039, 2023.

[62] M. Z. U. Haq, M. Z. Khan, H. U. Rehman et al., "An adaptive topology management scheme to maintain network connectivity in wireless sensor networks," *Sensors*, vol. 22, no. 8, p. 2855, 2022.

[63] G. Mehmood, M. Z. Khan, A. K. Bashir, Y. D. Al-Otaibi, and S. Khan, "An efficient QoS-based multi-path routing scheme for smart healthcare monitoring in wireless body area networks," *Computers and Electrical Engineering*, vol. 109, article 108517, 2023.