Multi-Radio Multi-Channel Assignment Algorithm in Maritime Wireless Mesh Networks

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ABSTRACT The recent growth in the maritime industry stemming to increase in global commerce as well as searching for hydrocarbons at offshore locations, the high data rate and cost affordable maritime communication is acquired. A mesh network is envisaged for maritime communications because of its expanded coverage, self-healing, and high-capacity. With the development of multi-radio technology, the frequency interference can be decreased sharply with proper channel assignment. The static channel assignment optimization is often applied to decrease the wireless frequency interference which is known as an NP-hard problem. In this paper, we focus on the static channel assignment issue and propose a heuristic algorithm to solve the optimization problem. The problem is addressed by assigning channels to communication links to minimize the interference from overall network. A modified particle swarm optimization (PSO) algorithm is proposed to optimize the problem, and a new merging solution is adopted to reassign channels for nodes, which violate the radio constraints. Multi-radio simulation is performed in NS-3 to validate the effectiveness of the proposed channel assignment algorithm. The results show that the algorithm is able to find an optimized assignment with fewer iterations than the previous work and improve network performance.

INDEX TERMS Multi-radio multi-channel, channel assignment, wireless mesh networks, marine communication.

I. INTRODUCTION

Wireless mesh network is envisaged for maritime communications because: firstly, the network coverage can easily be expanded as a mesh node to route and relay traffic for other nodes. Secondly, mesh network is capable of self-healing and has resilient paths. It is important in maritime wireless networks because the routing path may often fail due to sea wave rocking and occlusions. Thirdly, a mesh network can easily increase its capacity by simultaneous transmissions over nodes, which are separated by the several hops [1].

With the merits of self-organized, self-configured, high bandwidth, and fast deployment superiorities, wireless mesh networks have been a promising wireless communication technology, and applied to diverse application scenarios, e.g., transportation monitoring, car networks and especially marine communication as shown in Fig.1. Though there are great research topics on underwater acoustic sensor networks [1]–[4]. The wireless mesh network could be the promising architecture at sea. However, there are still challenging limitations to improve the network performance. One of them is the channel assignment between communication links that transmit data simultaneously [5]. An effective and efficient assignment is required to decrease interference,
and improve the network capacity. Moreover, equipping each node with multiple radio interfaces communicating on multiple channels (MRMC), the network quality can be improved dramatically.

Research has been done on channel assignment in the MRMC WMNs, and a number of algorithms have been presented. Generally, the solutions can be classified into three categories static, dynamic and hybrid, which depends on how frequently the channel assignment scheme is modified [6]. Static channel assignments are flexible to deploy but unsuccessful to sense the changes in the network environment [7]–[10]. The dynamic schemes enforce nodes to switch their interface channels dynamically between successive data transmissions in high synchronizations requirement [11]. Hybrid approaches combine the static and dynamic channels in which some part of interfaces are assigned to static channels and others to dynamic channels [12].

Common Channel Assignment (CCA) [7] is a simplest static approach for utilizing two channels in a dual-radio network but it is inefficient because it neglects various factors affecting the performance. To achieve efficient channel utilization, a greedy heuristic algorithm is proposed in [8], which aims to find connected and low interference topologies, and it formulates the base channel assignment as a topology control optimization problem. Similarly, Maryam Amiri Nezhad suggested an utility based channel assignment (UBCA) algorithm [9], which considers the node priority and delivery probability, simultaneously, useless links are removed to lead a more flexible choice for other links. However, the studies adopted the simplistic protocol interference model [6], and was not realistic and practical. To construct a physical interference model, Birui Shao described a model and proposed a pure integer quadratic programming (PIQP) model [10] to maximize the network capacity and used the physical interference model instead of protocol interference model to simulate more realistically. When the co-channel interference is taking into account, PIQP can no longer solve the problem. Llorenç presented a semi-dynamic and distributed algorithm named SICA [13] considering both external and internal interference. Furthermore, the same authors also validated SICA based on Markov chains in [11] and proposed an automated test module to verify the simulation [14]. However, it is complicated and requires high synchronization.

For static channel assignment, Arindam K. Das proposed two integer linear programming (ILP) models in [15]. The two models maximize the number of links which can be activated simultaneously. However, if the objective function differs, the model should be modified. Anand Prabhu Subramanian developed a semi-definite programming (SDP) model in [16], which minimized the average size of conflicting link sets in the whole network. In [17], the author proposed an integer quadratic programming (IQP) model to optimize the link channel assignment with the objective of minimizing the average network interference according to the network topology and the data transfer rate of each link. But the models need much computation time specially in dense network. To reduce the computation complexity effectively, a heuristic algorithm, based on discrete particle swarm optimization (DPSO) [18], was proposed, which is faster and produces better results. However, the network performance was not discussed, and even the assignment of multiple channels to each link was not considered. In this paper, we not only propose an improved PSO algorithm but also validate the network performance through Network Simulator.

When taking the traffic into consideration, the model turns more complex. Traffic-aware routing-independent channel assignment algorithm (TARICA) [19], which has two phases-initial channel setting and iterative improvement, is a centralized and static technique to assign channels to multi-radio WMN links. However, it does not guarantee that connectivity in a WMN is the minimizing process follows a greedy method. In [20], a centralized and quasi-static technique TICA was introduced to improve the medium access fairness among the mesh nodes. However, the external interference, traffic load, queuing delay and environmental effects were not considered. Besides, a static technique was proposed in [21] which designed a logical network topology with k-connected constraint and then performed channel assignment using minimum spanning tree (MST) search. Moreover, Genetic Algorithm (GA) was proposed in [22] to minimize total interfering traffic load over the network. This technique does not have any objective functions to maintain network connectivity. Another static technique Generic Tabu Search (GTS) assigned channels to a maximal independent set of WMN links [23]. It started with some randomly selected channel assignments for a conflict graph [5]. Similarly, the shortcoming of GTS is that it doesn’t take any measurement to maintain the network connectivity.

For dynamic channel allocation, [24] introduced an optimization algorithm that considers both throughput and delay for channel assignment with an objective to reduce packet delay without degrading the network throughput. Additionally, A.Hamed Mohsenian Rad proposed a Joint Optimal
Channel Assignment and Congestion Control (JOCAC) algorithm [25], which assigned not only non-overlapping channels, but also the partially-overlapping channels.

In this paper, we discuss the maritime communication environment including effect of sea surface movement and the channel properties. We focus on the channel assignment based on the protocol interference model and adopt a modified PSO algorithm to the optimization model. Multi-radio multi-channel simulation in NS-3 has been added to verify our algorithm. The simulation results show that the proposed algorithm is able to decrease the interference and network delay. It is concluded that the proposed algorithm can improve the network performance effectively and efficiently.

The remaining of this paper is organized as follows. Section II provides a detailed description on the network and system models. The problem formulation and channel assignment model are given in Section III. In Section IV, the idea of PSO in channel assignment and the channel merge are introduced in detail. Section V shows the discussion and simulation results. Finally, conclusion is drawn in section VI.

II. NETWORK AND SYSTEM MODELS

In this section, a short introduction on maritime communication environment and WMNs including its architecture and merits compared to some known wireless networks is given. Then, we set up the network model and interference model.

A. MARITIME COMMUNICATION ENVIRONMENT

In contrast to the land surface, the sea surface is complex and random. Movement of sea surface causes ships and buoys, and thus antennas installed on them, to move in various ways: pitch and roll, and rise or fall. Then, it leads to misalignment of the transmitter and receiver antennas, as well as changes the antenna heights. Misalignment of antennas is challenging, as high gain directional antennas with narrow bandwidth is used for maritime communications to overcome large path loss due to long distance. The signal strength variation due to misalignment of antennas can be quite significant.

Moreover, sea surface movement can also lead to wave occlusions, which may break the communication links. Those communication links can be disconnected within several seconds because of the long period of sea waves. In this period, increasing the maximum number of retransmissions before discarding a packet is not an effective way to improve the performance, so other effective methods must be applied.

B. MULTI-RADIO WIRELESS MESH NETWORK

The wireless mesh networks consist of mesh routers and mesh clients, where the mesh routers with wireless devices are connected as backbone of WMNs [5]. The mesh routers form the bridge between the mesh clients and Internet gateways as well as the routers in wired infrastructure. Data can be transmitted or relayed by wireless mesh routers in a multihop way, which can be deployed flexibly and reduce the cost of hardware devices.

As shown in Fig.2, the backbone consists of numerous stationary mesh routers. Each mesh router operates not only as a host but also as a router, forwarding packets on behalf of other nodes that may not be within direct wireless transmission range of their destinations. Moreover, mesh routers provide the accesses of different kinds of heterogeneous networks. Meanwhile, mesh clients can be stationary or mobile and are able to form a client mesh network with other clients and mesh routers. Therefore, the WMNs can improve the network robustness and node flexibility, providing a wider wireless communication coverage compared to other wireless networks, e.g., WLAN and ad-Hoc.

C. NETWORK AND INTERFERENCE MODEL

We consider a wireless mesh network with \( N \) stationary nodes and \( M \) links. The network can be represented in form of an undirected connectivity graph \( G = (V, E) \), where \( V \) indicates the set of nodes in the network while \( E \) is the set of edges. Every edge in the graph is referred to as a communication link between two nodes which can communicate with each other as long as they share a common channel. Each node in \( V \) is equipped with multiple radios. We use \( R_i \) to represent the number of radios on node \( i (i = 1, 2, \ldots, N) \). There are \( C \) available orthogonal channels that can be assigned to each link. For simplicity, we assume that all radios have the same characteristic and transmission range.

Practically, the connectivity graph is not sufficient to fully illustrate the wireless network, due to the interference of the wireless links transmitting on the same channel. Therefore, to consider the impact of interference, we need to adopt a conflict graph \( G_f = (V_f, E_f) \) to indicate the links interfering with each other. A vertex in the conflict graph represents an edge (or link) in the connectivity graph. There is an edge between two vertexes in the conflict graph if the corresponding links interfere with each other. Fig.3 (a) shows a graph of a four node network and (b) shows its corresponding conflict graph.
III. PROBLEM FORMULATION

In this section, we firstly discuss the basic channel assignment problem including the objective and constraints of the channel assignment. In addition, several matrices necessary for system model are defined to formulate the solution model.

A. OBJECTIVE AND CONSTRAINTS

In a multi-radio multi-channel wireless mesh network, this work focuses on the problem of allocating channels to the communication links in the network. Every mesh node is equipped with multiple interfaces to improve the network throughput. Each interface can utilize different orthogonal channels to transmit data simultaneously. Therefore, the channel assignment should follow some constraints related to the radios and channels.

To our knowledge, a channel assignment algorithm should satisfy the following constraints:

1) The total number of channels is fixed.
2) The maximum number of channels assigned to a mesh node depends on the radios the node owns.
3) Each link should be assigned one channel from available channels.

There are many feasible assignments that satisfy the above constraints. However, we need to find the optimal one which minimizes the average network interference. The interference can be considered as an objective function. And, our aim is to find the minimum value of objective function. The throughput can be the objective function but we need to find the maximum of the objective function. In this paper, we plan to use the previous object function in our model. In brief, the objective of our assignment is to find the allocation which is able to decrease the actual interfere links.

B. MATRICES DEFINITION

To formulate this problem, matrices need to be defined. All the matrices used in our optimization model are as follows.

Definition 1: A $|N| \times |N|$ matrix $A_{\text{link}}$ represents the relationship between links and nodes. If there is a link between two nodes, the corresponding element is set to 1, otherwise it is 0 as default.

$$A_{\text{link}} = \begin{cases} 1, & \text{there is a link between nodes } N_i \text{ and } N_j \\ 0, & \text{otherwise} \end{cases}$$

With the link matrix $A_{\text{link}}$, we can get another $|M| \times 2$ matrix $S$ to index every pair nodes of all links. Each line means a link, and the two elements in this line mean that the nodes belong to this link. We will use it to compute the potential interference matrix as defined in Definition 4.

Definition 2: A $|M| \times |C|$ matrix $A_{\text{ch}}$ is a channel assignment matrix which illustrates the channels assigned to links. Our object is to find an $A_{\text{ch}}$ that can reduce the interference.

As shown in Fig.3, the number of links in the network connectivity is equal to the vertex number in the conflict graph. All of the four links interfere with each other, so each pair vertexes have an edge in conflict.

The existence and extent of interference between a pair of links are determined by an interference model. There are two well-known interference models: (a) the protocol model and (b) the physical model. The protocol model is the simplest and most commonly used to represent the interference whereas the physical model is more complex but offers a more realistic model [26]. For simplicity, we adopt the protocol model for formulation.

The channel assignment aims to minimize the average network interference without sacrificing the network connectivity, and to improve the performance of the network. An edge in the conflict graph will not interfere only if the two corresponding vertexes (or two links) are assigned with different channels. Fig.4 shows a simple example of this matter and it clarifies that the actual interference links decrease sharply with appropriate channel assignment.

Through this paper, we use the connectivity graph to model the network topology, and the conflict graph based on the protocol model for the wireless interference.
as far as possible.

\[
A_{ij}^{ch} = \begin{cases} 
1, & \text{if link } M_i \text{ is assigned channel } C_j \\
0, & \text{otherwise} 
\end{cases} \tag{2}
\]

We deduce that the sum of each row of matrix \(A^{ch}\) equals to 1, because each link can be assigned to only one channel.

Definition 3: A \(|N| \times |C|\) matrix \(A^{node}\) is a channel assignment matrix which denotes the channels assigned to the nodes.

\[
A_{ij}^{node} = \begin{cases} 
1, & \text{channel } C_j \text{ is assigned to node } N_i \\
0, & \text{otherwise} 
\end{cases} \tag{3}
\]

Due to one node is equipped with multi-radio, it can be assigned more than one channel. Since \(S\) denotes the nodes to links, and \(A^{ch}\) expresses the links to channels, we can get \(A^{node}\) matrix through the two matrices.

Definition 4: An \(|M| \times |M|\) matrix is defined to represent the Potential Interference (PI) matrix. It only takes the nature locations of all nodes into account, ignoring multi-radio and multi-channel. Therefore, our goal is to decrease the actual interference links by considering a channel assignment.

\[
PI_{ij} = \begin{cases} 
1, & \text{link } M_i \text{ potentially interferes link } M_j \\
0, & \text{otherwise} 
\end{cases} \tag{4}
\]

Definition 5: An \(|M| \times |M|\) actual interference matrix \(AI\) is defined. It describes the real conflict links after an appropriate channel assignment. As aforementioned, \(AI\) is subsequent from \(PI\) in Definition 4.

\[
AI_{ij} = \begin{cases} 
1, & \text{link } M_i \text{ actually interferes link } M_j \\
0, & \text{otherwise} \end{cases} \tag{5}
\]

The object of the channel assignment is to find the minimum number of actual interference links. To formulate this problem in the mathematic model, we obtain the object function like the following equation:

\[
\min \left[ \frac{1}{2} \sum_{i=1}^{M} \sum_{j=1}^{M} AI(i,j) \right] \tag{6}
\]

We use the network shown in Fig.4 as a simple example to explain this process. Fig.5 describes the channel assignment mechanism with details.

IV. OPTIMIZATION BASED ON PSO ALGORITHM

The optimization of channel assignment is considered as an NP-hard problem. Though many intelligence algorithms [22], [23] can optimize this kind of objective function, they are not suitable for discrete non-linear optimization with constraints. In this section, a heuristic solution inspired by the PSO algorithm is introduced in detail, and a novel channel merging method is explained which ensures that the generated solution does not violate the radio number constraint.

A. PSO ALGORITHM

The algorithm is inspired by Particle Swarm Optimization which is a probabilistic technique for approximating the global optimum of a given function. The inspiration of PSO comes from the behavior of bird flocking finding food [27] as follows.

Each bird represents a particle and a group of birds constitute the swarm. All birds in the swarm cooperate on finding the food through sharing their locations and the current nearest distance to the food. By this means, every particle records its local best location and distance information and the swarm has the global best information. All particles update their velocity according to both the local and global best location and change their current location. Along with the iterations, particle will approach to the object gradually.

The PSO algorithm has generally two main updating formulas. One is velocity formula depending on the global and partial best position marked by \(pBest\) and \(gBest\). The other is the location formula updated with the velocity. They are given as:

\[
\begin{align*}
\dot{v}_i &= w \cdot v_i + c_1 r_1[\text{pBest}_i - x_i] + c_2 r_2[\text{gBest}_i - x_i], \\
x'_i &= x_i + \dot{v}_i,
\end{align*}
\]

where \(\dot{v}_i\) is the current velocity formula, \(w\) is the inertia weight deciding the effect of the previous velocities \(v\), \(c_1\) and \(c_2\) are acceleration coefficients, \(r_1\) and \(r_2\) are uniform random numbers between \([0, 1]\), \(x_i\) is the previous position of the particle and \(x'_i\) is the updated position. After iterations, the position \(x\) will finally be convergent to the best position where the best fitness value locates.

However, the channel assignment is a discrete nonlinear optimization problem. To adopt the PSO algorithm, the position form should be changed. The output of the PSO algorithm does not consider the radio constraints. A channel reassignment should be applied to fit the radio constraints. We will introduce a channel merge method in section B. The main process can be shown in Fig.6.
In the position and velocity updating part, the formula (7) is used to update the position according to both the global and partial position.

**B. CHANNEL MERGE**

As introduced in section A, the position of each particle represents a feasible solution. It is updated without considering the radio number constraint. Thus, in the second phase, we eliminate the interface constraints by a channel merge procedure. Compared with the existing method in [16], a new merge solution which takes the channel usage ratio into account to avoid increasing interference links drastically. The core idea visits all nodes in the connectivity graph to ensure that the node does not violate the radio constraint. If the channel number that a node is assigned exceeds its radio number, the node will reassign the channel to the links from reasonable channels. A reasonable channel with a lower usage ratio will be finally selected. The procedure will be repeated until the last node is visited.

The channel merge program takes the channel usage ratio into account. It finds the nodes that violate the radio constraint and reassigns channels to the later links from the channels used by previous links of this node. The usage ratio decides which channel to be assigned. If there is a reassignment in a link, the channel usage ratio must be updated. By this way, the solution can reassign the least interference channel to the current link and finally acquire the with constraints.

**V. SIMULATIONS**

In this section, we study the performance of the proposed channel assignment algorithm using the Matlab and NS-3 simulator. Matlab is used to realize the algorithm and compare the fractional network interference with different algorithms. The fractional network interference is defined as the number of conflicts remain after channel assignment relative to the number of conflicts in a single channel network. The NS-3 simulator is applied to verify our algorithm by analyzing the average packet delivery ratio, average network delay and network throughput.

**A. SIMULATION PARAMETERS**

For simplicity, the grid network topologies are adopted. Based on the topology, the mesh module in NS-3 [28] is used. The routing protocol is the implementation of Hybrid Wireless Mesh Protocol (HWMP) which is proposed by the 802.11s standard [29], [30]. The constant bitrate flows over UDP are generated by traffic flows. As for applications, OnOffApplication in NS-3 is installed on the nodes which generate traffic to a single destination according to the OnOff pattern. The detailed parameters are set in Table 1.

**B. SIMULATION RESULTS**

The simulation includes: Matlab simulation and NS-3 experiment. The Matlab simulation is to setup the mathematic model and simulate the performance of our algorithm in solving this problem. The NS-3 experiment is to simulate the real network performance.

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**Algorithm 1 Channel Merge Program**

| Input: Radios $R$, Channels $C$, BestPosition $G_{best,x}$, $S$ |
| Output: Channel Assignment Matrix $A^{ch}$ |

1. Begin
2. compute the usage ratio of each channel and $A^{ch}$ matrix
3. for each node $i = 1 : N$ do
4. calculate total orthogonal channels used by each node	
5. $Ch$
6. if $Ch_i > R$ do
7. $L \leftarrow$ find the links corresponding to node $i$
8. for $j = (R + 1) : |L|$ do
9. for $k = 1 : R$ do
10. $ch \leftarrow$ find the channels used by the first $R$ links
11. end
12. calculate the usage ratio of channels from $ch$
13. assign the minimum usage ratio channel to the $jth$ link of node $i$
14. end
15. end
16. end
17. end
18. calculate $A^{ch}$
TABLE 1. Simulation parameters.

| Parameter                | Value                                      |
|--------------------------|--------------------------------------------|
| Number of radios         | 2                                          |
| Number of channels       | 3                                          |
| Packet size              | 512 bytes                                  |
| Transmission rate        | OFDM Rate 54 Mbps                          |
| Propagation loss model   | LogDistancePropagationLossModel [26]      |
| Physical layer protocol  | WIFI PHY STANDARD 802.11a                  |
| Simulation time          | 100 s                                      |

1) MATLAB SIMULATION

Firstly, the algorithm proposed in this paper is implemented using Matlab program and is compared with an existing heuristic Simulate Anneal (SA) method. Fractional network interference is set to be the object and is computed according to the number of radios. We simulate both sparse network and dense network with 12 channels available. The results are shown in Fig.7 and Fig.8.

The two algorithms that we proposed are both random solutions. To acquire more accurate comparison, each algorithm runs 10 times and the average value is plotted. As shown in Fig.7 and Fig.8, PSO and SA algorithms decrease the total interference links sharply. The proposed algorithm could decrease the interference to a lower level by equipping each node with only 4 radios. The results show that our PSO algorithm has smaller fractional network interference than the SA and CCA algorithm. The merit of PSO becomes more obvious in dense network and it has less computational complexity than the SA as depicted in Fig.9.

Notice that the computation time increases with the growth of network size. We perform the simulation with 3 radios per node and 5 channels are available. It can be observed that the computation time of the PSO is much less than that of the SA. The growth rate of the PSO is more smooth than that of SA. The result explains that the advantage of PSO with the help of a group of particles. On the contrary, the SA algorithm will accept a worse solution possibly in every iteration. In a word, the algorithm simulation illustrates that the PSO algorithm performs better than the SA algorithm in the proposed channel assignment model.

Fig.10 shows a random topology with 25 nodes in a 50*50 area. To let the nodes locate as balanced. We used K-means algorithm to generate the location randomly. The figure in the left is the communication graph with 17 links connected. And the right is its corresponding conflict graph, which reflects the channel interference. Also, it represents the single channel network.

Compared with Fig.10, Fig.11 shows the channel assignment can decrease the network interference well. The left figure in Fig.11 shows the conflict graph before channel merging and the right shows that after channel merging. And
it outperforms the method in [16] as it considered the current channel usage rate.

2) NS-3 EXPERIMENT
Apart from Matlab simulation, we also do simulation on NS-3 for calculating the network performance like the real environment. The simulation parameters are listed in Table 1. To be stressed, the Log-distance path loss model is used as a radio propagation model which predicts the path loss of signal encounters over distances to add interference. For the application layer, random flows are generated in time and in duration time. The number of flows represents the interference level, it is set to be 40 percent of the nodes number. Besides, the transmitter and receiver in each flow are generated randomly too so as to introduce interference.

The grid network topology is adopted. We simulate different network size scenarios, and the results are shown in Fig.12, Fig.13 and Fig.14.

Fig.12 shows the receive bitrate (or throughput) varies with different sizes of the network. The throughput is the total receive bitrate of all flows. Therefore, it will experience a linear growth if all packets are received correctly. The result shows that the throughput decreases when the network size increases in single-radio scenario. It means that equipping a node with multi-radios greatly improves the network throughput. The CCA and SA algorithms are limited by the network size. Compared with them, the throughput of the proposed PSO is better than other algorithms even in a dense network.

Fig.13 shows the average end-to-end delay which is calculated from the first transmitted packet to the last received packet. With higher number of nodes (or links) in the network, the delay increases rapidly. The result shows that the proposed PSO algorithm has the lowest delay compared to the other algorithms. In a single-radio scenario, the delay linear increases because the data are not allowed to be transmitted simultaneously. The delay of SA and CCA are easily affected by the network size which means that they are unable to decrease the interference efficiently.

Fig.14 shows that with the increase of flows, the interference between flows grows and leads to errors in receiving packets. Therefore, the packet delivery ratio reflects the network interference. The result tells that the PSO algorithm decreases the interference efficiently and achieves the highest packet delivery ratio.

VI. CONCLUSION
This study presents a modified Particle Swarm Optimization for multi-radio multi-channel channel assignment. The network and system model is introduced in details. A novel channel merge scheme has been described based on channel usage ratio. The advantage of the proposed scheme is demonstrated by comparing the fractional network interference with different existing algorithms. A statistical analysis
of the fractional network interference suggests that interference decreases significantly by our proposed method with fewer radios. The simulation results suggest that the proposed assignment improves the network performance efficiently both in sparse and dense networks. However, the proposed measure did not take the routing into account. Through the simulations, problems were found that the channel assignment would change the routes. Therefore, the interaction between channel assignment and routing protocols to avoid unnecessary changes in channels will be further studied in the future.

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