ROUTING DESIGN IN WIRELESS MESH NETWORK

A thesis submitted to The University of Manchester for the degree of

Doctor of Philosophy

in the Faculty of Science and Engineering

2022

Yuan Chai

Department of Computer Science

Contents

Word Count: 50880

List of Tables

List of Figures

List of Abbreviations

WMN	Wireless Mesh Network
ARM	Advanced Risc Machines
IoT	Internet of Things
QoS	Quality-of-Service
PTF	Probability of Transmission Failure
GA	Genetic Algorithm
EH	Energy Harvesting
SINR	Signal to Interference and Noise Ratio
SNR	Signal to Noise Ratio
OSI	Open Systems Interconnection
MAC	Medium Access Control
PDF	Probability Density Function
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
ACK	Acknowledge
DCF	Distributed Coordination Function
SDN	Software-Defined Networking
RREQ	Route Request
RREP	Route Reply
ETT	Expected Transmission Time
ETX	Expected Transmission Count
PSO	Particle Swarm Optimization
MODE	Multi-Objective Differential Evolution
ACO	Ant Colony Optimization
MOEA	Multi-Objective Evolutionary Algorithm
NSGA-II	Non-dominated Sorting Genetic Algorithm-II
CD	Crowding Distance
MINLP	Mixed Integer Non-Linear Programming
DEARER	Distance-and-Energy-Aware Routing with Energy Reservation
CH	Cluster Head
AODV	Ad hoc On-demand Distance Vector
SBR	Source-Based Routing
LAM	Load-Aware Metric
WCETT	Weighted Cumulative Expected Transmission Time
ELARM	Energy-Load Aware Routing Metric
OLSR	Optimized Link State Routing
LA-CHRP	Load-Aware Cooperative Hybrid Routing Protocol
SJR	SCImago Journal Rank
SNIP	Source Normalized Impact per Paper

Abstract

Wireless mesh network (WMN) is self-constructing and self-healing. Because of its low cost and easy-deployment features, WMN can be used in many scenarios such as emergency communication, Internet of Things, communication in rural areas and so on. Mesh routers and mesh clients compose WMN, and mesh routers are more stable and have stronger abilities. Routing is very important and non-effective routing will bring more interference and unbalanced loads. Most existing routing methods for WMN are reactive, which does not take advantage of the stability of mesh routers. In addition, load, interference, and energy are not considered comprehensively.

In this thesis, we overcome the weaknesses of existing routing methods. As centralized proactive and distributed reactive routing methods are suitable for stable mesh routers and mobile mesh clients respectively, we first give a hybrid routing method for WMN including both static mesh routers and mobile mesh clients. In addition, the centralized proactive routing method among infrastructure WMN composed of stable mesh routers is very important. To improve the proactive routing in the proposed hybrid routing, delay is minimized in the optimization model in our second work. Then, to overcome the neglect of energy constraint in these two works, energy harvesting is considered in the third work. Finally, unlike the third work needing to set weight values for different objectives in the routing problem, our fourth work proposes a multi-objective routing with reinforcement learning. In general, the four main works of the thesis are given as follows.

First, a hybrid routing method is proposed. The current weaknesses of neglecting regional conditions and not considering whole proactive path conditions when mesh clients accessing mesh routers are overcome. The load conditions are considered for mesh routers. Mobility and energy are further researched for mesh clients. In addition, the region with heavy load will be avoided. This proposed method brings 10.19% and 33.29% improved performance than two current hybrid routing methods respectively.

Second, for the infrastructure WMN part, the centralized proactive routing method is designed. The routing problem is formulated as an optimization problem from a global network view. Minimizing delay is set as the objective, which is derived by considering interference, packet transmission failure, and bandwidth. The overhead of obtaining delay is reduced and load is balanced by an improved genetic algorithm. 29.03% and 50.20% better performance than two current methods is gotten.

Third, a centralized routing method with a long-term objective to balance load and energy consumption is further proposed. Load, channel condition, energy cost and energy harvesting are considered. This proposed routing can obtain 1.69%, 10.33% and 26.2% better performance compared with three other routing methods.

Fourth, to consider delay and energy efficiency at the same time without setting weight values like the previous third work, a multi-objective routing is proposed. The routing problem with uncertain network conditions can be solved. Dyna-Q is used to solve the multi-objective routing problem for the first time. The performance is 42.12%, 43.96% and 47.54% better than three other state-of-the-art routing methods.

Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Copyright

Acknowledgements

I would like to express my deepest appreciation to my supervisor Prof. Xiao-Jun Zeng for the very valuable guidance, suggestions, ideas, support, and patience throughout all my research and study. With his great help, I organize my research and make progress step by step. Through the discussions with him, I also learn a lot about the meaning and process of research, which is very precious for my future work. He is also a very nice and friendly person who let me feel warmth in my life in Manchester.

To my parents, thank them so much for their love and understanding. I may not catch such a rare opportunity to finish my PhD study without their moral support. The happy and relaxing family atmosphere gives me the courage to do what I like. To my friends and colleagues, I would like to sincerely thank them for the sharing and discussions. Thank them to accompany me to help and encourage me all the time.

Last but not least, I would also like to take this chance to thank the University of Manchester - China Scholarship Council scholarship and Chinese Student Awards funded by Great Britain China Educational Trust. With their financial support, I study smoothly and obtain a wonderful life in Manchester.

Chapter 1

Introduction

1.1 Wireless Mesh Network

Wireless mesh network (WMN) is a type of self-organization and self-configuration wireless network. With the ability to maintain connectivity, WMN can be established easily. In addition, no traditional fixed base station is needed, so the establishment is with low cost, low complexity, and high flexibility. With these advantages, WMN is an important architecture in the next generation of communication networks and can solve the last-mile bottleneck problem, which draws the interest of many researchers [1] [2] [3].

WMN is composed of two types of mesh nodes: mesh routers and mesh clients. The features of these two types of mesh nodes are different. Mesh routers are more stable with stronger processing ability. They are often with multiple radio interfaces to improve communication efficiency. Some of them even have the function of gateway to connect WMN to the Internet. Machines based on dedicated computer systems like advanced risc machines (ARM) or machines based on general-purpose computer systems like desktop PC can be mesh routers. Mesh clients are more mobile and with single radio interface. Although mesh clients also have the function for mesh networking and routing, they cannot be as a gateway. The hardware platform and the software for mesh clients are much simpler than mesh routers. Many different types of devices like laptops and smartphones can become mesh clients. Mesh clients often have more limited energy capacity.

Based on the features and functions of networking, WMN can be categorized into three types: infrastructure WMN, client WMN and hybrid WMN [4]. Mesh routers form the infrastructure WMN. The topology of infrastructure WMN is stable and mesh routers can provide access functions for mesh clients. As some mesh routers have the bridge and gateway function, infrastructure WMN can connect to different types of networks such as cellular and sensor networks. Client WMN is composed of mesh clients. The topology is flexible and mesh clients can communicate with each other through multiple hops. Like the mesh routers, mesh clients also can relay packets to destinations. Hybrid WMN combines infrastructure WMN and client WMN. Mesh clients can access mesh routers or directly communicate with other mesh clients. The coverage is extended by more flexible communication.

There are two types of traffic in WMN: gateway-oriented traffic and client-oriented traffic. In gateway-oriented traffic, the data goes to the gateway. If a source node wants to send packets to the gateway, mesh routers can be accessed and packets can then be transmitted through the infrastructure WMN. In client-oriented traffic, the destination is the mesh client. The source node can find a multi-hop path to achieve the destination.

Due to the low cost, easy deployment and flexible coverage, WMN has a wide range of applications. First, WMN can be used for emergency communication. Sometimes the traditional communication based on base stations is destroyed by disasters like earthquakes and floods. It will cost a lot of time to repair the stations. In this case, WMN can be established quickly with low cost to recover the urgent service of basic communication. In addition, in the concert or exhibition, users are temporarily crowded and WMN can provide the communication to the Internet with quick deployment. Second, WMN can serve the request of scalable topology and solve the isolation problem more easily. WMN is then suitable for enterprise networking, broadband home networking, health systems and so on. Third, because of the location and complex physiognomy, it is hard and expensive to build the traditional base stations and wired communication systems in some rural areas. Although wireless technologies develop fast, it is still hard for some people to use the Internet in some places. WMN is valuable to provide Internet service in this case. Fourth, as the Internet of Things (IoT) develops quickly and more and more data needs to be transmitted, edge computing is more and more popular to process data efficiently [5,6]. The features of interaction between mesh routers through multiple hops and cooperation between different types of devices in WMN bring a new computing paradigm [7]. The best features of cloud computing, fog computing and cooperative computing are integrated. Mesh topology can also improve reliability and enlarge the coverage of Bluetooth [8]. WMN is thus an essential technology in future IoT development. In general, WMN can be used in many different scenes. In addition to the cases mentioned above, WMN can also work well in many other situations. Multi-hop WMN without fixed infrastructure is one of the key components of next-generation wireless community networks [9].

1.2 Routing Design

Routing design is an important part of the network deployment. Different routing decisions will bring totally different network performance. The routing process can discover and maintain routes from source nodes to destination nodes. An effective routing method can use the constrained wireless resources efficiently and guarantee smooth communication. Multi-hop wireless communication brings complex topology and connection relationships. If bad routes are selected, congestion, interference, high cost and a large amount of energy consumption will be caused. Designing an effective routing method is thus essential to improve the whole network performance.

Based on the route established time, routing methods can be classified into proactive routing [10], reactive routing [11] and hybrid routing [12]. Hybrid routing is a combination of proactive and reactive routing. In proactive routing methods, nodes in the network actively discover and maintain routes to other nodes all the time. No matter whether data packets are needing to be transmitted, the proactive routing methods always find and store routes. Control packets are transmitted among the network periodically. When there is a communication request, less response time will be needed because routes are already known. However, the control overhead is large as the route discovery process is undertaken all the time. Unlike the proactive routing methods, reactive routing methods only start to find routes when nodes need to start communication and transmit packets. The control overhead is less because the routes do not need to be discovered and maintained all the way.

In terms of the place of making routing decision, routing methods can be divided into two groups: distributed routing [13,14,15,3,16,17,18] and centralized routing [19,20,21,22,23,24]. In distributed routing, nodes maintain local information themselves and each of them can decide the route selection. In centralized routing, nodes transmit their information to the network manager, and the network manager does the calculation and gives the best route selection. The global network information like topology is considered and used. In this way, the global best network performance can be obtained.

The changeable topology will bring more control overhead. The nodes move and connection relationships change, so routes are broken frequently. Once the routes are broken, control packets are sent to discover and store new routes. New neighbourhood and connection relationships are also needed to be updated frequently. If the proactive routing method which needs to maintain routes all the time is used in the network with high mobility, a very large amount of control packets will be transmitted. Congestion will be caused and the wireless resources are occupied, which will decrease the performance of the mobile network. Therefore, the reactive routing method rather than the proactive routing method is more suitable for mobile networks. In the reactive routing method, route discovery starts only when packets need to be transmitted. In addition, if the centralized routing method is used among the mobile nodes, the network manager needs to monitor the changeable topology. Each time of requesting a route, each mobile node needs to transmit its neighbour list to the network manager, and the network manager will have the whole network topology after collection. Then the best routes are computed by the manager according to the network topology. The overhead of transmitting neighbour list is high in this case. In the distributed routing method, mobile nodes do not need to transmit their neighbour list out to the network manager and they just maintain the neighbour information by themselves. The control overhead is reduced. Thus, in terms of overhead and resource consumption, distributed reactive routing is suitable for mobile nodes.

In stable topology, the connection relationships do not change so much, and it is easy to maintain stable routes without sending many control packets frequently. Proactive routing methods can work well in this case. Stable routes can be discovered and maintained among the static nodes without a large overhead. Existing routes can be used directly when communication requests exist, and discovery time is saved. In addition, centralized routing design with the view of the global network is also suitable because the network manager does not need to maintain the changeable topology. The overhead caused by each node transmitting its neighbour list to the network manager is avoided. Routes that can bring the best global network performance can be obtained by the centralized routing method. Therefore, centralized proactive routing works well for static nodes.

To explain clearly, the features and differences between proactive and reactive routing methods are concluded in Table 1.1.

Table 1.1 Comparison between proactive and reactive routing methods

Characteristics	Proactive routing	Reactive routing
Routing establishment time	Maintain routes all the time no matter whether there are packets needing to be transmitted	Establish routes only when packets are needing to be transmitted
Overhead	The amount of control packets is large in mobile networks. The control packets of discovering routes and updating connection relationships need to be transmitted frequently all the time.	Reduce the amount of control packets by only building paths when data is needed to be transmitted.
Response time	The response time to the data	Some time is needed to

	request from source node before transmission is small. When data packets are needed to be transmitted, the existing routes can be used directly and immediately.	establish routes before the source node can transmit data.

Similarly, the characteristics of centralized and distributed routing methods are summarized in Table 1.2.

Table 1.2 Comparison between centralized and distributed routing methods

Characteristics	Centralized routing	Distributed routing
Overhead	The overhead is large in mobile networks because the topology changes all the time and neighbour lists should be updated to the network manager frequently.	The overhead is less because the neighbour lists do not need to be sent to the network manager.
Information type used to select path	Global information of the whole network is used to select paths. The network performance can be improved with the view of global network.	Local information about neighbour nodes is used.
Location of making decision	After monitoring the whole network, the network manager selects the best routes and sends back the routes to mesh nodes.	The mesh node itself can select paths.

In general, the centralized proactive routing method is suitable for static mesh routers and the distributed reactive routing method adapts to mobile mesh clients. Thus, the hybrid routing method combining centralized proactive routing method and distributed reactive routing method can work well for WMN containing both static mesh routers and mobile mesh clients.

The routing metric is the main component of the routing design. It is the evaluation standard and objective of selecting paths. Different routing metrics can be designed according to applications with different quality-of-service (QoS) requests. The popular and traditional routing metric is the hop count. The path which has the least number of hops will be selected to transmit packets. The implementation is simple and easy. However, in wireless networks, many other important factors will influence network performance. Only considering hop count neglects other network conditions like load, interference, packet loss, delay, energy and so on. The way with the least hop count may have congestion and long delay, so it is important to also consider other factors based on QoS focuses. For some real-time applications such as automatic driving, video conferences and video games, little delay is requested. Delay is a metric that is influenced by other factors like load, interference, bandwidth, packet loss and so on. For some high reliable requests like the transmission in company communication, less packet loss is needed. For some networks with very limited energy, it is important to consider the energy condition. If the energy is not consumed in balance, the nodes which are overused will run out of energy quickly. Then these nodes will die and cannot serve any communication anymore. Some links and routes will be broken, and even some nodes can become isolated nodes. Therefore, it is essential to give an effective routing metric to guide route selection in terms of different requests.

1.3 Aim and Objectives

For a given scene, routing method should be designed effectively to adapt to the network features. The aim of routing design is to suit network features, overcome current weaknesses, satisfy communication requests, and improve the whole network performance.

For example, in a WMN such as a vehicular network in our life, which includes static stations, mobile buses, cars and pedestrians, routing design should consider the different features of these different nodes. The static nodes can be seen as mesh routers, and the mobile nodes can be seen as mesh clients. The structure of the designed routing method in such network should be determined first. As stations are static, a centralized proactive routing method can be used among them. For the mobile cars and pedestrians, a distributed reactive routing method can be applied to discover routes reactively. The static stations have stronger capabilities and compose the network infrastructure, so the design of centralized proactive routing method should be put the emphasis on. Once a mobile car or pedestrian accesses the static station, the proactive path to the gateway can be used directly to save the route discovery time. In general, such hybrid routing method which combines both centralized proactive and distributed reactive routing methods is suitable for the network with both static and mobile nodes. The structure of a desirable routing method should take advantage of the stability features of different nodes effectively.

After determining the routing method structure, the routing metric should be designed based on the application requests and network conditions. Reactions in self-driving cars need to be fast, so the information transmission in this case should be with least delay. Some cars and pedestrians may gather in some areas, which will cause congestion. The congested neighbouring nodes cannot forward packets for others. Such areas should be avoided being used to balance load. At the same time, the interference will also increase delay, so the network conditions like interference should also be considered. The overhead of obtaining network conditions should be as little as possible to save network resources. Unlike static stations, cars and pedestrians are mobile. The mobility of them needs to be taken into account too. The stable route will be better so the nodes with less speed can be used first. In addition, the energy capacity is often very limited, and the energy consumption should be balanced to avoid some nodes being dead quickly. Therefore, the factors considered in a desirable routing metric should be related to node characteristics and network conditions. Routes can be adaptively selected according to different scenes.

In general, routing design should consider the node features, application requests, and network conditions. Then, the objectives of routing design can be concluded as:

- Designing the structure of routing method according to the mobility of nodes. Existing research about hybrid routing methods is not much. For static mesh routers, they can use both proactive and reactive routing methods. The mobile mesh clients should use the reactive one. The proactive routing can have higher priority, because the proactive path is much more stable and reliable.
- Designing effective centralized proactive and distributed reactive routing methods respectively to overcome current weaknesses and satisfy requests. Load balance, interference, energy, regional conditions, etc. should be considered. For the centralized proactive routing, it can be formulated as an optimization model. The objectives should be set according to the application requests such as delay and energy. Energy harvesting (EH), load and interference can be considered simultaneously. In addition, the objective can be considered as a long-term one. The good network performance should be achieved during a whole operation period. For the distributed reactive routing, different features of different types of nodes should be considered. Network conditions are dynamic, so the design of both centralized proactive and distributed reactive routing methods should consider such characteristic. Further, the overhead of implementing routing methods should be small, which it is not often considered.
- Improving the whole network performance. The most important value of a newly proposed routing method is to improve the network performance.

After designing the routing methods for WMN, the performance of the designed routing methods should be evaluated to check whether they can improve the whole network performance. As they overcome some weaknesses of current routing methods, some current state-of-the-art routing methods need to be compared. The network performance in terms of the criteria like network throughput, delay, packet loss rate, etc. should be measured.

Above all, the system model and objectives of routing design can be shown in the Figure 1.1.

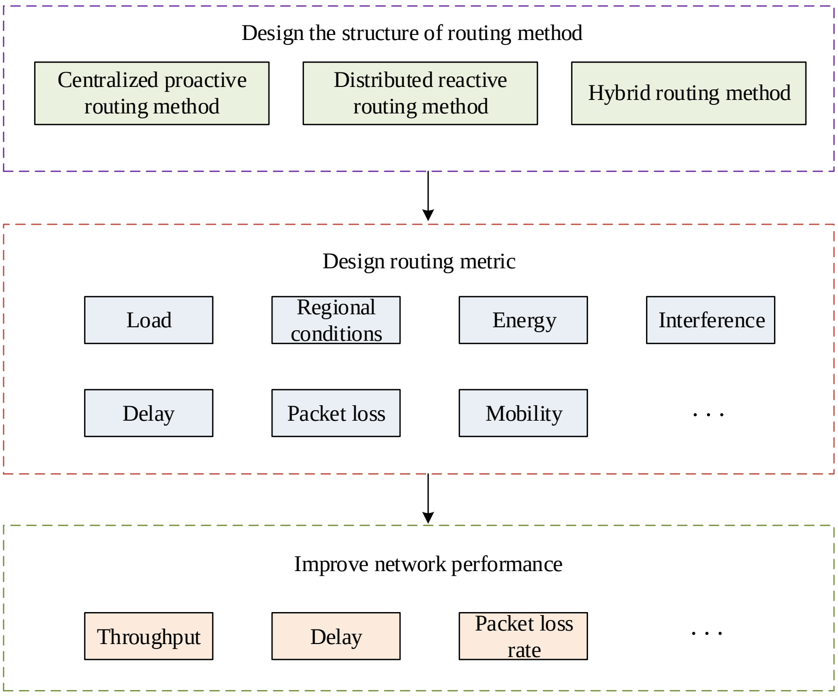


Figure 1.1 System model of routing design

1.4 Contributions

As mentioned in the section 1.2, according to the mobility of nodes, the hybrid routing methods that combine both centralized proactive routing and distributed reactive routing are suitable for WMN including both stable and mobile nodes. First, we analyze the architecture of hybrid routing and propose an effective hybrid routing method. Then, the proactive and reactive routing methods are designed according to the features of mesh routers and mesh clients respectively. Unlike mesh clients, mesh routers are stable and have stronger processing ability. They can form the infrastructure and influence network performance to a great extent. Thus, the centralized proactive routing part among infrastructure WMN should be further designed to fully consider network conditions in order to improve network performance. In general, the main contributions of this thesis are:

1. Designing a hybrid routing method that considers the different features of mesh routers and mesh clients. As mesh routers are stable, the proactive routing method is used among mesh routers according to the analyses in section 1.2. The reactive routing method is used among mesh clients. The detailed contributions are as follows.

(1) Considering regional condition. Current hybrid routing methods haven't considered the regional condition. The regional condition is the performance of neighbouring nodes. A node in the network cannot work individually and it must communicate and cooperate with other nodes. The conditions at neighbouring nodes can then influence the current node. The node with little load itself but heavy regional load is not a good choice to forward packets, because the heavy neighbouring load will bring heavy congestion and interference in this area. In addition to the condition of a node itself, the regional conditions should also be considered. For mesh routers, the load of themselves, the load and speed of neighbouring mesh clients are considered. For mesh clients, the load of themselves and the number of neighbouring mesh routers are considered. In addition, energy is also taken into account.

(2) Considering gateway- and client-oriented traffic respectively. The destination of gateway-oriented traffic is the gateway which is the mesh router with a gateway function. Thus, when a mesh router receives the data packets and becomes the intermediate mesh node, the proactive route can be used to reach the gateway. Before the first reached mesh router, the reactive routing method is used. Once a mesh router is reached, the existing proactive route to the gateway can be applied. The destination of the client-oriented traffic is the mesh client rather than the mesh router. The reactive

routing method is used in this case.

2. As mesh routers are stable and with stronger processing ability, it is important to carefully select effective proactive paths among mesh routers. Therefore, a centralized proactive routing method for infrastructure WMN is proposed with the global network view. The detailed contributions are:

(1) Deriving the mathematical relationship between delay and the number of interfering nodes, which will reduce the overhead of obtaining delay. As many applications urge short delay, minimizing delay is the objective of the formulated routing optimization problem. Obtaining delay by probe packets in current common methods will bring high cost, so it is essential to derive delay based on simple factors. The relationship between delay and the number of interfering nodes is then built. The bandwidth, interference, and the probability of transmission failure (PTF) are all considered.

(2) Solving the routing optimization problem by an improved genetic algorithm (GA). The basic GA does not consider the load balance in the particular routing problem. The situation that several data flows use the same mesh node is avoided here. According to the built relationship between delay and the number of interfering nodes, the common node used by several data flows will be replaced by another node with the least number of interfering nodes. The analyses and the rationality are also given.

3. Further designing a centralized routing method with a long-term objective. The routes are generally decided at a time in existing centralized routing methods. However, the traffic in the network can often change, so the objective of the formulated routing problem is further set to be long-term. The routing update problem is further considered here. Routes can be selected and updated according to real-time traffic. The detailed contributions are:

(1) In addition to load, energy is also considered in the long-term weighted sum cost. The load is influenced by interference, bandwidth, PTF and path loss. The PTF is derived as the same method as that in previous contribution 2(1). As green communication is quite beneficial, EH which is always neglected by existing routing for WMN is also considered. The remaining energy is calculated based on the

consumed and harvested energy amount.

(2) Using dynamic programming (DP) to solve the dynamic optimization model. The time is divided into several time epochs. The queue length and remaining energy are calculated based on the conditions and actions of the last time epoch. The actions are the selections of the next hops at the current nodes. The routes during a period can be obtained by balancing load and energy consumption.

4. Designing a multi-objective routing with learning ability to effectively select routes in a network with uncertain conditions. In the multi-objective model, delay and energy are considered respectively without setting weight values like the contribution 3. To solve such multi-objective routing problem, reinforcement learning is applied. The detailed contributions are:

(1) Building a multi-objective routing model with objectives of delay and energy. When evaluating delay, the grey physical interference model is further used to obtain the PTF more accurately. PTF is based on the probabilities that signal to interference and noise ratio (SINR) is within different periods. For energy, consumed energy and energy capacity are considered. In this multi-objective model, delay and energy are individually, and they are not merged into one single objective anymore.

(2) Solving the multi-objective routing problem by reinforcement learning method Dyna-Q for the first time. Reinforcement learning does not need to know prior information, which can adapt to the dynamic routing problem well. As a type of improved Q learning, Dyna-Q further increases the convergence speed. When solving the problem in an iterative manner, the learning rate and exploration rate are dynamically adjusted.

After designing the four routing methods, the performance of them is evaluated and compared with other popular and state-of-the-art routing methods respectively. The simulation results have shown the effectiveness of the proposed routing methods.

1.5 Thesis Organization

This thesis is presented in Journal Format, which includes four published peer-reviewed journal papers. The four papers which are produced during my PhD study are:

1. **Y. Chai**, X. J. Zeng, Regional condition-aware hybrid routing protocol for hybrid wireless mesh network, Computer Networks. 148 (2019) 120-128. [25]
2. **Y. Chai**, X. J. Zeng, Delay-and Interference-Aware Routing for Wireless Mesh Network, IEEE Systems Journal. 14(3) (2020) 4119-4130. [26]
3. **Y. Chai**, X. J. Zeng, Load balancing routing for wireless mesh network with energy harvesting, IEEE Communications Letters. 24(4) (2020) 926-930. [27]
4. **Y. Chai**, X. J. Zeng, A multi-objective Dyna-Q based routing in wireless mesh network, Applied Soft Computing. 108 (2021) 107486. [28]

In the above papers, as the first author, I contributed to propose the main ideas and novelties, planed research, concluded the existing research, implemented the experiments, analyzed the experiment results, wrote papers and revised papers according to the reviewers' comments. Xiao-Jun Zeng, who is my supervisor guided my research, provided some very insightful suggestions about directions, ideas and writing. According to the policy, these papers are presented as offprint formats. As each of these papers has the completed structure including abstracts, related works, methodologies, conclusions and references, it is reasonable to have some degree of repetition in the Journal Format thesis.

Paper [25] proposes a hybrid routing method considering the characteristics of mesh routers and clients. In addition, the regional conditions are considered to avoid the areas with bad performance. The first contribution in section 1.4 is given in this paper.

The emphasis of the paper [25] is to give a completed structure of the hybrid routing method and design the reactive routing part and the routing method when proactive paths exist. However, how to build proactive paths is also very important and should be carefully considered. As the mesh routers with multiple radio interfaces and strong processing ability can influence network performance dramatically, it is essential to design an effective proactive routing method typically for mesh routers. Paper [26] then gives a centralized routing method among mesh routers and formulates the routing problem as a constrained optimization problem. Minimizing delay is the objective. Interference, the PTF and bandwidth are considered. An improved GA that can balance load is proposed to solve the optimization problem. The second contribution in section 1.4 is from this paper.

Paper [26] neglects energy, while energy is an important factor nowadays. Based on the paper [26], paper [27] proposes a centralized routing method that further considers a long-term objective. In addition to load, energy is also considered in the objective. The remaining energy is influenced by the consumed energy and harvested energy. The detailed novelty is given in the third contribution of section 1.4. Although paper [27] considers both load and energy, these two factors are merged into one formula as the problem of a single objective function. In addition, learning and adaptive ability is not considered. [28] then proposes a multi-objective routing method considering delay and energy respectively. The reinforcement learning method Dyna-Q is applied to be adaptive for the network with uncertain conditions. The detailed contribution of this paper is shown as the fourth point in section 1.4.

The structure of the rest of this thesis is: Chapter 2 presents the background theory and related works. The background theory which is the basis of the routing design is given. Existing routing methods for WMN are also summarized and analyzed. Chapter 3, Chapter 4, Chapter 5, and Chapter 6 show the details of the paper [25], the paper [26], paper [27] and paper [28] respectively. After showing the core contributions, the conclusions are given in Chapter 7. The main works of the thesis are concluded and analyzed together. In addition, the open issues and future directions are also expressed.

1.6 List of Publications

1.6.1 Journal Papers

1. **Y. Chai**, X. J. Zeng, Regional condition-aware hybrid routing protocol for hybrid wireless mesh network, Computer Networks. 148 (2019) 120-128. [25]
2. **Y. Chai**, X. J. Zeng, Delay-and Interference-Aware Routing for Wireless Mesh Network, IEEE Systems Journal. 14(3) (2020) 4119-4130. [26]
3. **Y. Chai**, X. J. Zeng, Load balancing routing for wireless mesh network with energy harvesting, IEEE Communications Letters. 24(4) (2020) 926-930. [27]
4. **Y. Chai**, X. J. Zeng, A multi-objective Dyna-Q based routing in wireless mesh network, Applied Soft Computing. 108 (2021) 107486. [28]
5. **Y. Chai**, X. J. Zeng, The development of green wireless mesh network: A survey, Journal of Smart Environments and Green Computing. 1(1) (2021) 47-59. [29]

1.6.2 Conference Papers

1. **Y. Chai**, X. J. Zeng, Load-and interference-balance hybrid routing protocol for hybrid wireless mesh network, in: Wireless Days (WD), 2019, pp. 1-4. [30]
2. **Y. Chai**, X. J. Zeng, Load and Energy Aware Hybrid Routing Protocol for Hybrid Wireless Mesh Networks, in: IEEE 90th Vehicular Technology Conference (VTC2019-Fall), 2019, pp. 1-5. [31]
3. **Y. Chai**, X. J. Zeng, An effective routing with delay minimization for multi-hop wireless mesh network, in: IEEE Global Communications Conference (GLOBECOM), 2019, pp. 1-6. [32]

Although there are many published papers during my PhD study, considering the main contributions and relatedness with each other, the first four journal papers are used to compose the Journal Format thesis.

Chapter 2

Background Theory and Related Works

This chapter gives the related background theory of communication in WMN. To make it clear and have a general idea about communication, we give the primary architectural model of communication first, which is the open systems interconnection (OSI) model [33]. Then based on our work and focuses, the wireless transmission model and medium access control (MAC) protocol are explained. The existing routing methods for WMN are further concluded and the weaknesses are analyzed, which is the basis of the proposed routing design in this thesis.

2.1 OSI Model for Communication

The OSI model describes the process of transferring information in computer networks, which is composed of seven layers. Communication operations between source and destination can be expressed through the process in these layers. The structure of the OSI model is shown in Figure 2.1.

Application Layer
Presentation Layer
Session Layer
Transport Layer
Network Layer
Data Link Layer
Physical Layer

Figure 2.1 OSI model

The detailed functions of these layers are:

1. The application layer is the place where the network application stores. Application requests like file transfers from users are supported directly in

this layer. The information packet is named message here.

2. The presentation layer makes applications explain the meaning of exchanged data and avoid the problem of different expression or internal formats at different end users. In addition, data compression and data encryption are provided in this layer.
3. The session layer provides the function of delimitation, building check point and recovery scheme. Internet protocol stack does not include the above presentation layer and session layer. These two layers are not necessary on the Internet. If an application on the Internet needs the functions provided by these two layers, developers can decide the importance of such functions and whether to build these functions.
4. The transport layer can transport messages between application users. The message can be split up into segments and then be passed to the network layer.
5. Routing function is implemented in the network layer, and the packets named datagram in this layer will be transmitted to the destination.
6. To transfer data from one node to the next hop according to the route, the network layer must rely on the link services provided by the data link layer. The packet in this layer is named frame. The data link layer is composed of MAC layer and logical link control layer. MAC layer controls the media access process so that nodes can communicate through the shared resources. The logical link control layer takes charge of frame synchronization, error detection and flow control.
7. The duty of the physical layer is to transmit bits which are from frames in the data link layer from one node to another. The transmission is related to the wireless media and channel condition.

In the whole process of communication on the Internet, the source node first transmits data from the application layer to the physical layer. The intermediate nodes with routing function will then receive data from the physical layer to the network layer. After obtaining the route information in the network layer, data will be sent down through the physical layer to the next hop. This process among intermediate nodes will continue until the destination node is achieved. The destination node will receive the data from the physical layer to the application layer. The communication between the source and destination node is completed in this way. This communication process is shown in Figure 2.2.

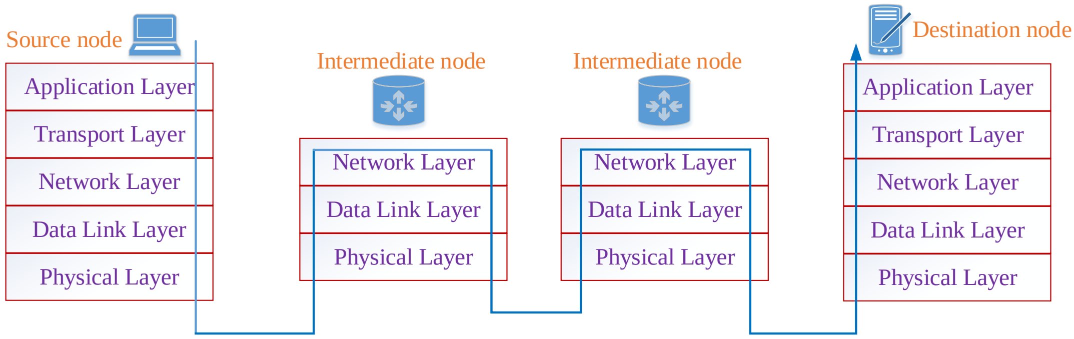


Figure 2.2 An example of communication process

According to the communication process, our work focuses on routing design, so wireless transmission model in the physical layer, MAC protocol in data link layer and routing procedure in network layer are mainly related, and they are introduced in the following sections 2.2, 2.3 and 2.4 respectively.

2.2 Wireless Transmission Model

Wireless communications are through wireless channels. The channel gain is influenced by large-scale fading [34,35] and small-scale fading [36]. Large-scale fading is the electromagnetic fading influenced by the transmission distance. The longer distance will bring more signal fading. Small-scale fading is multi-path fading, which is caused by the transmissions through multiple paths. The channel gain then affects the received signal power.

In large-scale fading, the path loss is related to the distance between the source and destination. Both free-space propagation model and two-ray ground fading model are considered, and they are used according to the different distances [34]. The free-space model [37] is used when the distance between source and destination is shorter than the critical distance. Otherwise, the two-ray ground fading model is used to describe the path loss. The critical distance (denoted as d_0) is

$$d_0 = \frac{4\pi h_t h_r}{\lambda} \tag{2.1}$$

where h_t and h_r are heights of transmitting and receiving antennas, and λ is the wavelength. Then the effect caused by large-scale path loss between source node *i* and destination node *j* (denoted as PL_{ij}) can be expressed as

$$PL_{ij} = \frac{P_{rj}}{P_{Ti}} = \begin{cases} \dfrac{G_t G_r \lambda^2}{(4\pi d_{ij})^2}, 0 < d_{ij} \le d_0 \\ \dfrac{G_t G_r h_t^2 h_r^2}{(d_{ij})^4}, d_0 < d_{ij} \le r_T \end{cases} \tag{2.2}$$

where P_{rj} is the receiving power at destination node *j* from source node *i*. P_{Ti} is the transmission power of source node *i*. G_t and G_r are the gain of transmitting and receiving antennas respectively. d_{ij} is the distance between source node *i* and destination node *j*. r_T is the transmission range. The longer distance brings more path loss.

In small-scale fading, the Rayleigh fading model is used when there is no line-of-sight communication between the source and destination [38,39,40,41]. If the line-of-sight communication exists, the Rician channel fading model can be used [42]. Different types of fading models mean the envelopes of the received signal submit to different types of probability density functions (PDF). Because of the features of the real channel, the Rayleigh fading model is often adapted. In Rayleigh fading, the PDF of the envelope of the received signal is

$$f_X(x_{ij}) = \frac{x_{ij}}{\sigma_{ij}^2} e^{-\frac{x_{ij}^2}{2\sigma_{ij}^2}}, x_{ij} \ge 0 \tag{2.3}$$

where x_{ij} is the received signal at node *j* from node *i*. σ_{ij}^2 is the power of the multipath components. The power of the received signal (denoted as p_{ij}) is

$$p_{ij} = x_{ij}^2 \tag{2.4}$$

According to the formula (2.3), the PDF of p_{ij} (denoted as $f_P(p_{ij})$) is

$$f_P(p_{ij}) = \frac{dx_{ij}}{dp_{ij}} f_X(\sqrt{p_{ij}}) = \frac{1}{2\sigma_{ij}^2} e^{-\frac{p_{ij}}{2\sigma_{ij}^2}}, p_{ij} \geq 0 \tag{2.5}$$

We can see that p_{ij} submits to the exponent distribution. Then the expected value of p_{ij} (denoted as E(p_{ij})) is

$$E(p_{ij}) = 2\sigma_{ij}^2 \tag{2.6}$$

which is the effect of the small-scale channel fading to the power of received signal. The small-scale fading can be solved by the technologies like rake receiver and cyclic prefix.

According to the formulas (2.2) and (2.6), the power of received signal (denoted as P_{ij}) is

$$P_{ij} = P_{Ti} \cdot PL_{ij} \cdot E(p_{ij}) \tag{2.7}$$

where P_{Ti} has the same meaning with that in the formula (2.2). The large-scale and small-scale fading compose the effects on the received signal power.

2.3 MAC Protocol

In the MAC layer, IEEE 802.11 standard [43,44,45] is used. The carrier sense multiple access with collision avoidance (CSMA/CA) method is used to avoid collisions when different mesh nodes try to access the wireless channels. When a mesh node intends to access the wireless channel, it will detect the channel condition first. If some other nodes are using the channel at this time and the channel is busy, the backoff process will start to wait for some time before transmitting data [46]. The number of backoff slots is randomly selected from [0,CW_s-1]. CW_s is the contention window size of the current transmission stage s. CW_s is between the CW_{min} and CW_{max}, where CW_{min} and CW_{max} are the minimum and maximum contention window sizes respectively. The acknowledge (ACK) frame will be sent by the receiver if the packet is successfully received. Otherwise, the ACK is not sent by the receiver and the sender cannot receive the ACK, which means the transmission is failed. The transmitter will then retransmit the packet with the doubled CW_s. Until CW_s reaches CW_{max}, the CW_s

will be doubled each time of retransmission. The detailed expression of CW_s is

$$CW_s = \begin{cases} 2^{s-1} \cdot CW_{\min}, 2^{s-1} \cdot CW_{\min} < CW_{\max} \\ CW_{\max}, 2^{s-1} \cdot CW_{\min} \geq CW_{\max} \end{cases} \tag{2.8}$$

where s is the number of times of transmission, which is the times of retransmission plus 1.

CW_s is the number of backoff time slots, which is used to evaluate the backoff time before the sender transmits the packet. If the channel is busy during a time slot, the backoff timer will be frozen and will remain the same. If the channel in a time slot is idle, the backoff timer will be minus 1. When the backoff timer reaches 0, the packet will be sent out from the sender. If some other nodes just send packets at the same time and the collision is caused, the next backoff stage will be operated. If the packet is not received by the receiver successfully, another backoff stage is also needed. After the successful transmission of the packet, the CW_s will be set back as CW_{min}.

In the IEEE 802.11 distributed coordination function (DCF), the allowed maximum retransmission number is 7. If the packet still cannot be successfully received by the receiver after the maximum allowed number of transmissions, the packet will be dropped.

When a sender wants to send data, the backoff process is not needed only if the channel is idle and the data frame is the first one that the sender needs to transmit. The detailed cases of generating backoff process are: When the wireless channel is detected to be busy before sending the first data frame; Each time after retransmission; Each time after the successful transmission. In this case, the backoff process provides a fair mechanism to access the wireless channels for different mesh nodes. When the channel is busy before transmitting packets, the backoff process helps avoid the collision and try to let different nodes access channels at different time. If the data is still not transmitted successfully after retransmission, the channel condition seems not very good. Another retransmission is needed, and the contention window size is doubled to avoid frequently contending the wireless channel. In addition, the node which has contended the wireless channel successfully cannot transmit packets and occupy the wireless resource all the time. This node should give other nodes a chance to access the wireless channel, so the backoff process also starts after the successful transmission. The backoff process then balances the use of wireless channels by different nodes.

2.4 Routing Procedure Introduction

Route discovery, data forwarding, and route maintenance compose the routing operation process. The first step is to discover routes when some data packets need to be transmitted. The path between the source and destination is discovered and selected in this step. Routing metric helps to evaluate the route performance, and the best route can be determined based on the routing metric value. After the route is selected and established, data starts to be forwarded. If the destination can receive data successfully, the routing process finishes. Sometimes the routes will be broken. For example, when a mobile node moves out of the coverage of its original neighbours, the links will be broken. In this case, the route maintenance needs to start. The network controller or upstream nodes can receive the route error message, and the broken routes are reported. A new route needs to be established and the route discovery needs to be implemented again. The routing operation process is shown in Figure 2.3.

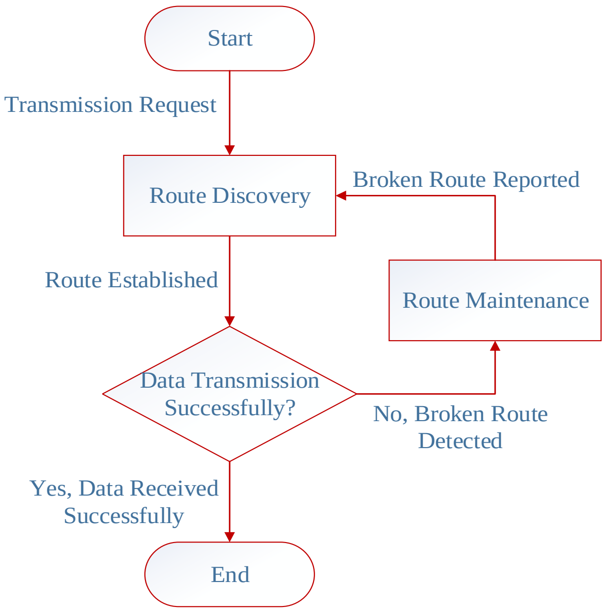


Figure 2.3 Routing operation process

As routing aims to select effective paths between sources and destinations, the route discovery part needs to be focused on. The procedures of how to implement a routing method to discover routes in different cases are given as follows.

2.4.1 Route Discovery Procedure in Centralized Proactive Routing

With the fast development of software-defined networking (SDN), the centralized routing method is more and more popular because routes can be obtained by considering the whole network conditions. According to the global network view, the best routes can be selected to improve the whole network performance.

The network controller is responsible to collect and maintain the whole network conditions. The controller can communicate with all nodes in the network. The control packets including the neighbour list and link conditions are sent from each node to the network controller. Different channels can be used to transmit control packets and data packets, which avoids the interference between transmitting control packets and data packets [23]. The wireless technology used by transmitting control packets can even be different from that used by forwarding data packets among mesh nodes [47]. For example, the cellular network can support the transmission of control packets, and data packets can be forwarded through Wi-Fi links. After receiving the control packets from all nodes in the network, the network controller can obtain the whole network topology and conditions.

According to the global network view, the network controller can find the best routes to satisfy the QoS request. The routing algorithm is implemented at the network controller to select paths. After calculation, the best routes are sent back from the network controller to mesh nodes. Mesh nodes can then transmit and forward data packets through the best paths. The flowchart of the route discovery procedure in centralized proactive routing is shown in Figure 2.4.

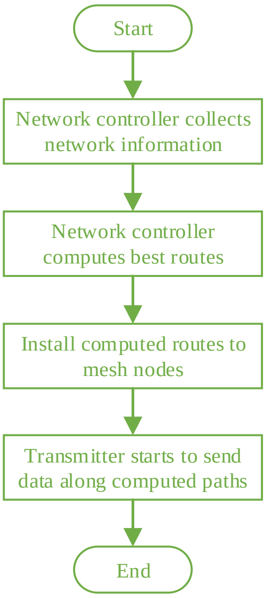


Figure 2.4 Route discovery procedure in centralized proactive routing

2.4.2 Route Discovery Procedure in Distributed Reactive Routing

In the distributed reactive routing like ad hoc on-demand distance vector (AODV) [13], route discovery starts when a node wants to communicate with another one. The source node will broadcast the route request (RREQ) packet including the source and the destination address to its neighbours. If the neighbours also do not know the valid route to the destination, they will rebroadcast the RREQ until the destination or the intermediate node which knows a valid path to the destination receives the RREQ. As the RREQ is broadcasted, a node may receive an RREQ packet sent by itself. This RREQ will be dropped. In addition, if an RREQ packet from the same upstream node is received, it will also be discarded. After receiving the RREQ, the node needs to update the routing table to the source node. The routing metric value from the current node to the source is obtained by adding the local information between the current node to the upstream neighbouring node. The whole route can finally be achieved by the hop-by-hop behaviour.

When the destination or the intermediate node that maintains a valid path to the destination receives the RREQ, the RREQ will be dropped and the route reply (RREP) packet is unicasted back to the upstream nodes. The RREP will be received by the source finally. The detailed process of sending RREQ and RREP in the network is shown in Figure 2.5.

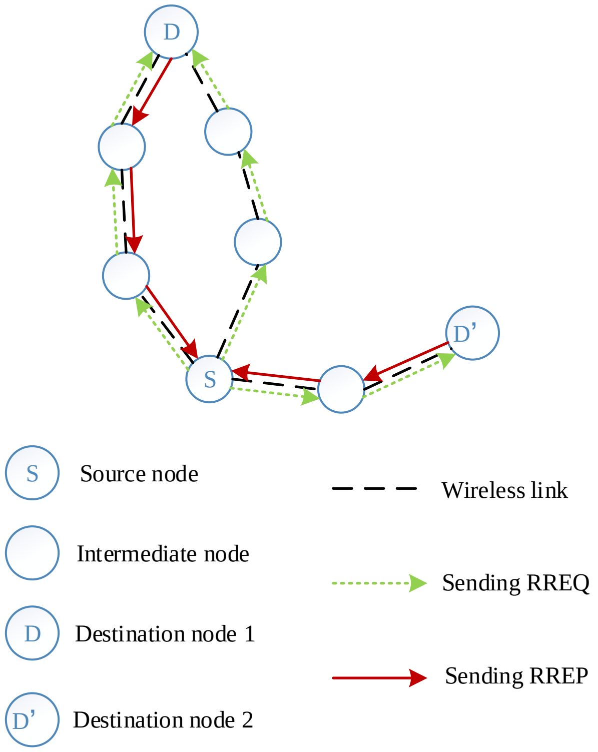


Figure 2.5 Process of transmitting RREQ and RREP packets

The destination node D can receive several RREQ packets, which means there are several paths from the source S to destination D. The destination D can reply to the upstream node which sends the RREQ with a better routing metric. Similarly, destination D' will also send RREP to its upstream node. Finally, the routing table containing the destination node, next-hop node, and the metric value from the source to the destination will be built.

2.4.3 Route Discovery Procedure in Hybrid Routing

The hybrid routing method combines centralized proactive routing and distributed reactive routing. When using the hybrid routing method in WMN, the proactive routes among mesh routers and routes from each mesh router to the gateway can be discovered according to the procedure mentioned in section 2.4.1. The distributed reactive routing method is then used among both mesh routers and mesh clients.

As mesh routers are stable with the stronger ability and can serve both gateway- and client-oriented traffic, they can use both centralized proactive routing and distributed reactive routing, and the centralized proactive routing method has higher priority. When a mesh router needs to send packets, it will first check whether there is an existing valid path in the proactive routing table. If there is a proactive path, the mesh router will use this proactive path directly and does not need to discover the route. If no proactive path exists, the mesh router will then implement the reactive routing method to find paths. If both proactive and reactive routing tables have valid paths to the destination, the route in the proactive routing table will be used. The reason is that the proactive route composed of mesh routers is more stable.

For mobile mesh clients, only distributed reactive routing method is equipped. When a mesh client wants to communicate with other nodes, the route discovery procedure mentioned in section 2.4.2 will start. To clearly show the route discovery procedure of the hybrid routing, an example of explaining how centralized proactive routing and distributed reactive routing work cooperatively is shown in Figure 2.6.

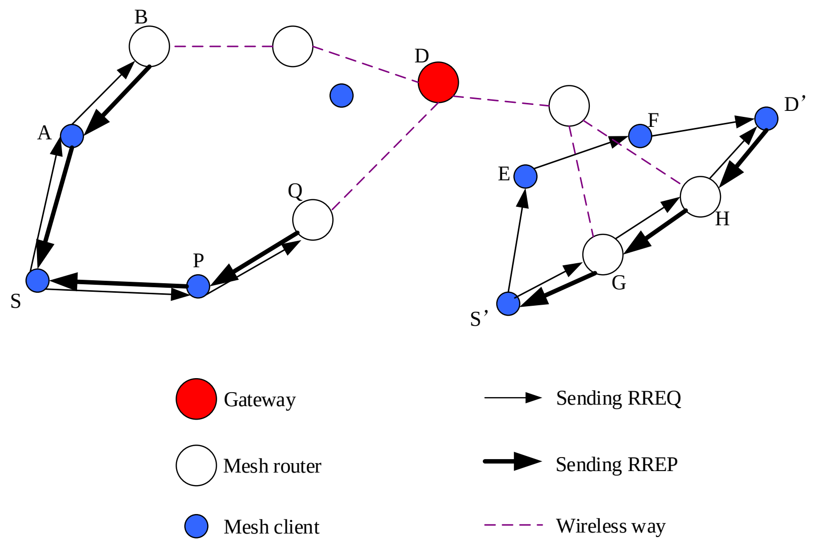


Figure 2.6 An example of route discovery procedure in hybrid routing method

The centralized proactive routing method used among mesh routers helps all mesh routers know the routes to the gateway. In the gateway-oriented traffic, when the mesh client S needs to send packets to the gateway, it will broadcast RREQ to its neighbours. After neighbouring mesh client A and mesh client P receive the RREQ, both of them check whether they have valid paths to the gateway. If they do not know the paths, the RREQ will be rebroadcasted. Then mesh routers B and Q will receive the RREQ. As they are mesh routers and already know the proactive routes to the gateway, they will drop the RREQ and directly unicast RREP back to mesh clients A and P respectively. Mesh clients A and P will then unicast RREP to the source mesh client S. S can select one route based on the routing metric.

In the client-oriented traffic, when the mesh client S' wants to communicate with another mesh client D', S' will also broadcast RREQ. The mesh client E and mesh router G can receive the RREQ. Similarly, they need to check whether there are existing routes to D'. As the destination is a mesh client, even the mesh routers also do not know the valid paths because the proactive routing method does not maintain routes to mobile mesh clients. Both mesh client E and mesh router G will rebroadcast RREQ by using the distributed reactive routing method. The rebroadcast will be implemented until the RREQ is received by destination D'. D' sends RREP back to upstream nodes. After S' receives the RREP, the best route according to the routing metric will be established.

2.5 Current Routing Methods for WMN

Existing routing methods for WMN have different focuses. Based on the route discovery methods, some routing methods are centralized proactive routing [47,23,21,48,49], and some are distributed reactive routing [50,51,52,53,54,55]. A few are hybrid routing [56,57]. In terms of whether distinguishing the mesh node type, some routing methods are node type aware [58,12,59,15,60,61] and some others do not distinguish mesh routers and mesh clients [62,63,14,64,65,66,67]. In terms of the traffic type, some routing methods consider the gateway-oriented traffic [4,62,59,65,68,69]. Some consider the client-oriented traffic [47,23,70,71,72], and there are also some routing methods consider both gateway- and client-oriented traffic [73]. With the aspect of routing discovery procedure, some routing research considers flood control problem [73,74,75,76]. The energy cost and throughput will be balanced by adjusting the transmission rate of control packets [76]. To guarantee the network performance request in some applications, control packets are forwarded only if the link quality is good [77]. Some use the multi-path method to store some alternative routes [20,78,79,80]. Considering the routing metric, some consider load and congestion balance problem [51,52,22,53,81,82]. Some consider the interference problem [83,14,55,84]. Some take energy into account [58,85,86,87,88,68,89,90]. There are many standards to categorize existing routing methods. The network performance can be improved in different cases with different views. Our research considers the different features of mesh routers and mesh clients. According to their features, centralized proactive routing, distributed reactive routing and hybrid routing are designed. Thus, the related existing routing methods categorized by the standard of centralized proactive, distributed reactive and hybrid routing are further explained as follows.

2.5.1 Centralized Proactive Routing Methods

In centralized proactive routing, the routing problem can be formulated as an optimization problem with a global network view, and the objective is the standard of selecting the best route. Considering different request of QoS, different aspects like expected transmission time (ETT) [17,19], expected transmission count (ETX) [18,91], throughput [83,92], packet error ratio [93], energy consumption [90,94], hop count [37] and so on can be considered in the objective. Some routing methods consider one aspect as the objective [19,83], and others consider several aspects all together in the objective [91,95,96]. When considering multiple factors in the objective, the multiple aspects can be converted into a single objective by giving each factor a weight value [97,98], or the multiple factors can be used to build a multi-objective optimization model without setting weight values for different objectives [91,99,90].

When solving the established routing optimization problem, GA [19,100], particle swarm optimization (PSO) [101,102], multi-objective differential evolution (MODE) [103,104], ant colony optimization (ACO) [105,106], reinforcement learning [107,70,108], etc. can be used. [102] builds the load-balanced, interference and flow-capacity models, and solves them by PSO and GA. The routing algorithms proposed by Murugeswari [91,104] consider delay, ETX and packet delivery ratio, and solve the optimization model by discrete MODE. The optimization can be implemented periodically or when the network performance cannot meet the requests [90]. Some particular centralized proactive routing methods are given in detail as follows.

1. SDN-based routing [24]

The SDN, which is a fast-developing technology, can effectively support the centralized proactive routing methods. The SDN-based centralized routing in [24] maximizes the throughput and builds a mixed integer non-linear programming (MINLP) problem to solve access association problem, select gateway and assign it to every source. The global network information is collected from Wi-Fi clients. The number of gateways is given first to maximize the throughput. Then the best number of gateways will be found by an iterative process. To solve the NP-hardness problem, the MINLP problem is relaxed and a suboptimal solution can be obtained.

Although throughput is considered, the delay which is an important QoS factor nowadays is not considered. In addition, the network conditions are often dynamic with different routing solutions. Therefore, such traditional programming method is not very adaptive for the dynamic conditions. Some metaheuristic methods like GA can be effective to search routes.

2. Multi-objective evolutionary algorithm based QoS routing [91]

Delay is considered here, and minimizing transmission delay and ETX are set as the objectives of the routing problem. The multi-objective evolutionary algorithm (MOEA) is chosen to solve the optimization because multiple optimal solutions can be obtained in one single simulation run [110]. The solution algorithm is based on non-dominated sorting genetic algorithm-II (NSGA-II) because NSGA-II is one of the most popular and effective MOEA [111]. To keep the diversity of the solutions, the dynamic crowding distance (CD) is used in NSGA-II to make the different degrees of CD in different objectives more obvious. The expression of dynamic CD for the individual i is

$$DCD = \frac{CD_i}{\log\left(\frac{1}{V_i}\right)} \tag{2.9}$$

where V_i is the variance of CD_i. The CD_i is the same as that in NSGA-II, which can be expressed as

$$CD_i = \frac{1}{r}\sum_{k=1}^{r}\left| f_{i+1}^{k} - f_{i-1}^{k} \right| \tag{2.10}$$

where r is the number of objectives, f_{i+1}^{k} and f_{i-1}^{k} are the values of kth objective of individual i+1 and individual i-1 respectively. Based on the CD_i, the V_i is

$$V_i = \frac{1}{r}\sum_{k=1}^{r}\left(\left| f_{i+1}^{k} - f_{i-1}^{k} \right| CD_i\right)^2 \tag{2.11}$$

When the number of non-dominated solutions is larger than the population size, the solutions with least DCD values will be removed.

The simulation results show the effectiveness of the improved NSGA-II.

3. A routing algorithm for wireless multimedia sensor networks [99]

The QoS requirements of delay and ETX are also satisfied here. The delay includes processing delay, queuing delay, transmission delay and propagation delay. ETX shows the link loss condition and can help find high throughput routes in multi-hop wireless networks. When solving the routing problem, the MOEA is also used, and the already found good solutions are only replaced when better solutions are discovered. In this case, good solutions will be maintained.

The delay and ETX of links among static nodes are obtained through the network simulator NS-2 [112,113], then they are assumed to be the same during the routing selection process. The performance of the proposed routing method is compared with the popular and traditional routing protocol DSR [114]. The results show the effectiveness of the proposed routing and the MOEA.

The routing methods proposed in [91] and [99] both consider the delay and prove the effectiveness of evolutionary algorithm. However, the method and overhead of obtaining delay is not clarified.

4. Search-based routing [19]

ETT and hop count are considered in the fitness function. ETT is the expected delay of transmitting a packet along a link, which is obtained by using probe packets. The detailed fitness function is

$$PathCost = HopCount \times \sum_{l=1}^{n} ETT_l \tag{2.12}$$

where l is the link between two neighbours, and n is the number of links on the path from source to destination. According to the fitness function, the path with less hop count and aggregated ETT will be selected.

GA is applied as a search-based method to find the optimal path in WMN. The chromosome is encoded as a string of integers representing the ID numbers of nodes. The one-point crossover [109] is used, and the parts before and after the crossover point are exchanged. The maximum number of iterations is given to stop the GA process. With the different number of mesh nodes, the experimental results show the proposed search-based routing has better performance than traditional minimum hop count routing method. The performance of GA in different cases is then evaluated.

Although delay is considered, using probe packets to obtain ETT will bring large overhead. The probe packets will occupy the storage and wireless resources. A method to get delay with less overhead should be proposed. In addition, energy has not been considered yet.

5. Distance-and-energy-aware routing with energy reservation (DEARER) [58]

DEARER is a cluster-based routing protocol that further considers energy and can improve energy efficiency. The nodes in the network are static, and EH is also considered. As the cluster head (CH) nodes often suffer from the energy shortage problem, the nodes with a high received energy rate or being close to the sink are selected as CH nodes. To balance the energy consumption and avoid the same node being as the CH node for a long time, the routing method is operated in rounds. In each round, CH nodes are reassigned. The nodes which are close to the sink consume less energy to transmit and have a high received energy rate, so they have more chance to become CH nodes. The nodes which are not CH nodes can reserve a portion of the harvested energy. In this case, energy shortages can be avoided if they are selected as CH nodes in future.

With the advantage of hierarchical features caused by clustering, nodes do not need to transmit to the remote sink directly and the energy consumption is saved. In addition, the non-CH nodes have time to store energy, and energy consumption can be balanced by reassigning CH nodes periodically. Energy is considered and consumed in balance, which can prolong the network lifetime, but load and interference are not roundly considered.

These existing centralized routing algorithms satisfy different QoS requests and show the effectiveness of GA in the routing problem. However, the load, interference and energy are not fully and roundly considered at the same time. In addition, the overhead of obtaining network conditions is not focused on. Although the probe packets can help get the network conditions, the overhead will be high and the network resource is consumed.

2.5.2 Distributed Reactive Routing Methods

To adapt to the mobile feature of mesh clients, many distributed reactive routing methods are proposed. Factors like delay [46,115,50], load [51,116,117,52], interference [118,62,63], mobility [119,69], security [120,3], energy [121,122] and so on can be considered. The factors can influence each other, so more than one factor can be considered at the same time. [14] considers the delay influenced by intra- and inter-flow interference. When the delay cannot meet the set threshold, the transmission rate will be reduced. ETX and ETT are often used as the basis of many research works. In addition to ETX, available bandwidth and channel diversity are considered in [50]. With larger retransmission times, the energy consumption will be more [88]. In addition to ETT, [52] considers load conditions. SINR is also a popular factor that is used in many works considering interference. Based on SINR, energy consumption [122], packet error rate [84] and expected bandwidth [123] can be obtained. The ratio of SINR to signal to noise ratio (SNR) can show the interference level [62,64]. When multiple gateways are in the network, the gateway with better capacity and less interference should be selected [118,124].

Some typical distributed reactive routing methods are given as follows.

1. An adaptive load-aware routing algorithm [52]

A dynamic adaptive channel load-aware metric (LAM) is proposed. ETT and load are considered to set the link metric:

$$LL(l^i) = ETT(l^i) \times Q(l^i) \tag{2.13}$$

where $ETT(l^i)$ and $Q(l^i)$ are ETT and queue length of link l on channel i. The load condition of gateway g_m is

$$LL(g_m) = \sum LL(l_k^i) \tag{2.14}$$

where k is the neighbour of gateway g_m. To guarantee the diversity of selected channels on a path, similar to the idea of weighted cumulative expected transmission time (WCETT) [17,125], the routing metric LAM is designed.

$$LAM = (1-\alpha)\times\sum_{j=1}^{m} CL(j) + \alpha\times\max_{1\le j\le m}\{CL(j)\} \qquad (2.15)$$

where $CL(j)$ is the sum of LL on channel j, which means the total load on links using the same channel in a path. m is the number of available channels on the current path. α is a tradeoff factor between 0 and 1.

Although load and channel diversity are considered, the interference and gateway conditions are not taken into consideration.

2. Source-based routing (SBR) [118]

SBR considers interference and the load condition of gateways when selecting the gateway. The load at gateways can be balanced. The available capacity at different interfaces at the gateway is divided into four levels. Then the level values and the current queue lengths at interfaces are both considered to evaluate the load condition of the gateway (denoted as *CI*). Larger *CI* means the gateway is with more remaining capacity.

When setting the link metric, the packet delivery ratio and interference are both considered. The metric is

$$LM_l = \left(1-\left(\frac{1}{2}\right)^n\right)\times IR + \left(\frac{1}{2}\right)^n \times ELQ \qquad (2.16)$$

where n is the number of neighbours. IR is the ratio of interference power sum over the allowed maximum interference power, which represents the interference condition. ELQ is the expected link quality, which is the reciprocal value of delivery ratio.

Based on the link metric, the path cost is

$$PM = \underset{k\in p}{Max}\left(LM_k\right) + \prod_{k\in p} LM_k \qquad (2.17)$$

where k is a node on path p. The path cost considers the metric values of bottleneck link and all links on a path.

After adding the performance of the gateway to the path cost, the routing metric is

$$SBR = \beta\left(1-CI\right) + (1-\beta)PM \qquad (2.18)$$

where $0<\beta<1$.

SBR effectively considers the interference, delivery ratio, and the gateway conditions. However, the differences between mesh routers and mesh clients are still not focused.

3. Multi-link and load-aware routing protocol SafeMesh [12]

SafeMesh is based on the popular reactive routing protocol AODV [13]. It distinguishes mesh routers and mesh clients in WMN. The designed routing metric is

$$SafeMeshMetric = \alpha \times MeshClientCount + \beta \times MeshRouterCount \qquad (2.19)$$

where α and β are weight values for mesh clients and mesh routers respectively. Based on large number of experiments, α is 4 and β is 1. *MeshClientCount* and *MeshRouterCount* are the numbers of mesh clients and mesh routers on the path. The weight values for mesh clients are larger than mesh routers, so mesh routers are preferentially selected to transmit packets and the chosen path will be stable.

In addition to the routing metric, SafeMesh also proposes a multi-link routing method. Multiple links between neighbours will be discovered and maintained by Hello packets. When selecting links, the interface queue length and data rate on the link are considered. The detailed metric of selecting links is

$$QDI = \frac{IFQ}{BW} \qquad (2.20)$$

where *QDI* is the time of emptying all queuing packets. *IFQ* is the queue length at the radio interface. *BW* is the bandwidth of the wireless link. The link with least *QDI* will be chosen. When the best link between two neighbours is broken, the second-best link will be directly selected. If no alternative link exists, the route discovery process will start.

Mesh routers and mesh clients are distinguished, and mesh routers have larger probability to be used because of their smaller weight values. Therefore, the selected routes will be more stable. However, energy is not considered at the same time.

4. Energy-load aware routing metric (ELARM) [121]

As energy is also a very important factor, in addition to the ETT, residual energy is also considered in ELARM. The minimum remaining energy of the node on a path is used to evaluate the energy condition of the path. This minimum remaining energy replaces the cumulative value of ETT in the original WCETT. The detailed expression of the routing metric is

$$ELARM = (1-\beta)\times(1-RE_{path}) + \beta\times\max X_j \tag{2.21}$$

where RE_{path} is the minimum remaining energy of the node on a path, and $\max X_j$ is the sum of ETT on the busiest channel. β is between 0 and 1.

Although remaining energy is considered in ELARM, the original energy capacity is neglected. In fact, the same amount of consumed energy has less influence on the node with more original energy capacity.

Above all, existing distributed reactive routing methods consider link conditions like ETT, load, delivery ratio and energy. However, as mentioned in the section 1.2, the reactive routing protocols cannot take full advantage of the static mesh routers in WMN. The routes between static mesh routers still need to be found reactively, which is undesired and will cause extra cost and delay. For mesh routers, in addition to the distributed reactive routing method, they should also be installed with the centralized proactive routing method. In addition, the routing methods like those based on WCETT are non-isotonic [126,127]. The cost and complexity to compute and store the path information will be high. Therefore, the simple distributed reactive routing method considering link conditions and energy should be designed. When the distributed reactive routing method is used among both mesh routers and mesh clients, the different features between mesh routers and clients should also be considered.

2.5.3 Hybrid Routing Methods

Hybrid routing methods combine proactive and reactive routing methods. They can work well in the WMN with both static mesh routers and mobile mesh clients.

Technology like clustering is a way to distinguish and categorize nodes. Higher reliability will be obtained by using proactive routing among nodes with low mobility [128,129]. Proactive and reactive routing methods can then be used within or between different clusters [60,130]. However, the cluster-based routing needs to separate nodes into different clusters first. WMN includes static mesh routers and mobile mesh clients in nature, so proactive routing methods can be used among mesh routers and reactive routing methods can be equipped for both mesh routers and mesh clients naturally. Such existing hybrid routing methods for WMN are few. Some of them are given as follows.

1. Hierarchy routing protocol [56]

The WMN is layered into a static infrastructure network and a mobile access network. Gateway, static infrastructure mesh routers and edge mesh routers compose the infrastructure network. Mobile mesh clients compose the mobile access network. Both mesh routers and mesh clients can communicate with each other, and mesh clients also have the relaying ability. When a mesh client moves out of the coverage of the original neighbouring mesh node, the mesh client under coverages of both the source mesh client and the original neighbouring mesh node can be used as the relay node. The connection between the source mesh client and the original neighbouring mesh node is guaranteed. Mesh routers use two routing protocols: optimized link state routing protocol (OLSR) [131] and AODV. OLSR and AODV are popular proactive and reactive routing protocols respectively. Two routing tables for these two routing protocols are maintained at mesh routers. Each mesh router has a route to any other mesh router. Mesh clients only use AODV to serve client-oriented traffic. Only hop count is used as the routing metric to select paths.

2. Hybrid routing approach combining tree-based routing and AODV [4]

The tree-based routing is used between the gateway and mesh routers. All mesh routers are linked with the gateway through the tree-based topology. AODV is used for mesh clients. When the mesh client wants to communicate with the gateway, they will broadcast RREQ. When mesh routers receive the RREQ, they will drop it and send back RREP. Unlike mesh routers, if mesh clients receive the RREQ, they will discard the RREQ directly to avoid the instability of the established routes. In addition, the overhead of flooding RREQ is also reduced. However, only gateway-oriented traffic is considered, and the client-oriented traffic is neglected. Similar to [56], only the hop count is used to evaluate the goodness of routes. Load is not considered, so the route with heavy load may be selected.

3. Load-aware cooperative hybrid routing protocol (LA-CHRP) [57]

Load condition especially the load at access mesh routers is considered in LA-CHRP. If a mesh client can access multiple mesh routers, the mesh router with the least load will be selected. The load at the border mesh routers is balanced and excessive partial load is avoided. Mesh routers are not unconditionally accessed by mesh clients. For mesh clients, in addition to the load, the energy condition is also taken into account. A mesh client with adequate energy and less load will be chosen.

Although the load condition at access mesh routers is considered, the condition of the whole proactive path is neglected. In addition, only the condition of the current node is considered, and the regional condition of neighbouring nodes has not been considered. Regions with a heavy load may be selected, which will decrease the network performance.

Therefore, a hybrid routing method considering regional condition needs to be designed. In addition, when a border mesh router is accessed, the status of the whole proactive path should also be considered.

2.5.4 Weaknesses of Existing Routing Design for WMN

Although there are many routing methods designed for WMN, some weaknesses still exist. Mesh routers are stable and with better processing ability, so they play an important role in WMN. The proactive routing method used among mesh routers should be designed effectively. As WMN also has mobile mesh clients, the different features of mesh routers and mesh clients should be considered. Based on the current routing methods for WMN, the weaknesses and problems needed to be solved in routing design for WMN are concluded as follows.

1. Mesh routers and mesh clients in WMN have different features. When designing the structure of routing method, most existing routing methods for WMN do not fully consider the differences. The hybrid routing methods are few. Using reactive routing methods among mesh routers to find routes will bring extra cost and delay.
2. In terms of the routing metric, the regional condition of neighbouring nodes is not fully considered. However, the packets at neighbouring nodes can transmit to the current node, which can potentially influence the performance of selected path.
3. Mesh routers are stable and with multiple radio interfaces, which need to be taken full advantage of. When designing the proactive routing method among mesh routers, existing centralized proactive routing methods do not sufficiently consider the load and interference.
4. Many existing routing methods have not considered the overhead of obtaining network conditions. Overhead will be caused by probe packets and control packets. A large amount of overhead will consume the wireless resources a lot, which is not desired. A simple way to obtain network conditions should be designed.
5. Energy is an important factor in green communication. A mesh node which runs out of energy cannot be used to forward packets anymore. The topology will change, and some nodes even become isolated nodes. It is essential to balance energy consumption and consider EH. However, many existing routing methods do not consider energy along with load and interference at the same time.

6. When designing routing methods, network conditions are often uncertain. Many existing works assume the network conditions are static when finding paths, which needs to be further considered.

2.6 Related Methodologies and Algorithms

When solving the routing optimization problem, different algorithms can be used in different cases. Metaheuristic algorithms are widely used to search solutions, and they can also be used in the routing problem. Here for the routing problem in WMN, based on the routing design features, objectives and requests, several popular and effective methodologies are introduced in this section.

1. GA [19,100]

GA is a type of the evolutionary algorithm, which is a search algorithm to solve the optimization problems. GA initially refers to some phenomena in evolutionary biology, including heredity, mutation, crossover, natural selection, and so on. An individual solution can be expressed as a chromosome. The evolution starts from random chromosomes and develops generation by generation. The fitness value is used to evaluate the goodness of chromosomes. New solutions are generated by natural selection, crossover, and mutation.

There are several parameters which are needed to be set in GA. The population size is the number of chromosomes in each population. The probability of performing crossover is the frequency of crossover. The larger value can increase the convergence speed. The probability of mutation is the frequency of chromosome mutating. The termination criteria tell the condition when GA can stop. It can be the number of iterations, human intervention, satisfaction degree of the obtained solutions, and so on.

The process of GA is:

- Select initial population.
- Update solutions in an iterative way. Fitness values are used to evaluate

chromosomes, and crossover and mutation can build new chromosomes.

- Stop until satisfying the termination criteria.

GA has been successfully applied to solve some routing problems. GA is a very effective approach to find an optimal solution, and it is even regarded as the best choice to find the optimal path [19]. In addition, the solution of routing can influence the network condition in turn, so the conventional optimization algorithms such as mathematical programming is not suitable, and GA is an effective method in this case.

2. DP [132]

DP is a way of solving decision problems by finding an optimal strategy. DP can get the global solution of the whole problem by finding the solutions of sub-problems. The sub-problems are not independent, common sub-problems can be included in each sub-problem. DP will solve each sub-problem only once, and the results will be stored to save time and reduce complexity. When the same sub-problem is needed to be solved later, the obtained result can be checked directly rather than computing again. In general, the idea of DP is to divide the original problem into several sub-problems and solve the sub-problems to get the solution of original problem.

According to the features of DP, the suitable cases for DP include:

- The solution of sub-problems contained by the optimal solution of the original problem is also optimal. This means the problem has optimal sub-structure. Whether such optimal sub-structure exists is a good clue for whether DP can adapt to the original problem.
- The problem submits to the non-aftereffect property. Once the solution of a sub-problem is determined, it will not change. The solution of other sub-problem containing such determined sub-problem cannot influence the already determined solution.
- There are overlapping sub-problems from the original problem. During the recursively finding solution process, some sub-problems will be computed several times. DP can compute each overlapping sub-problem only once to reduce complexity and improve efficiency.

In a long-term routing problem, the period can be divided into some time epochs. The network states at current time epoch are only related to the states and actions at previous time epoch. The optimal solution throughout the whole period can be obtained by the optimal solution of each time epoch. Therefore, the original problem can be divided into some sub-problems. Based on the suitable cases for DP, we can see that DP can adapt to the long-term routing problem.

3. Reinforcement learning [70,107]

Reinforcement learning is a process of trying and evaluating. The interaction between the environment can bring rewards. If an action brings positive reward, the tendency of selecting such action later will increase. Otherwise, the action will be avoided as much as possible.

Q-learning is one of the most famous reinforcement learning algorithms. There is a Q table which stores the Q value. The Q value is the expected profit under a given state and action. Through the interaction with the environment, the Q table is updated according to the obtained reward. The Q value is iteratively updated in each interaction. The best action under a given state is selected based on the Q value. To explore the solution space and avoid converging to a suboptimal solution, exploitation and exploration should be balanced. In the process of training Q values, the non-optimal solutions will also be selected sometimes based on the exploration probability. At the end of learning, a good Q table will be achieved. In general, the process of Q learning is:

- Initialize Q values.
- Learn Q table. In this step, at a given state, choose actions and measure reward to update Q values.
- After training, a good Q table can be obtained.

Based on the Q learning, Dyna-Q is an improved method to increase the convergence speed [107]. It can not only learn from the interaction between environment, but also learn from the previously updated state-action pairs.

For the routing problem, reinforcement learning methods like Q learning and

Dyna-Q are effective because the network conditions are often uncertain. The prior knowledge such as the transition matrix in the DP is no longer needed to be known in advance. The solution can be obtained just through the learning from the interaction between environments. The learning ability helps the route selection converge and online feature makes the selected route adaptive for the dynamic network conditions.

2.7 Summary

This chapter first introduces the related background theory of communication in WMN. Large-scale and small-scale fading will influence the channel gain. Based on the distance, the free-space propagation model and two-ray ground fading models are used in large-scale fading. In small-scale fading, the Rayleigh fading model is often used because of the real features of wireless channels. In MAC-layer communication, based on the IEEE 802.11 DCF protocol, the backoff procedure is used to avoid collisions.

The procedures of discovering routes in different types of routing methods are also given. Then the existing routing methods designed for WMN are concluded. The weaknesses and challenges are analyzed. Mesh routers with multiple interfaces compose the infrastructure of WMN, so the routing design among mesh routers is very important. Existing centralized proactive routing methods for mesh routers do not fully consider the load, interference, cost and energy. In addition to static mesh routers, when also considering the mobile mesh clients, hybrid routing method can work well for WMN. However, existing hybrid routing methods neglect the regional condition, which can potentially influence the condition of current node.

For the summarized weaknesses in routing design for WMN, chapter 3 proposes a hybrid routing method considering different features of mesh routers and mesh clients. Regional conditions are also taken into account. Weaknesses 1 and 2 are addressed. Chapter 4 solves weaknesses 3 and 4, and designs a particular centralized routing for mesh routers. Load and interference are both considered. Chapter 5 designs a load balancing routing with a long-term objective. The factor of energy is also considered. Therefore, weaknesses 3 and 5 are addressed. To better adapt to the uncertain network conditions, chapter 6 proposes a multi-objective routing method with reinforcement learning. Delay and energy are two considered objectives, and weakness 6 is further overcome. The details of the routing design are given in the following four chapters.

Chapter 3

Regional Condition-Aware Hybrid Routing Protocol for Hybrid Wireless Mesh Network

This chapter presents the peer-reviewed paper about hybrid routing protocol considering regional condition. The formal permission of reusing it is given in the Appendix A. The most recent impact factor, h-index, Cite Score, the SCImago journal rank (SJR) and the source normalized impact per paper (SNIP) are given according to the official website [133,134,135].

Published in Journal *Computer Networks*,
Volume: 148,
Pages: 120-128,
Publisher: Elsevier

Impact Indicators:

- Impact Factor (2020): 4.474
- Impact Factor Quartile: Q1
- h-index: 119
- SJR (2020): 0.798
- SNIP (2020): 1.731
- Cite Score (2020): 8.10

The final version of this paper is available online at
https://www.sciencedirect.com/science/article/pii/S1389128618312076

Summary: When mesh clients access mesh routers, the close mesh routers may be used unreasonably in existing hybrid routing methods. The condition of the whole path and regional condition of mesh nodes is neglected. This paper proposes a regional condition-aware hybrid routing protocol to consider the conditions of mesh routers and mesh clients respectively. Both gateway- and client-oriented traffic are considered.

Comments on authorship: I proposed the main idea of this paper, concluded the existing hybrid routing design in WMN, considered the different features of mesh routers and mesh clients, implemented the experiments, wrote and revised the paper. My supervisor, Xiao-Jun Zeng, guided the whole research direction, proofread the paper and gave me insightful suggestions about the idea.

Key contribution: Contribution 1 in section 1.4.

Regional Condition-Aware Hybrid Routing Protocol for Hybrid Wireless Mesh Network

Yuan Chai and Xiao-Jun Zeng
Department of Computer Science, University of Manchester,
Manchester, UK, M13 9PL
{yuan.chai, x.zeng}@manchester.ac.uk

Abstract

A proper routing protocol can improve the performance of whole network dramatically. Due to the character of hybrid wireless mesh network, hybrid routing protocol combining both proactive and reactive routing protocols suits hybrid wireless mesh network well. However, existing research of hybrid routing protocol is quite few, and mesh routers may be used unreasonably during the process of mesh clients accessing mesh routers. Besides, the condition of whole path and regional condition of mesh nodes is neglected. This paper proposes a regional condition-aware hybrid routing protocol (RCA-HRP). In RCA-HRP, regional conditions of mesh routers and mesh clients are considered respectively. Furthermore, the state of whole proactive path is taken into account to make the access process more effective, and gateway- and client-oriented traffic is taken into consideration comprehensively. The simulation results by ns-3 show the strengths of RCA-HRP in terms of average throughput, latency, and packet loss rate.

Index Terms

Hybrid wireless mesh network, Hybrid routing protocol, Gateway-oriented traffic, Client-oriented traffic

I. Introduction

As homogeneous wireless networks have poor performance and scalability, the research of heterogeneous networks has attracted the attention of researchers during the recent years [1]. Some researches have studied the related wireless issues [2] [3]. Hybrid wireless mesh network (WMN) is a kind of heterogeneous network, and it is flexible and extensible. Hybrid WMN is composed of two kinds of nodes, which are mesh routers and mesh clients [4]. Mesh routers are usually static with multiple radio interfaces. Infrastructure WMN is composed of mesh routers. Mesh clients are mobile and always only have one radio interface, constituting client WMN. Different from mesh routers, mesh clients have limited energy. Then, infrastructure WMN and client WMN form hybrid WMN. As mesh routers have multiple radio interfaces, the technology of Multi-Radio Multi-Channel (MRMC) can be used in hybrid WMN to extend network capacity [5]. The network architecture of hybrid WMN is shown in Fig. 1.

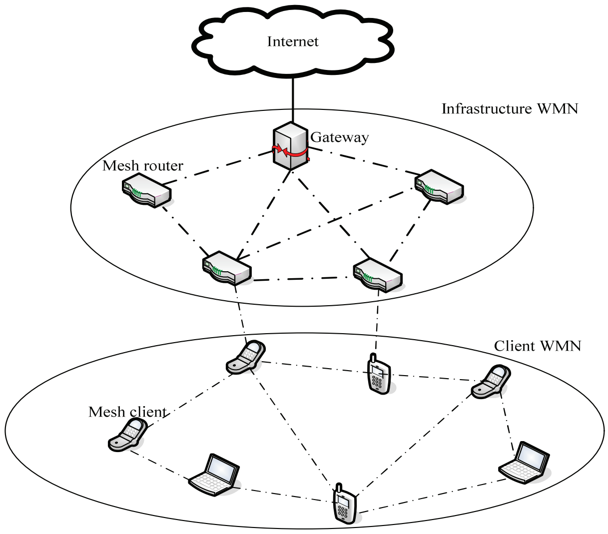


Fig. 1: Network architecture of hybrid WMN

There are two types of traffic in hybrid WMN. One is gateway-oriented traffic, and the other is client-oriented traffic. The gateway-oriented traffic means that the data flow is connected to the Internet. For instance, if a mesh client wants to send data to the Internet, it can access a mesh router first, and then connect the Internet through the gateway in infrastructure WMN. The data flow in client-oriented traffic is towards mesh client. The data packets can be conveyed to the destination mesh client by multiple hops.

Routing protocol provides an approach to find the route between source and destination. A proper routing protocol can improve the performance of whole network dramatically. In general, routing protocols can be categorized into three types: proactive routing protocol, reactive routing protocol and hybrid routing protocol [6]. In the proactive routing protocol, routes can be established before data packets are sent [7]. Some control packets are always used in the whole network to find and maintain routing, which may cause high cost in a mobile network. Thus, proactive routing protocol can work well in a static network. Reactive routing protocol only builds routes when data packets are conveyed in the network, which fits well for mobile network [8]. Hybrid routing protocol combines the features of both proactive and reactive routing protocols [9]. As there are both static and mobile nodes in hybrid WMN, hybrid routing protocol is ideal for hybrid WMN. However, existing hybrid routing protocols designed for hybrid WMN are quite few, and all of them neglect the condition of whole proactive path during the access process. Besides, for a mesh router or a mesh client, only its own condition is considered, and the situation of its neighbors is overlooked. To overcome these weaknesses, regional condition-aware hybrid routing protocol (RCA-HRP) is proposed in this paper. The main contributions are:

- Considering regional condition of mesh nodes, and setting weight values for mesh nodes by using the situation of neighbors. The weight values of mesh routers and mesh clients are set in different ways based on their different roles and features. For mesh routers, the load of themselves, the load and speed of neighboring mesh clients are considered. For mesh clients, the load of themselves and the number of neighboring mesh routers are taken into account. Further, not only considering the condition of a node itself, RCA-HRP also considers the situation of neighboring nodes. The obtained regional condition is then utilized and employed in the process of route discovery. As a consequence, the overall performance of a region and whole network can be improved.
- Taking both gateway- and client-oriented traffic into consideration, and processing them respectively. For the gateway-oriented traffic, during the process of mesh clients accessing mesh routers, the condition of the whole proactive path is considered, which is different from the existing hybrid routing protocols. The proactive path with a better condition will be used to convey packets. Only the access mesh router in this proactive path can send route reply (RREP) message. In client-oriented traffic, in addition to load and speed, the limited energy of mesh clients is also taken into account. The mesh nodes with a better regional condition will be selected.

Simulation results by ns-3 [10] show that the proposed RCA-HRP can help hybrid WMN achieve better performance in terms of average throughput, latency, and packet loss rate.

The rest of the paper is organized as follows. Section II introduces some related work about routing protocols designed for hybrid WMN. Section III presents the details of RCA-HRP. The simulation results and analyses are given in Section IV. Section V presents conclusions and future work.

II. Related works

There are only a few research results on routing protocols for hybrid WMN. These works concern a few different aspects, such as capacity [11], stability [12], [13], security [14], [15], [16], [17], and energy [18], [19]. Most of the research focuses only on reactive routing protocol. ALARM [20] uses time of emptying data queue to evaluate link condition during the process of route discovery. AODV-HM [12] makes use of the hop count of mesh clients as routing metric, choosing the route with least count of mesh clients. As mesh clients are mobile, AODV-HM can select a route with more stability. SafeMesh [21] selects links based on congestion and channel diversity. Multi-link discovery and node type-aware routing are used in SafeMesh. AODV-DF [22] reduces the number of route request (RREQ) packets and controls the flooding effectively. The occupancy of resources can be reduced, and heavy load caused by control packets is avoided. EPTR [23] considers expected throughput, interference and path length, which can maximum network throughput. EFMMRP [24] preserves network resource by using fuzzy logic. Delay, bandwidth and residual energy are considered in EFMMRP. NSR [25] takes network stability into account, and gateway selection and loop-free algorithm are proposed in NSR.

Reactive routing protocol cannot make full use of static mesh routers. Once some data packets need to be sent, static mesh routers also need to find routes to reach other mesh routers. High overhead may be caused in this case. In hybrid routing protocol, proactive routing protocol can help mesh routers transfer packets to gateway directly, and reactive routing protocol is just used for the route discovery between mesh clients. Therefore, hybrid routing protocol is more adaptive and could be more effective for hybrid WMN.

However, the existing researches of hybrid routing protocol for hybrid WMN are even less. HMesh [26] combines the proactive routing protocol OLSR [27] and reactive routing protocol AODV [28]. OLSR is used among mesh routers, and AODV is used among mesh clients. HDV [9] makes use of tree-based proactive routing for communication between mesh routers and gateway, and set reactive routing among mesh clients. Both HMesh and HDV only use the hop count as the routing metric. CHRP [29] improves the routing metric, considering interference, channel condition and energy of mesh clients. All the above existing hybrid routing protocols for hybrid WMN neglect the access process. When a mesh client wants to access a mesh router, this mesh router can be used unconditionally and replies RREP directly if it knows the way to the destination. Then this same access mesh router and proactive path may be used frequently, which will cause heavy load and congestion. LA-CHRP [30] can choose the mesh router with less load as the access node. However, LA-CHRP only considers load condition of the access mesh router, and neglects the condition of the whole proactive path. The access mesh router indeed has less load, but the condition of whole proactive path may not be the same. In addition, all existing hybrid routing protocols only consider the condition of the current node, neglecting the situation of nodes in the neighboring region. To overcome these weaknesses, a new approach is going to be proposed in the next section.

III. Regional condition-aware hybrid routing protocol

Unlike all existing hybrid routing protocols for hybrid WMN, the proposed RCA-HRP makes use of regional conditions to help mesh nodes make more effective route selection. In addition, both gateway-oriented traffic and client-oriented traffic are considered in RCA-HRP. For gateway-oriented traffic, when a mesh client wants to access a mesh router, RCA-HRP considers the condition of the whole proactive path where this access mesh router is located. There are many factors which RCA-HRP considers for mesh routers in the proactive path, aiming to evaluate the condition of the whole proactive path more accurately. For these mesh routers, the number of neighboring mesh clients, neighboring mesh clients' load and speed are taken into account. In client-oriented traffic, regional network conditions such as neighbors' energy, speed and load are taken into consideration. During the process of obtaining regional information, the cross-layer approach [31] is used. The energy and speed of mesh clients can be collected from the application layer, and the queue length which reflects load condition at each radio interface of node can be obtained from the Media Access Control (MAC) layer.

A. Gateway-oriented traffic

1) Regional condition-aware weight value of proactive path: When a mesh client wants to access a mesh router, the condition of the whole proactive path where the access mesh router is located is considered in RCA-HRP. For the mesh routers in the proactive path, RCA-HRP considers the number and detailed condition of neighboring mesh clients to reflect the condition of the proactive path.

For each mesh client, its load condition is considered. As the load condition can be indicated by queue length [21], queue length is used to evaluate the weight of a mesh client. In addition, the number of neighboring mesh routers is also an important factor which can influence the performance of routes. More neighboring mesh routers can provide more stable routes and chances of communication. For instance, if a mesh client has several neighboring mesh routers, when a route between this mesh client and a mesh router is broken, the mesh client can connect to another neighboring mesh router to communicate. The weight value of mesh client i (denoted as W_c^i) can be expressed as

$$W_c^i = \begin{cases} \dfrac{queue\_length_i}{m}, m \neq 0 \\ queue\_length_i, m = 0 \end{cases} \tag{1}$$

where $queue\_length_i$ is the queue length of mesh client i, and m is the number of neighboring mesh routers of mesh client i. W_c^i indicates the situation of packet forwarding and load of mesh client i. Based on the above expression, for a mesh client, when its queue length is longer which means it has heavier load, then the weight value calculated by equation (1) will become bigger to reflect such a fact. On the other hand, when the number of the neighboring mesh routers is bigger which means the mesh client has more resource to communicate and as a result its relative load is lower, then the weight value calculated by equation (1) will become smaller to reflect such a fact. In other words, the weight value defined in (1) gives a comprehensive and balanced measure of the load for a mesh client.

As mesh clients can access their neighboring mesh routers at any time, mesh clients with packets to forward near a mesh router can indeed influence the condition of this mesh router. Thus, for each mesh router, the queue length of its neighboring mesh clients is considered in RCA-HRP. Here, the queue length condition of neighboring mesh clients can be represented by weight value W_c^i. In addition, for each mesh router, the speed of neighboring mesh clients can also influence the condition of this mesh router. High-speed mesh clients may access mesh routers frequently and irregularly, which causes instability of route and decreases network performance. Therefore, the speed of neighboring mesh clients is also taken into consideration in RCA-HRP.

In short, the regional condition of a mesh router includes the weight and speed of its neighboring mesh clients. Therefore, the weight of mesh router *j* (denoted as W_r^j) in the proactive path can be expressed as

$$W_r^j = \begin{cases} \dfrac{queue\_length_j}{queue\_length^r_{\max}} + \dfrac{\sum\limits_{client\ i \in N_j} W_c^i}{queue\_length^c_{\max}} + \dfrac{\sum\limits_{client\ i \in N_j} v_i}{n \times v_{\max}}, \ n \neq 0 \\ \dfrac{queue\_length_j}{queue\_length^r_{\max}}, \ n = 0 \end{cases} \tag{2}$$

where v_i is the speed of mesh client *i*, $queue\_length_j$ is the queue length of mesh router *j*, and N_j is the set of neighboring mesh clients of mesh router *j*. $queue\_length^r_{\max}$ and $queue\_length^c_{\max}$ are the maximum lengths of queue that are allowed for mesh routers and mesh clients, respectively. $v_{\max}$ is the maximum allowable speed of mesh clients in the whole network. *n* is the number of neighboring mesh clients of mesh router *j*. The weight defined in (2) represents the operation condition of a mesh router. The smaller the weight is, the better the condition is for the router.

As the proactive route is composed of mesh routers, the condition of the whole proactive path is related to each mesh router located in this path. Therefore the weight value of the whole proactive path (denoted as $Weight_p$) in RCA-HRP can be expressed as

$$\mathrm{W}eight_p = \sum_{j=1}^{k} W_r^j + \frac{k}{hop_{\max}} \tag{3}$$

where *k* is the hop count of the proactive path, and $hop_{\max}$ is the maximum hop count of all proactive paths. Based on the measure defined in (3), smaller $Weight_p$ means better condition of the given proactive path.

To clearly explain how to calculate the weight value of a proactive path in RCA-HRP, a simple example is shown in Fig. 2.

In Fig. 2, the dotted circles denote the transmission ranges of mesh client a and mesh router 1. We can see that mesh client a has three neighboring mesh routers. Thus, the value of *m* is 3. Mesh router 1 has two neighboring mesh

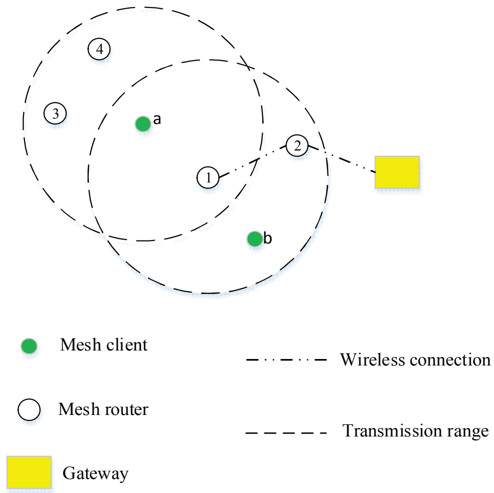


Fig. 2: An example for calculating the weight value of proactive path in RCA-HRP

clients, so the value of *n* is 2. Assuming that the queue length of mesh client a (i.e., $queue\_length_a$) is 6, then according to formula (1), the value of W_c^a can be calculated, which is 2. Mesh client b can get the value of W_c^b in the same way, and we assume that the value is 3 here. Assume the speed values of mesh client a and b are 1m/s and 2m/s respectively, and the queue length of mesh router 1 (i.e., $queue\_length_1$) is 5 here. The maximum queue lengths set for mesh routers and mesh clients (i.e., $queue\_length^r_{\max}$ and $queue\_length^c_{\max}$) are 20 and 10 respectively. The maximum speed of mesh clients (i.e., $v_{\max}$) which is allowed in the network is 10m/s. Based on formula (2), the value of W_r^1 is 0.9. Similarly, the value of W_r^2 for mesh router 2 can be calculated and is assumed to be 1.5 here. Further, $hop_{\max}$ is set as 5 in this example. Then based on the formula (3), the value of $Weight_p$ for this proactive path is the sum of W_r^1, W_r^2 and 2/5, which is 2.8.

2) Access mechanism: When a mesh client needs to access its neighboring mesh router *j*, the weight value for the whole proactive path of this router will be calculated, that is, $Weight_p$ is obtained. After calculating all weight values for all neighboring mesh routers for the given mesh client, that is, calculating all $Weight_p$, the mesh router with the smallest $Weight_p$ will be selected. That is, the router and its corresponding proactive path with the best condition will be used to transport packets. An example to illustrate such an access mechanism is shown in Fig. 3.

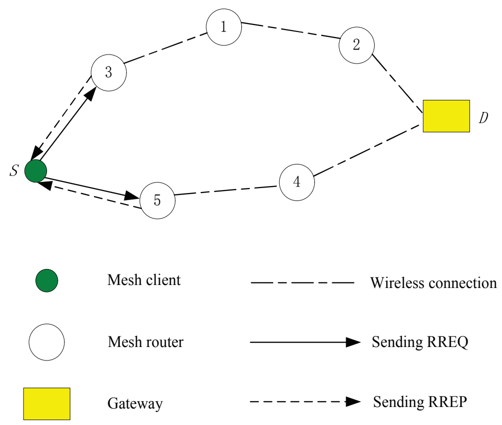


Fig. 3: An example of the access mechanism in RCA-HRP

In Fig. 3, mesh routers are connected to gateway *D* according to the proactive routing protocol. When mesh client *S* wants to communicate with gateway *D*, it broadcasts RREQ message, and both mesh routers 3 and 5 can receive this message. In RCA-HRP, each of mesh routers 3 and 5 will check whether they have valid routes to *D* in their proactive routing tables. If both of them have the valid routes, they will send RREP message to mesh client *S*. We assume that the $Weight_p$ of path 3-1-2-*D* is 2.1 and the $Weight_p$ of path 5-4-*D* is 1.9. Because $Weight_p$ for the corresponding path of router 5 is smaller, *S* will select mesh router 5 and its corresponding path 5-4-*D* to transmit data packets.

B. Client-oriented traffic

In the client-oriented traffic, W_r^j is still used here to set the weight of mesh router *j*. For a mesh client, as its weight value W_c^i is used to measure the effect of itself to other neighboring mesh routers, W_c^i only measures the load condition from the point of view of both the queue length and the number of its neighboring mesh routers as the communication resource. The calculation of W_c^i overlooks the residual energy of mesh client *i*. Because the energy of mesh clients is limited, energy is actually also an important factor needed to be considered during the process of routing. The remaining energy percent of mesh client *i* (denoted as P_{energy}^i) is

$$P_{energy}^i = \frac{R_{energy}^i}{I_{energy}^i} \tag{4}$$

where R_{energy}^i and I_{energy}^i are the remaining and initial energy of mesh client *i* respectively.

The improved weight of mesh client i (denoted as $Weight_c^i$) is then expressed as

$$Weight_c^i = W_c^i + (1 - P_{energy}^i) \tag{5}$$

Based on the above weigh, the reactive routing metric of RCA-HRP (denoted as $Metric_{reactive}$) is

$$Metric_{reactive} = \sum_{client\, i \in q} Weight_c^i + \sum_{router\, j \in q} W_r^j \tag{6}$$

where q represents the path which is formed by all mesh clients and routers on the path.

Thus, the route with smallest $Metric_{reactive}$ will be chosen to forward packets. As a result, the mesh routers whose neighboring mesh clients have lower speed and less packets to be transported will be chosen. At the same time, the mesh clients with more neighboring mesh routers and more residual energy will be selected.

When a node receives a RREQ, the process mechanism is shown in Fig. 4.

IV. Performance evaluation

The detailed simulation environment, performance metrics, simulation results and analyses are given in this section.

A. Simulation environment

Network simulator ns-3 is used to evaluate the performance of RCA-HRP in multi-radio multi-channel hybrid WMN. There are 25 mesh routers and 50 mesh clients in the area of 1000m×1000m. Mesh routers are deployed randomly and into a grid respectively. Mesh clients can always move arbitrarily in the network, and the MRMC environment is used. The Constant Bit-Rate (CBR) traffic flows are conveyed in the simulation. Both gateway- and client-oriented traffic exist simultaneously, and they are half and half. Details of simulation parameters are shown in Table I.

B. Performance metrics

Average throughput, average latency, and average packet loss rate defined as below are used as metrics to evaluate the network performance.

- Average throughput is the number of bits which are received successfully by the destination node every second.

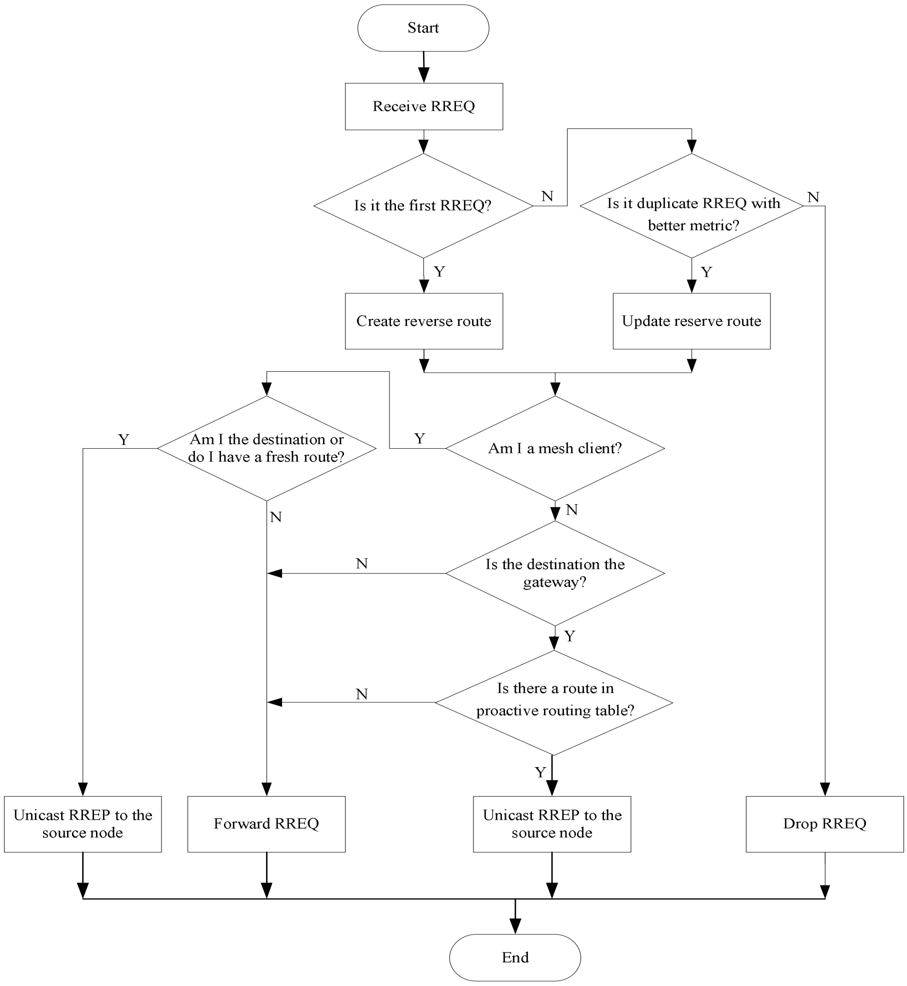


Fig. 4: The process mechanism of RREQ

- Average latency is the average delay of each packet delivered in success.
- Average packet loss rate is a ratio, that is the number of lost packets divided by the total number of packets sent by source node.

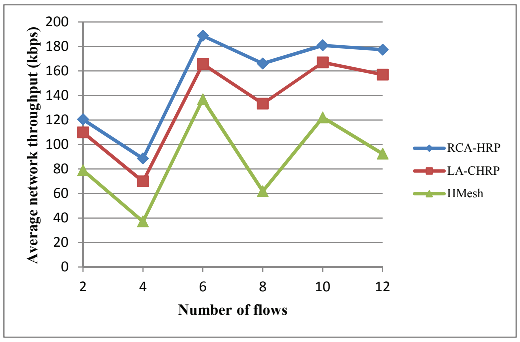
C. Simulation results and analyses

1) Hybrid WMN with grid backbone: Mesh routers are deployed into a 5×5 grid here, and mesh clients move randomly. There are two simulation cases. One is that the speed of mesh clients is fixed to 2m/s and the number of data flows is changed. The other is that the flow number is 8 and the mesh client speed is different. Simulation results are shown in Fig. 5, Fig. 6 and Fig. 7.

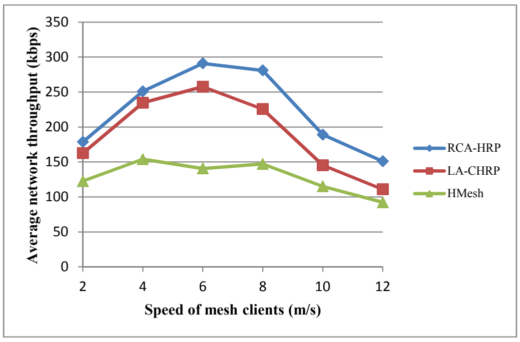
From Fig. 5, we can see that the average network throughput of RCA-HRP is always higher than LA-CHRP and HMesh. As the regional condition of mesh routers and mesh clients are considered comprehensively in RCA-HRP, during the

TABLE I: Simulation parameters

Simulation Parameters	Values
Simulation time	100 s
Traffic type	UDP
Packet size	1024 bytes
Packet rate	80 kbps
Number of radio interfaces in each router	3
Number of channels in each router	3 channels (1, 6, and 11)
Number of radio interfaces in each client	1
Number of channels in each client	1 channel (1)
Initial energy of each router	10000J
Initial energy of each client	500J
Transmission range	250 m
Interference range	550 m
Propagation model	Two Ray Ground
Mobility model of mesh clients	Random direction 2d mobility model
Antenna	Omnidirectional



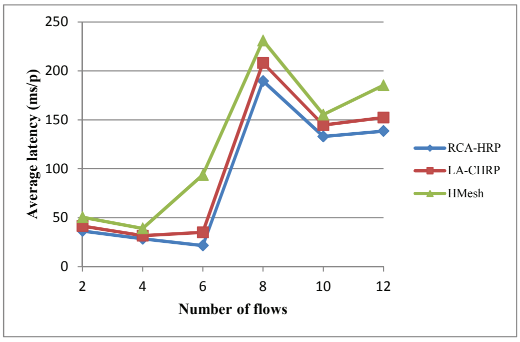
(a) Different number of flows



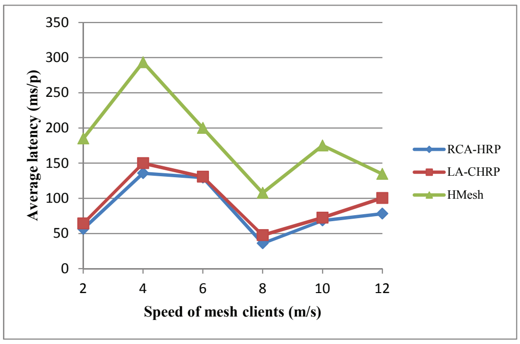
(b) Different speed of mesh clients

Fig. 5: Average network throughput of hybrid WMN with grid backbone

process of route discovery, the situation of all neighbors is considered. The area with heavy load and congestion can be avoided, and the node with better regional condition will be selected. Not only the condition of an individual node itself, but the condition of its neighbors is also taken into account. Then, the whole network performance has been improved, which makes RCA-HRP achieve higher average network throughput.



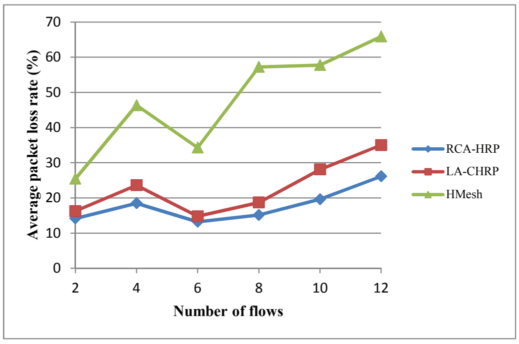
(a) Different number of flows



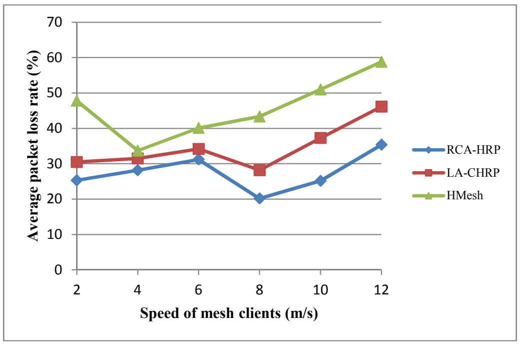
(b) Different speed of mesh clients

Fig. 6: Average latency of hybrid WMN with grid backbone

Fig. 6 demonstrates that the average latency of RCA-HRP is lower than LA-CHRP and HMesh. HMesh only uses the hop count as the routing metric. Route with the least hop count may have heavy load and congestion, and as a result the performance of HMesh is not good. LA-CHRP is a load-aware routing protocol, but it only considers the load condition of the access mesh router. Although the mesh router with less load and better condition will be selected as the access node, the condition of the whole proactive path is neglected and as a result the selected path is often not a good one. To avoid this situation, during the access process, in addition to the condition of the access mesh router, the situation of whole proactive path is taken into account in RCA-HRP. Then the proactive path with low load and better condition is chosen to transfer packets, which helps RCA-HRP choose better path effectively and get lower average latency.



(a) Different number of flows

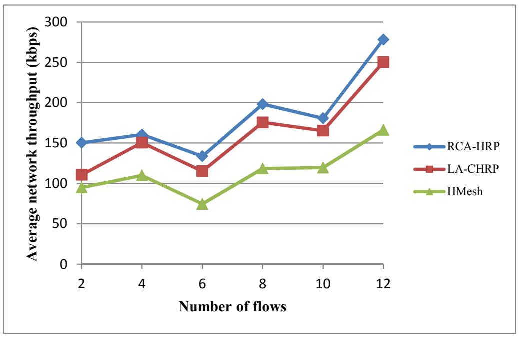


(b) Different speed of mesh clients

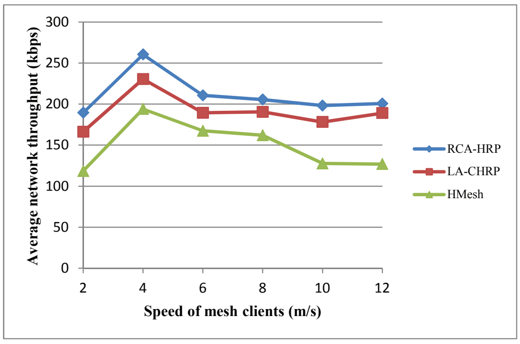
Fig. 7: Average packet loss rate of hybrid WMN with grid backbone

Fig. 7 shows that RCA-HRP can always obtain lower average packet loss rate than LA-CHRP and HMesh in different cases. RCA-HRP considers the different features of mesh routers and mesh clients. For mesh routers, the queue length of themselves, the speed and queue length of neighboring mesh clients are taken into consideration. For mesh clients, as they have limited energy, the energy condition of them is also considered in the process of route discovery. In addition, gateway- and client-oriented traffic are processed respectively and properly in RCA-HRP. In gateway-oriented traffic, the situation of whole proactive path is considered during access process. The more stable path with less load and congestion will be selected. In client-oriented traffic, besides the condition of node itself, regional condition is also considered. The node with better own and regional condition will be selected. As heavy load and congestion can be avoided in both gateway- and client-oriented traffic, the packet loss rate of RCA-HRP is lower than others.

2) Hybrid WMN with general backbone: In this part, mesh clients also move randomly, but mesh routers in backbone are deployed at random. Simulation results in terms of average network throughput, average latency and average packet loss rate are shown in Fig. 8, Fig. 9 and Fig. 10.



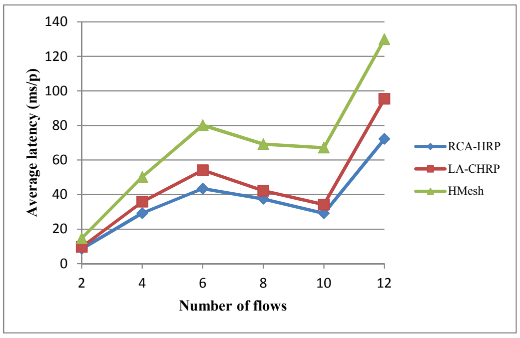
(a) Different number of flows



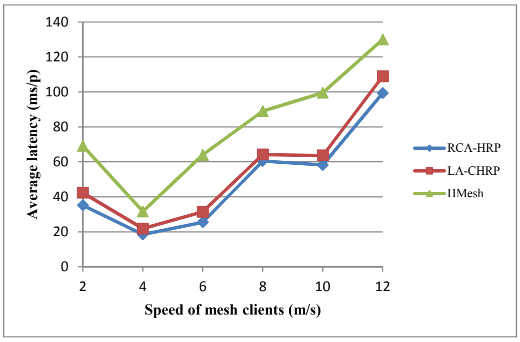
(b) Different speed of mesh clients

Fig. 8: Average network throughput of hybrid WMN with general backbone

From Fig. 8, Fig. 9 and Fig. 10, we can see that, similar to the simulation results in hybrid WMN with grid backbone, average network throughput, average latency and average packet loss rate by RCA-HRP are also better than LA-CHRP and HMesh, as RCA-HRP considers the condition of whole network more completely and comprehensively. Both gateway- and client-oriented traffic is considered, and regional condition is taken into account in these two kinds of traffic. A node in a more stable region, whose neighbors are with less load and congestion, can be selected in priority. Thus, the region with high congestion will be avoided effectively. Besides, gateway- and client-oriented traffic is processed separately. For gateway-oriented traffic, when a RREQ arrives at an access mesh router, this mesh router can reply a RREP directly if it has a valid proactive path to the gateway. The delay cost by finding paths can then be decreased. The performance of whole



(a) Different number of flows



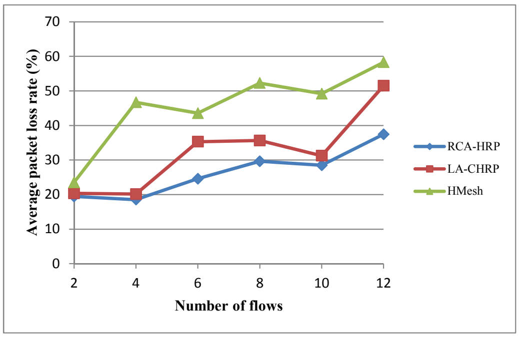
(b) Different speed of mesh clients

Fig. 9: Average latency of hybrid WMN with general backbone

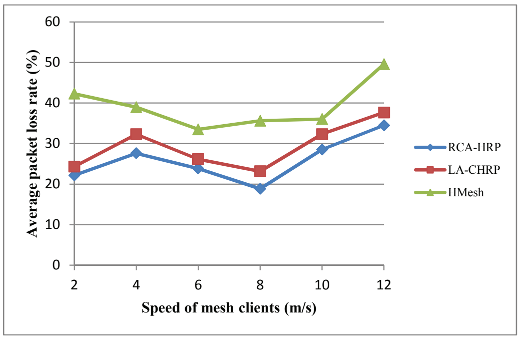
proactive path is also considered during the access process. Then RCA-HRP can select paths effectively according to the holistic condition. For client-oriented traffic, besides queue length and load condition, energy is also considered for mesh clients. The disconnection caused by running out of energy of one overused mesh client can be avoided. Due to these advantages, RCA-HRP can help hybrid WMN obtain better network performance.

V. Conclusions and Future Work

A right routing protocol can improve the performance of whole network dramatically. There are two different kinds of nodes (i.e., static mesh routers and mobile mesh clients) in hybrid WMN. Reactive routing protocols do not consider the different features of mesh routers and mesh clients, which cannot adapt well to hybrid WMN. Hybrid routing protocols combining both proactive and reactive routing protocols are more effective for hybrid WMN. However, current research about hybrid routing protocols is quite limited and few. Further, all of these hybrid routing protocols overlook regional condition of mesh nodes, and do not consider the situation of whole proactive path in the access process. RCA-HRP proposed in



(a) Different number of flows



(b) Different speed of mesh clients

Fig. 10: Average packet loss rate of hybrid WMN with general backbone

this paper has overcome these weaknesses. Regional condition of mesh routers and mesh clients are taken into account respectively. For mesh routers, queue length of themselves, speed and queue length of neighboring mesh clients are considered. For mesh clients, the number of their neighboring mesh routers, queue length and energy of themselves are all taken into consideration, and both gateway- and client-oriented traffic are considered in RCA-HRP. In gateway-oriented traffic, when a mesh client wants to access a mesh router, the condition of whole proactive path where the access mesh router is located is considered. In client-oriented traffic, a node with better own and regional condition will be selected to transport packets. Simulation results have shown the advantage of RCA-HRP in terms of average network throughput, average latency and average packet loss rate.

As the resource of a wireless network is constrained [32], making full use of resource is very important. To transport as many data packets as possible with limited resource and guarantee the quality of service (QoS) request [33] [34] is a goal in a wireless network. To do resource allocation in an effective and balanced way is our future work.

REFERENCES

[1] X. Du, M. Guizani, Y. Xiao, H.H. Chen, Transactions papers a routing-driven Elliptic Curve Cryptography based key management scheme for Heterogeneous Sensor Networks, IEEE Transactions on Wireless Communications. 8(3) (2009) 1223-1229.

[2] X. Du, F. Lin, Designing Efficient Routing Protocol for Heterogeneous Sensor Networks, in: 24th International Performance, Computing, and Communications Conference (IPCCC), 2005, pp. 51-58.

[3] H. Zhang, S. Chen, X. Li, H. Ji, X. Du, Interference Management for Heterogeneous Network with Spectral Efficiency Improvement, IEEE Wireless Communications. 22(2) (2015) 101-107.

[4] D. Benyamina, A. Hafid, M. Gendreau, Wireless mesh networks design-A survey, IEEE Communications surveys & tutorials. 14(2) (2012) 299-310.

[5] P. B. Duarte, Z. M. Fadlullah, A. V. Vasilakos, N. Kato, On the partially overlapped channel assignment on wireless mesh network backbone: A game theoretic approach, IEEE Journal on Selected Areas in Communications. 30(1) (2012) 119-127.

[6] A. Al-Saadi, R. Setchi, Y. Hicks, S.M. Allen, Routing Protocol for Heterogeneous Wireless Mesh Networks, IEEE Transactions on Vehicular Technology. 65(12) (2016) 9773-9786.

[7] Z. Wang, Y. Chen, C. Li, PSR: A lightweight proactive source routing protocol for mobile ad hoc networks, IEEE Transactions on vehicular technology. 63(2) (2014) 859-868.

[8] A. Boukerche, B. Turgut, N. Aydin, M.Z. Ahmad, L. Bölöni, D. Turgut, Routing protocols in ad hoc networks: A survey, Computer networks. 55(13) (2011) 3032-3080.

[9] A. Le, D. Kum, Y. Cho, An Efficient Hybrid Routing Approach for Hybrid Wireless Mesh Networks, Advances in Information Security and Assurance. (2009) 532-542.

[10] ns-3. http://www.nsnam.org/. Accessed October 9, 2017. (2017).

[11] A. Pirzada, M. Portmann, Establishing high capacity routes in wireless mesh networks, in: Asia-Pacific Conference on Communications, 2007, pp. 285-288.

[12] A. Pirzada, M. Portmann, J. Indulska, AODV-HM: A hybrid mesh ad-hoc on-demand distance vector routing protocol, Journal of Research and Practice in Information Technology. 41(1) (2009) 65-84.

[13] W. Song, X. Fang, Cross-layer routing with link quality and stability-aware in ITS hybrid wireless Mesh networks, in: Sixth International Conference on Advanced Language Processing and Web Information Technology, 2007, pp. 304-308.

[14] S. Khan, J. Loo, Cross layer secure and resource-aware on-demand routing protocol for hybrid wireless Mesh networks, Wireless Personal Communications. 62(1) (2012) 201-214.

[15] J. Hu, H. Lin, L. Xu, Energy-Aware Secure Routing for Hybrid Wireless Mesh Networks, in: IEEE 17th International Conference on Computational Science and Engineering, 2014, pp. 915-922.

[16] X. Du, H. H. Chen, Security in wireless sensor networks, IEEE Wireless Communications. 15(4) (2008) 60-66.

[17] X. Du, Y. Xiao, M. Guizani, H.H. Chen, An effective key management scheme for heterogeneous sensor networks, Ad Hoc Networks. 5(1) (2007) 24-34.

[18] A. K. Kiani, R. F. Ali, U. Rashid, Energy-load aware routing metric for hybrid wireless mesh networks, in: IEEE 81st Vehicular Technology Conference, 2015, pp. 1-5.

[19] C. Luo, S. Guo, S. Guo, L.T. Yang, G. Min, X. Xie, Green communication in energy renewable wireless mesh networks: Routing, rate control, and power allocation, IEEE Transactions on Parallel and Distributed Systems. 25(12) (2014) 3211-3220.

[20] A. A. Pirzada, R. Wishart, M. Portmann, J. Indulska, ALARM: an adaptive load-aware routing metric for

hybrid wireless mesh networks, in: Proceedings of the 32nd Australasian Conference on Computer Science, 2009, pp. 37-46.

[21] A. A. Pirzada, M. Portmann, R. Wishart, J. Indulska, SafeMesh: A wireless mesh network routing protocol for incident area communications, Pervasive and Mobile Computing. 5(2) (2009) 201-221.

[22] D. Kum, A. Le, Y. Cho, C. Toh, I. Lee, An efficient on-demand routing approach with directional flooding for wireless mesh networks, Journal of Communications and Networks. 12(1) (2010) 67-73.

[23] X. Deng, L. He, Q. Liu, X. Li, L. Cai, Z. Chen, EPTR: expected path throughput based routing protocol for wireless mesh network, Wireless Networks. 22(3) (2016) 839-854.

[24] A. K. Yadav, S. K. Das, S. Tripathi, EFMMRP: Design of efficient fuzzy based multi-constraint multicast routing protocol for wireless ad-hoc network, Computer Networks. 118 (2017) 15-23.

[25] M. Boushaba, A. Hafid, M. Gendreau, Node stability-based routing in Wireless Mesh Networks, Journal of Network and Computer Applications. 93 (2017) 1-12.

[26] L. Zhao, Z. Yu, J. Niu, H. Zhang, W. Ding, A Hybrid Routing Protocol for Hierarchy Wireless Mesh Networks, in: 6th International Conference on Wireless Communications Networking and Mobile Computing, 2010, pp. 1-4.

[27] T. Clausen, P. Jacquet, Optimized link state routing protocol (OLSR). (2003).

[28] C. Perkins, E. Belding-Royer, S. Das, Ad hoc on-demand distance vector (aodv) routing, RFC 3561. (2003)

[29] Y. Chai, W. Shi, T. Shi, X. Yang, An efficient cooperative hybrid routing protocol for hybrid wireless mesh networks, Wireless Networks. 23(5) (2017) 1387-1399.

[30] Y. Chai, W. Shi, T. Shi, Load-aware cooperative hybrid routing protocol in hybrid wireless mesh networks, AEU-International Journal of Electronics and Communications. 74 (2017) 135-144.

[31] B. Fu, Y. Xiao, H. Deng, H. Zeng, A survey of cross-layer designs in wireless networks, IEEE Communications Surveys & Tutorials. 16(1) (2014) 110-126.

[32] Y. Xiao, V. K. Rayi, B. Sun, X. Du, F. Hu, M. Galloway, A survey of key management schemes in wireless sensor networks, Computer communications. 30(11-12) (2007) 2314-2341.

[33] Y. Xiao, X. Du, J. Zhang, Internet protocol television (IPTV): the killer application for the next-generation internet, IEEE Communications Magazine. 45(11) (2007) 126-134.

[34] X. Du, QoS Routing Based on Multi-Class Nodes for Mobile Ad Hoc Networks, Ad Hoc Networks. 2(3) (2004) 241-254.

Chapter 4

Delay- and Interference-Aware Routing for Wireless Mesh Network

This chapter presents the peer-reviewed journal paper about centralized routing method considering delay and interference. The formal permission of reusing it is given in the Appendix A. The most recent impact factor, h-index, Cite Score, the SJR and the SNIP of the journal are given as below [133,135,136].

Published in Journal *IEEE Systems Journal*,

Volume: 14,

Issue: 3,

Pages: 4119 – 4130,

Publisher: IEEE.

Impact Indicators:

- Impact Factor (2020): 3.931
- Impact Factor Quartile: Q1
- h-index: 54
- SJR (2020): 0.864
- SNIP (2020): 1.736
- Cite Score (2020): 7.70

The final version of this paper is available online at
https://ieeexplore.ieee.org/abstract/document/8995471

Summary: Routing design among mesh routers is very important because mesh routers compose the infrastructure WMN. With the global network view, the routing problem can be formulated as an optimization problem. This paper proposes a delay- and interference-aware routing to select routes with the least delay. To derive delay, interference and the PTF are considered. Congestion is also avoided when solving the routing optimization model by the improved GA.

Comments on authorship: I proposed the main idea of this paper, concluded the existing centralized proactive routing methods in WMN, built the relationship between delay and the number of interfering nodes, improved the GA, wrote and revised the paper. My supervisor, Xiao-Jun Zeng, guided the research direction, proofread the paper and gave me suggestions about the idea.

Key contribution: Contribution 2 in section 1.4.

Delay- and Interference-Aware Routing for Wireless Mesh Network

Yuan Chai and Xiao-Jun Zeng

Department of Computer Science, University of Manchester,

Manchester, UK, M13 9PL

{yuan.chai, x.zeng}@manchester.ac.uk

Abstract

Effective routing design can significantly improve the whole network performance. In order to achieve the global best network performance, the problem of routing can be formulated as a constrained optimization problem. A delay- and interference-aware routing (DIAR) method using optimization is proposed in this paper to find effective routes in a wireless mesh network. With the rapid development of wireless communication, next-generation networks urge shorter delay. DIAR aims at selecting routes with minimum end-to-end delay for several concurrent data flows. Delay is derived according to interference, bandwidth and the probability of transmission failure. Then the relationship between delay and the number of interfering nodes is built for the first time, which makes the estimation of delay more simple. When solving the optimization problem, an improved genetic algorithm is proposed to balance load. Besides, DIAR considers dynamic network condition caused by selecting different paths to transmit packets and evaluates the network condition while finding the solution of routing. The paths with least end-to-end delay, will be finally chosen as the solution. Simulation results show that DIAR can obtain better network performance.

Index Terms

Wireless mesh network, routing, optimization model, delay, interference.

I. Introduction

Due to the features of low cost, high robustness and reliability, wireless mesh network (WMN) is an essential architecture in next generation of communication network, which attracts the attention of many researchers [1] [2]. The self-construction and self-configuration peculiarities can dramatically reduce the complexity of network deployment and maintenance. As WMN can be established flexibly with low cost, it can be used in temporary networks like communication networks deployed in an exhibition, where users are temporarily crowded. Besides, WMN can recover communication fast when disasters or accidents happen, so it is very suitable for emergency communication, military communication and enterprise wireless communication, and so on. Smart home devices can also build a WMN, and multiple hops can extend the coverage area. Although communication technology develops very fast, and 5G starts being used, there are and will be still many rural areas where it is very hard and too costly to deploy traditional base stations to access the Internet. These scattered areas with complex physiognomy are far away from cities and towns so that the traditional deployment will cost a lot. In this case, WMN is valuable to provide Internet service. The network model is shown in Fig. 1.

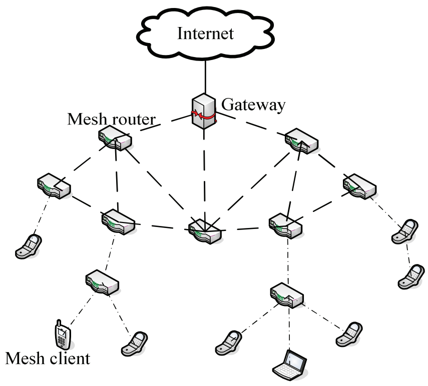


Fig. 1: Network model of WMN.

There are two types of mesh nodes in WMN: mesh routers and mesh clients [3] [4]. Mesh routers are always equipped with multiple radio interfaces connected with multiple wireless channels, while mesh clients have a single radio interface. A common channel must be set for both mesh routers and clients, which makes it possible to communicate between mesh routers and clients smoothly. The data traffic in WMN includes gateway-oriented and client-oriented traffic [5]. In gateway-oriented traffic, data flows are convergent through the gateway to the Internet. In client-oriented traffic, different mesh clients or mesh routers are connected by multiple hops.

Routing is very important in network design to improve network performance [6]. Bad path selections will cause congestion, high interference, long delay, and so on. Thus, designing an effective routing method considering link quality is essential

[7]. Nowadays, more and more communication services require little delay, so a delay- and interference-aware routing (DIAR) method minimizing end-to-end delay is proposed in this paper. The main contributions of DIAR can be summarized as follows:

- Derive the mathematical relationship between delay and the number of interfering nodes, and formulate routing into an optimization problem. As the delay is a crucial criterion of network performance, minimizing delay is the objective of routing optimization model. As a result, the route with the least end-to-end delay will be selected. To evaluate delay accurately, DIAR considers bandwidth, interference and the probability of transmission failure (PTF) at the same time. Both transmission and backoff delay are considered. As directly obtaining delay by a proactive method will cause high cost, establishing the relationship between delay and fundamental network factors is vital. As far as we know, DIAR firstly builds the relationship between delay and the number of interfering nodes, which can estimate delay and select paths effectively with low cost.
- Extend the basic genetic algorithm (GA) to balance the load when solving the routing optimization problem. The basic GA finds solutions by random crossover and mutation, and it cannot obtain the routing solution effectively. Heavy congestion and load will occur if more than one data flow use the same mesh node, and the basic GA does not consider this particular condition. DIAR overcomes this weakness, which produces a more adaptive method to solve the routing problem. If a common node is used by multiple data flows, another mesh node with the least number of interfering nodes will be selected as a replacement node. The rationality of this method is given according to the derived relationship between delay and the number of interfering nodes. In addition, as different selected routes can influence and change network condition in turn, the improved GA considers the dynamic condition as input parameters and evaluates the condition iteratively to find optimal paths.

II. Related Works

The research of routing optimization designed for the WMN includes the formulation of the optimization model and solution of the optimization model. Some research studies do not particularly consider interference. A search-based routing using GA [8] is proposed in [9]. This method considers Expected Transmission Time (ETT) [10] in addition to hop count as the routing metric. The fitness function is based on hop count and aggregated ETT. The end-to-end delay, according to ETT, is minimized, and results are better than traditional hop count metric. The performance of GA in the context of routing in WMN is then evaluated. A robust GA-based QoS routing method is proposed in [11]. Multiple feasible paths are found in this method, which can improve the robustness. For each chromosome, the normalized cost based on all types of QoS metrics is used as the fitness value. Different QoS parameters can be considered at the same time, but the link metrics are generated uniformly. The routing algorithm proposed in [12] considers delay, throughput and packet error ratio separately according to different types of communication applications. The interaction between Medium Access Control (MAC) and routing algorithms is considered sufficiently. Besides, the resource for QoS flows is reserved. The routing algorithm proposed in [13] uses Expected Transmission Count (ETX) [14]to evaluate link conditions and develops a multi-objective approach for the routing problem. The modified non-dominated sorting GA is used to discover better and diverse routing solutions.

Some other research studies consider the interference influence. The routing method in [15] maximizes throughput by analyzing different types of interference. The two types of interference are distinguished by the distance between the interferer link and the reference link. Then, the maximum throughput that the network can support is obtained. The mixed-integer linear program model is established to formulate this routing problem. Spatial reusability-aware single-path routing (SASR) and spatial reusability-aware anypath routing (SAAR) [16] consider the spatial reusability problem in routing. The interference relationship is influenced by the node location. The path with minimized cost, which is composed of noninterfering links, is selected. Load-balance and interference-aware (LBIA) [17] considers the load balance problem in the situation of multicast sessions, and the link with less load is selected. Intra-flow and inter-flow interference are considered separately in LBIA. The process of finding paths in LBIA is the approach of building a multicast tree. The method proposed in [18] is based on a greedy algorithm [19], and it can choose the path with minimum cost by considering the usage of wireless channels. An end-to-end throughput model based on the IEEE 802.11 protocol [20] is proposed in [21], which can guide routing design. Load-aware route selection (LARS) [22] selects load-balance paths and gateways by using queuing model and estimating the residual capacity of network paths. Network bottlenecks are identified, and the network paths to upstream Internet flows are allocated to improve the network capacity. In this way, wireless network resources and gateways are utilized in a balanced way. Distributed delay-aware routing (DDAR) [23] is a multihop multipath routing in a joint distributed scheduling and routing problem. Based on the conflict graph model and Lyapunov optimization, the delay of each commodity flow is minimized. Although these research studies consider interference, the particular way to obtain delay with low cost is not derived. The cost of obtaining network conditions is not sufficiently considered.

Some research studies typically focus on finding effective solutions for optimization models. Jiang *et al*. [24] consider delay, bandwidth and packet loss ratio to satisfy the communication request. The solution algorithm of this research combines GA and ant colony optimization (ACO) [25]. The algorithm proposed in [26] minimizes the cost to guarantee the QoS request, and it combines GA and particle swarm optimization (PSO) [27] to solve the optimization problem. Cuckoo search optimization ad-hoc on-demand distance vector (CSO-AODV) [28] applies Cuckoo Search and uses the best fitness value computation to find the best path when multiple routes are available. It satisfies QoS constraints like load, energy and hop count when discovering routes. However, the congestion caused by using a common node in particular routing problem is not effectively taken into account in these research studies.

In general, existing research studies satisfy different focuses, but the approach and cost of obtaining network conditions are overlooked. Collecting information by using probe packets can cause high load and cost, which will degrade the network performance. So finding an effective and easy way to evaluate link performance is essential. Besides, when the solution of routing is different, the network condition will also be different. That is, the solution can influence the network condition in turn. The process of finding routes and evaluating network condition should be done at the same time.

III. System Model

WMN is modelled by a network connectivity graph G=(V, L), where V and L are the sets of all mesh nodes and links in WMN, respectively. Nodes are deployed uniformly, and multiple wireless channels for mesh routers are allocated randomly. The set of source-destination traffic (denoted as F) is given. For the sake of clarity, all notations used in this paper are listed in Table I.

TABLE I: Variable Notations

Notation	**Denotation**
V	Set of mesh nodes
L	Set of wireless links in WMN
F	Traffic of data flows
h_t	Height of transmitting antennas
h_r	Height of receiving antennas
λ	Wavelength
G_t	Gain of transmitting antennas
G_r	Gain of receiving antennas
d_0	Critical distance of different transmission models
i	The source node of a link
j	The destination node of a link
d_{ij}	Distance between source node i and destination node j
PL_{ij}	Path loss between i and j
$E(p)$	Channel fading between i and j
P_{ij}^{loss}	Receiving power only considering path loss
P_{ij}^{fading}	Receiving power only considering channel fading
(i,j)	A wireless link
σ_{ij}^2	Power of multipath components on link (i,j)
e	A data flow
X_{ij}^e	(binary)=1, when link (i,j) is used to service flow e
N_i^e	The number of queuing packets at node i in data flow e
$T_{(i,j)}^e$	Delay cost by transmitting each packet on link (i,j) for flow e
S	Set of source nodes

D	Set of destination nodes
c^e_{ij}	(binary)=1, when link (*i*,*j*) exists
$P_{(i,j)}$	Probability of transmission failure on link (*i*,*j*)
Length	Size of data packet
K	Largest allowed number of retransmission
k	Total number of transmission
$B_{(i,j)}$	Available bandwidth of link (*i*,*j*)
SlotTime	Time of a slot
CW_s	Duration of the s^{th} backoff window
CW_{min}	Minimum backoff window
P_{Ti}	Transmission power of source node *i*
P_{ij}	Receiving power at destination node *j* from source node *i*
P_{aj}	Receiving power of interference at node *j* from node *a*
I_{ij}	Interference to link (*i*,*j*)
γ_{ij}	SINR of link (*i*,*j*)
N	Power of background noise
B_0	Nominal bandwidth
r_T	Transmission range
r_I	Interference range
β	Threshold of SINR
I_j	Set of interfering nodes of node *j*
n	The number of interfering nodes of receiving node *j*
δ	Adjustment parameter
ξ	Difference between critical values of piecewise function

A. Transmission Model

The transmission model considers both path loss and fading channel model. The path loss model is chosen according to the distance between the source and destination [31]. If the distance is shorter than the critical distance, the free space propagation model will be used. If the distance is larger than the critical distance, then the two-ray ground reflection model will be selected. The critical distance (denoted as d_0) is

$$d_0 = \frac{4\pi h_t h_r}{\lambda} \tag{1}$$

where h_t and h_r are heights of transmitting and receiving antennas; λ is wavelength. The path loss effect between source node *i* and destination node *j* (denoted as PL_{ij}) can be expressed as

$$PL_{ij} = \frac{P_{ij}^{loss}}{P_{Ti}} = \begin{cases} \frac{G_t G_r \lambda^2}{(4\pi d_{ij})^2}, 0 < d_{ij} \leq d_0 \\ \frac{G_t G_r h_t^2 h_r^2}{(d_{ij})^4}, d_0 < d_{ij} \leq r_T \end{cases} \tag{2}$$

where P_{ij}^{loss} is the receiving power at destination node *j* from source node *i*, which is affected by path loss. P_{Ti} is the transmission power of source node *i*. G_t and G_r are the gain of transmitting and receiving antennas, respectively. d_{ij} is the distance between source node *i* and destination node *j*.

To describe the realistic channel feature, Rayleigh fading channel model [32] is also used. The envelope of the received signal from node *i* to node *j* (denoted as x_{ij}) is Rayleigh distributed, and the probability density function of x_{ij} (denoted as $f_X(x_{ij})$) is

$$f_X(x_{ij}) = \frac{x_{ij}}{\sigma_{ij}^2} e^{-\frac{x_{ij}^2}{2\sigma_{ij}^2}}, x_{ij} \geq 0 \tag{3}$$

where σ_{ij}^2 is the power of multipath components.

Let received signal power $p_{ij} = x_{ij}^2$, so the distribution of p_{ij} (denoted as $f_P(p_{ij})$) is

$$f_P(p_{ij}) = \frac{dx_{ij}}{dp_{ij}} f_X(\sqrt{p_{ij}}) = \frac{1}{2\sigma_{ij}^2} e^{-\frac{p_{ij}}{2\sigma_{ij}^2}}, p_{ij} \geq 0 \tag{4}$$

Therefore, the received signal power is exponent distributed, and its expected value (denoted as $E(p_{ij})$) is

$$E(p_{ij}) = 2\sigma_{ij}^2 \tag{5}$$

Based on (5), the average receiving power only influenced by channel fading (denoted as P_{ij}^{fading}) is

$$P_{ij}^{fading} = P_{Ti} \cdot E(p_{ij}) \tag{6}$$

where P_{Ti} has the same meaning as that in (2).

According to the path loss and channel fading effects, the final received signal power (denoted as P_{ij}) can be expressed as

$$P_{ij} = P_{Ti} \cdot PL_{ij} \cdot E(p_{ij}) \tag{7}$$

B. MAC Protocol

IEEE 802.11 standard is used as the MAC-layer protocol, and the distributed coordination function is applied [20]. To avoid collisions of contending wireless channel, the backoff mechanism is used. If a packet is not successfully received by the destination, the source will retransmit until the number of retransmission reaches the maximum value. Before sending packets, the node detects channel condition lasting a random number of backoff window. The maximum range of the backoff window will be doubled in each retransmission. When the times of retransmission reaches the maximum value, the packet will be dropped.

IV. DIAR Model Design

DIAR is a type of centralized routing method, where the gateway and network manager makes the selection of routes according to the statistics and topology information collected from each mesh node. The network manager will then do the calculation and send back the best route to mesh nodes [22] [29]. DIAR formulates the route selection issue as an optimization problem and overcomes the current weaknesses. Signal to interference plus noise ratio (SINR) [30], bandwidth, PTF and delay can describe the network condition, and delay is influenced by the other three network factors. To overcome the difficulty of obtaining delay, we derive the mathematical expression of PTF according to the number of interfering nodes. Then, as the delay is related to PTF, the relationship between delay and the number of interfering nodes is firstly given in DIAR. Besides, DIAR improves the GA to balance load in the typical routing problem. When different paths and combination of wireless links are selected, the number of interfering nodes for each used node will be different, and the network condition and delay will change. The improved GA method also evaluates the dynamic network condition in each iteration. The optimization process and GA are started every time when a flow demand arrives. When a new traffic flow arrives, the source node will send a request message to the network manager, which makes the new flow be detected. The network manager will then execute the optimization process. Finally, DIAR can select the effective routes with less delay, less interference, less PTF, and larger available bandwidth for multiple data flows at the same time, which can achieve better whole network performance.

A. Establishment of Optimization Model

1) Objective: Minimizing end-to-end delay is the objective of the optimization model of DIAR, and it is given as

$$minimize \left\{ \sum_{(i,j)\in L} \sum_{e\in F} X_{ij}^{e} T_{(i,j)}^{e} (N_i^e + 1) \right\}, \forall e \in F \tag{8}$$

where *L* is the set of links in the network, *e* is a data flow, *F* is the set of all data flows. X_{ij}^e is the binary decision variable of the optimization problem to show whether flow *e* is via link (*i*,*j*). If link (*i*,*j*) is chosen to transmit packets of data flow *e*, X_{ij}^e is 1, or X_{ij}^e is 0. $T_{(i,j)}^e$ is the delay cost by transmitting each packet on link (*i*,*j*) for data flow *e*. N_i^e is the number of queuing data packets waiting to be transmitted at node *i* in data flow *e*. For each data flow, the end-to-end delay will be minimized, and it indicates the goodness level of routing solution. The detailed mathematical expression of delay will be given in Section V.

2) Constraints: Constraints in the optimization model guarantee smooth communication. The detailed constraints of DIAR are listed as follows.

The source node of each data flow must connect one neighbor node to transmit data packets out

$$\sum_{(i,j)\in L} X_{ij}^e = 1, i \in S, \forall e \in F \tag{9}$$

where *S* is the set of source nodes. Similarly, the destination node of each data flow also must connect one neighbor node to receive data packets

$$\sum_{(i,j)\in L} X_{ij}^e = 1, j \in D, \forall e \in F \tag{10}$$

where *D* is the set of destination nodes. Then the intermediate nodes should guarantee that all receiving packets can leave through another link. This request is shown as

$$\sum_{(i,j)\in L} X_{ij}^e = \sum_{(j,u)\in L} X_{ju}^e, \forall j \in V - \{S, D\}, \forall e \in F \tag{11}$$

where *u* is the next hop of node *j* in data flow *e*. Formulas (9)-(11) represent the flow conservation. If a loop exists in a route, there will be an intermediate node with different number of input and output links, that is, $\sum_{(i,j)\in L} X_{ij}^e \neq \sum_{(j,u)\in L} X_{ju}^e$, which is conflicted with the constraint (11). Thus, the path identified by DIAR, which meets constraints (9)-(11) is loop-free.

Besides, the wireless links selected to be used must can exist in the WMN

$$c_{ij}^e \geq X_{ij}^e, \forall (i,j) \in L, \forall e \in F \tag{12}$$

where c_{ij}^e is a binary constant to show whether link (*i*,*j*) exists in the network. If the distance between node *i* and *j* is within the transmission range of each other, then link (*i*,*j*) exists and the value of c_{ij}^e is 1. Otherwise, link (*i*,*j*) cannot appear, and the value of c_{ij}^e is 0. This constraint means that the end nodes of selected links must be within the transmission range of each other.

The value of variable X_{ij}^e in the optimization model is binary

$$X_{ij}^e \in \{0,1\}, \forall (i,j) \in L, \forall e \in F \tag{13}$$

Then, the optimization model is formulated with the objective given in (8), subject to the constraints given (9)-(13). Based on smooth communication, the end-to-end delay of the whole network is minimized during the process of routing.

B. Solution of the Optimization Model

Due to the interaction between the solution of routing and the network condition, the optimization problem formulated in the last two subsections is difficult to be solved by the conventional optimization algorithms such as mathematical programming. On the other hand, the GA is applicable to the given optimization problem, and it has been successfully applied to solve some routing problems, as stated in Section II. The GA is a very effective approach to find an optimal solution [33], and it is even regarded as the best choice to find the optimal path [9]. For these reasons, the GA is used here to solve the formulated optimization model. The GA obtains the solution by iterations, and it will stop when either the maximum number of iterations is reached or no improvement can be achieved by further iterations. The set of solutions in each iteration is known as a population. Each population includes some chromosomes, and every chromosome represents the selected path for data flows. The chromosome is composed of a sequence of node numbers, which are the ones selected to transmit data packets. Some random and valid paths are set as the initial population. As DIAR considers the dynamic network condition, the delay of selected links is evaluated and updated for each chromosome in the iterative optimization.

Crossover and mutation can explore new solutions. In DIAR, to avoid some elite parent chromosomes becoming worse after crossover and mutation, all parent and offspring chromosomes are sorted together according to their levels of goodness. The worst chromosomes that are over the population size will be deleted. Besides, when the duplicated chromosomes are produced, only one of them will be kept; the others will be deleted.

The quality and goodness of chromosomes in the constrained optimization problem is evaluated by the fitness function (denoted as $Fit(i)$), which is

$$Fit(i) = \begin{cases} \frac{T(i)-T_{\min}}{T_{\max}-T_{\min}}, J\_vio(i) = 0 \\ \sqrt{\frac{\sum\limits_{j=1}^{J}\left(\frac{\max(0,f(j))}{G_{\max}^{j}}\right)^2}{J\_vio(i)}}, J\_vio(i) \neq 0 \end{cases} \tag{14}$$

where $J\_voi(i)$ is the number of violative constraints in chromosome *i*. $T(i)$ is the end-to-end delay value of chromosome *i*; therefore, it is the objective of the optimization model shown in (8). T_{min} and T_{max} are the minimum and maximum delay values among all chromosomes of the generation. $f(j)$ is the degree of violation (absolute value of the difference between both equation sides) in terms of constraint *j*. If the *j*th constraint is satisfied, $f(j)$ is 0. $G_{\max}^{j}$ is the maximum violation value of constraint *j* in the generation. *J* is the total number of constraints in the optimization model.

If $J\_voi(i)$ is 0, the chromosome is feasible. The constraints from (9) to (13) are satisfied, where flow conservation and transmission rule are met. The fitness function can show the goodness of chromosomes. The chromosome with less fitness value is better, as it means that the corresponding feasible solution has the smaller delay. If $J\_voi(i)$ is not 0, the chromosome is non-feasible. The fitness function is used to show the degree of constraint violation. The smaller value of the fitness function means that a nonfeasible solution has less violation degree. When sorting the chromosomes, the reasonable chromosomes are followed by the nonreasonable ones. Each type of chromosomes is sorted by the fitness function values from small to large. The first chromosome will be considered as the best solution. This process of finding better solutions is executing until the maximum number of iterations is reached. Applying elitism also helps to make solutions better and better. Although the final verdict of the least delay cannot be given in advance to stop the iterations, optimal solutions usually can be obtained at the current state of art of computation [9]. Finally, the reasonable solution with minimum fitness value (i.e., delay) will be selected as the optimal path.

The original GA finds a solution by random crossover and mutation, which ignores some particular features of routing in WMN. Such negligence could lead to some undesired performance. For example, a high congested route, which uses the same node by multiple data flows, can be obtained by original GA. To avoid this, DIAR improves GA to solve the optimization model. The main improvements are shown as follows.

1) Crossover: Single-point crossover [39] is used in DIAR. To ensure that the paths generated by crossover are still valid paths, the selected pair of parent chromosomes must have at least one common node in addition to the source and destination nodes. The common node of two parent chromosomes is then used as the crossover point. The former and latter parts of each chromosome are exchanged to build two new chromosomes. For instance, if the chromosomes [1-3-4-8-0] and [1-2-4-7-9-0] are selected as parent chromosomes, the common node 4 will be the crossover point. [1-3-4-7-9-0] and [1-2-4-8-0] are obtained after crossover.

2) Mutation: In original mutation, one random point in the selected chromosome is replaced with another random neighbor node, which does not particularly consider the congestion situation in the routing problem. However, when a common node is used by multiple data flows, the queuing packets at this common node will increase, and congestion will be caused. Thus, the basic GA needs to be improved to find routes more effectively. Based on the relationship between delay and the number of interfering nodes, which will be given in detail in Section V, when one node is used by more than one data flows, the improved algorithm in DIAR will choose another neighbor node with least number of interfering nodes as a replacement node. For example, if five flows (flows 1-5) are transmitted to the next node A, one of them (e.g. flow 1) will be still transmitted to A, and the other four (flows 2-5) will try to find other alternative nodes to replace the previous next node A. Ideally, the four alternative nodes chosen by flows 2-5 are different. However, if there are still some flows selecting the same alternative node B (e.g. flows 2-5 select node B at the same time in the worst case scenario), one flow will transmit to the alternative node B (e.g. flow 2), and others (flows 3-5) will try to find another new replacement node again. This process will be executed until all flows have new and different alternative nodes or in imperfect case, until obtaining best performance improvement. The imperfect case is that all allowed alternative nodes have already been used when a flow looks for an alternative node, so a shared node with other flows has to be selected. In this case, the shared node with the least number of interfering nodes will be chosen. The best performance improvement is then obtained in the imperfect conditions. Congestion will be avoided, and load can be balanced effectively in this way. To guarantee the normal and smooth communication, the new replacement node is within the transmission range of both previous and next hops of the common node.

To clearly explain the algorithm, a flow chart is given in Fig. 2.

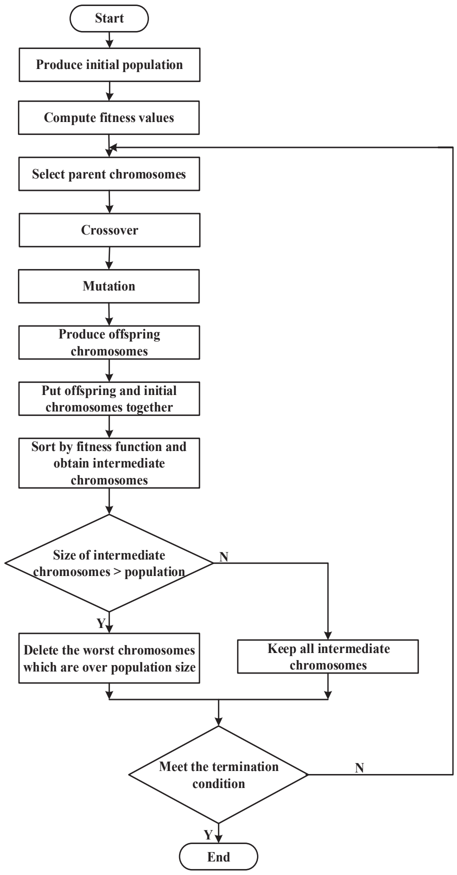


Fig. 2: Flow chart of proposed GA.

V. Key Parameters and Relationships in the Optimization Model of DIAR

A. *Expression of Delay*

Transmission and backoff time compose the delay of transmitting each data packet successfully on the link (*i*,*j*) (denoted as $T_{(i,j)}$) [34]. The transmission time is the period cost by emptying a packet, and the backoff time is the waiting time before transmission. Therefore, the expected value of delay (denoted as $E[T_{(i,j)}]$) can be expressed as

$$\begin{aligned} E[T_{(i,j)}] = & \sum_{k=1}^{K+1} p_{(i,j)}^{k-1}(1-p_{(i,j)})^{I\{k<K+1\}} \\ & \cdot \sum_{s=1}^{k} (E[CW_s] \cdot SlotTime + \tfrac{Length}{B_{(i,j)}}) \\ = & \tfrac{Length}{B_{(i,j)}}[\tfrac{1-p_{(i,j)}^K}{1-p_{(i,j)}}] + E[backoff] \end{aligned} \tag{15}$$

where $p_{(i,j)}$ is the PTF on the link (*i*,*j*), *Length* is the size of a data packet, *K* is the largest allowed number of retransmission, *k* is the total number of transmission, and $B_{(i,j)}$ is the bandwidth of link (*i*,*j*). The indicator *I(A)* is equal to 1 if *A* is true. When the number of retransmission is beyond the maximum allowed number *K*, the packet will be dropped. *SlotTime* is the time of a slot. CW_s is the size of the *s*th backoff window.

The packet may be transmitted successfully in the *k*th transmission, and the probability of the *k*th transmission being successful is $p_{(i,j)}^{k-1}(1-p_{(i,j)})^{I\{k<K+1\}}$. Then the expected delay value of a successful transmission is the sum of all cases [the successful transmission may happen in the 1st to (*K*+1)th attempt].

CW_s can be expressed as

$$CW_s = 2^{s-1} \cdot CW_{min} \tag{16}$$

where CW_{min} is the minimum backoff window. Then, the expected value of CW_s (denoted as $E[CW_s]$) is

$$E[CW_s] = \frac{CW_s - 1}{2} = \frac{2^{s-1} \cdot CW_{min} - 1}{2} \tag{17}$$

So, the expected value of backoff time (denoted as *E*[*backoff*]) is

$$\begin{aligned} E[backoff] = & \sum_{k=1}^{K+1} p_{(i,j)}^{k-1}(1-p_{(i,j)})^{I\{k<K+1\}} \sum_{s=1}^{k} E[CW_s] \\ = & \frac{CW_{min}[1-(2p_{(i,j)})^{K+1}]}{2(1-2p_{(i,j)})} - \frac{1-p_{(i,j)}^K}{2(1-p_{(i,j)})} \end{aligned} \tag{18}$$

Thus, according to (15) and (18), the expected value of delay of link (*i*,*j*) (denoted as $E[T_{(i,j)}]$) can be expressed as

$$\begin{aligned} E[T_{(i,j)}] = & \tfrac{Length}{B_{(i,j)}}[\tfrac{1-p_{(i,j)}^K}{1-p_{(i,j)}}] \\ & + \tfrac{CW_{min}[1-(2p_{(i,j)})^{K+1}] \cdot SlotTime}{2(1-2p_{(i,j)})} \\ & - \tfrac{(1-p_{(i,j)}^K) \cdot SlotTime}{2(1-p_{(i,j)})} \end{aligned} \tag{19}$$

Delay of link (*i*,*j*) is, therefore, influenced by the available bandwidth (i.e., $B_{(i,j)}$) and the PTF (i.e., $p_{(i,j)}$). The approach of obtaining these two factors in DIAR is shown as follows.

B. Available Bandwidth

According to (7), the receiving power at destination node *j* from source node *i* (denoted as P_{ij}) is related to the path loss and channel fading between *i* and *j*, and it is

$$P_{ij} = \begin{cases} 2P_{Ti} \cdot \sigma_{ij}^2 \cdot \frac{G_t G_r \lambda^2}{(4\pi d_{ij})^2}, & 0 < d_{ij} \le d_0 \\ 2P_{Ti} \cdot \sigma_{ij}^2 \cdot \frac{G_t G_r h_t^2 h_r^2}{(d_{ij})^4}, & d_0 < d_{ij} \le r_T \end{cases} \tag{20}$$

where P_{Ti} is the transmission power of source node *i*.

The total interference to link (*i*,*j*) (denoted as I_{ij}) is

$$I_{ij} = \sum_{\forall a \in V, a \neq i} \sum_{\forall b \in V, b \neq j} P_{Ta} \cdot PL_{aj} \cdot E(p_{aj}) \cdot X_{ab} \cdot X_{ij} \ , \quad \forall i, j \in V, i \neq j \tag{21}$$

where *a* and *b* are the source and destination nodes of interfering link (*a*,*b*), respectively. Interference exists when interfering links and data transmission link (*i*,*j*) are used at the same time. The interference to link (*i*,*j*) is the sum of interference caused by all interfering links. According to the receiving power and interference, the SINR of link (*i*,*j*) (denoted as γ_{ij}) is

$$\gamma_{ij} = \frac{P_{ij}}{N + I_{ij}}, \forall i, j \in V, i \neq j \tag{22}$$

where *N* is the power of background noise in the network. Then, the available bandwidth (denoted as $B_{(i,j)}$) can be expressed as

$$B_{(i,j)} = B_0 \cdot log_2(1+\gamma_{ij}), \forall i, j \in V, i \neq j \tag{23}$$

where B_0 is the nominal bandwidth.

C. PTF

When the SINR is lower than the threshold, the transmission will be failed. The threshold is the minimum requested value of SINR that can guarantee data packets to be decoded successfully by the receiving node. PTF is, thus, the probability of the SINR lower than the threshold. As the SINR is influenced by the receiving data signal power (i.e., P_{ij}) and interference (i.e., P_{aj}) based on (22), PTF is also related to both P_{ij} and P_{aj}.

1) Probability Density Function of Receiving Power P_{ij}: As P_{ij} is related to the distance between transmitting node *i* and receiving node *j* (i.e., d_{ij}), the cumulative distribution function of P_{ij} can be derived according to the cumulative distribution function of d_{ij}. The cumulative distribution function of d_{ij} is

$$p(\mathrm{d}_{ij} < r_i) = \frac{\pi r_i^2}{\pi r_T^2} = \frac{r_i^2}{r_T^2}, 0 < r_i \leq r_T \tag{24}$$

where r_i is a particular distance from source node *i*, and r_T is the transmission range. The probability density function of d_{ij} is

$$f_{d_{ij}}(r_i) = \frac{2r_i}{r_T^2}, 0 < r_i \leq r_T \tag{25}$$

Based on the relationship between P_{ij} and d_{ij} in (20) and the cumulative distribution function of d_{ij} in (24), the cumulative distribution function of P_{ij} can be expressed as

$$p(P_{ij} < P_x) = \begin{cases} p(d_{ij} > \sqrt{\frac{2\sigma_{ij}^2 P_{Ti} G_t G_r \lambda^2}{16\pi^2 P_x}}) \\ = 1 - \frac{2\sigma_{ij}^2 P_{Ti} G_t G_r \lambda^2}{16\pi^2 r_T^2 P_x}, \\ \frac{2\sigma_{ij}^2 P_{Ti} G_t G_r \lambda^2}{16\pi^2 d_0^2} \leq P_x < +\infty \\ p(d_{ij} > \sqrt[4]{\frac{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}{P_x}}) \\ = 1 - \frac{\sqrt{\frac{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}{P_x}}}{r_T^2}, \\ \frac{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}{r_T^4} \leq P_x < \frac{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}{d_0^4} \end{cases} \tag{26}$$

Thus, the probability density function of P_{ij} can be derived as

$$f_{P_{ij}}(P_x) = \begin{cases} \frac{2\sigma_{ij}^2 P_{Ti} G_t G_r \lambda^2}{16\pi^2 r_T^2} \cdot P_x^{-2}, \\ \frac{2\sigma_{ij}^2 P_{Ti} G_t G_r \lambda^2}{16\pi^2 d_0^2} \leq P_x < +\infty \\ \frac{\sqrt{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}}{2r_T^2} \cdot P_x^{-\frac{3}{2}}, \\ \frac{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}{r_T^4} \leq P_x < \frac{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}{d_0^4} \end{cases} \tag{27}$$

2) Probability Density Function of Interference Power P_{aj}: P_{aj} is the power of interference at node *j* from node *a*. The process of getting the probability density function of P_{aj} is similar to P_{ij}.

The cumulative distribution function of distance d_{aj} is

$$p(\mathrm{d}_{aj} < r_a) = \frac{\pi {r_a}^2}{\pi r_I^2} = \frac{{r_a}^2}{r_I^2}, 0 < r_a \leq r_I \tag{28}$$

where r_a is a particular distance from interfering source node *a*, and r_I is the interference range. Similar to the process of obtaining cumulative distribution function of P_{ij}, the cumulative distribution function of P_{aj} is

$$p(P_{aj} < P_a) = \begin{cases} 1 - \frac{\sigma_{aj}^2 P_{Ta} G_t G_r \lambda^2}{8\pi^2 r_I^2 P_a}, \frac{\sigma_{aj}^2 P_{Ta} G_t G_r \lambda^2}{8\pi^2 d_0^2} \leq P_a < +\infty \\ 1 - \frac{\sqrt{\frac{2\sigma_{aj}^2 P_{Ta} G_t G_r h_t^2 h_r^2}{P_a}}}{r_I^2}, \\ \frac{2\sigma_{aj}^2 P_{Ta} G_t G_r h_t^2 h_r^2}{r_I^4} \leq P_a < \frac{2\sigma_{aj}^2 P_{Ta} G_t G_r h_t^2 h_r^2}{d_0^4} \end{cases} \tag{29}$$

The probability density function of P_{aj} is then derived as

$$f_{P_{aj}}(P_a) = \begin{cases} \frac{\sigma_{aj}^2 P_{Ta} G_t G_r \lambda^2}{8\pi^2 r_I^2} \cdot P_a^{-2}, \frac{\sigma_{aj}^2 P_{Ta} G_t G_r \lambda^2}{8\pi^2 d_0^2} \leq P_a < +\infty \\ \frac{\sqrt{2\sigma_{aj}^2 P_{Ta} G_t G_r h_t^2 h_r^2}}{2r_I^2} \cdot P_a^{-\frac{3}{2}}, \\ \frac{2\sigma_{aj}^2 P_{Ta} G_t G_r h_t^2 h_r^2}{r_I^4} \leq P_a < \frac{2\sigma_{aj}^2 P_{Ta} G_t G_r h_t^2 h_r^2}{d_0^4} \end{cases} \tag{30}$$

3) Expression of the PTF: According to the probability density function of P_{ij} and P_{aj} shown as (27) and (30), the PTF on link (*i*,*j*) (denoted as $p_{(i,j)}$) is

$$\begin{aligned} & p_{(i,j)} = p(\gamma_{ij} < \beta) = p(\frac{P_{ij}}{N + \sum\limits_{a \in I_j} P_{aj}} < \beta) \\ & \approx p(P_{ij} < \beta \sum_{a \in I_j} P_{aj}) = p(P_x < \beta n P_a) \\ & = \int_{-\infty}^{+\infty} f_{P_{aj}}(P_a) \cdot p(P_x < n\beta P_a | P_a) dP_a \\ & = \int_{-\infty}^{+\infty} f_{P_{aj}}(P_a) \int_{-\infty}^{n\beta P_a} f_{P_{ij}}(P_x) dP_x dP_a \end{aligned} \tag{31}$$

where β is the threshold of SINR. I_j is the set of interfering nodes of node *j*. *n* is the number of interfering nodes of receiving node *j*. In the interference limited network, interference from other transmitters is much larger than the white noise at receivers, so the background noise can be ignored [35] [36].

If $\frac{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}{r_T^4} \leq n\beta P_a \leq \frac{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}{d_0^4}$, (31) can be expressed as

$$\begin{aligned} & p_{(i,j)} = \int_{-\infty}^{+\infty} f_{P_{aj}}(P_a) \cdot \left(1 - \frac{\sqrt{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}}{\sqrt{n\beta} r_T^2} P_a^{-\frac{1}{2}}\right) dP_a \\ & = \int_{\frac{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}{n\beta r_T^4}}^{\frac{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}{n\beta d_0^4}} \frac{\sqrt{2\sigma_{aj}^2 P_{Ta} G_t G_r h_t^2 h_r^2}}{2r_I^2} P_a^{-\frac{3}{2}} \\ & \cdot \left(1 - \frac{\sqrt{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}}{\sqrt{n\beta} r_T^2} P_a^{-\frac{1}{2}}\right) dP_a \\ & = \frac{\sqrt{n\beta P_{Ti} P_{Ta}} \left(r_T^4 - 2r_T^2 d_0^2 + d_0^4\right) \sigma_{aj}}{2\sigma_{ij} P_{Ti} r_I^2 r_T^2} \end{aligned} \tag{32}$$

If $\frac{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}{d_0^4} < n\beta P_a < +\infty$, (31) can be expressed as

$$\begin{aligned}
p_{(i,j)} &= \int_{-\infty}^{+\infty} f_{P_{aj}}(P_a)\cdot\left(1-\frac{\sigma_{ij}^2 P_{Ti} G_t G_r \lambda^2}{8\pi^2 n\beta P_a r_T^2}\right) dP_a \\
&= \int_{\frac{\sigma_{aj}^2 P_{Ta} G_t G_r \lambda^2}{8\pi^2 d_0^2}}^{+\infty} \frac{\sigma_{aj}^2 P_{Ta} G_t G_r \lambda^2}{8\pi^2 r_I^2} P_a^{-2}\cdot\left(1-\frac{\sigma_{ij}^2 P_{Ti} G_t G_r \lambda^2}{8\pi^2 n\beta P_a r_T^2}\right) dP_a \\
&+ \int_{\frac{\sigma_{ij}^2 P_{Ti} G_t G_r \lambda^2}{8\pi^2 n\beta d_0^2}}^{\frac{2\sigma_{aj}^2 P_{Ta} G_t G_r h_t^2 h_r^2}{d_0^4}} \frac{\sqrt{2\sigma_{aj}^2 P_{Ta} G_t G_r h_t^2 h_r^2}}{2r_I^2} P_a^{-\frac{3}{2}}\cdot \\
&\qquad \left(1-\frac{\sigma_{ij}^2 P_{Ti} G_t G_r \lambda^2}{8\pi^2 n\beta P_a r_T^2}\right) dP_a \\
&= \frac{(3d_0^2 r_T^2 - d_0^4)\sigma_{aj}\sqrt{n\beta P_{Ta}}}{3\sigma_{ij} r_I^2 r_T^2 \sqrt{P_{Ti}}} - \frac{P_{Ti}\sigma_{ij}^2 d_0^4}{6n\beta r_I^2 r_T^2 \sigma_{aj}^2 P_{Ta}}
\end{aligned} \tag{33}$$

Thus, the relationship between the PTF (i.e., $p_{(i,j)}$) and the number of interfering nodes (i.e., *n*) is built. As the PTF can influence the delay, which is shown in (19), the relationship between delay and the number of interfering nodes is, therefore, established. Although different nodes have different channel conditions, the power gain of channel fading is relatively stable. Many pieces of research typically assume that all links have a unit power gain of Rayleigh fading [37] [38]. Therefore, after network configuration, the number of interfering nodes is an essential factor affecting PTF. DIAR can then evaluate delay by using the number of interfering nodes, which makes the process of obtaining delay easier. According to the position of mesh nodes and interference range, the number of interfering nodes can be obtained. Thus, DIAR can obtain delay easily without extra overhead caused by probe packets as usual.

DIAR takes the dynamic condition into account and checks the number of interfering nodes every time of finding optimal paths in the iterative optimization. Finally, paths for different data flows are selected to improve network performance globally.

VI. Reasonability Analysis of DIAR

The reasonability of DIAR, including the explanation of the improved solution method and the cost of DIAR, is given in this section.

A. Relationship Between the PTF and the Number of Interfering Nodes

According to (32), the derivative of $p_{(i,j)}$ for *n* is

$$p_{(i,j)}{}' = \frac{\sqrt{\beta P_{Ti} P_{Ta}}\left(r_T^2 - d_0^2\right)^2}{4P_{Ti} r_I^2 r_T^2} n^{-\frac{1}{2}} \tag{34}$$

As *n* is the number of interfering nodes, $n > 0$. Besides, based on the physical significance of each parameter, all of them are greater than 0. Thus, ${p_{(i,j)}}' > 0$, and $p_{(i,j)}$ is a monotone increasing function of *n*.

In addition, according to (33), the derivative of $p_{(i,j)}$ for *n* is

$$p'_{(i,j)}=\frac{2\pi h_t h_r \sigma_{aj} d_0 \sqrt{P_{Ta}}\left(3r_T^2-d_0^2\right)}{3\lambda r_I^2 \sigma_{ij}\sqrt{\beta P_{Ti}} r_T^2} n^{-\frac{1}{2}}+\frac{\sigma_{ij}^2 P_{Ti} d_0^4}{6r_I^2 r_T^2 \beta \sigma_{aj}^2 P_{Ta}} n^{-2} \tag{35}$$

Similarly, as n and other parameters are greater than 0 and r_T is greater than d_0, ${p_{(i,j)}}' > 0$. Thus, $p_{(i,j)}$ is also a monotone increasing function of *n* in this case. Both (32) and (33) are monotone increasing functions of *n*. The relationship between the PTF and the number of interfering nodes is a piecewise function combining (32) and (33). Although each one has monotonicity, such property may not hold after the combination. Therefore, the monotonicity is checked after the combination of both cases. If *n* is a real number, the critical value of *n* is $\frac{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}{\beta P_a d_0^4}$. However, as *n* is the number of interfering nodes, it is a positive integer. Then, we use an adjustment parameter $\delta(0 \leq \delta < 1)$ to obtain the critical value of *n* in different cases. For any δ, the maximum value of (32) (denoted as p_{1max}) is

$$\begin{aligned} p_{1\max} &= p_1\left(n=\tfrac{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}{\beta P_a d_0^4}-(1-\delta)\right) \\ &= \tfrac{(r_T^2-d_0^2)^2 \sigma_{aj}\sqrt{16\sigma_{ij}^2 P_{Ti}^2 G_t G_r h_t^2 h_r^2 P_{Ta}-8d_0^4 \beta P_a P_{Ti} P_{Ta}(1-\delta)}}{4\sqrt{2}\sigma_{ij} P_{Ti} r_I^2 r_T^2 d_0^2 \sqrt{P_a}} \end{aligned} \tag{36}$$

The minimum value of (33) (denoted as p_{2min}) can be expressed as

$$\begin{aligned} p_{2\min} &= p_2\left(n=\tfrac{2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2}{\beta P_a d_0^4}+\delta\right) \\ &= \tfrac{(3d_0^2 r_T^2-d_0^4)\sigma_{aj}\sqrt{P_{Ta}(2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2+\delta d_0^4 \beta P_a)}}{3\sigma_{ij} r_I^2 r_T^2 d_0^2 \sqrt{P_{Ti} P_a}} \end{aligned} \tag{37}$$

So, the difference between p_{2min} and p_{1max} (denoted as ξ) is

$$\begin{aligned} \xi &= p_{2\min}-p_{1\max} \\ &= \tfrac{2d_0^2(r_T^2-d_0^2)\sigma_{aj}\sqrt{P_{Ti}P_{Ta}(2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2+\delta d_0^4 \beta P_a)}}{6\sigma_{ij} P_{Ti} r_I^2 r_T^2 d_0^2 \sqrt{P_a}} \\ &\quad -\tfrac{3(r_T^2-d_0^2)^2 \sigma_{aj}\sqrt{P_{Ti}P_{Ta}(2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2+\delta d_0^4 \beta P_a-d_0^4 \beta P_a)}}{6\sigma_{ij} P_{Ti} r_I^2 r_T^2 d_0^2 \sqrt{P_a}} \end{aligned} \tag{38}$$

To simplify (38), let $\mathrm{A} = P_{Ti}P_{Ta}(2\sigma_{ij}^2 P_{Ti} G_t G_r h_t^2 h_r^2 + \delta d_0^4 \beta P_a)$. According to the values of each parameter in A, $A > 0$.

Then, ξ can be expressed as

$$\xi=\frac{\sigma_{aj}(r_T^2-d_0^2)\left(2d_0^2\sqrt{\mathrm{A}}-3(r_T^2-d_0^2)\sqrt{\mathrm{A}-P_{Ti}P_{Ta}d_0^4\beta P_a}\right)}{6\sigma_{ij}P_{Ti}r_I^2 r_T^2 d_0^2\sqrt{P_a}} \tag{39}$$

Let $\mathrm{B} = 2d_0^2\sqrt{\mathrm{A}}-3(r_T^2-d_0^2)\sqrt{\mathrm{A}-P_{Ti}P_{Ta}d_0^4\beta P_a}$; ξ can then be further simplified as

$$\xi=\frac{\sigma_{aj}(r_T^2-d_0^2)\mathrm{B}}{6\sigma_{ij}P_{Ti}r_I^2 r_T^2 d_0^2\sqrt{P_a}} \tag{40}$$

Since $\mathrm{B} > 2d_0^2\sqrt{\mathrm{A}} - 3(r_T^2 - d_0^2)\sqrt{\mathrm{A}} = \sqrt{\mathrm{A}}(5d_0^2 - 3r_T^2)$, when network configuration satisfies $r_T^2 < \frac{5}{3}d_0^2$, $B > 0$. In addition, as $r_T > d_0$, $\xi > 0$, which means $p_{2min} > p_{1max}$. Thus, after combining (32) and (33), $p_{(i,j)}$ is still a monotone increasing function of *n*. In general, the PTF will increase with increasing number of interfering nodes.

B. Relationship Between the Delay and the PTF

According to (19), the derivative of delay for $p_{(i,j)}$ is

$$
\begin{aligned}
E[T_{(i,j)}]' = & \frac{\left((K-1)p_{(i,j)}^{K} - Kp_{(i,j)}^{K-1} + 1\right)(2Length - B_{(i,j)}SlotTime)}{2B_{(i,j)}(p_{(i,j)}-1)^2} \\
& + \frac{CW_{\min}SlotTime\left(2^{K+1}Kp_{(i,j)}^{K+1} - 2^{K}(K+1)p_{(i,j)}^{K} + 1\right)}{(1-2p_{(i,j)})^2}
\end{aligned}
\quad (41)
$$

As $p_{(i,j)}$ is the PTF, $0 < p_{(i,j)} < 1$. Therefore, $E[T_{(i,j)}]' > 0$, and $E[T_{(i,j)}]$ is a monotone increasing function of $p_{(i,j)}$. That is, the delay will increase when the PTF increases. At the same time, as proved before, the PTF will increase with an increasing number of interfering nodes, so the delay will increase when the number of interfering nodes increases.

C. Delay of Adjacent Two Links Connected by a Common Node

An example of two data flows using a common node is shown in Fig. 3.

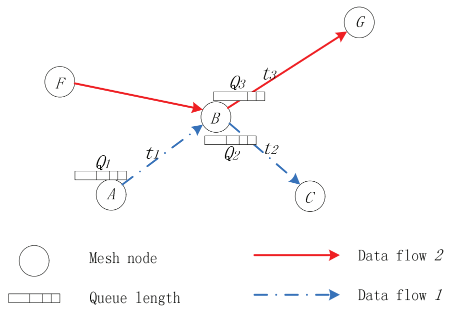


Fig. 3: Explanation of congestion and high delay at common node.

Congestion will occur at the common node *B*, and the delay of serving the data flow *1* (denoted as $Delay_{original}$) is

$$
Delay_{original} = t_1 + t_2 + t_3 \quad (42)
$$

where t_1 is the time cost by transmitting Q_1 packets of data flow *1* from the previous hop *A* to the common node *B*. t_2 is the time cost by transmitting Q_2 packets in data flow *1* from the common node *B* to the next node *C*. t_3 is the time cost by transmitting Q_3 packets in data flow *2* from the common node *B* to the other next node *G*. Q_2 is the queue length at the common node *B*, which needs to be transmitted in data flow *1* to the next hop *C*. Q_3 is the queue length also at the common node *B*, which needs to be transmitted in data flow *2* to the other next hop *G*. The congestion occurs at node *B* because besides data packets of flow *1*, the packets of flow *2* at the common node also need to be emptied.

To avoid the congestion and balance load, DIAR will choose a new node with the least number of interfering nodes to replace the original common node. After using another replacement node to serve data flow *1*, there will be no data packets of data flow *1* waiting at the original common node *B*, and the situation that two data flows use the same node can be avoided. Because $p_{(i,j)}$ is a monotone increasing function of *n*, after choosing the node with the least number of interfering nodes as the replacement node, the new replacement link will have the least PTF. This PTF (denoted as p_{1_new}) is

$$p_{1\_new} = p_1^{min} < p_1 \tag{43}$$

Then, the new replacement link will have the least delay, and it (denoted as t_{1_new}) is

$$t_{1\_new} = t_1^{min} < t_1 \tag{44}$$

Therefore, after using the node with the least number of interfering nodes as the replacement node, the new delay (denoted as $Delay_{new}$) is

$$Delay_{new} = Delay_{min} = {t_1}^{min} + t_2 = t_{min} \tag{45}$$

The difference between the new and original delay is

$$\begin{aligned} &Delay_{new} - Delay_{original} = Delay_{min} - Delay_{original} \\ &= (t_1^{min} + t_2) - (t_1 + t_2 + t_3) = t_1^{min} - t_1 - t_3 < 0 \end{aligned} \tag{46}$$

Thus, $Delay_{new} < Delay_{original}$, which means choosing the node with the least number of interfering nodes to replace the original common node can avoid congestion at the common node, balance load, and finally reduce delay.

Furthermore, if other nodes which are not with the least number of interfering nodes are chosen, the delay of the adjacent two links at the replacement node (denoted as $Delay_{other}$) is

$$Delay_{other} = t_1^{other} + t_2 \tag{47}$$

Then, the relationship between $Delay_{new}$ and $Delay_{other}$ is

$$\begin{aligned} &Delay_{new} - Delay_{other} = Delay_{min} - Delay_{other} \\ &= (t_1^{min} + t_2) - (t_1^{other} + t_2) = t_1^{min} - t_1^{other} < 0 \end{aligned} \tag{48}$$

Therefore, choosing the node with the least number of interfering nodes as the replacement node can bring the least delay. A simple example of this method is shown in Fig. 4.

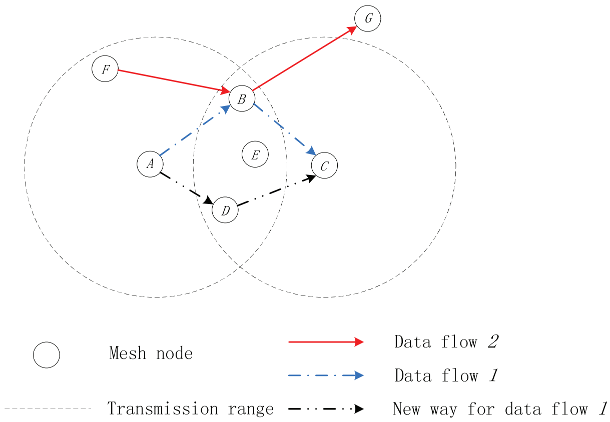


Fig. 4: An example of selecting the replacement node.

There are two data flows in Fig. 4, and node *B* is the original common node used by both data flows *1* and *2*. Congestion and long queuing delay will then occur at node *B*. To avoid this congestion, the improved algorithm of DIAR will choose another node to transmit data flow *1*. Besides node *B*, nodes *E* and *D* are also within the transmission range of nodes *A* and *C*, so nodes *E* and *D* can be used to replace node *B*. Assume that the numbers of interfering nodes of nodes *B*, *E* and *D* (i.e., n_B, n_E, n_D) are 5, 6, 3, so node *D* will be selected to replace node *B* to transmit data flow *1* as node *D* has the least number of interfering nodes.

D. Cost of DIAR

Considering delay, ETT is a very popular and common method to obtain delay in routing problem, and it is used as the routing metric in the relevant reference [9]. Therefore we compare the cost of DIAR and ETT.

1) Cost in Space: Unlike ETT, DIAR no longer needs to broadcast extra probe packets when obtaining network conditions. Thus, the cost of extra probe packets and wireless resource is saved. However, to enable DIAR to find the neighbor with the least number of interfering nodes, DIAR needs some storage space in the existing Hello packets to record the number of interfering nodes. Besides, the network manager needs to store the topology showing neighboring and interfering relationships among nodes.

As ETT uses the technique of broadcasting probe packet pairs to evaluate delay [10], the cost in space of ETT in the whole network (denoted as O_{ETT}) is

$$O_{ETT} = (O_1 + O_2)n_a \cdot m \tag{49}$$

where O_1 is the cost of sending small probe packet, which is 137 bytes. O_2 is the cost of sending a large probe packet, which is 1137 bytes. n_a is the number of active mesh nodes in the network, which need to detect network conditions and select paths. m is the average number of neighboring nodes of active nodes.

DIAR does not have the cost of sending probe packets, but it has more storage cost in Hello packets and network manager. The cost in space to store the number of interfering nodes for one node in each Hello packet and the cost in space of each element in the neighboring and interfering matrix at the network manager are both 4 bytes (denoted as O_e). Therefore, the cost in space of DIAR is

$$O_{DIAR} = (n + 2n^2)O_e \tag{50}$$

where n is the number of mesh nodes, and n^2 is the matrix size of the neighboring and interfering matrixes. From (49) and (50), we can see that the cost in space of DIAR is much less than ETT as long as $\frac{2}{637}(2n^2 + n) < n_a \cdot m$, which is easy to satisfy in a common network.

2) Computational Complexity: In DIAR, delay is computed by (19) for each node. The computational complexity depends on obtaining PTF and available bandwidth. According to the derived relationship between PTF and the number of interfering nodes, PTF can be obtained directly based on the number of interfering nodes. Assuming that the number of nodes in a whole network is *n*, the maximum number of interfering nodes is *n*-2. When obtaining available bandwidth as (23), the maximum required number of times of adding interference power is *n*-2. Thus, the computational complexity to calculate the delay for each node is *O*(*n*) in general. For ETT, as extra probe packets are used to obtain delay without computing, the computational complexity of ETT is *O*(*1*).

VII. SIMULATION EVALUATION

A. Simulation Environment

For the optimization process, our experiments with 200-iteration GA are taken on a processor Core i7-6700 at 3.4 GHz. The time to reach a good solution is around several seconds. This time can be significantly saved further by using a machine with strong computation ability like a GPU [40]. For the network performance, simulation through NS3 [41] has been implemented. Mesh routers and clients are deployed in an area of 1000m $\times$ 1000m. Mesh routers are equipped with three radio interfaces, and mesh clients are with a single radio interface. Each radio interface is banded with an orthogonal channel. The packet transmission rate and the number of origin-destination data flows are changed during the simulation. As emergency and rural communications are very important applications of WMN, instant messaging like VoIP and streaming multimedia communication is used. These applications rely on UDP, so UDP is used as the transport layer protocol. The data flows are constant-bit-rate flows arriving uniformly with random sources and destinations, including both short and long ones. The detailed simulation parameters are shown in Table II.

TABLE II: Simulation Parameters

Simulation Parameters	**Values**
Simulation time	100s
Traffic type	UDP
Packet size	1024 bytes
Number of mesh routers	25
Number of mesh clients	50
Number of radio interfaces in each router	3
Number of channels in each router	3 channels
Number of radio interfaces in each client	1
Number of channels in each client	1 channel
Transmission range	250m
Interference range	550m
Antenna	Omnidirectional

B. Performance Metrics

Average packet loss rate, average delay and average network throughput are used as the performance metrics to evaluate the network performance.

- Average packet loss rate (denoted as *Pl*)

$$Pl = \frac{N_{loss}}{N_{total}} = \frac{N_{total} - N_{received}}{N_{total}} \tag{51}$$

  where N_{loss} is the number of packets which are lost during transmission, N_{total} is the total number of packets sent by the source, and $N_{received}$ is the number of packets received successfully by the destination.

- Average delay (denoted as *D*)

$$D = \frac{\sum_{i=1}^{m} D_i}{m} \tag{52}$$

  where D_i is the delay cost by transmitting packet *i* and *m* is the total number of packets received by the destination in success.

- Average network throughput (denoted as *Th*)

$$Th = \frac{N_{received} \cdot Byte \cdot 8}{(T_{end} - T_{start}) \cdot 1024} \tag{53}$$

  where $N_{received}$ is the number of packets received by the destination. *Byte* is the number of bytes contained in one data packet. T_{end} is the time when the last packet is received successfully, and T_{start} is the time of starting sending the first data packet. The unit of average network throughput is kb/s.

C. Simulation Results and Analyses

To evaluate the performance of DIAR roundly, the rate of sending data packets and the number of end-to-end data flows are changed. The performance of DIAR, DIAR with basic GA (i.e., DIAR_basic_GA), search-based routing [9], DIAR with ETX (i.e., DIAR_ETX), and routing method with minimized hop count (minHop) is evaluated and compared. DIAR_basic_GA has the same mathematical optimization model with DIAR, but uses the traditional GA rather than the improved one to solve the optimization problem. The minHop is the most widely used routing method, and it is always used as the benchmark [39] [42]. ETX is another popular routing metric to evaluate link condition. To evaluate the performance of the objective in DIAR, we change the objective of DIAR into ETX and still use the improved GA to solve the routing problem. Besides, according to the relevance and timeliness, the search-based routing proposed in [9] is also compared. When the number of data flows is 4, the obtained performance results with different packet transmission rate are shown and compared in Fig. 5 - Fig. 7.

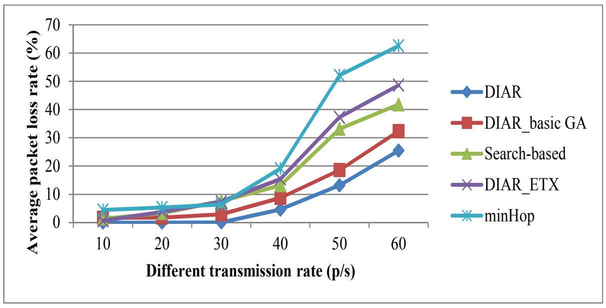


Fig. 5: Average packet loss rate with different transmission rate under 4 data flows.

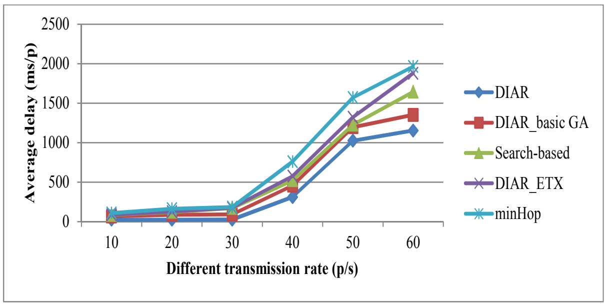


Fig. 6: Average delay with different transmission rate under 4 data flows.

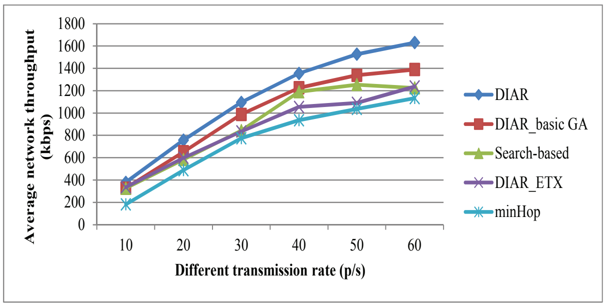


Fig. 7: Average network throughput with different transmission rate under 4 data flows.

Fig. 5 - Fig. 7 show that DIAR achieves lower average packet loss rate, lower average delay, and higher network throughput. With the increase of the packet transmission rate, the advantage of DIAR is more significant, because DIAR can balance load and congestion effectively. DIAR improves the basic GA and avoids

the congestion caused by using one common node to serve multiple data flows. Besides, DIAR considers the interference and dynamic network condition during the process of selecting routes, which can help it choose the routes to gain better whole network performance. The search-based routing considers ETT in addition to hop count, so it also takes network condition into account and gets better performance than minHop. However, ETT neglects the backoff delay and brings high overhead. In addition, the search-based routing detects ETT of all links at the beginning of optimization and assumes they are static during selecting paths. When different links are chosen to transmit packets in route discovery process, the ETT values in the network will actually change. They should be evaluated in each iteration of GA, but the search-based routing does not consider this influence during the process of optimization, which makes it less accurate and its performance worse than DIAR. ETX also considers the packet loss condition, but it neglects bandwidth. Then the performance of DIAR_ETX is generally a bit worse than ETT. The network performance by using DIAR is 23.1 %, 37.8%, 43.7% and 55.1% better than that of DIAR_basic GA, Search-based, DIAR_ETX and minHop in average.

Similarly, when the number of data flows is 7, the obtained performance results with different packet transmission rate are shown and compared in Fig. 8 - Fig. 10.

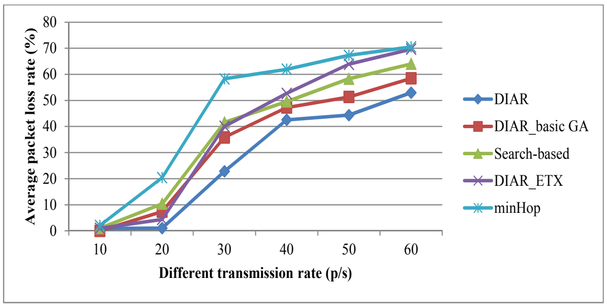


Fig. 8: Average packet loss rate with different transmission rate under 7 data flows.

Fig. 8 - Fig. 10 show that DIAR achieves better network performance in terms of average packet loss rate, average delay and average network throughput, which is similar to the performance when the number of data flows is 4. When the number of data flows increases, the probability of congestion will increase. Then, the gap between the DIAR and other three routing methods is wider and the advantage of DIAR is more significant, because it can avoid using the same node too often.

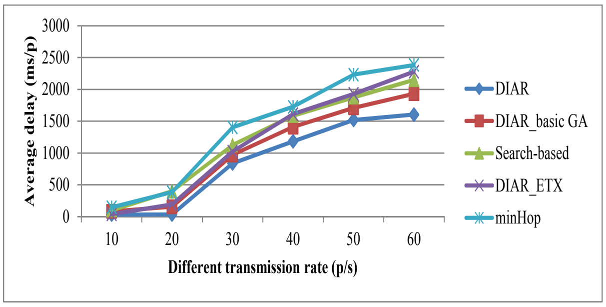


Fig. 9: Average delay with different transmission rate under 7 data flows.

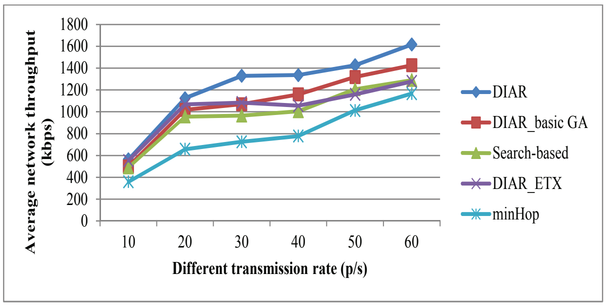


Fig. 10: Average network throughput with different transmission rate under 7 data flows.

Instead, another node with the least number of interfering nodes will be selected as the replacement node. The heavy load can be balanced in this case. In addition, based on the process of optimization, DIAR can select paths with less delay, less interference, less PTF, and larger available bandwidth, which brings better network performance. When changing the objective of DIAR into ETX, the performance will be worse than DIAR because ETX neglects bandwidth, delay, and interference. However, its performance is sometimes better than others because it still uses the improved GA, which can balance load to solve the routing problem. The load-balance solution helps to cover the shortage of ETX in DIAR_ETX to some extent. minHop does not consider any network factors, and only selects the path with least hop count to transmit packets, which may cause heavy load and congestion. Thus, minHop gets worst performance. Although the search-based routing considers both hop count and ETT, the relationship of them is product. The factor of hop count can influence the selection of routes in large extent. The search-based routing tends to still choose ways with less hop count when the sums of ETT on diverse routes are not so different. Congested ways with less hop count and long delay may be chosen. The network condition of ETT is not predominant in search-based routing.

Therefore, DIAR performs better than search-based routing. The performance of DIAR is 16.2%, 26.6%, 24.9%, and 44.9% better compared to DIAR_basic GA, Search-based, DIAR_ETX, and minHop, respectively.

When the packet transmission rate is 40 packets per second, the obtained performance results with different number of random end-to-end data flows are shown and compared in Fig. 11 - Fig. 13.

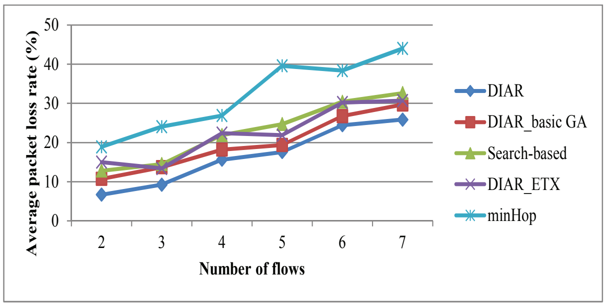


Fig. 11: Average packet loss rate with different number of flows.

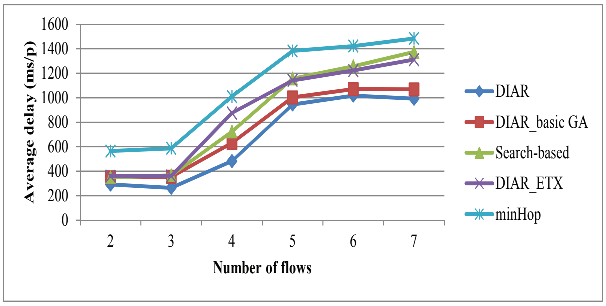


Fig. 12: Average delay with different number of flows.

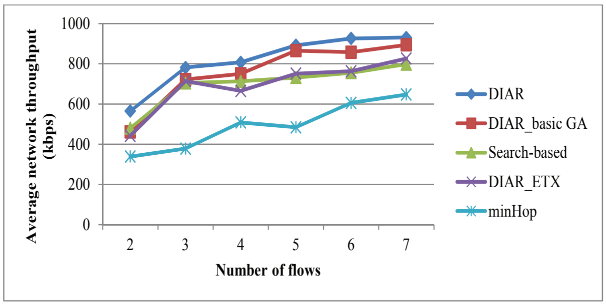


Fig. 13: Average network throughput with different number of flows.

As shown in Fig. 11 - Fig. 13, with different number of data flows, DIAR can always get better network performance. When the number of data flows increases, the interfering relationships in the network will be more complicated. Large interference will bring bad network performance. minHop does not consider interference, so its performance is worst and fluctuating. ETX considers PTF, but interference and bandwidth are also neglected. However, the load-balance feature of the solution helps DIAR_ETX bring not bad performance with the increasing amount of flows. For DIAR, after establishing the relationship between delay, PTF, and the number of interfering nodes, it can easily obtain delay with low cost and effectively choose the path with better condition. It can also evaluate the dynamic network condition of different path solutions in iterative optimization, which the search-based routing cannot do. DIAR can find paths for several given data flows as a whole and considers both transmission and backoff delay. Thus, DIAR can improve the whole network performance globally and effectively. The network performance of DIAR is 11.5 %, 22.7%, 22.6%, and 50.6% better compared to DIAR_basic GA, Search-based, DIAR_ETX, and minHop, respectively, on average.

VIII. Conclusion

Effective paths to serve data flows can improve network performance dramatically. Therefore, a good method of selecting paths with high quality is essential. DIAR builds a routing optimization model to minimize the end-to-end delay. In the process of evaluating delay, the bandwidth, interference, and PTF are considered at the same time. The relationship between delay and the number of interfering nodes is first built in DIAR, so DIAR can obtain delay with low cost. In order to solve the optimization problem more effectively, an improved GA is proposed in DIAR. The improved GA is more adaptive to solve the routing problem. When multiple data flows use a common node, this common node will be replaced by another neighbor node with the least number of interfering nodes. In this way, congestion can be avoided, and load can be balanced effectively. Besides, because the solution of routing can change the interference relationship and network condition, the network condition is, therefore, dynamic. DIAR considers such a dynamic condition and evaluates the network condition every time of finding routes in the iterative optimization. The simulation results through NS3 show that DIAR can achieve better network performance in different cases.

References

[1] I. F. Akyildiz, X. Wang, W. Wang, Wireless mesh networks: a survey, Computer Networks. 47(4) (2005) 445-487.

[2] S. Paris, C. Nita-Rotaru, F. Martignon, A. Capone, Cross-layer metrics for reliable routing in wireless mesh networks, IEEE/ACM Transactions on Networking. 21(3) (2013) 1003-1016.

[3] D. Benyamina, A. Hafid, M. Gendreau, Wireless mesh networks design-A survey, IEEE Communications Surveys & Tutorials. 14(2) (2012) 299-310.

[4] S. K. Dhurandher, I. Woungang, M. S. Obaidat, K. Kumar, M. Joshi, M. Verma, A distributed adaptive admission control scheme for multimedia wireless mesh networks, IEEE Systems Journal. 9(2) (2014) 595-604.

[5] S. Khan, K. K. Loo, N. Mast, T. Naeem, SRPM: Secure routing protocol for IEEE 802.11 infrastructure based wireless mesh networks, Journal of Network and Systems Management. 18(2) (2010) 190-209.

[6] A. Al-Saadi, R. Setchi, Y. Hicks, S. M. Allen, Routing protocol for heterogeneous wireless mesh networks, IEEE Transactions on Vehicular Technology. 65(12) (2016) 9773-9786.

[7] M. Boushaba, A. Hafid, M. Gendreau, Source-based routing in wireless mesh networks, IEEE Systems Journal. 10(1) (2014) 262-270.

[8] M. Srinivas, L. M. Patnaik, Genetic algorithms: A survey, Computer. 27(6) (1994) 17-26.

[9] K. Mahmood, B. Nazir, I. A. Khan, N. Shah, Search-based routing in wireless mesh network, EURASIP Journal on Wireless Communications and Networking. 2017(1) (2017) 1-15.

[10] R. Draves, J. Padhye, B. Zill, Routing in multi-radio, multi-hop wireless mesh networks, in: 10th ACM Annual International Conference on Mobile Computing and Networking, 2004, pp. 114-128.

[11] S. Yussof, O. H. See, A robust GA-based QoS routing algorithm for solving multi-constrained path problem, Journal of Computers. 5(9) (2010) 1322-1334.

[12] C. H. Liu, A. Gkelias, K. K. Leung, A cross-layer framework of QoS routing and distributed scheduling for mesh networks, in: IEEE Vehicular Technology Conference (VTC Spring), 2008, pp. 2193-2197.

[13] R. Murugeswari, S. Radhakrishnan, D. Devaraj, A multi-objective evolutionary algorithm based QoS routing in wireless mesh networks, Applied Soft Computing. 40 (2016) 517-525.

[14] D. Couto, D. Aguayo, J. Bicket, R. Morris, A high-throughput path metric for multi-hop wireless routing, Wireless Networks. 11(4) (2005) 419-434.

[15] E. Alotaibi, V. Ramamurthi, M. Batayneh, B. Mukherjee, Interference-aware routing for multi-hop wireless mesh networks, Computer Communications. 33(16) (2010) 1961-1971.

[16] T. Meng, F. Wu, Z. Yang, G. Chen, A. V. Vasilakos, Spatial reusability-aware routing in multi-hop wireless networks, IEEE Transactions on Computers. 65(1) (2016) 244-255.

[17] W. Shi, E. Wang, Z. Li, Z. Wang, S. Wang, A load-balance and interference-aware routing algorithm for multicast in wireless mesh network, in: IEEE International Conference on Information and Communication Technology Convergence (ICTC), 2016, pp. 206-210.

[18] S. Middha, P. Singh, Channel assignment with greedy algorithm for wireless mesh network, International Journal of Modern Computer Science Application. 3(3) (2015) 21-26.

[19] Y. Wang, G. Cong, G. Song, K. Xie, Community-based greedy algorithm for mining top-k influential nodes in mobile social networks, in: 16th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, 2010, pp. 1039-1048.

[20] F. Cali, M. Conti, E. Gregori, IEEE 802.11 protocol: Design and performance evaluation of an adaptive backoff mechanism, IEEE Journal on Selected Areas in Communications. 18(9) (2000) 1774-1786.

[21] V. A. Siris, G. Stamatakis, E. Tragos, A simple end-to-end throughput model for 802.11 multi-radio multi-rate wireless mesh networks, IEEE Communications Letters. 15(6) (2011) 635-637.

[22] E. Ancillotti, R. Bruno, M. Conti, A. Pinizzotto, Load-aware routing in mesh networks: Models, algorithms and experimentation, Computer Communications. 34(8) (2011) 948-961.

[23] X. Cao, L. Liu, W. Shen, Y. Cheng, Distributed scheduling and delay-aware routing in multihop MR-MC wireless networks, IEEE Transactions on Vehicular Technology. 65(8) (2016) 6330-6342.

[24] H. Jiang, L. Zheng, Y. Liu, M. Zhang, Multi-constratined qos routing optimization of wireless mesh network based on hybrid genetic algorithm, in: IEEE International Conference on Intelligent Computing and Integrated Systems (ICISS), 2010, pp. 862-865.

[25] M. Dorigo, M. Birattari, T. Stutzle, Ant colony optimization, IEEE Computational Intelligence Magazine. 1(4) (2006) 28-39.

[26] V. Sarasvathi, N. C. S. Iyengar, S. Saha, QoS guaranteed intelligent routing using hybrid PSO-GA in wireless mesh networks, Cybernetics and Information Technologies. 15(1) (2015) 69-83.

[27] Y. Shi, Particle swarm optimization: Developments, applications and resources, in: IEEE Congress on Evolutionary Computation, 2001, pp. 81-86.

[28] V. V. Mandhare, V. R. Thool, R. R. Manthalkar, QoS Routing enhancement using metaheuristic approach in mobile ad-hoc network, Computer Networks. 110 (2016) 180-191.

[29] H. Huang, P. Li, S. Guo, W. Zhuang, Software-defined wireless mesh networks: architecture and traffic orchestration, IEEE Networks. 29(4) (2015) 24-30.

[30] O. Dousse, M. Franceschetti, N. Macris, R. Meester, P. Thiran, Percolation in the signal to interference ratio graph, Journal of Applied Probability. 43(2) (2006) 552-562.

[31] A. U. Chaudhry, R. H. Hafez, O. Aboul-Magd, S. A. Mahmoud, Throughput improvement in multi-radio multi-channel 802.11 a-based wireless mesh networks, in: IEEE Global Telecommunications Conference (GLOBECOM), 2010, pp. 1-5.

[32] R. Morsi, D. S. Michalopoulos, R. Schober, Multiuser scheduling schemes for simultaneous wireless information and power transfer over fading channels, IEEE Transactions on Wireless Communications. 14(4) (2015) 1967-1982.

[33] M. A. Mohammed, M. K. A. Hamed, R. I. Ghani, S. A. Mostafa, M. S. Ahmad, D. A. Ibrahim, Solving vehicle routing problem by using improved genetic algorithm for optimal solution, Journal of computational science. 21 (2017) 255-262.

[34] H. Li, Y. Cheng, C. Zhou, W. Zhuang, Minimizing end-to-end delay: A novel routing metric for multi-radio wireless mesh networks, in: IEEE INFOCOM, 2009, pp. 46-54.

[35] S. Kandukuri, S. Boyd, Optimal power control in interference-limited fading wireless channels with outage-probability specifications, IEEE Transactions on Wireless Communications. 1(1) (2002) 46-55.

[36] N. Chakchouk, B. Hamdaoui, Traffic and interference aware scheduling for multiradio multichannel wireless mesh networks, IEEE Transactions on Vehicular Technology. 60(2) (2011) 555-565.

[37] J. Kim, K. Kim, J. Lee, Energy-efficient relay selection of cooperative HARQ based on the number of transmissions over Rayleigh fading channels, IEEE Transactions on Vehicular Technology. 66(1) (2017) 610-621.

[38] Y. Hu, A. Schmeink, J. Gross, Blocklength-limited performance of relaying under quasi-static Rayleigh channels, IEEE Transactions on Wireless Communications. 15(7) (2016) 4548-4558.

[39] C. Lozano-Garzon, M. Camelo, P. Vilà, Y. Donoso, A multi-objective routing algorithm for wireless mesh network in a smart cities environment, Journal of Networks. 10(1) (2015) 60-69.

[40] D. Akg*ün*, P. Erdo*ğ*mus, GPU accelerated training of image convolution filter weights using genetic algorithms, Applied Soft Computing. 30 (2015) 585-594.

[41] NS3. http://www.nsnam.org/. Accessed November 9, 2018.

[42] M. Camelo, C. Omana, H. Castro, QoS routing algorithms based on multi-objective optimization for mesh networks, IEEE Latin America Transactions. 9(5) 875-881.

Chapter 5

Load Balancing Routing for Wireless Mesh Network with Energy Harvesting

This chapter presents the peer-reviewed journal paper about centralized routing method considering long-term objective and EH. The formal permission of reusing it is given in the Appendix A. The journal evaluation metrics including the most recent impact factor, h-index, Cite Score, the SJR and the SNIP are given as below [133,135,137].

Published in Journal *IEEE Communications Letters*,
Volume: 24,
Issue: 4,
Pages: 926-930,
Publisher: IEEE.

Impact Indicators:

- Impact Factor (2020): 3.436
- Impact Factor Quartile: Q1
- h-index: 127
- SJR (2020): 0.929
- SNIP (2020): 1.478
- Cite Score (2020): 7.90

The final version of this paper is available online at
https://ieeexplore.ieee.org/abstract/document/8968321

Summary: Energy is an important factor that should be considered in green communication. Existing centralized routing methods do not sufficiently consider the load, interference, and energy at the same time. This paper proposes an effective load balancing routing considering energy. The queue length, channel condition, energy cost and EH are considered.

Comments on authorship: I proposed the main idea of this paper, analyzed the weaknesses of existing centralized proactive routing methods in WMN, built the routing optimization model with long-term weighted sum cost, solved the optimization problem, wrote and revised the paper. My supervisor, Xiao-Jun Zeng, guided the research direction, proofread the paper and gave me suggestions about the idea of optimization.

Key contribution: Contribution 3 in section 1.4.

Load Balancing Routing for Wireless Mesh Network with Energy Harvesting

Yuan Chai and Xiao-Jun Zeng
Department of Computer Science, University of Manchester,
Manchester, UK, M13 9PL
{yuan.chai, x.zeng}@manchester.ac.uk

Abstract

Centralized routing is beneficial as it provides a global network view to plan and achieve the best and effective path for real-time traffic. With the rapid development of software defined networking, centralized routing has aroused more and more concern of researchers. An effective centralized load balancing routing (LBR) for wireless mesh network considering energy harvesting is proposed in this letter. LBR can provide flexible and optimal routes for real-time traffic. To minimize the long-term weighted sum cost which includes load and energy condition, LBR considers the queue length, channel condition, energy cost and energy harvesting. The problem of making dynamic decisions based on real-time traffic conditions is solved by the dynamic programming approach. Simulation results demonstrate the advantages of LBR.

Index Terms

Wireless mesh network, load balancing, energy harvesting, long-term objective, dynamic programming.

I. Introduction

Wireless mesh network (WMN) is a self-organizing network with high robustness, which is a key component in next-generation wireless community networks [1]. Integrating WMN into the Internet of Things networks is ideal due to the multi-hop scalability [2]. Energy harvesting (EH) [3] can overcome energy constraints and extend the lifetime of traditional WMN. Devices can obtain energy from environment, like solar, wind and radio frequency signals.

Distributed routing methods have different focuses like multiple paths [4], load at interfering nodes [5] and tradeoff between trust and energy consumption [6].

However, distributed routing uses local information, which is hard to support real-time traffic and cannot always find the best route [7]. With the rapid development of Software Defined Networking (SDN), the centralized routing using global information is a more and more heated topic. SDN is a next-generation network paradigm which can decouple control and data planes as well as providing network programmability [1] [8].

Traditional centralized routing methods for WMN do not consider the EH. The SDN-based routing [9] maximizes the throughput and finds a suboptimal solution by solving the simplified MILP problem. Although QoS is considered, EH for WMN is neglected and the network condition for a whole operation period is not considered. Few works consider EH when designing routing, such as the cluster-based routing DEARER [10] and the method in [11]. However, interference is still not sufficiently considered.

In general, the centralized routing can find the best routes by using global information. Traditional centralized routing methods do not consider EH and neglect the energy condition. Few recent works overcome this weakness but do not take into full account the interference, link conditions, and EH in the same framework with a long-term optimization goal.

To overcome the inadequacy of the current centralized routing methods, a centralized load balancing routing (LBR) for WMN is proposed in this letter. The major contributions of LBR can be summarized as follows:

- Unlike existing routing algorithms for WMN, LBR develops a system model to represent the dynamic behavior and flow traffic of WMN. A long-term weighted sum cost considering both load and energy is built. Load is expressed by packet queue length in the whole network, which is obtained by considering interference, bandwidth, the probability of transmission failure (PTF) and path loss. For energy, existing routing for WMN always neglect EH, but LBR calculates residual energy based on both consumed and harvested energy.
- Dynamic programming (DP) [12] is used to solve the established dynamic optimization model with a long-term objective. The packet queue length and residual energy of the current time epoch can be deduced by the conditions and actions of the last time epoch. Here, the action is routing selection which can direct data traffic. Numerical results show LBR can effectively improve

the network performance.

The rest of the letter is: Section II presents the detail of LBR. Some numerical results and analyses are given in Section III. Finally, Section IV concludes this letter.

II. Load balancing routing (LBR) design

In the SDN-based WMN, each mesh node can send its network condition like queue length and available energy to the network controller. Thus, the global controller can monitor the whole network and maintain a network topology [1]. When a source node does not know a route, it will send a request message to the network controller. The network controller will then implement the LBR. After calculation, the network controller will send back the best route to mesh nodes [13]. LBR overcomes the weaknesses of existing centralized routing and formulates the routing problem into a dynamic optimization model to balance load and energy. A long-term weighted sum cost is proposed to control dynamic flow traffic.

A. System model

A connectivity graph $\mathcal{G} = (\mathcal{M}, \mathcal{L})$ describes WMN, where $\mathcal{M}$ and $\mathcal{L}$ are the sets of mesh nodes and links, respectively. Mesh nodes are uniformly deployed. As this letter focuses on the routing method, wireless channels are allocated simply and randomly for multiple interfaces to avoid the influence of channel allocation on the network performance. The wireless channel used on each connection is randomly selected from all available channels. Mesh routers have 3 interfaces, while mesh clients only have 1 interface. Once the channels are allocated, they are fixed. Time horizon is discrete into epochs with the duration τ. The current system state space $\mathcal{S}$ is composed of queue lengths and residual energy of all nodes. The sets of packet queue lengths and residual energy of mesh nodes at the beginning of time epoch t are respectively denoted by $\mathcal{X}(t) = \{x_1^t, x_2^t, ..., x_M^t\}$ and $\mathcal{E}(t) = \{e_1^t, e_2^t, ..., e_M^t\}$. Both of them are M-dimensional vectors. M is the size of $\mathcal{M}$. Then the network state at time epoch t is $\mathcal{S}(t) = \mathcal{X}(t) \times \mathcal{E}(t)$, where $\times$ denotes Cartesian product. The action at node i over time epoch t is a_i^t, which decides the next hop of node i. For each data flow f in flow space $\mathcal{F}$, a policy is a selected path, which is the set of decisions in the whole network. Therefore, a policy is an M by M-dimensional matrix $\mathcal{A} = [a_{ij}^f]_{M\times M}$. If node i selects node j as its next hop, a_{ij}^f is equal to 1.

If not, a_{ij}^{f} is 0. $\forall i, j \in \mathcal{M}$ $, \forall f \in \mathcal{F}$. Network conditions at each time epoch are influenced by the system state and actions. As the residual energy is influenced by transmitted packet queue length, the packet queue length is used to represent the system state.

1) Channel gain: For the large-scale fading, both free-space loss and two-ray ground fading are considered [14]. The path loss between node *i* and its receiver node *j* caused by large-scale fading over time epoch *t* (denoted as $PL_{ij}^{t}(x_i^t, a_i^t)$) is

$$PL_{ij}^{t}(x_i^t, a_i^t) = \begin{cases} \frac{G_t G_r \psi^2}{(4\pi d_{ij}^t(x_i^t, a_i^t))^2}, 0 < d_{ij}^t(x_i^t, a_i^t) \le d_0 \\ \frac{G_t G_r h_t^2 h_r^2}{(d_{ij}^t(x_i^t, a_i^t))^4}, d_0 < d_{ij}^t(x_i^t, a_i^t) \le r_T \end{cases} \tag{1}$$

where h_t and h_r are the heights of transmitting and receiving antennas. ψ is the wavelength. $d_{ij}^t(x_i^t, a_i^t)$ is the distance between node *i* and its next-hop node *j* according to its decision a_i^t. r_T is the transmission range. G_t and G_r are the gains of transmitting and receiving antennas, respectively. Further $d_0 = \frac{4\pi h_t h_r}{\psi}$, which is the critical distance.

In addition to the large-scale fading, the small-scale fading caused by Rayleigh fading is also considered. Then the channel gain between node *i* and its receiving node *j* over time epoch *t* (denoted as $CG_{ij}^{t}(x_i^t, a_i^t)$) is

$$CG_{ij}^{t}(x_i^t, a_i^t) = \eta_{ij}^{t}(x_i^t, a_i^t) \cdot PL_{ij}^{t}(x_i^t, a_i^t) \tag{2}$$

where $\eta_{ij}^{t}(x_i^t, a_i^t)$ presents the small-scale fading.

2) Bandwidth: Channel condition, interference, and PTF are considered. According to the Shannon theorem, the maximum transmission rate from the node *i* to the receiving node *j* based on a_i^t over time epoch *t* (denoted as $B_{ij}^{t}(x_i^t, a_i^t)$) is

$$B_{ij}^{t}(x_i^t, a_i^t) = B_0 \cdot \log_2 \left(1 + \frac{P_{Ti} \cdot CG_{ij}^{t}(x_i^t, a_i^t)}{\sigma^2 + I_j^t}\right) \tag{3}$$

where B_0 is the nominal bandwidth. P_{Ti} is the transmission power of node *i*, σ^2 is the power of additive white Gaussian noise (AWGN). I_j^t is the total interference to node *j*:

$$I_j^t = \sum_{\forall w \in \mathcal{I}(j)} P_{Tw} \cdot CG_{wj}^{t}(x_w^t, a_w^t) \tag{4}$$

where $\mathcal{I}(j)$ is the interfering node set of node *j*, and P_{Tw} is the transmission power of node *w*.

Based on the relationship between receiving power and distance shown in the formulas (1) and (2), the probability density function (PDF) of receiving signal and interference power can be obtained according to the known PDF of distance when the nodes are uniformly deployed. The PTF of the directed link (*i*,*j*) (denoted as $p_{(i,j)}$) is the probability of SINR lower than the threshold, so it can be obtained according to the PDF of receiving signal and interference power. After some simplification, $p_{(i,j)}$ can be expressed as

If $\frac{P_{Ti}G_tG_rh_t^2h_r^2\eta_{ij}^t(x_i^t,a_i^t)}{r_T^4} \leq \beta I_j^t \leq \frac{P_{Ti}G_tG_rh_t^2h_r^2\eta_{ij}^t(x_i^t,a_i^t)}{d_0^4}$

$$p_{(i,j)} = \frac{\sqrt{n\beta P_{Ti}P_{Tu}}\left(r_T^4-2r_T^2d_0^2+d_0^4\right)}{2P_{Ti}r_I^2r_T^2}\sqrt{\frac{\eta_{uj}^t(x_u^t,a_u^t)}{\eta_{ij}^t(x_i^t,a_i^t)}}, \quad \forall i,j \in \mathcal{M}, u \in \mathcal{I}(j) \tag{5}$$

If $\frac{P_{Ti}G_tG_rh_t^2h_r^2\eta_{ij}^t(x_i^t,a_i^t)}{d_0^4} \leq \beta I_j^t < +\infty$

$$p_{(i,j)} = \frac{(3r_T^2d_0^2-d_0^4)}{3r_I^2r_T^2}\sqrt{\frac{n\beta P_{Tu}\eta_{uj}^t(x_u^t,a_u^t)}{P_{Ti}\eta_{ij}^t(x_i^t,a_i^t)}} - \frac{P_{Ti}\eta_{ij}^t(x_i^t,a_i^t)d_0^4}{6n\beta r_I^2r_T^2P_{Tu}\eta_{uj}^t(x_u^t,a_u^t)}, \forall i,j \in \mathcal{M}, u \in \mathcal{I}(j) \tag{6}$$

where *n* is the number of interfering nodes of node *j*, β is the threshold of SINR, and r_I is the interfering range. Other parameters have the same meanings as those in formulas (1), (2) and (4).

Given the derived PTF leaving and receiving at node *i* (denoted as $p_{fi}^t(x_i^t,a_i^t)$ and $p_{ri}^t(x_i^t,a_i^t)$ respectively), the ETX at node *i* over time epoch *t* (denoted as $ETX_i^t(x_i^t,a_i^t)$) is

$$ETX_i^t(x_i^t,a_i^t) = \frac{1}{\left(1-p_{fi}^t(x_i^t,a_i^t)\right)\cdot\left(1-p_{ri}^t(x_i^t,a_i^t)\right)} \tag{7}$$

which is the average number of attempts for a successful transmission in IEEE 802.11 [15]. The medium access control (MAC) protocol is CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). Then the maximum transmission rate for a successful transmission based on each attempt is

$$B_{ij\_s}^t(x_i^t,a_i^t) = \frac{B_{ij}^t(x_i^t,a_i^t)}{ETX_i^t(x_i^t,a_i^t)} = B_0\cdot\log_2\left(1+\frac{P_{Ti}\cdot CG_{ij}^t(x_i^t,a_i^t)}{\sigma^2+I_j^t}\right) \cdot\left(1-p_{fi}^t(x_i^t,a_i^t)\right)\cdot\left(1-p_{ri}^t(x_i^t,a_i^t)\right) \tag{8}$$

Although collision overhead will impact on the transmission rate, to be simple, this impact is neglected and only the maximum transmission rate is considered here.

3) Packet queue length: The packet queue length of the next time epoch (denoted as x_i^{t+1}) is deduced by the state and action of the current time epoch. It can be expressed as

$$x_i^{t+1} = \min\left\{\left[x_i^t - Out_i^t(x_i^t, a_i^t)\right]^+ + In_i^t, Q_{\max\_i}\right\}, \forall i \in \mathcal{M} \tag{9}$$

where $Out_i^t(x_i^t, a_i^t)$ is the packet queue length that is transmitted out from node *i* following action a_i^t at time epoch *t*, and it is influenced by the available bandwidth. $[x]^+$ guarantees the value of queue length is non-negative. If *x* is a negative number, $[x]^+ = 0$. Otherwise, $[x]^+ = x$. In_i^t is the incoming packets including the packets received from other nodes (denoted as f_i^t) and the newly generated packets (denoted as ξ_i^t). $Q_{\max\_i}$ is the maximum packet queue length that can be stored at node *i*. $Out_i^t(x_i^t, a_i^t)$ is

$$Out_i^t(x_i^t, a_i^t) = \min\left\{\left\lfloor \frac{\tau B_{ij\_s}^t(x_i^t, a_i^t)}{L} \right\rfloor, x_i^t, \left\lfloor \frac{e_i^t}{E_T} \right\rfloor\right\}, \forall i \in \mathcal{M} \tag{10}$$

where τ is the time epoch length. *L* is the number of bits in each data packet. e_i^t is the residual energy of node *i* at time epoch *t*. E_T is the energy cost by transmitting a packet. $\lfloor \cdot \rfloor$ means rounding down. (10) means the queue length transmitted from node *i* in time epoch *t* is the minimum value among the total packets that can be transmitted according to the bandwidth, the current queue length at node *i*, and the total amount of packets that will run out of node *i*'s energy. In_i^t is

$$In_i^t = f_i^t + \xi_i^t = \sum_{m \in N(i), des\, a_m^t = i} Out_m^t(x_m^t, a_m^t) + \xi_i^t, \forall i, m \in \mathcal{M} \tag{11}$$

where *N*(*i*) is the set of node *i*'s neighbors. $des\, a_m^t$ is the next hop of node *m* at time epoch *t*. ξ_i^t subjects to Poisson distribution with parameter λ_{i_q}:

$$P_r\left\{\xi_i^t = k\right\} = \frac{{\lambda_{i\_q}}^k}{k!} e^{-\lambda_{i\_q}} \tag{12}$$

where $P_r\{\xi_i^t = k\}$ is the probability of ξ_i^t being equal to positive integer *k*. ξ_i^t can also be obtained by effective prediction.

4) Residual energy: Node *i*'s residual energy of the next time epoch (denoted as e_i^{t+1}) can be obtained according to the consumed and harvested energy. It can be expressed as

$$e_i^{t+1} = \min\left\{\left[e_i^t - \mathcal{E}_i^t(x_i^t, a_i^t)\right]^+ + \mathcal{H}_i^t \cdot E_0, E_{\max\_i}\right\}, \forall i \in \mathcal{M} \tag{13}$$

where $\mathcal{E}_i^t(x_i^t, a_i^t)$ is the consumed energy by transmitting packets based on action a_i^t at time epoch *t*. $\mathcal{H}_i^t$ is the harvested energy queue length over time epoch *t*. For each node, $\mathcal{H}_i^t$ follows the Poisson distribution with parameter λ_{i_eh} [10]. E_0 is the unit of harvested energy. $E_{\max\_i}$ is the maximum energy that node *i* can have. $\mathcal{E}_i^t(x_i^t, a_i^t)$ can be expressed as

$$\mathcal{E}_i^t(x_i^t, a_i^t) = Out_i^t(x_i^t, a_i^t) \cdot E_T \tag{14}$$

B. Optimization model establishment

As one deployment scheme cannot guarantee controlling dynamic flows, an optimization model is built to serve the real-time traffic based on the dynamic load and energy states.

1) Problem formulation: For the cost function, both load and energy conditions in the whole network are considered. The cost function (denoted as $\mathcal{C}^t$) is

$$\mathcal{C}^t = (1-\gamma) \cdot \frac{1}{M} \sum_{i \in \mathcal{M}} x_i^t + \gamma \cdot \frac{1}{M} \sum_{i \in \mathcal{M}} \left(E_{\max\_i} - e_i^t \right) \tag{15}$$

where γ is a weight factor which balances the load and energy. Then, an optimal model to minimize the long-term cost is built:

$$\begin{aligned} &\min_{\gamma, \mathcal{A}} \sum_{t=1}^{\mathcal{N}} \mathcal{C}^t \\ s.t.\ &C_1 : 0 \le \gamma \le 1 \\ &C_2 : 0 \le x_i^t \le Q_{\max\_i} \\ &C_3 : 0 \le e_i^t \le E_{\max\_i} \\ &C_4 : a_{ij}^f \le ex_{ij} \\ &C_5 : \sum_{j \in N(i)} a_{ij}^f = 1 \\ &C_6 : a_{ij}^f + a_{ji}^f \le 1 \\ &C_7 : a_{ij}^f = a_{jg}^f \\ &C_8 : \sum_{i,j \in \mathcal{M}} a_{ij}^f \le H_{\max} \\ &C_9 : a_{ij}^f \in \{0, 1\} \end{aligned} \tag{16}$$

where $i, j, g \in \mathcal{M}$. $\mathcal{N}$ is the number of time epochs. ex_{ij} shows whether link (*i*,*j*) exists according to the network topology. Link (*i*,*j*) exists if nodes *i* and *j* are within the transmission range of each other. When link (*i*,*j*) exists, $ex_{ij} = 1$. Otherwise, $ex_{ij} = 0$. H_{max} is the allowed maximum hop count to serve a data flow. We set it as 6 because when the route has more than 6 hops, the network will be unusable [2]. C_1 means the weight parameter γ should be between 0 and 1. C_2 guarantees the queue length of node *i* is in the range of 0 and Q_{max_i}. Similarly, C_3 guarantees the residual energy of node *i* should be between 0 and E_{max_i}. C_4 constrains that the action of node *i* selecting node *j* as the next hop can be implemented only when the link (*i*,*j*) exists. C_5 makes sure that each node can only select one node as its next hop. C_6 avoids the loop route. C_7 guarantees the intermediate nodes which can receive packets must forward them out. C_8 means the hop count of each path cannot be longer than the allowed maximum hop count. C_9 denotes the binary variable a_{ij}^{f}, which is the action of node *i* to serve flow *f*.

2) Dynamic programming: The long-term cost is given by

$$V(s, \mathcal{A}) = \sum_{t=1}^{\mathcal{N}} \mathcal{C}^t, s \in \mathcal{S} \tag{17}$$

The focus of solving the optimization problem is to find the optimal policy $\mathcal{A}^*$ that can minimize the cost $V(s, \mathcal{A})$. For any given network state *s*, $\mathcal{A}^*$ can be obtained by

$$\mathcal{A}^* = \arg\min_{\mathcal{A}} \ V(s, \mathcal{A}), \forall s \in \mathcal{S} \tag{18}$$

The network state in the current time epoch is deterministic given the state and policy of last time epoch. To solve the problem, DP is used. Bellman's equations are introduced.

For *t*=1,

$$V_1\left(s(1)\right) = \min_{\mathcal{A}_1} \mathcal{C}^1 \tag{19}$$

For $t = 2, 3, ..., \mathcal{N}$,

$$V_t\left(s(t)\right) = \min_{\mathcal{A}_t} \mathcal{C}^t + V_{t-1}\left(s(t-1), \mathcal{A}_{t-1}\right) \tag{20}$$

Then the cumulative cost is minimized. The process starts from epoch 1, and (19) is solved to obtain the minimum cost and reward $\mathcal{C}^1$ for all the constrained possible actions based on the initial given queue length and energy state (i.e., *s*(1)). If there is a feasible solution satisfies the constraints from C_4 to C_8 in formula (16), it guarantees a feasible path exists. The feasible actions are determined according to the source node and possible next-hop neighboring nodes. Afterwards, for $t = 2, 3, ..., \mathcal{N}$, formula (20) is computed recursively. As a result, the optimal policy $\mathcal{A}^*$, which is a reasonable loop-free path satisfying flow conservation from source to destination is obtained. The future information on packet arrival and energy arrival rates is required and assumed to follow the Poisson distribution as mentioned in Section II-A (3) and (4).

3) Computational complexity: The computational complexity of updating the cost value in each time epoch is related to the number of nodes and hops because they will influence the size of states and actions. If the number of nodes is M and the average hop count is h, the most number of neighboring nodes at each hop is $(M-1)/h$. Thus, considering all the possible states and actions, the computational complexity is $O\left(\left(\frac{M-1}{h}\right)^h\right)$. h is not a big number because the allowed maximum hop count to serve a data flow (i.e., H_{max}) is 6. h is no more than H_{max}.

III. Numerical results

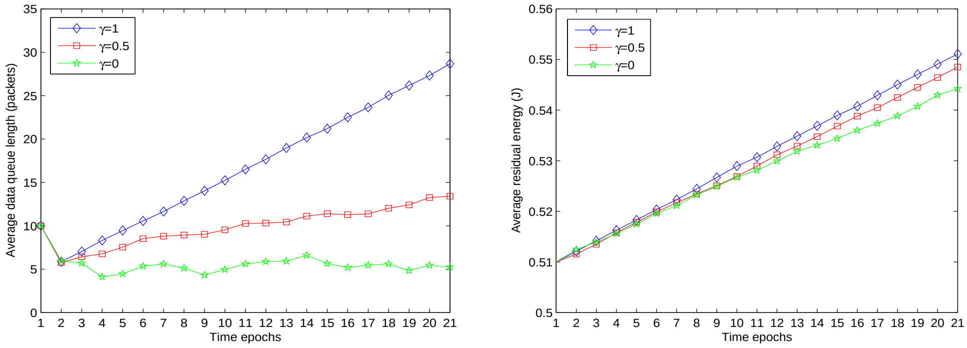
In this section, the performance of LBR is evaluated. Unlike the heuristic reinforcement learning with iterative trying and strengthening based on the partial information to obtain the suboptimal solution, the DP is to find the real global optimal path by taking account of the whole dynamic process and selecting the best action by analyzing all the possible states and actions. The relationship between the actions and system states is related to the topology, because the current node can only send packets to its neighbors, and the system states are determined by actions. Each neighbor can receive the broadcasted route request message, so all neighbors have the same ability to forward packets from the current node. Thus, in our work, the transition probabilities from a current node to its neighbors (except the previous-hop node) in the DP are considered to be equal. Many researches consider ETX to improve network performance. minHop is a widely used routing method and it is usually used as a general benchmark. The SDN-based routing proposed in [9] is a recent centralized routing. In addition, to see the effectiveness of DP, Genetic algorithm (GA) is compared and used to solve the optimization problem with the same objective in LBR. This new method is named as LBR-GA. Therefore, the performance of LBR is compared with LBR-GA, the SDN-based routing, ETX and minHop. As the number of nodes should not be too large due to the computational complexity, 10 mesh nodes are deployed uniformly in an area of 250m $\times$ 250m. However, the LBR can still be used in a large network by applying clustering method [16]. CSMA/CA is the MAC protocol. Detailed simulation parameters are given in Table I [11][17].

In addition to the average queue length, average residual energy and cumulative weight sum of cost $\mathcal{C}$, packet loss rate and network throughput are used as criteria to evaluate network performance. Average packet loss rate is a ratio of the number

TABLE I: Simulation parameters

Simulation Parameters	Values
ψ	0.125m
Time epoch length	10ms
Packet size L	1024 bytes
Transmission power P_{Ti}	250mW
β	3
$Q_{\max\_i}$	30
$E_{\max\_i}$	1J
E_0	0.0025J
B_0	20MHz
σ^2	$-174 + 10log_{10}(B0)$ (dBm)

of lost packets to the number of total sent packets. Average network throughput is an end-to-end metric to evaluate the successfully received number of bits in unit time.

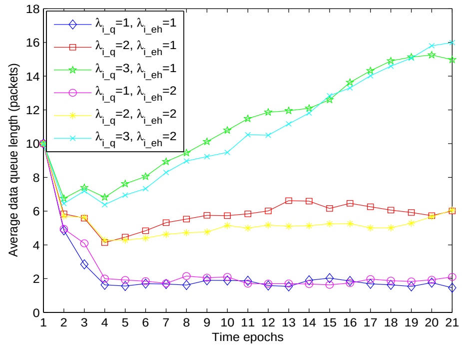


(a) Average packet queue length

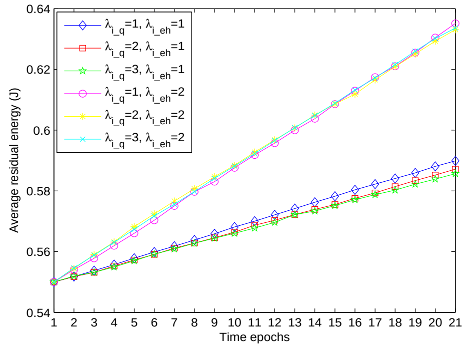
(b) Average residual energy

Fig. 1: Performance versus different time epochs with different γ

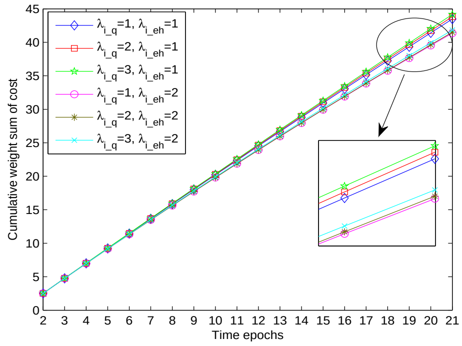
Fig. 1(a) and Fig. 1(b) demonstrate respectively the curves of average data queue length and average residual energy versus time epochs with different weight parameter γ. The λ_{i_q} is 2 and λ_{i_eh} is 1 here. When γ is 0, only the queue length condition is considered as the optimization objective. Best performance of queue length and worst performance of energy can be obtained. When γ is 1, LBR will select mesh nodes with more residual energy, but neglect the available bandwidth and capacity of paths. Worst queue length performance and best energy performance can be gained. When γ is 0.5, queue length and energy have equal importance. The whole network performance is then between those with $\gamma = 0$ and $\gamma = 1$. As both load and energy are important to network performance, γ is then



(a) Average packet queue length



(b) Average residual energy

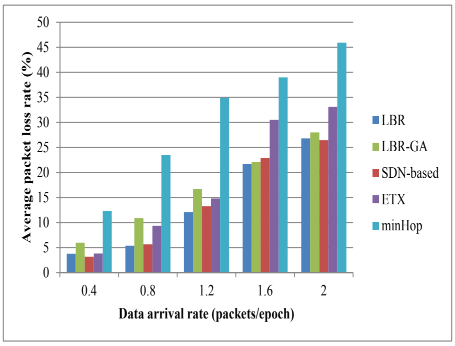


(c) Cumulative weight sum of cost

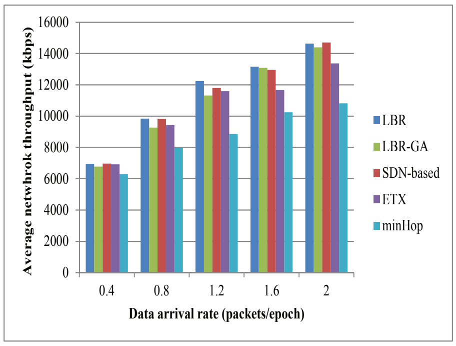
Fig. 2: Performance comparison under different data and energy arrival rate

set as 0.5 in the following simulation to obtain the tradeoff between the importance of queue length and energy.

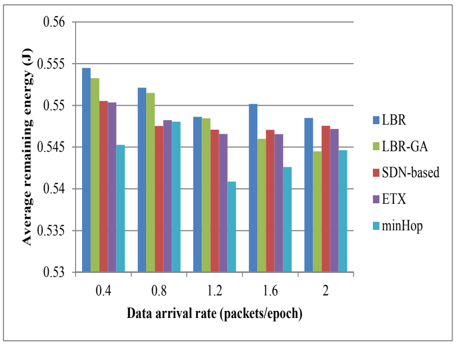
Fig. 2(a) and Fig. 2(b) give the average data queue length and average residual energy respectively under different data arrival rate λ_{i_q} and energy arrival rate λ_{i_eh}. The average queue length is increasing with the increase of λ_{i_q} because of more load. With the same λ_{i_q}, the average queue length is similar. The reason is that λ_{i_q} is the factor which directly influences data packet amount. λ_{i_eh} has effect on energy rather than queue length. When λ_{i_eh} is larger, harvested energy will be much more than the consumed energy. With smaller λ_{i_eh}, the effect of λ_{i_q} on residual energy is more obvious. The average residual energy decreases with larger λ_{i_q} because more energy is used to transmit more arrived packets. Fig. 2(c) gives the cumulative weight sum of cost $\mathcal{C}$. Under the same λ_{i_eh}, the cost will increase with larger λ_{i_q} because of the longer queue length and more consumed energy. With the same λ_{i_q}, the cost is decreasing with larger λ_{i_eh}, since more energy is harvested. In short, larger λ_{i_eh} and smaller λ_{i_q} can bring less cost and better performance.



(a) Average packet loss rate



(b) Average network throughput



(c) Average residual energy

Fig. 3: Network performance versus data arrival rate

Fig. 3 shows the network performance comparison among LBR, LBR-GA, SDN-based routing, ETX and minHop with different data arrival rate. LBR can obtain the least packet loss rate, largest throughput and most residual energy because it effectively considers the channel condition, interference, load, available bandwidth and energy. With the increase of data arrival rate, the load is heavier, and the advantage of LBR is more obvious. LBR also balances energy, which achieves more average residual energy. LBR-GA uses the GA to find solutions by the random crossover and mutation, so it may not find the optimal solution. The SDN-based routing can sometimes obtain similar throughput with LBR because it maximizes throughput and considers the number of interfering nodes. However, it neglects the energy, so it consumes more energy. ETX neglects load and energy, but considers the packet loss, so it has the not bad performance by selecting links with fewer retransmission attempts. minHop overlooks the network condition, which may cause congestion and more consumed energy. Therefore, minHop has the worst performance.

IV. Conclusion

Centralized routing can globally optimize network performance. As traffic in the network is changeable, it is essential to direct data flows in real time. LBR builds an optimization model and puts forward a long-term weighted sum cost, which can minimize and balance load and energy consumption. DP solves the optimization problem with a long-term objective. The path with the best reward and minimized cumulative weight sum of cost is selected. Simulation results show the superior performance of LBR. The time epoch length is an important parameter, which can influence network performance. The approach to select the length of a time epoch is a trade-off problem between the accuracy and overhead. We will do the research about choosing the time epoch length in future.

References

[1] H. Huang, P. Li, S. Guo, W. Zhuang, Software-defined wireless mesh networks: architecture and traffic orchestration, IEEE Networks. 29(4) (2015) 24-30.

[2] Y. Liu, K. F. Tong, X. Qiu, Y. Liu, X. Ding, Wireless mesh networks in IoT networks, in: International Workshop on Electromagnetics: Applications and Student Innovation Competition, 2017, pp. 183-185.

[3] S. Ulukus, A. Yener, E. Erkip, O. Simeone, M. Zorzi, P. Grover, K. Huang, Energy harvesting wireless communications: A review of recent advances, IEEE Journal on Selected Areas in Communications. 33(3) (2015) 360-381.

[4] T. Ming-hao, Y. Ren-lai, L. Shu-jiang, W. Xiang-dong, Multipath routing protocol with load balancing in WSN considering interference, in: 6th IEEE Conference on Industrial Electronics and Applications, 2011, pp. 1062-1067.

[5] Y. Chai, X. J. Zeng, Load-and Interference-Balance Hybrid Routing Protocol for Hybrid Wireless Mesh Network, in: Wireless Days (WD), 2019, pp. 1-4.

[6] A. Ahmed, K. A. Bakar, M. I. Channa, K. Haseeb, A. W. Khan, TERP: A trust and energy aware routing protocol for wireless sensor network, IEEE Sensors Journal. 15(12) (2015) 6962-6972.

[7] H. Yang, B. Chen, P. Fu, Openflow-based load balancing for wireless mesh network, in: International Conference on Cloud Computing and Security, 2015, pp. 368-379.

[8] D. Sajjadi, M. Tanha, J. Pan, A comparative study of channel switching latency for conventional and SDN-based routing in multi-hop multi-radio Wireless Mesh Networks, in: 13th IEEE Annual Consumer Communications & Networking Conference (CCNC), 2016, pp. 330-334.

[9] D. Sajjadi, R. Ruby, M. Tanha, J. Pan, Fine-grained traffic engineering on SDN-aware Wi-Fi mesh networks, IEEE Transactions on Vehicular Technology. 67(8) (2018) 7593-7607.

[10] Y. Dong, J. Wang, B. Shim, D. I. Kim, DEARER: A distance-and-energy-aware routing with energy reservation for energy harvesting wireless sensor networks, IEEE Journal on Selected Areas in Communications. 34(12) (2016) 3798-3813.

[11] Q. Yao, A. Huang, H. Shan, T. Q. Quek, W. Wang, Delay-aware wireless powered communication networks-Energy balancing and optimization, IEEE Transactions on Wireless Communications. 15(8) (2016) 5272-5286.

[12] J. Rust, Dynamic programming, The New Palgrave Dictionary of Economics, (2016) 1-26.

[13] M. Labraoui, M. M. Boc, A. Fladenmuller, Software defined networking-assisted routing in wireless mesh networks, in: IEEE International Wireless Communications and Mobile Computing Conference (IWCMC), 2016, pp. 377-382.

[14] A. U. Chaudhry, R. H. Hafez, O. Aboul-Magd, S. A. Mahmoud, Throughput improvement in multi-radio multi-channel 802.11 a-based wireless mesh networks, in: *IEEE Global Telecommunications Conference GLOBECOM*, 2010, pp. 1-5.

[15] Y. Cheng, X. Ling, W. Song, L. X. Cai, W. Zhuang, X. Shen, A crosslayer approach for WLAN voice capacity planning, IEEE Journal on Selected Areas in Communications. 25(4) (2007) 678-688.

[16] J. Li, B. N. Silva, M. Diyan, Z. Cao, K. Han, A clustering based routing algorithm in IoT aware Wireless Mesh Networks, Sustainable cities and society. 40 (2018) 657-666.

[17] B. K. Chalise, A. Czylwik, Robust uplink beamforming based upon minimum outage probability criterion, in: IEEE Global Telecommunications Conference (GLOBECOM), 2004, pp. 3974-3978.

Chapter 6

A Multi-Objective Dyna-Q Based Routing in Wireless Mesh Network

This chapter presents the peer-reviewed paper about a multi-objective routing solved by reinforcement learning Dyna-Q. The formal permission of reusing it is given in the Appendix A. The most recent impact factor, h-index, Cite Score, the SJR and the SNIP are given according to the official website [133,135,138].

Published in Journal *Applied Soft Computing*,

Volume: 108,

Publisher: Elsevier

Impact Indicators:

- Impact Factor (2020): 6.725
- Impact Factor Quartile: Q1
- h-index: 110
- SJR (2020): 1.290
- SNIP (2020): 2.472
- Cite Score (2020): 11.20

The final version of this paper is available online at

https://www.sciencedirect.com/science/article/abs/pii/S1568494621004099

Summary: When network conditions are uncertain, nodes should have the ability to adapt to the dynamic conditions. Reinforcement learning is a good way to solve such problems by interacting with the environment. This paper proposes a multi-objective routing method, which sets minimizing delay and energy consumption as the objectives. When solving the routing problem, the reinforcement learning method Dyna-Q is used for the first time. As Dyna-Q can learn from the visited state-action pairs while interacting with the environment, the convergence speed is faster than the traditional Q learning.

Comments on authorship: I proposed the main idea of this paper, built the multi-objective routing model, solved the optimization problem, wrote and revised the paper. My supervisor, Xiao-Jun Zeng, guided the whole research direction, gave me the idea about reinforcement learning, and proofread the paper.

Key contribution: Contribution 4 in section 1.4.

A Multi-Objective Dyna-Q Based Routing in Wireless Mesh Network

Yuan Chai and Xiao-Jun Zeng
Department of Computer Science, University of Manchester,
Manchester, UK, M13 9PL
{yuan.chai, x.zeng}@manchester.ac.uk

Abstract

Routing is an essential part for network deployment to maintain and improve the network performance. With the rapid demands of various wireless applications, delay and energy efficiency are two fundamentally important aspects in the next-generation communication. A multi-objective Dyna-Q based routing (MODQR) approach to improve both delay and energy performances is proposed in this paper. For delay, the interference, asymmetrical link condition and probability of transmission failure (PTF) are considered. When deriving the PTF, the gray physical interference model is used. For energy, the ratio of consumed energy to energy capacity is used to monitor energy condition. Reinforcement learning is an effective way to solve the routing problem in a network with uncertain conditions. A path can be chosen by iterative exploration and exploitation. Dyna-Q is an effective reinforcement learning algorithm which can increase the convergence speed. To the best of our knowledge, Dyna-Q is used to solve the multi-objective routing problem for the first time. The path with least end-to-end delay and largest energy efficiency will be selected. Simulation results show that MODQR can obtain up to 80.97%, 83.48% and 86.15% better network performance than three other state-of-the-art routing methods.

Index Terms

Wireless mesh network, Routing, Reinforcement learning, Delay, Energy

I. Introduction

Wireless mesh network (WMN) is easy to be built with low cost. WMN is beneficial in next-generation communication with flexibility and extended coverage. Lots of people living in the rural areas still cannot access Internet easily with cheap charges even today. WMN can be used to serve people in such circumstances.

WMN includes multi-radio mesh routers and single-radio mesh clients. Unlike mesh routers, mesh clients always have very limited energy capacity.

With people's increased need of communication, the communication operations need to be developed all the time [1]. Efficient job scheduling can satisfy users' requests by sending packets in a particular policy according to the priorities of different communication applications like video, game, voice, mail, etc. When and where each job should be processed will be determined to improve network performance [2]. For a specific traffic type, routing is to find an effective or optimal path from a source to a destination in order to achieve a good overall network performance, which is a very important part in network design [3]. The broadcasting communication technology is often used to transmit control packets when discovering routes. In this way, nodes can exchange information with their neighbors to maintain network information. The control of broadcasting can reduce overhead and save energy [4]. Some routing researches focus on a single objective like throughput, delay and packet loss. Load balancing is also essential to be considered to avoid congestion [5], and the network resources like energy can be consumed in balance [6]. However, with the rapidly increasing demands from users, only one objective often fails to improve the whole network performance. For this reason, multi-objective routing has attracted the attentions from more and more researchers. Some existing multi-objective routing approaches combine different objectives into one formula by using weighted cost [7][8]. In this case, the weight values of different objectives are needed to be decided in advance. To avoid setting the weight values, some researches set the different objectives independently, and develop improved algorithms to solve the multi-objective problems [9][10]. To advance the technology along this line, in particular, addressing the challenge that more and more services require little delay and high energy efficiency, this paper proposes a multi-objective Dyna-Q based routing (MODQR) considering delay and energy without setting weight values beforehand, due to the advantage of Dyna-Q which is a special and effective reinforcement learning method with fast convergence speed. The main contributions of MODQR are:

- Build a multi-objective routing model and set the delay and energy as the objectives. The delay is derived by considering interference, bandwidth and probability of transmission failure (PTF) on asymmetrical links. When obtaining the PTF, the gray physical interference model is used to derive the PTF more accurately. The PTF is not either 1 or 0 with different SINR, and there is a transitional period with the PTF between 0 and 1. The PTF is then derived according to the probabilities that the SINR is within different periods. For the energy, not only the consumed energy but also the energy capacity is considered.

- Use Dyna-Q to solve the established optimization model for the first time. Reinforcement learning is an effective way to solve the routing problem when the network condition is uncertain. Dyna-Q is a type of improved Q learning which can improve the convergence speed. To find the effective route with less delay and more energy efficiency, an improved Dyna-Q method which can solve the multi-objective problem by considering Chebyshev distance is proposed. The learning rate is dynamic according to the visit count and iteration number, and the exploration rate is computed based on the Q values of all different possible actions.

As reinforcement learning method is used in MODQR to find paths, MODQR is suitable for the dynamic and complex networks. For instance, the laptops, smart phones, sensors and so on can move and have time-varying patterns, which causes dynamic network condition and topology and different energy status at different times. In this case, MODQR can learn the changeable network condition in a real-time manner and try to find the best route adaptively and automatically. In addition, as the objectives of MODQR are minimizing delay and optimizing energy condition, MODQR can suit the traffic with delay request like videos and autonomous cars well. The devices with limited energy like sensors and smart phones can also be well served (for example, under the same traffic patterns, MODQR can take different actions dependent on the different energy status), and the energy can be used in balance.

The structure of this paper is: Some related works are given in Section II. Section III shows the system model. Section IV gives the key parameters in MODQR. Section V explains the optimization problem of MODQR. Simulation results are shown in section VI, and section VII concludes the paper finally.

II. Background and related works

A. Background

The problems of designing and deploying network are often formulated as an optimization problem. Many recent heuristic and metaheuristic approaches are popular and adaptive to find the solutions. Humpback whale optimization algorithm can be used to solve the task scheduling problem in cloud computing. Cost and energy consumption are reduced, and the utilization of resources is maximized [11]. Sea lion optimization [12] can effectively find the optimal solution for the maximum flow problem [13]. Grey wolf optimization replicating the social and hunting behaviour of grey wolves can find the optimized cluster number in clustering problem [14]. In optimal design of circular antenna arrays, the most valuable player algorithm can maximize sidelobe levels reduction [15].

As an important part in network design, routing can also be formulated as an optimization problem which can be solved by these heuristic and metaheuristic approaches. In addition to the good performance in scheduling [16], chemical reaction optimization has also been successfully used in discrete multi-objective vehicle routing problem with simultaneous delivery and pickup and time windows [17]. Some recent formulated routing methods designed for WMN consider different multiple factors. Delay- and Interference-Aware Routing (DIAR) minimizes delay, and uses an improved genetic algorithm to find the route solution [18]. Bandwidth, interference and the PTF are considered at the same time when deriving delay. To balance the load and avoid congestion when solving the routing optimization problem, the node with least number of interfering nodes will be selected to replace the common node used by multiple data flows in mutation process. The dynamic network condition caused by different route selection is also considered. However, DIAR does not have the ability of learning, and does not consider the asymmetrical link condition and energy. Search-based routing method proposed in [19] minimizes the expected transmission time in addition to hop count. Better performance than traditional hop count metric can be obtained by using genetic algorithm in path searching. As the expected transmission time is obtained through probe packets, cost and overhead will be high. Besides, the interference, transmission failure probability and energy are neglected.

B. Related Works

The research of multi-objective routing algorithm designed for WMN generally has two focuses: the establishment of optimization model and solution of optimization model. The research focuses on the establishment of optimization model are given as follows. The algorithm in [20] minimizes energy, delay and packet loss, and uses NSGA-II [21] to solve the problem. Based on this algorithm, the multi-objective routing algorithm in [22] considers hop count, energy, delay and ETX [23], and satisfies the bandwidth request. MQoSR [24] researches the multi-path routing, and converts the multi-objective problem into the single-objective one. Each objective is multiplied with a degree to show the importance of different objectives. The research in [25] optimizes the problem of deployment cost and network throughput, and finds the proper locations of routers and gateways. The algorithm in [26] balances load based on clustering, and uses the method of Lagrange multipliers to solve. The routing in [9] balances the energy cost of individual nodes and whole network. The experiment is done in a library in London. The algorithm in [27] minimizes the path length and overhead.

Some other research focuses on the solution methods. After building the load-balanced, interference and flow-capacity models, the algorithm in [28] combines multi-objective particle swam optimization (PSO) [29] and genetic algorithms [30] to solve the three models. The algorithm in [31] sets delay and energy consumption as the objectives, and compares the performance of NSGA-II and Multi-Objective Differential Evolution (MODE) [32]. Algorithms proposed by Murugeswari [10][33][34] solves problems by discrete PSO, NSGA-II and discrete MODE. Delay, ETX and packet delivery ratio are considered. The algorithm in [35] is based on SPEA [36] to consider hop count, free space loss and QoS restrictions. Paths from a source to all destinations can be found.

All these existing related works detect the network condition at the beginning of routing, and assume the condition will be stable and fixed during the process of finding routes. However, the network condition will dynamically change during finding routes, because the interference relationship will change when different links and paths are selected. Thus, considering the influence of finding routes to the network condition is essential, which can find the dynamic optimal paths based on the real-time network condition and can make the process of selecting paths more accurate.

Reinforcement learning is beneficial to find paths when network conditions are dynamic. Reinforcement learning is an unsupervised learning technique that allows the agent to autonomously take actions based on the sensed information. Thus, it is adaptive for the network routing where the node and link states are uncertain and complex. Each node can select its next hop just based on the rewards learnt from the reinforcement learning, which can adapt to the dynamic network condition and reduce the complexity [37]. Q learning is a popular reinforcement learning method and does not need a model of the system to learn from delayed reinforcement. The Q table is updated based on the reward dynamically. Q learning is proved to be effective in the problem of finding paths, such as for unmanned aerial vehicles and vehicular ad hoc networks [38][39]. The real-time routing algorithm in [40] uses Q learning to find path with less delay, more success rate and less hop count. The actions can be adjusted based on the real-time dynamic network condition. The group of nodes will be first selected by considering delay and success rate. Then the node with the lowest number of hops in the selected group will be chosen as the next node. However, energy, congestion and interference are not considered. Dyna-Q is an improved Q learning method with fast convergence speed, so it is also adaptive in routing problem. However, there is no routing research based on Dyna-Q currently [41].

III. System model

WMN is expressed by a connectivity graph $G = (V, L)$, where V is the mesh node set and L is the wireless link set. For the path loss, the two-ray ground reflection model is used. At the same time, small-scale fading is also considered. Thus, the receiving power at node *j* from node *i* (denoted as P_{ij}) is

$$P_{ij} = P_{Ti} \times \frac{G_t G_r h_t^2 h_r^2 \delta_{ij}}{(d_{ij})^4} \tag{1}$$

where P_{Ti} is the transmission power of node *i*. G_t and G_r are the gain of transmitting and receiving antennas. h_t and h_r are the heights of transmitting and receiving antennas. δ_{ij} is the small-scale fading. d_{ij} is the distance between nodes *i* and *j*.

Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) in IEEE 802.11 is the MAC protocol. A packet will be retransmitted after the failed transmission. When the maximum number of retransmission is reached, the packet will be dropped. The notations used in this paper are given in Table I.

TABLE I: Variable notations

Notation	Description
V	Set of mesh nodes
L	Set of wireless links
h_t	Height of transmitting antennas
h_r	Height of receiving antennas
δ_{ij}	Small-scale fading
G_t	Gain of transmitting antennas
G_r	Gain of receiving antennas
d_{ij}	Distance between nodes *i* and *j*
P_{Ti}	Transmission power of node *i*
P_{ij}	Receiving power at node *j* from node *i*
(*i*,*j*)	A wireless link between nodes *i* and *j*
$E[T_{(i,j)}]$	Average delay on link (*i*,*j*)
Length	Size of data packet
$P_{l(i,j)}$	Final PTF of link *l*
K	Largest allowed number of retransmission
$B_{(i,j)}$	Bandwidth of link (*i*,*j*)
SlotTime	Duration of a slot
CW_{min}	Minimum backoff window
B_0	Nominal bandwidth
γ_{ij}	SINR of link (*i*,*j*)
$p_{ij}(\gamma_{ij})$	Instantaneous PTF of a directional link (*i*,*j*)
β_0	The lower bound of the transition region
β_c	The upper bound of the transition region
p_{i_j}	Expected value of the $p_{ij}(\gamma_{ij})$
$f_{SINR}(\gamma)$	The probability density function of SINR
M	The number of segmentations divided between β_0 and β_c
A_m	The average PTF in each segmentation
m	The sequence number of a segmentation
$p_{(i,j)}$	The probability of the SINR lower than a specific threshold
n_j	The number of interfering nodes at node *j*
r_T	Transmission range

r_I	Interference range
E_t	The amount of consumed transmission energy in unit time
$E_{backoff}$	The consumed energy of backoff in unit time
$E^i_{consumed}$	The consumed energy at node i
$E^i_{available}$	The current available energy of node i
$E^i_{condition}$	Energy condition of node i
F	Data flow set
e	A data flow
X^e_{ij}	(binary)=1, when link (i,j) is used to service flow e
N_i	The number of packets waiting at node i
S	Set of source nodes
D	Set of destination nodes
c_{ij}	(binary)=1, when nodes i and j are neighbors
α	Learning rate
ξ	Discount factor
$Q(s,a,o)$	Q value from current node s to the next hop a in objective o
$r(s,a,o)$	Reward from current node s to the next hop a in objective o
ρ	Weight parameter
$visitcount(s,a)$	The times of current node s selecting node a as the next hop
iternum	The current number of iteration
$iternum_{max}$	The maximum number of iteration
w	An adjustment parameter for learning rate
$\pi(s_{current}, a_{hop})$	Probability of selecting action a_{hop} at current state $s_{current}$
$SQ(s_{current}, a_{hop})$	Computed comprehensive Q value from $s_{current}$ to a_{hop}
τ	Temperature parameter
τ_0	Initial temperature
$\tau_{iternum_{\max}}$	Final temperature in the end
Ω	Total number of objectives
$Q_{o\_\min}$	Minimum Q value among all actions from $s_{current}$ in objective o
$Q_{o\_\max}$	Maximum Q values among all actions from $s_{current}$ in objective o

IV. KEY PARAMETERS IN MODQR

As delay and energy are most important with the rapid development of wireless communication, reducing delay and improving energy efficiency are two objectives of MODQR. Thus, computing delay, energy and the related parameters is important.

A. Delay

Interference, bandwidth and PTF are considered to derive delay. The average delay on link (*i,j*) (denoted as $E[T_{(i,j)}]$) is the expected value of the required time with different number of retransmissions [42]. $E[T_{(i,j)}]$ includes transmission and backoff delay, which can be expressed as

$$\begin{aligned} E[T_{(i,j)}] &= \sum_{k=1}^{K+1} p_{(i,j)}^{k-1}(1-p_{(i,j)})^{I\{k<K+1\}} \cdot \sum_{s=1}^{k} \left(\frac{Length}{B_{(i,j)}} + E[CW_s] \cdot SlotTime\right) \\ &= E[T_{(i,j)}^{trans}] + E[T_{(i,j)}^{backoff}] \\ &= \frac{Length}{B_{(i,j)}}\left[\frac{1-p_{l(i,j)}^{K}}{1-p_{l(i,j)}}\right] + \frac{CW_{min}[1-(2p_{l(i,j)})^{K+1}] \cdot SlotTime}{2(1-2p_{l(i,j)})} - \frac{(1-p_{l(i,j)}^{K}) \cdot SlotTime}{2(1-p_{l(i,j)})} \end{aligned} \tag{2}$$

where *I*(*A*) is equal to 1 if *A* is true. CW_s is the size of the *s*th backoff window, and $E[CW_s]$ is the expected value of CW_s. $E[CW_s] = \frac{CW_s-1}{2} = \frac{2^{s-1} \cdot CW_{min}-1}{2}$. CW_{min} is the minimum backoff window. *Length* is the number of bits in a data packet. $P_{l(i,j)}$ is the PTF of link *l* considering the condition of both forward and reverse links. *k* is the number of transmissions. *K* is the allowed maximum number of retransmissions. *SlotTime* is the duration of a time slot. $B_{(i,j)}$ is the bandwidth between nodes *i* and *j* can be expressed as

$$B_{(i,j)} = B_0 \cdot log_2(1+\gamma_{ij}), \forall i,j \in V, i \neq j \tag{3}$$

in which B_0 is the nominal bandwidth, and γ_{ij} is the SINR of link (*i,j*).

Based on formula (2), the delay can be obtained if the PTF $P_{l(i,j)}$ is derived. The $P_{l(i,j)}$ can be obtained as shown in the next section PTF.

B. PTF

As links are bidirectional, the PTF of a link (*i,j*) is based on both forward link from node *i* to *j* and the reverse link from node *j* to *i*. A successful packet transmission from nodes *i* to *j* needs not only node *j* receiving the packet successfully, but also node *i* receiving ACK. For the forward link, the PTF is derived according to the gray physical interference model [43]. The relationship between the instantaneous PTF of a directional link (*i*,*j*) (denoted as $p_{ij}(\gamma_{ij})$) and the SINR (i.e., γ_{ij}) is

$$p_{ij}(\gamma_{ij}) = \begin{cases} 0, \gamma_{ij} \geq \beta_c \\ \frac{\beta_c - \gamma_{ij}}{\beta_c - \beta_0}, \beta_0 \leq \gamma_{ij} < \beta_c \\ 1, \gamma_{ij} < \beta_0 \end{cases} \tag{4}$$

where β_0 is the lower bound of the transition region, and β_c is the upper bound. [β_0,β_c] is the transition region. Thus, the expected value of $p_{ij}(\gamma_{ij})$ (denoted as p_{i_j}) is

$$\begin{aligned} & p_{i\_j} = \int_0^{+\infty} p_{ij}(\gamma_{ij}) \cdot f_{SINR}(\gamma) d\gamma \\ & = \int_0^{\beta_0} 1 \cdot f_{SINR}(\gamma) d\gamma + \int_{\beta_0}^{\beta_c} \frac{\beta_c - \gamma_{ij}}{\beta_c - \beta_0} \cdot f_{SINR}(\gamma) d\gamma + \int_{\beta_c}^{+\infty} 0 \cdot f_{SINR}(\gamma) d\gamma \end{aligned} \tag{5}$$

where $f_{SINR}(\gamma)$is the probability density function (PDF) of SINR. The third part of formula (5) is zero, so the job is to get the first and second integration parts. The first part is

$$\int_0^{\beta_0} 1 \cdot f_{SINR}(\gamma) d\gamma = p(\gamma < \beta_0) = p_{(i,j)}(\beta = \beta_0) \tag{6}$$

where p means the probability of SINR γ in the specific range, and it can be obtained according to the given probability of the SINR being lower than a specific threshold (denoted as $p_{(i,j)}$). $p_{(i,j)}$ can be derived according to the PDF of receiving signal and interference power. When the nodes are uniformly deployed, the PDF of distance is known. Then based on formula (1), the PDF of receiving signal and interference power can be obtained. The detailed expression of $p_{(i,j)}$ is

$$p_{(i,j)} = \frac{\sqrt{n_j \beta P_{Ti} P_{Ta} \delta_{ij} \delta_{aj} r_T^2}}{2 P_{Ti} \delta_{ij} r_I^2} \tag{7}$$

where n_j is the number of interfering nodes at node *j*. P_{Ti} and P_{Ta} are the transmission power of source node *i* and interfering node *a* respectively. r_T and r_I are transmission and interference ranges.

For the second part integration of formula (5), as it cannot be obtained analytically, we use the numerical integration to calculate it. That is, by even dividing the continuous period of [β_0,β_c] into several segmentations, the second part of formula (5) can then be expressed as

$$\begin{aligned} & \int_{\beta_0}^{\beta_c} \frac{\beta_c - \gamma_{ij}}{\beta_c - \beta_0} \cdot f_{SINR}(\gamma) d\gamma = \sum_{m=1}^{M} A_m \cdot p(\beta_0 + \tfrac{\beta_c - \beta_0}{M} \cdot (m-1) < \gamma < \beta_0 + \tfrac{\beta_c - \beta_0}{M} \cdot m) \\ & = \sum_{m=1}^{M} A_m \cdot \Big(p_{(i,j)}(\beta = \beta_0 + \tfrac{\beta_c - \beta_0}{M} \cdot m) - p_{(i,j)}(\beta = \beta_0 + \tfrac{\beta_c - \beta_0}{M} \cdot (m-1)) \Big) \end{aligned} \tag{8}$$

where *M* is the number of segmentations divided between β_0 and β_c. *m* is the sequence number of a segmentation. A_m is the average PTF in each segmentation, which can be expressed as

$$\begin{aligned} A_m &= \frac{p_{ij}(\gamma_{ij}=\beta_0+\frac{\beta_c-\beta_0}{M}\cdot m)+p_{ij}(\gamma_{ij}=\beta_0+\frac{\beta_c-\beta_0}{M}\cdot(m-1))}{2} \\ &= \frac{\frac{\beta_c-(\beta_0+\frac{\beta_c-\beta_0}{M}\cdot m)}{\beta_c-\beta_0}+\frac{\beta_c-(\beta_0+\frac{\beta_c-\beta_0}{M}\cdot(m-1))}{\beta_c-\beta_0}}{2} \\ &= 1-\frac{2m-1}{2M} \end{aligned} \tag{9}$$

According to formulas (6) and (8), the formula (5) can be expressed as

$$\begin{aligned} p_{i\_j} = p_{(i,j)}(\beta=\beta_0) + \sum_{m=1}^{M} A_m \cdot \Big(p_{(i,j)}(\beta=\beta_0+\tfrac{\beta_c-\beta_0}{M}\cdot m) \\ -p_{(i,j)}(\beta=\beta_0+\tfrac{\beta_c-\beta_0}{M}\cdot(m-1))\Big) \end{aligned} \tag{10}$$

Similarly, the PTF for reverse link (denoted as p_{j_i}) can be obtained. As the transmission between nodes *i* and *j* can be successful only when the transmission on forward and reverse links are both successful. According to the PTF on forward and reverse links, the final PTF between nodes *i* and *j* (i.e., $p_{l(i,j)}$) can be expressed as

$$p_{l(i,j)} = 1-(1-p_{i\_j})(1-p_{j\_i}) \tag{11}$$

C. Energy

The consumed energy is related to the node state and the duration of states. As the consumed transmission energy is much larger than receiving energy, the energy cost by receiving packets is neglected [44]. The consumed energy can be expressed as the energy cost by transmitting and backoff. When the amount of consumed energy in conditions of transmission and backoff during unit time is E_t and $E_{backoff}$ respectively, the consumed energy at node *i* (denoted as $E^i_{consumed}$) is

$$E^i_{consumed} = E_t \cdot E[T^{trans}_{(i,j)}] + E_{backoff} \cdot E[T^{backoff}_{(i,j)}] \tag{12}$$

As different mesh nodes have different energy capacity and available energy, not only the amount of consumed energy, the available energy should also be considered. Thus, the ratio of the consumed energy to the total available energy is used to evaluate the energy condition. Then the energy condition of node *i* (denoted as $E^i_{condition}$) is

$$E^i_{condition} = \frac{E^i_{consumed}}{E^i_{available}} = \frac{E_t \cdot E[T^{trans}_{(i,j)}] + E_{backoff} \cdot E[T^{backoff}_{(i,j)}]}{E^i_{available}} \tag{13}$$

where $E^i_{available}$ is the current available energy of node *i*. Thus, the smaller $E^i_{condition}$ means the stronger ability in terms of energy, and the node with less $E^i_{condition}$ should be selected.

V. Optimization problem in MODQR

The routing problem is formulated as an optimization problem in MODQR. Both delay and energy are taken into account. When solving the multi-objective routing problem model, the reinforcement learning Dyna-Q is used. The detailed optimization model and solution are given as follows.

A. *Optimization model establishment*

The objectives of delay and energy are based on formulas (2) and (13). Then the optimal model with constraints to minimize delay and optimize energy condition is

$$\begin{aligned}
&\min \sum_{(i,j)\in L} X^e_{ij} E[T_{(i,j)}](N_i+1), \forall e \in F \\
&\min \sum_{(i,j)\in L} X^e_{ij} E^i_{condition}, \forall e \in F \\
s.t.\ &C_1 : \sum_{(i,j)\in L} X^e_{ij} = 1, i \in S, \forall e \in F \\
&C_2 : \sum_{(i,j)\in L} X^e_{ij} = 1, j \in D, \forall e \in F \\
&C_3 : \sum_{(i,j)\in L} X^e_{ij} = \sum_{(j,u)\in L} X^e_{ju} = 1, \forall j \in V - \{S, D\}, \forall e \in F \\
&C_4 : X^e_{ij} \le c_{ij}, \forall (i,j) \in L, \forall e \in F \\
&C_5 : X^e_{ij} \in \{0,1\}, \forall (i,j) \in L, \forall e \in F
\end{aligned} \tag{14}$$

where X^e_{ij} is the binary decision variable. If link (*i,j*) is chosen to serve flow *e*, X^e_{ij} is 1, otherwise X^e_{ij} is 0. N_i is the number of packets waiting at node *i* to be served. *F* is the set of data flows in the network. *S* and *D* are the sets of source and destination nodes respectively. c_{ij} is a binary constant showing whether nodes *i* and *j* are neighbors. If they are neighbors, c_{ij} is 1, otherwise c_{ij} is 0. C_1 to C_3 guarantee the flow conservation, and only one path without loop for a flow is determined. C_4 shows that the selected link must exist, which means the selected next hop *j* must be the neighbor of the current node *i*. C_5 means X^e_{ij} is binary.

B. *Solution of the multi-objective optimization model: Dyna-Q*

When solving the routing and optimization problem, the network conditions are dynamic, and it is hard for the agent to know the prior information which is affected by the environment. Therefore, in the routing problem, the model-free reinforcement learning approach is effective to make selections without requiring the prior knowledge of environment statistics before taking actions [45]. Dyna-Q is an effective reinforcement learning method, which can be used in the WMN to dynamically solve the optimization problem with large amount and uncertain states [41]. The faster convergence speed of Dyna-Q is also greatly needed for routing. However, no existing research is based on Dyna-Q, and this paper overcomes this weakness and adapts Dyna-Q to the proposed routing problem.

1) Q values: Similar to Q learning [46], Dyna-Q also needs to maintain and update Q values based on different actions. As the optimization model of MODQR considers two objectives, each node maintains two Q tables for delay and energy separately. For each objective o, the method of updating Q values is

$$Q(s,a,o) \leftarrow (1-\alpha)Q(s,a,o) + \alpha \left[r(s,a,o) + \xi \min_{a'} Q(a,a',o) \right] \tag{15}$$

where s is the current node. a is the action of s, which is the selected next hop of s. a' is the action of a. $\min\limits_{a'} Q(a,a',o)$ is the minimum Q value among all possible actions from the next hop a in objective o. If a is the destination node, no a' exists and $\min\limits_{a'} Q(a,a',o)$ is 0. $r(s,a,o)$ is the reward from current node s to the next hop a in the objective o. When a is valid and the constraints in formula (14) can be submitted to, the reward values in terms of delay and energy can be obtained from formulas (2) and (13) respectively. If there is no valid a that can be selected, for example a loop in the path must exist, a penalty parameter θ is given to all visited links in this iteration as the rewards. α is the learning rate, and determines to what extent newly acquired information overrides old information. ξ is the discount factor which determines the importance of future rewards.

2) Learning rate: The learning rate α is no longer a fixed value in MODQR, and it is related to the visit count and the iteration number, which can be expressed as

$$\alpha{=}\rho \cdot \frac{visitcount(s,a)^w}{iternum_{\max}^w} + (1-\rho) \cdot \left(1{-}\frac{iternum^w}{iternum_{\max}^w} \right) \tag{16}$$

where ρ is a weight parameter showing the importance of visit count and iteration number. $visitcount(s,a)$ is the times of current node s selecting node a as the next hop. *iternum* is the current number of iteration, and $iternum_{max}$ is the maximum number of iteration. w is an adjustment parameter for learning rate, and $w \in (0.5,1)$ [47]. Formula (16) shows that a larger visit count and smaller iteration number will bring a larger α. A larger visit count means node *s* has selected *a* for several times, which means *a* is the best action from *s* for several times. Thus, the learning rate α comes larger to learn more from this better solution. Besides, the learning rate should be less and less in the process of iterative trying and strengthening to converge. With the increase of iteration number, α becomes smaller and smaller.

3) Exploration and exploitation: In the part of exploration and exploitation, to avoid converging to a suboptimal solution, MODQR uses the softmin policy [48] rather than the greedy strategy. The action selection is based on Boltzmann distribution in each iteration, and the probability of selecting action (next hop) a_{hop} at current state $s_{current}$ (denoted as $\pi(s_{current}, a_{hop})$) is

$$\pi(s_{current}, a_{hop}) = \frac{\exp(-SQ(s_{current}, a_{hop})/\tau)}{\sum\limits_{a_i \in A} \exp(-SQ(s_{current}, a_i)/\tau)} \tag{17}$$

where *A* is the set of all available actions at current state $s_{current}$. τ is the temperature parameter. High values of τ will make actions having almost equal probabilities, while small τ brings great differences in the selection probability. As more exploration should be made in the beginning and the solution should converge in the end, τ should become smaller with the increase of iteration number. Because MODQR considers multiple objectives, all objectives should be taken into account when selecting action. $SQ(s_{current}, a_{hop})$ is the computed comprehensive Q value from the current state $s_{current}$ to the next hop a_{hop} according to the Q values in all objectives. a_{hop} with less $SQ(s_{current}, a_{hop})$ will bring larger $\pi(s_{current}, a_{hop})$ so that a_{hop} has larger probability to be selected. The expressions of τ and $SQ(s_{current}, a_{hop})$ are given as follows.

The expression of τ is

$$\tau = \tau_0 - \frac{(\tau_0 - \tau_{iternum_{\max}})iternum}{iternum_{\max}} \tag{18}$$

where τ_0 is the initial temperature, and $\tau_{iternum_{\max}}$ is the final temperature in the end. *iternum* and $iternum_{max}$ have the same meanings with those in formula (16).

The expression of $SQ(s_{current}, a_{hop})$ is

$$SQ(s_{current}, a_{hop}) = \max_{o=1\ldots\Omega} \left| \frac{Q(s_{current}, a_{hop}, o) - Q_{o\_\min}}{Q_{o\_\max} - Q_{o\_\min}} \right| \tag{19}$$

where Ω is the total number of objectives. $Q_{o\_\min}$ and $Q_{o\_\max}$ are the minimum and maximum Q values among all actions from $s_{current}$ in terms of the objective *o*, respectively. The denominator is to normalize, which can avoid the big difference

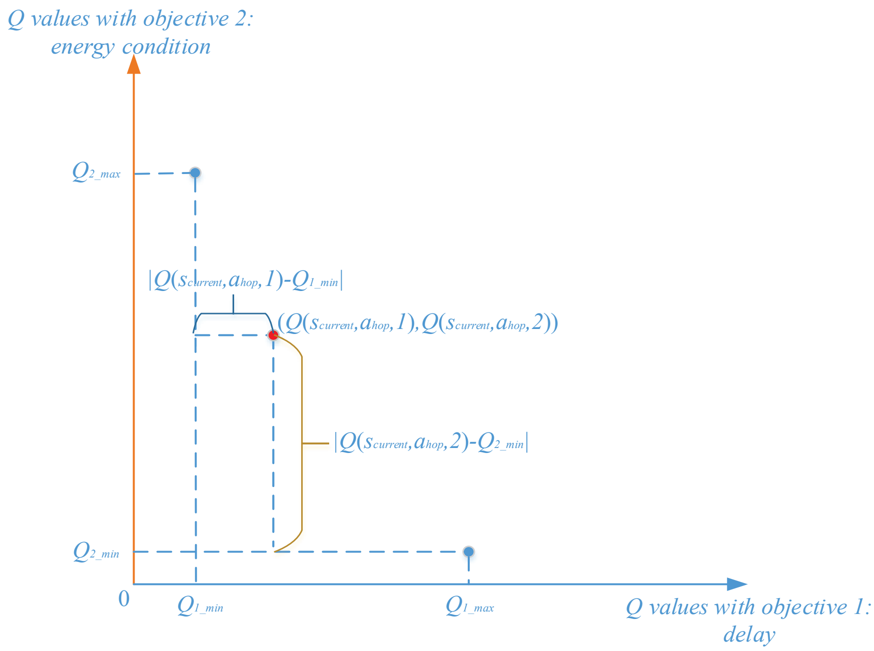


Fig. 1: An example of $SQ(s_{current}, a_{hop})$

in the order of magnitude among different objectives. $SQ(s_{current}, a_{hop})$ is based on the Chebyshev distance [49] because we hope to select the action with good performance in each objective. The selected action does not have poor performance in any objective. If we use the Euclidean distance for instance, an action may be selected when this action has good performance in one objective but poor performance in the other. When finding the best solution by using Chebyshev distance, different objectives are considered respectively and they are not merged into one objective. Therefore, the weight values which are used to combine different objectives into one aggregated formula to show the importance degree for each objective can be avoided.

To show the meaning of $SQ(s_{current}, a_{hop})$ clearly, an example is given in Fig. 1.

In Fig. 1, there are three solution points, and we compute $SQ(s_{current}, a_{hop})$ of the middle red solution point with coordinate $(Q(s_{current}, a_{hop}, 1)$,$Q(s_{current}, a_{hop}, 2))$. We assume $Q_{1\_\min}$ and $Q_{2\_\min}$ are 1 and 0.5, and $Q_{1\_\max}$ and $Q_{2\_\max}$ are 5 and 6.5. $Q(s_{current}, a_{hop}, 1)$ and $Q(s_{current}, a_{hop}, 2)$ are 2 and 4.5. Thus, $\left|\frac{Q(s_{current},a_{hop},1)-Q_{1\_\min}}{Q_{1\_\max}-Q_{1\_\min}}\right| = \left|\frac{2-1}{5-1}\right| = \frac{1}{4}$ and $\left|\frac{Q(s_{current},a_{hop},2)-Q_{2\_\min}}{Q_{2\_\max}-Q_{2\_\min}}\right| = \left|\frac{4.5-0.5}{6.5-0.5}\right| = \frac{2}{3}$. As $\left|\frac{Q(s_{current},a_{hop},2)-Q_{2\_\min}}{Q_{2\_\max}-Q_{2\_\min}}\right| > \left|\frac{Q(s_{current},a_{hop},1)-Q_{1\_\min}}{Q_{1\_\max}-Q_{1\_\min}}\right|$,
$SQ(s_{current}, a_{hop}) = \left|\frac{Q(s_{current},a_{hop},2)-Q_{2\_\min}}{Q_{2\_\max}-Q_{2\_\min}}\right|$.

Algorithm 1 Process of the Dyna-Q in MODQR

Initialization

Initialize parameters: discount factor ξ, penalty parameter θ, weight parameter ρ, the maximum number of iteration $iternum_{max}$, initial temperature τ_0, final temperature $\tau_{iternum_{\max}}$.

Initialize action-value function Q.

Set *iternum*:=1.

Procedure

while $iternum \le iternum_{\max}$ **do**
    while (1) **do**
        if valid a_{hop} submitting to constraints in formula (14) exist
            Select action a_{hop} according to $\pi(s_{current}, a_{hop})$.
            Calculate rewards by formulas (2) and (13).
            if destination node is reached
                Update Q values by formula (15) with $\min_{a'} Q(a, a', o)$ is 0.
                Randomly select some visited state-action pairs to update Q values by rewards obtained before.
                break;
            else
                Update Q values by formula (15).
                Randomly select some visited state-action pairs to update Q values by rewards obtained before.
                $s_{current} \leftarrow a_{hop}$.
            end if
        else
            Give the penalty parameter θ to all visited actions as rewards.
            break;
        end if
    end while
    Set *iternum*:= *iternum* +1.
end while

4) The process of Dyna-Q in MODQR: Dyna-Q can increase the convergence speed of Q learning by also learning from existed rewards and visited selections, and such a fast convergence makes it particular useful for the routing problem considered in the paper. Unlike the traditional Q learning only learning by interaction with real environment, Dyna-Q can also update Q values for the visited selections by using the rewards obtained before. The detailed process of Dyna-Q in MODQR is shown in the Algorithm 1.

From Algorithm 1 we can see that during the while (1) (line 2) in each iteration, a valid path is obtained. The Q values and selected path are updated by iterative trying.

5) Complexity analysis: As shown in the Algorithm 1, the computing complexity of MODQR is related to the number of iterations, hops in each iteration and the number of updating already visited state-action value in each environment interaction. Each time of interaction with environment, one hop in the path is completed. When selecting this hop, the Q values of several visited state-action pairs are learned and updated at the same time. In each iteration, the path from source to destination composed by some hops is obtained. When the number of nodes in a network is n, the maximum number of hops in a path is n-1. Therefore, if the iteration number is I and the number of selected state-action pairs whose Q values are needed to be updated in each environment interaction is U, the computational complexity of MODQR is $O(InU)$.

VI. Performance evaluation

A. Simulation environment

Mesh nodes are random in an area of 1000m $\times$ 1000m. To avoid the existence of isolated nodes, for each mesh node, there is at least one neighbor node within the transmission distance. Mesh routers and mesh clients have three and one interface respectively. The performance of MODQR is evaluated and compared with DIAR [18], search-based [19] and real-time routing algorithm [40] because of the timeliness and relevance. As mentioned in section II, DIAR and search-based routing comprehensively consider multiple factors like delay, PTF, and interference, and they are proposed for WMN recently. The real-time routing algorithm using Q learning can select path with less delay, more success rate and less hop count. In addition, the real-time routing algorithm and DIAR also consider the dynamic network condition. Therefore, they are used to be compared with MODQR. The experiments are taken on an Intel Core i3-8145U at 2.3 GHz. Random access memory (RAM) is 4.0 GB and the system type is 64 bit. The software platform ns-3 network simulator [50] is used to obtained the detailed performance comparisons. The detailed simulation parameters are given in Table II, and the initial position of the mesh nodes is shown in Fig. 2.

TABLE II: Simulation parameters

Simulation Parameters	Values
Simulation time	100 s
Traffic type	constant-bit-rate
Packet size	1024 bytes
K	7
CW_{min}	15
$SlotTime$	20μs
r_T	250m
r_I	550m
Number of mesh routers	25
Number of mesh clients	50
Number of radio interfaces in each router	3
Number of channels in each router	3 channels (1, 6, and 11)
Number of radio interfaces in each client	1
Number of channels in each client	1 channel (1)
Antenna	Omnidirectional

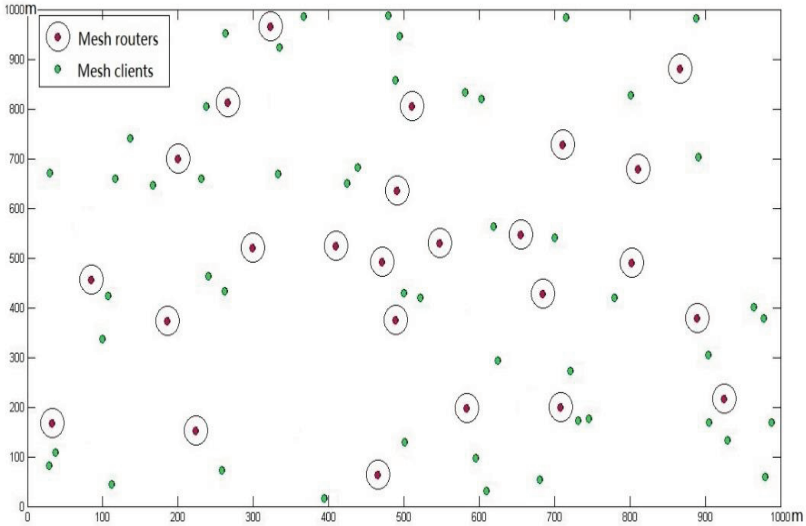


Fig. 2: Initial position of mesh nodes

B. Performance metrics

- Average packet loss rate: The ratio of lost packet number to the total transmitted packet number.
- Average delay: The time cost by transmitting a packet successfully between source and destination.

- Average network throughput: The successfully transmitted bit number in unit time in the whole network.
- Average energy consumption: The energy cost by transmitting a packet successfully.

C. Numerical results

The effectiveness of Dyna-Q is shown in this section. The performance of Dyna-Q in MODQR with different learning rate and exploration probability is also tested. Besides, the performance comparison between MODQR, DIAR, real-time and search-based is given.

To see the advantage of convergence speed of Dyna-Q, the comparison between original Q learning and Dyna-Q is shown in Fig. 3.

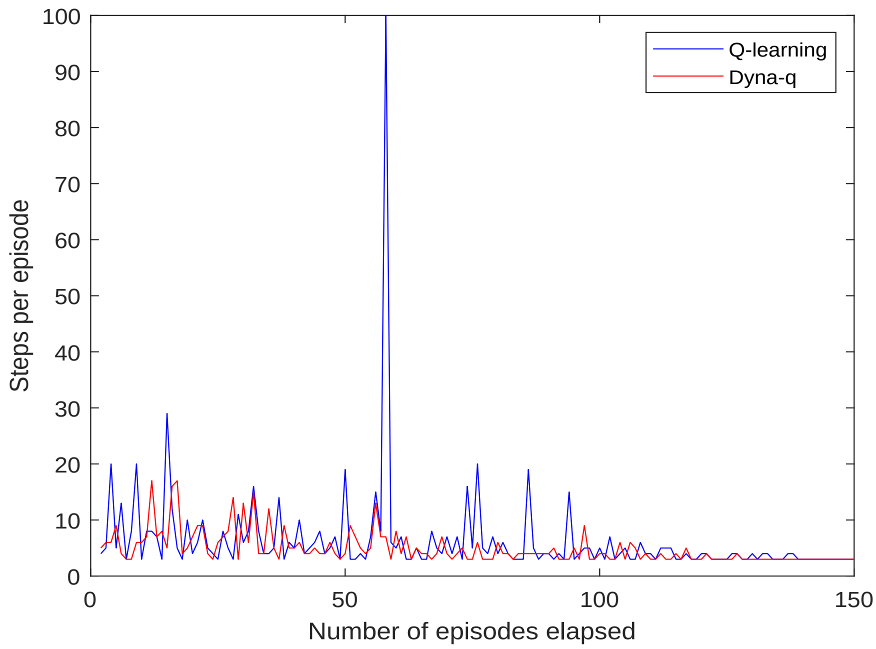


Fig. 3: Convergence speed comparison between original Q learning and Dyna-Q

From Fig. 3, both Q learning and Dyna-Q can converge but Dyna-Q converges with a much faster speed. At first, the number of steps in each iteration is large and fluctuant because exploration and trying are implemented. The solution with 100 steps means an invalid path with loop is found. In this case, the penalty parameter θ is given to all selected actions to avoid being used in future. The rewards and conditions of actions are gradually learned. After trying in some iterations, actions with better performance are learned and they will have larger probability to be selected. Thus, the solution will converge and become stable. Finally, the tested best action will be selected in most cases and other actions are still be tried in small probability. Dyna-Q can converge faster because it learns from not only the environment, but also the already visited states and actions. The cost of interaction with real environment can also be reduced. In the experiment, the convergence time of Dyna-Q is about 0.667s while that of original Q learning is 1.109s. The convergence speed of Dyna-Q is 39.86% faster than original Q learning. Dyna-Q is then a very effective reinforcement learning method.

When changing the learning rate, the performance of Dyna-Q is shown in Fig. 4.

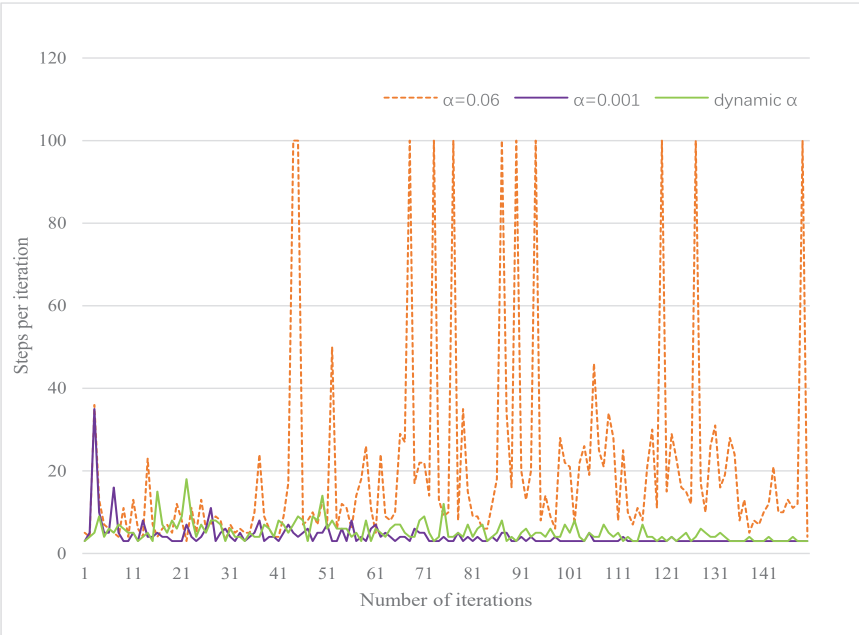


Fig. 4: Performance of Dyna-Q under different learning rate α

Fig. 4 shows small learning rate α can bring faster convergence speed. The orange line shows the performance of large α. When α is large, the current obtained rewards will be over focused and the historical Q values are neglected. The trying in each time is essential, and the condition in each trying will influence the total Q values in large extent. As the selected actions are based on Q values, they are nearly all according to current rewards. Historical information is overlooked, so the selected next hop of each mesh node is always changing during iterations. The solution, that is the chosen path, is fluctuant, and even some invalid paths with loops are found. When α is small, the historical information is taken seriously, and the Dyna-Q will converge to a solution with fast speed as shown by the purple line. However, besides the best action at each mesh node, many other probable actions are overlooked and never tried in this case. Some potential better solutions are missed because the historical information is over focused and current rewards are neglected. To avoid setting a too large or too small α, dynamic α which is explained in Section V is used in MODQR, and the performance is shown by the green line. The α is large when the number of iterations is small and the historical visited number of the selected action is large. Thus, with the increase of the iteration number, α is smaller and smaller so that the algorithm can explore at first and converge later. In addition, the actions with more historical visited amount will be more learned with larger α. The dynamic α adapts well to the routing problem and can avoid the weakness of setting a fixed too large or too small α.

With different exploration probability, the performance of Dyna-Q is shown in Fig. 5.

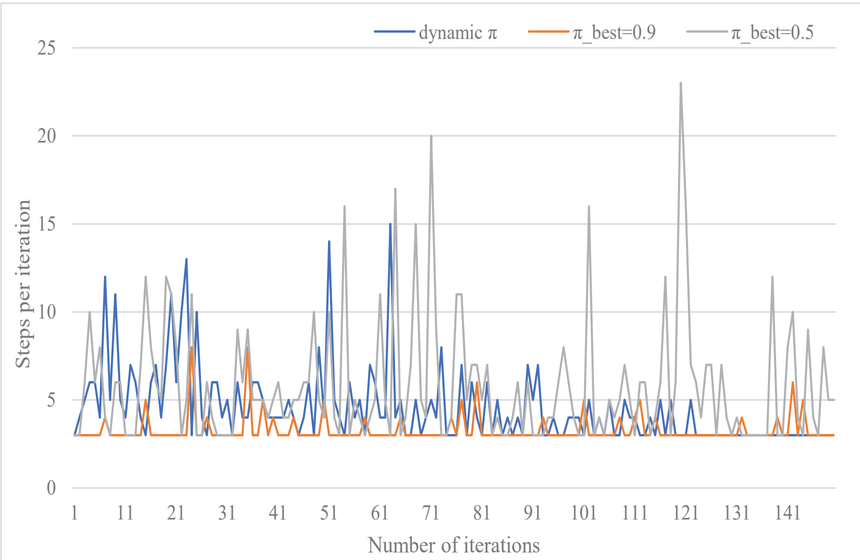


Fig. 5: Performance of Dyna-Q under different exploration probability

Fig. 5 shows the performance comparison between greedy strategy and the dynamic exploration probability in MODQR. π_best is the parameter in greedy strategy, which is the probability of the current node $s_{current}$ selecting next hop with the minimum $SQ(s_{current}, a_{hop})$. Large π_best means mesh nodes have very large probability to select the next-hop node with the best $SQ(s_{current}, a_{hop})$. The probability of trying other next-hop nodes will be very small. The convergence will be reached quickly as shown by the orange line. However, the algorithm may converge to a bad solution and never try other potential better solutions. Small π_best will bring opposite effect to the large π_best, which is shown by the gray line. It will be harder to converge and excessive exploration will be caused. To avoid the weakness caused by setting a fixed exploration probability, MODQR changes the exploration probability dynamically. The performance is shown by the blue line. The exploration probability is according to the conditions of all next-hop nodes. The next hop with better condition (i.e., less $SQ(s_{current}, a_{hop})$) will has larger probability to be selected. As τ in formula (18) is related to the iteration number, after iterative learning, the better next-hop nodes from current node will have larger and larger probability of being chosen. Then the Dyna-Q algorithm will converge gradually. Both exploration and convergence can be achieved by changing exploration probability dynamically.

To see the effectiveness of the selected path in MODQR, the network performance comparison between MODQR, DIAR, real-time and search-based is shown in Fig. 6 - Fig. 9.

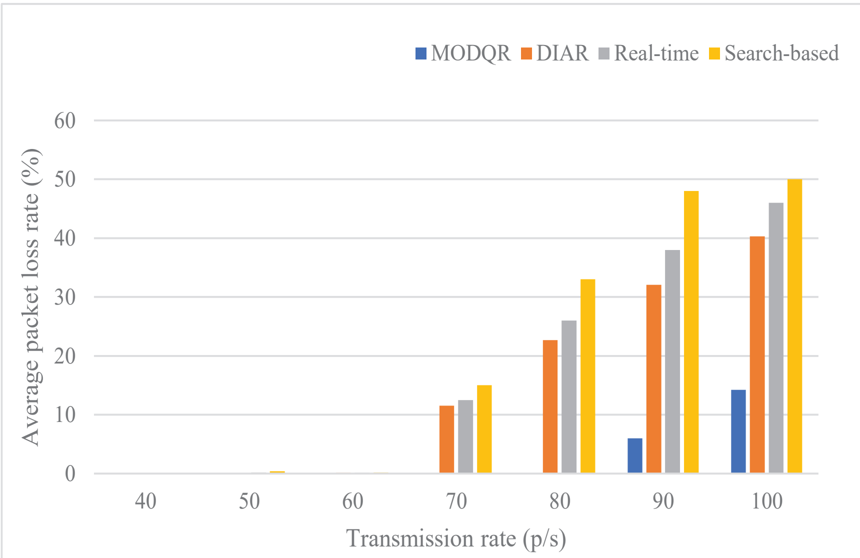


Fig. 6: Average packet loss rate with different transmission rate

Fig. 6 shows that with the increase of transmission rate, the average packet loss rate is increasing for all the routing methods, and MODQR has smaller packet loss rate than others. When the transmission rate is larger, the network is more congested. There will be more dropped packets because of the congestion. MODQR drops much less packets because it considers the asymmetric conditions of forward and reverse links. In this case, the total PTF of a link between two neighbors is considered soundly. In addition, the gray physical interference model helps MODQR evaluate the PTF more accurately. Thus, MODQR obtains lower average packet loss rate. DIAR only considers the forward link condition and real-time routing does not consider interference. The search-based routing neglects the PTF, so it has the worst average packet loss rate. The average packet loss rate by using MODQR is 80.97%, 83.48% and 86.15% better than DIAR, real-time, and search-based routing respectively.

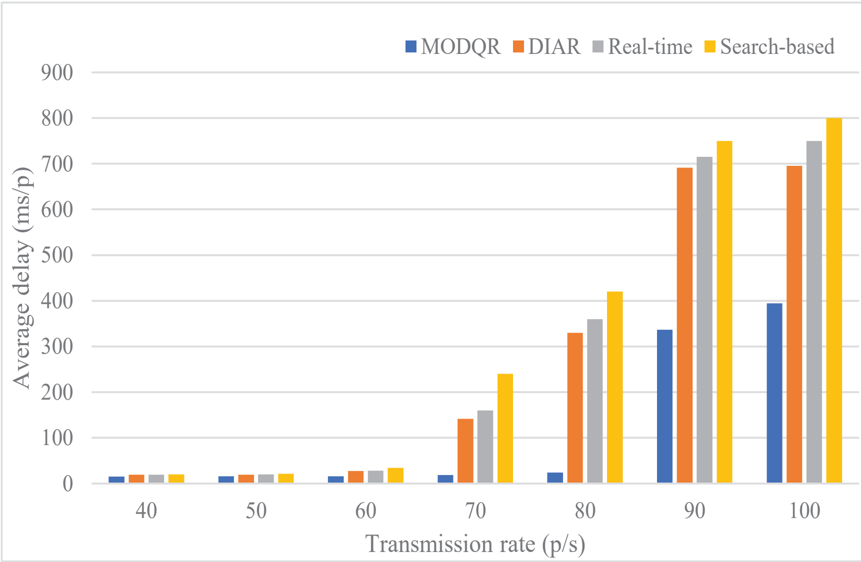


Fig. 7: Average delay with different transmission rate

Fig. 7 shows MODQR has less average delay than DIAR, real-time and search-based routing with different transmission rate. With larger transmission rate, the average delay increases. Congestion will cause longer packet queues and more waiting time to transmit data packets, so the delay becomes longer when transmission rate is larger. Although all these four routing methods consider delay, DIAR neglects the reverse link condition, so it transmits less data packets successfully. The real-time and search-based routing methods do not consider any congestion avoidance, and they have more probability to cause congestion. Therefore, DIAR, real-time and the search-based routing have worse performance of average delay than MODQR. The average delay of MODQR is 57.30%, 59.96% and 64.00%

better than that of DIAR, real-time, and search-based routing.

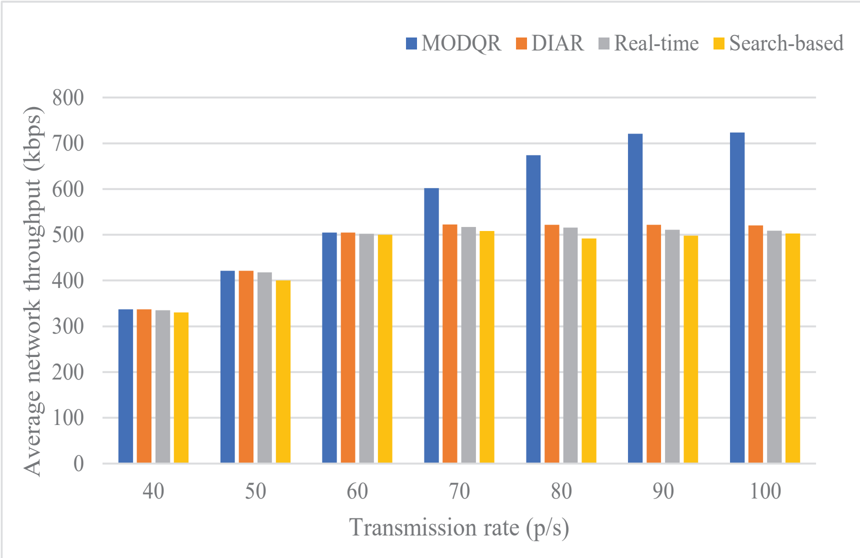


Fig. 8: Average network throughput with different transmission rate

Fig. 8 shows MODQR has better performance of average network throughput than DIAR, real-time and the search-based routing. MODQR considers the bandwidth, PTF of forward and reverse link, the influence of interference on PTF and delay at the same time, and more effective path with better condition and capacity will be selected. MODQR has better ability of transmitting more packets successfully during the same time period. When the transmission rate is large, the advantage of MODQR is more obvious because of the wider bandwidth and less PTF of the selected path. DIAR does not sufficiently consider the asymmetric condition of links. The real-time and search-based routing method do not consider congestion, which brings less capacity of them. In addition, the reinforcement learning Dyna-Q used in MODQR will converge to the solution by trying and learning. With the iterative learning, the solution will be better and better. Although the real-time routing also uses reinforcement learning to adapt to the dynamic network, it may not select the best next hop due to the mechanism of group selection. The real-time routing will first choose the node group with best performance of delay and success rate. The node with least hop count in the chosen group will then be selected as the next hop. However, this selected node may be the one only with least hop count but have bad performance like long delay and heavy load. The reason is that the performance of a node group is related to every node in the group. The better performance of a node group may be achieved by other nodes rather than the selected next-hop node. Therefore, the real-time routing cannot obtain very good performance. The genetic algorithm used in DIAR and search-based routing does not have the ability of learning and the historical actions are not fully used. The average network throughput of MODQR is 15.90%, 16.97% and 18.90% better than that of DIAR, real-time, and search-based routing respectively.

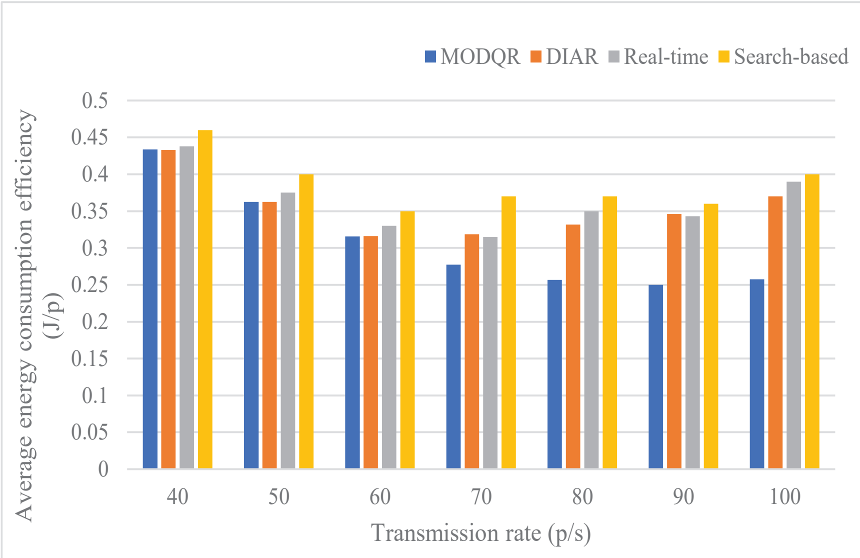


Fig. 9: Average energy consumption with different transmission rate

Fig. 9 shows MODQR has less average energy consumption than DIAR, real-time and search-based routing method. In addition to link conditions and delay, MODQR also considers energy. It is the only routing method considering energy among these four routing algorithms. Thus, MODQR has better performance in terms of energy. As the search-based routing method neglects the PTF, it will drop more packets and successfully transmit fewer packets. Many packets are transmitted but not successfully received by the destination. Then the search-based routing has the worst average energy consumption performance. With the increase of transmission rate, the average energy consumption decreases first and then has the tendency of increase. The total consumed energy includes the energy cost by transmission and backoff. The energy consumed by transmission not only contains the energy cost by transmitting successfully, but also the energy of retransmission. When the transmission rate is not very large, the packet loss rate is low and the retransmission amount is small. The consumed energy of backoff is similar. The cost energy of transmission and the amount of successful received packets increase by multiples. Then the average energy consumption decreases with the growth of transmission rate. When the transmission rate is large, the packet loss rate is high and the retransmission amount is large. The energy cost by retransmission increases fast and the number of successful received packets grows slowly. Thus, the average energy consumption per successful packet starts to increase. The average energy consumption efficiency of MODQR is 14.30%, 15.43% and 21.10% better than that of DIAR, real-time, and search-based routing respectively.

VII. Conclusion

An effective routing method can improve network performance dramatically. The MODQR proposed in this paper formulates the routing problem into a multi-objective optimization problem to minimize delay and maximize energy efficiency. When evaluating delay, bandwidth, PTF of bidirectional links and backoff are all considered. Gray physical interference model is used to derive PTF more accurately. When obtaining the energy efficiency, both available total energy and consumed energy are considered as energy capacities of different types of mesh nodes are different. The total consumed energy includes the energy cost in conditions of transmission and backoff. In the process of solving the routing optimization problem, fast convergent Dyna-Q is introduced and used for the first time. It is revised and improved to make it usable and effective for the multi-objective routing problem. The Q values in terms of different objectives are updated separately. The computed comprehensive Q value according to the Q values in all objectives is then used to select actions. To avoid setting fixed parameters, the dynamic learning rate and exploration probability are proposed and used to balance convergence speed and exploration in MODQR. After iterative trying and learning, the paths with better performance in all objectives will be determined. Simulation results show the effectiveness of MODQR. The performance of MODQR is 42.12%, 43.96% and 47.54% better than DIAR, real-time and search-based routing in average. Especially in average packet loss rate, 80.97%, 83.48% and 86.15% better performance than DIAR, real-time and search-based routing can be achieved respectively.

References

[1] C. Sudhakar, T. Ramesh, K. Waghmare, Path Based Optimization of MPI Collective Communication Operation in Cloud, in: International Conference on Computing, Power and Communication Technologies

(GUCON), 2018, pp. 595-599.

[2] J. Feng, Z. Liu, C. Wu, Y. Ji, Mobile Edge Computing for the Internet of Vehicles: Offloading Framework and Job Scheduling, IEEE Vehicular Technology Magagazine. 14(1) (2019) 28-36.

[3] A. Al-Saadi, R. Setchi, Y. Hicks, S. M. Allen, Routing Protocol for Heterogeneous Wireless Mesh Networks, IEEE Transactions on Vehicular Technology. 65(12) (2016) 9773-9786.

[4] S. Kumar, S. Mehfuz, Efficient fuzzy logic based probabilistic broadcasting for mobile ad hoc network, International Journal of Computational Intelligence Systems. 9(4) (2016) 666-675.

[5] A. Robert singh, D. Devaraj, R. Narmatha Banu, Genetic algorithm-based optimisation of load-balanced routing for AMI with wireless mesh networks, Applied Soft Computing. 74 (2019) 122-132.

[6] A. A. Aouiz, S. B. Hacene, P. Lorenz, Channel Busyness Based Multipath Load Balancing Routing Protocol for Ad hoc Networks, IEEE Networks. 33(5) (2019) 118-125.

[7] M. Boushaba, A. Hafid, M. Gendreau, Node stability-based routing in wireless mesh networks, Journal of Network and Computer Applications. 93 (2017) 1-12.

[8] V. Sarasvathi, N. C. S. Iyengar, S. Saha, QoS Guaranteed Intelligent Routing Using Hybrid PSO-GA in Wireless Mesh Networks, Cybernetics and Information Technologies. 15(1) (2015) 69-83.

[9] A. A. A. M. Rahat, R. M. Everson, J. E. Fieldsend, Multi-objective routing optimisation for battery-powered wireless sensor mesh networks, in: Annual Conference on Genetic and Evolutionary Computation, 2014, pp. 1175-1182.

[10] R. Murugeswari, S. Radhakrishnan, D. Devaraj, A multi-objective evolutionary algorithm based QoS routing in wireless mesh networks, Applied Soft Computing. 40 (2016) 517-525.

[11] R. Masadeh, A. Sharieh, B. Mahafzah, Humpback whale optimization algorithm based on vocal behavior for task scheduling in cloud computing, International Journal of Advanced Science and Technology. 13(3) (2019) 121-140.

[12] R. Masadeh, B. Mahafzah, A. Sharieh, Sea Lion Optimization Algorithm, International Journal of Advanced Computer Science and Applications. 10(5) (2019) 388-395.

[13] N. K. T. El-Omari, Sea Lion Optimization Algorithm for Solving the Maximum Flow Problem, International Journal of Computer Science and Network Security. 20(8) (2020) 30-68.

[14] M. Fahad, F. Aadil, S. Khan, P. A. Shah, K. Muhammad, J. Lloret, H. Wang, J. Lee, I. Mehmood, Grey wolf optimization based clustering algorithm for vehicular ad-hoc networks, Computers & Electrical Engineering. 70 (2018) 853-870.

[15] H. R. E. Bouchekara, A. Orlandi, M. Al-Qdah, F. de Paulis, Most Valuable Player Algorithm for Circular Antenna Arrays Optimization to Maximum Sidelobe Levels Reduction, IEEE Transactions on Electromagnetic Compatibility. 60(6) (2018) 1655-1661.

[16] J. Xu, A. Y. Lam, V. O. Li, Chemical reaction optimization for task scheduling in grid computing, IEEE Transactions on Parallel and Distributed systems. 22(10) (2011) 1624-1631.

[17] H. Li, L. Wang, X. Hei, W. Li, Q. Jiang, A decomposition-based chemical reaction optimization for multi-objective vehicle routing problem for simultaneous delivery and pickup with time windows, Memetic Computing. 10(1) (2018) 103-120.

[18] Y. Chai, X. J. Zeng, Delay- and Interference-Aware Routing for Wireless Mesh Network, IEEE Systems Journal. (2020).

[19] K. Mahmood, B. Nazir, I. A. Khan, N. Shah, Search-based routing in wireless mesh network, EURASIP Journal on Wireless Communications and Networking. 2017(1) (2017) 1-15.

[20] M. Camelo, C. Omaña, H. Castro, QoS routing algorithm based on multi-objective optimization for wireless mesh networks, in: IEEE Latin-American Conference on Communications, 2010, pp. 1-6.

[21] K. Deb, A. Pratap, S. Agarwal, T. A. M. T. Meyarivan, A fast and elitist multiobjective genetic algorithm: NSGA-II, IEEE Transactions on Evolutionary Computation. 6(2) (2002) 182-197.

[22] N. Magaia, N. Horta, R. Neves, P. R. Pereira, M. Correia, A multi-objective routing algorithm for Wireless Multimedia Sensor Networks, Applied Soft Computing. 30 (2015) 104-112.

[23] D. S. De Couto, D. Aguayo, J. Bicket, R. Morris, A high-throughput path metric for multi-hop wireless routing, Wireless Networks. 11(4) (2005) 419-434.

[24] H. Alwan, A. Agarwal, Multi-objective QoS routing for wireless sensor networks, in: International Conference on Computing, Networking and Communications (ICNC), 2013, pp. 1074-1079.

[25] D. Benyamina, A. Hafid, M. Gendreau, Wireless mesh network planning: A multi-objective optimization approach, in: 5th International Conference on Broadband Communications, Networks and Systems, 2008, pp. 602-609.

[26] K. W. Choi, W. S. Jeon, D. G. Jeong, Efficient load-aware routing scheme for wireless mesh networks, IEEE Transactions on Mobile Computing. 9(9) (2010) 1293-1307.

[27] M. O. de Mello, V. C. Borges, L. D. L. Pinto, K. V. Cardoso, Load balancing routing for path length and overhead controlling in wireless mesh networks, in: IEEE Symposium on Computers and Communications (ISCC), 2014, pp. 1-6.

[28] D. Benyamina, A. Hafid, N. Hallam, M. Gendreau, J. C. Maureira, A hybrid nature-inspired optimizer for wireless mesh networks design, Computer Communications. 35(10) (2012) 1231-1246.

[29] Y. Shi, Particle swarm optimization: developments, applications and resources, in: 2001 congress on evolutionary computation (IEEE Cat. No. 01TH8546), 2001, pp. 81-86.

[30] M. Srinivas, L. M. Patnaik, Genetic algorithms: A survey, Computer. 27(6) (1994) 17-26.

[31] H. Yetgin, K. T. K. Cheung, L. Hanzo, Multi-objective routing optimization using evolutionary algorithms, in: IEEE Wireless Communications and Networking Conference (WCNC), 2012, pp. 3030-3034.

[32] F. Xue, A. Sanderson, R. Graves, Multi-objective routing in wireless sensor networks with a differential evolution algorithm, in: IEEE International Conference on Networking, Sensing and Control, 2006, pp. 880-885.

[33] R. Murugeswari, D. Devaraj, Multiconstrained QoS Multicast Routing for Wireless Mesh Network Using Discrete Particle Swarm Optimization, in: Artificial Intelligence and Evolutionary Computations in Engineering Systems, 2017, pp. 847-859.

[34] R. Murugeswari, S. Radhakrishnan, Discrete multi-objective differential evolution algorithm for routing in wireless mesh network, Soft Computing. 20(9) (2016) 3687-3698.

[35] C. Lozano-Garzon, M. Camelo, P. Vila, Y. Donoso, A multi-objective routing algorithm for wireless mesh network in a smart cities environment, J. Networks. 10(1) (2015) 60-69.

[36] E. Zitzler, L. Thiele, Multiobjective evolutionary algorithms: a comparative case study and the strength Pareto approach, IEEE Transactions on Evolutionary Computation. 3(4) (1999) 257-271.

[37] N. Coutinho, R. Matos, C. Marques, A. Reis, S. Sargento, J. Chakareski, A. Kassler, Dynamic dual-reinforcement-learning routing strategies for quality of experience-aware wireless mesh networking, Computer Networks. 88(269) (2015) 269-285.

[38] C. Qu, W. Gai, M. Zhong, J. Zhang, A novel reinforcement learning based grey wolf optimizer algorithm for unmanned aerial vehicles (UAVs) path planning, Applied Soft Computing. 89 (2020).

[39] F. Li, X. Song, H. Chen, X. Li, Y. Wang, Hierarchical Routing for Vehicular Ad Hoc Networks via Reinforcement Learning, IEEE Transactions on Vehicular Technology. 68(2) (2019) 1852-1865.

[40] A. Ghaffari, Real-time routing algorithm for mobile ad hoc networks using reinforcement learning and heuristic algorithms, Wireless Networks. 23 (2017) 703-714.

[41] S. Karunaratne, H. Gacanin, An Overview of Machine Learning Approaches in Wireless Mesh Networks, IEEE Communications Magazine. 57(4) (2019) 102-108.

[42] H. Li, Y. Cheng, C. Zhou, W. Zhuang, Minimizing end-to-end delay: A novel routing metric for multi-radio wireless mesh networks, in: IEEE INFOCOM, 2009, pp. 46-54.

[43] J. Su, J. Cao, W. Wu, Gray physical interference model based link scheduling algorithms, Science China Information Sciences. 55(6) (2012) 1337-1350.

[44] K. Han, Y. Liu, J. Luo, Duty-cycle-aware minimum-energy multicasting in wireless sensor networks, IEEE/ACM Transactions on Networking. 21(3) (2012) 910-923.

[45] G. Czibula, I. G. Czibula, Z. Marian, An effective approach for determining the class integration test order using reinforcement learning, Applied Soft Computing. 65 (2018) 517-530.

[46] A. Serhani, N. Naja, A. Jamali, QLAR: A Q-learning based adaptive routing for MANETs, in: IEEE/ACS 13th International Conference of Computer Systems and Applications (AICCSA), 2016, pp. 1-7.

[47] E. Even-Dar, Y. Mansour, Learning rates for Q-learning, Journal of Machine learning Research, (2003) 1-25.

[48] M. Maleki, V. Hakami, M. Dehghan, A reinforcement learning-based Bi-objective routing algorithm for energy harvesting mobile ad-hoc networks, in: 7th International Symposium on Telecommunications (IST'2014), 2014, pp. 1082-1087.

[49] K. Van Moffaert, M. M. Drugan, A. Nowé, Scalarized multi-objective reinforcement learning: Novel design techniques, in: IEEE Symposium on Adaptive Dynamic Programming and Reinforcement Learning (ADPRL), 2013, pp. 191-199.

[50] ns-3. 2020. https://www.nsnam.org/ Last accessed 24 November 2020.

Chapter 7

Conclusions and Future Work

This chapter gives the main works, conclusions and contributions of the thesis, analyses the limitations of the current work and discusses the work we can do in future.

7.1 Conclusions

7.1.1 Summary of the Main Works

WMN is a type of flexible network which can be used in different applications. It has both stable mesh routers and mobile mesh clients. Effective routing methods can be designed based on the different features of different types of mesh nodes. Centralized proactive routing methods are suitable for mesh routers, while distributed reactive routing methods can work well for mesh clients. Both mesh routers and mesh clients can use distributed reactive routing to serve client-oriented traffic flows. Therefore, a hybrid routing structure combining proactive and reactive routing methods can perform well for WMN. However, existing routing methods for WMN are few, and they do not fully consider the differences between mesh routers and clients. The regional condition is neglected. In particular, mesh routers with multiple radio interfaces can provide an infrastructure function for WMN, so the routing design among mesh routers is very important to guarantee high capacity for the whole network. However, current centralized proactive routing methods do not fully take load, interference, cost and energy into account at the same time.

To overcome the current weaknesses, this thesis designs effective routing methods for WMN. Firstly, the hybrid routing method RCA-HRP, which considers regional conditions, is proposed. Areas with heavy load and high mobility will be avoided, so the selected routes will be stable and can avoid congestion. For mesh routers, their queue length along with the queue length and the speed of neighbouring mesh clients are all considered. For mesh clients, in addition to load conditions, energy is taken into account. Gateway- and client-oriented traffic are considered respectively. In gateway-oriented traffic, the accessed mesh routers will first check whether there are valid proactive paths. If there are, the mesh routers will unicast RREP back directly to save route discovery time. In client-oriented traffic, the reactive routing method will be used to find routes. The proactive and reactive routing methods thus work cooperatively to consider different features of different types of mesh nodes. The proactive routes have higher priority than the reactive paths because the proactive routes are more stable. The experiment results through a network simulator show that RCA-HRP can be 10.19% and 33.29% better than two current hybrid routing methods.

Secondly, as mesh routers play an important role in WMN, the centralized proactive routing method is particularly designed for mesh routers in this thesis. The DIAR method considering delay, interference and the PTF is proposed. The routing problem is formulated as an optimization model. As many current applications need a short delay, minimizing delay is set as the objective. When evaluating delay, both backoff and transmission delay are considered. Delay is then related to the PTF, which is the probability of SINR smaller than the threshold. We derive the PTF according to the PDF of the receiving signal and interference power. This PDF is derived from the known PDF of distance and the relationship between distance and receiving power. The derived PTF is related to the number of interfering nodes. Therefore, the relationship between delay and the number of interfering nodes is built, and the cost by obtaining delay can be saved. In the process of solving the optimization problem, the improved GA can balance the load. When multiple data flows use a common node, congestion can be caused. To avoid heavy load at the common node, the node with the least number of interfering nodes will be selected to replace the common node in the improved GA. The reasonability of such method is also given. In addition, because the route selection can influence the network condition in turn, the condition is evaluated iteratively in the improved GA. From the experiment implemented by the network simulator, we can see that DIAR can obtain 29.03% and 50.20% better performance than two other existing proactive routing methods.

Thirdly, to further consider energy and a long-term objective, LBR is proposed in this thesis. The long-term weighted sum cost considers both load and energy. Energy is an important factor because a node will be dead if it runs out of energy. To extend the lifetime of mesh nodes, EH is an effective way nowadays. Energy can be obtained from the environment. However, most traditional centralized routing methods do not consider EH. A few works overcome this weakness but neglect the interference and link conditions. Therefore, LBR takes into account load, interference, bandwidth, PTF and EH at the same time. Energy conditions can be evaluated based on the consumed and harvested energy over time. The load is reflected by the queue length, and the queue length of a node is based on the packets received from others, newly generated packets and packets transmitted out over time. The network conditions during the current time epoch are deduced from the conditions and actions of the last time epoch. To solve such an optimization model with a long-term objective, DP is used to get the optimal solution. The numerical results show the effectiveness of the LBR. 1.69%, 10.33% and 26.2% better performance than other recent routing methods can be obtained.

Finally, to avoid merging different objectives into one single formula and to further adapt to the uncertain network conditions, MODQR is proposed. MODQR also considers the factor of energy, but energy is considered independently with delay. The method of obtaining delay is similar to DIAR, but asymmetrical link condition is considered and the grey physical interference model is used. Energy condition is evaluated by the ratio of consumed energy to energy capacity. To solve this multi-objective routing problem, reinforcement learning is applied because it can adapt well to dynamic and uncertain network conditions. We use Dyna-Q here and it is applied in such a routing process for the first time. The convergence speed of Dyna-Q is faster than traditional Q learning because Dyna-Q can learn from visited state-action pairs as well as the interaction with the environment. The learning rate and exploration probability are set to be dynamic according to the iteration number. With a larger iteration number, the learning rate and the exploration probability will be smaller in order to make the finding solution process converge. Q tables are updated in terms of each objective, and the normalized Chebyshev distance of Q values in terms of the two objectives is used to select the next hops. During the route discovery process, if a loop occurs and there is no valid next hop, a penalty parameter will be given to the selected actions to avoid doing the same selections again in future. From the network simulation, the MODQR has 42.12%, 43.96% and 47.54% better performance than three other state-of-the-art routing methods.

In general, to adapt to the features of WMN and overcome the current weaknesses of routing design, four routing methods are proposed. The characteristics of both mesh routers and mesh clients are considered.

7.1.2 Comparative Analysis

The proposed four routing methods are suitable for different cases. If a network contains both static mesh routers and very mobile mesh clients, RCA-HRP is a good choice to find paths. The nodes with bad regional conditions will be avoided. For some given traffic flow requests among mesh routers, DIAR can be used to find routes with least delay and interference. If the static mesh nodes also have very limited energy, and the network designer wants to achieve the long-term network performance, LBR can be used. The global optimal route selection is done by analyzing all the possible states and actions. However, unlike LBR, if only partial neighbouring information is known, and the network is with uncertain conditions, MODQR will be suitable to find a path considering delay and balanced energy consumption. A suboptimal route will be selected by iterative trying and strengthening a good suboptimal solution.

RCA-HRP focuses on the structure of hybrid routing and serves gateway- and client-oriented traffic respectively. Compared with the mobile mesh clients, stable mesh routers will be selected with higher priority. When the mesh clients can access mesh routers to communicate with the gateway, the proactive paths composed of stable mesh routers will be used. The existing proactive path with better routing metric, that is the one with less regional load, less hops, and more regional stability, will be selected. The hybrid routing for WMN containing very mobile mesh clients is designed. However, the proactive routing design for the infrastructure part of WMN is not carefully considered. The infrastructure WMN is stable and with strong capability, so the centralized proactive routing method among infrastructure WMN should be properly designed. Therefore, DIAR, LBR, and MODQR are proposed to improve the proactive routing part. They formulate the routing problem as an optimization model. Delay is minimized in DIAR, and load is balanced. The overhead of obtaining delay is also considered. The relationship between delay and the number of interfering nodes is built. However, energy is not considered in DIAR. If a mesh node runs out of energy, it will be dead and cannot be used anymore. The number of nodes that can forward packets will reduce, so energy is also a very important factor which should be considered when designing routing methods. LBR considers energy and load together in a long-term objective. The technology of EH helps to overcome the energy constraints. The average remaining energy of LBR is larger, so the network lifetime can be extended. Although energy is considered in LBR, the load and energy are merged into a single objective where weight values for different factors are needed. In addition, LBR uses DP to explore the optimal route by analyzing all the possible states and actions. When the network is large and the network condition is uncertain, LBR may be not suitable. In this case, MODQR is proposed. Delay and energy are considered at the same time without setting weight values for them. The reinforcement learning Dyna-Q is used to solve such multi-objective routing problem for the first time. No prior knowledge is needed, and the routes can be learnt and obtained according to the simple neighbouring information.

To evaluate the effectiveness of the proposed four routing methods, simulation is implemented through the network simulator. Simulation results show that the proposed routing methods are better than existing ones and can improve network performance.

7.2 Future Work

In our recent work, we do not consider the resource allocation problem. The wireless channels are randomly assigned between neighbours, which may not use the wireless resource efficiently. With the increasing communication request with high QoS, the wireless resource needs to be allocated more efficiently [139]. Especially in next-generation communication, data transmission speed is faster in the limited wireless resources. More data should be transmitted by using fewer resources. In addition, the allocation results will influence the route selection because different resource allocation methods will bring different interference relationships. Thus, resource allocation should also be considered when designing routing methods [140]. The resource allocation and routing design can be researched jointly in future.

In next-generation communication, IoT is an important research area. With the rapid growth in requests for intellectual connection anytime and anywhere, IoT develops quickly. IoT devices have very limited energy and the energy will be consumed quickly if the IoT devices transmit information to a server that is far away. WMN can be applied in IoT to reduce the communication distance by multiple hops and energy can be saved [141]. In addition, as the amount of data that needs to be computed increases rapidly, cloud computing will bring long delay. WMN can provide the edge computing ability to reduce response delay and computation pressure at the network server. As there are various IoT devices in next-generation communication, WMN is an essential network structure to be combined with IoT. WMN can combine different types of networks, and process the information collected from different devices [59,7]. The increasing number of devices brings a much denser network topology, interference will become a very severe problem. Although the number of devices could be very large, the transmission data size per device may be small. Therefore, the scheduling of data transmission in this case should be carefully designed. Edge computing and task allocation in such architecture to satisfy QoS can be researched in the future.

SDN is also an important technology in 5G communication. SDN provides programmability of the control plane and decouples the data and control planes [142]. SDN can be applied to an existing WMN to combine the advantages of centralized control in SDN and the low cost of WMN [21,143,144]. The structure of WMN in future will be more complex due to the diversity of application requests and devices. The whole network conditions should be carefully monitored and coordinated. In this case, SDN is a good technology to help manage and control WMN flexibly with a global view, yielding effective resource allocation results [9]. Best routes, considering global network conditions, can be selected to serve dynamic and real-time data flows. The rules of routing or resource control computed by the controller will be transferred and installed to the nodes in the network [23]. Service requests can be satisfied by simply updating software rather than changing hardware. Current research about SDN in WMN is not very much, and most of them are structure design in theory. Experiments in real platforms are still needed in the future.

Machine learning is a more and more heated topic nowadays, which can provide new intelligent ideas in network deployment in future. The changeable task management in WMN can be solved by machine learning [107,145]. Machine learning may even remove and replace routing protocols in future wireless networks [146]. Past mistakes and good decisions can be learnt to avoid future mistakes and predict network conditions. No specific complicated models are needed anymore, the actions and decisions can be selected according to the previous data. We can adapt the advantages of machine learning to data flow control [147], traffic and link quality prediction [148], routing design, resource allocation and task management in WMN in next-step research. Technologies of SDN and machine learning can be combined to automatically manage traffic [149].

WMN is an effective network structure in next-generation communication. We need to take full advantage of the highly robust, flexible and self-healing features of WMN in future research.

Bibliography

[1] P. H. Pathak, R. Dutta, A survey of network design problems and joint design approaches in wireless mesh networks, IEEE Communications surveys & tutorials. 13(3) (2010) 396-428.
[2] I. F. Akyildiz, X. Wang, W. Wang, Wireless mesh networks: a survey, Computer networks. 47(4) (2005) 445-487.
[3] S. Paris, C. Nita-Rotaru, F. Martignon, A. Capone, Cross-layer metrics for reliable routing in wireless mesh networks, IEEE/ACM Transactions On Networking. 21(3) (2012) 1003-1016.
[4] A. N. Le, D. W. Kum, Y. Z. Cho, An efficient hybrid routing approach for hybrid wireless mesh networks, in: International Conference on Information Security and Assurance, 2009, pp. 532-542.
[5] E. Liu, X. Deng, Z. Cao, H. Zhang, Design and evaluation of a prediction-based dynamic edge computing system, in: IEEE Global Communications Conference (GLOBECOM), 2018, pp. 1-6.
[6] X. Liu, Z. Qin, Y. Gao, Resource allocation for edge computing in IoT networks via reinforcement learning. in: IEEE International Conference on Communications (ICC), 2019, pp. 1-6.
[7] Y. Sahni, J. Cao, S. Zhang, L. Yang, Edge mesh: A new paradigm to enable distributed intelligence in internet of things, IEEE access. 5 (2017) 16441-16458.
[8] J. Yin, Z. Yang, H. Cao, T. Liu, Z. Zhou, C. Wu, A survey on Bluetooth 5.0 and mesh: New milestones of IoT, ACM Transactions on Sensor Networks (TOSN). 15(3) (2019) 1-29.
[9] H. Huang, P. Li, S. Guo, W. Zhuang, Software-defined wireless mesh networks: architecture and traffic orchestration, IEEE network. 29(4) (2015) 24-30.
[10] R. Kaur, M. K. Rai, A novel review on routing protocols in MANETs. Undergraduate Academic Research Journal (UARJ). 1(1) (2012) 103-108.
[11] S. J. Bachega, D. M. Tavares, Simulation of Reactive Routing Protocols in Wireless Mesh Networks: a Systematic Literature Review, in: Proceedings of the International Conference on Wireless Networks (ICWN), 2014, pp. 1-6.
[12] A. A. Pirzada, M. Portmann, R. Wishart, I J. ndulska, SafeMesh: A wireless mesh network routing protocol for incident area communications, Pervasive and Mobile Computing. 5(2) (2009) 201-221.
[13] C. Perkins, E. Belding-Royer, S. Das, Ad hoc on-demand distance vector (aodv) routing, RFC 3561. (2003).
[14] D. G. Narayan, U. Mudenagudi, A cross-layer framework for joint routing and rate adaptation in infrastructure Wireless Mesh Networks, Computers & Electrical Engineering. 56 (2016) 113-129.
[15] S. K. Das, S. Tripathi, Intelligent energy-aware efficient routing for MANET, Wireless Networks. 24(4) (2018) 1139-1159.
[16] R. Langar, N. Bouabdallah, R. Boutaba, G. Pujolle, Interferer link-aware routing in wireless mesh networks, in: IEEE International Conference on Communications

(ICC), 2010, pp. 1-6.
[17] R. Draves, J. Padhye, B. Zill, Routing in multi-radio, multi-hop wireless mesh networks, in: Proceedings of the 10th annual international conference on Mobile computing and networking (MobiCom), 2004, pp. 114-128.
[18] D. S. De Couto, D. Aguayo, J. Bicket, R. Morris, A high-throughput path metric for multi-hop wireless routing, in: Proceedings of the 9th annual international conference on Mobile computing and networking (MobiCom), 2003, pp. 134-146.
[19] K. Mahmood, B. Nazir, I. A. Khan, N. Shah, Search-based routing in wireless mesh network, EURASIP Journal on Wireless Communications and Networking. 2017(1) (2017) 1-15.
[20] S. Yussof, O. H. See, A robust GA-based QoS routing algorithm for solving multi-constrained path problem, Journal of Computers. 5(9) (2010) 1322-1334.
[21] H. Xu, X. Y. Li, L. Huang, H. Deng, H. Huang, H. Wang, Incremental deployment and throughput maximization routing for a hybrid SDN, IEEE/ACM Transactions on Networking. 25(3) (2017) 1861-1875.
[22] F. Yang, V. Gondi, J. O. Hallstrom, K. C. Wang, G. Eidson, OpenFlow-based load balancing for wireless mesh infrastructure, in: IEEE 11th Consumer Communications and Networking Conference (CCNC), 2014, pp. 444-449.
[23] M. Labraoui, M. M. Boc, A. Fladenmuller, Software defined networking-assisted routing in wireless mesh networks, in: International Wireless Communications and Mobile Computing Conference (IWCMC), 2016, pp. 377-382.
[24] D. Sajjadi, R. Ruby, M. Tanha, J. Pan, Fine-grained traffic engineering on SDN-aware Wi-Fi mesh networks, IEEE Transactions on Vehicular Technology. 67(8) (2018) 7593-7607.
[25] Y. Chai, X. J. Zeng, Regional condition-aware hybrid routing protocol for hybrid wireless mesh network, Computer Networks. 148 (2019) 120-128.
[26] Y. Chai, X. J. Zeng, Delay-and Interference-Aware Routing for Wireless Mesh Network, IEEE Systems Journal. 14(3) (2020) 4119-4130.
[27] Y. Chai, X. J. Zeng, Load balancing routing for wireless mesh network with energy harvesting, IEEE Communications Letters. 24(4) (2020) 926-930.
[28] Y. Chai, X. J. Zeng, A multi-objective Dyna-Q based routing in wireless mesh network, Applied Soft Computing. 108 (2021) 107486.
[29] Y. Chai, X. J. Zeng, The development of green wireless mesh network: A survey, Journal of Smart Environments and Green Computing. 1(1) (2021) 47-59.
[30] Y. Chai, X. J. Zeng, Load-and interference-balance hybrid routing protocol for hybrid wireless mesh network, in: Wireless Days (WD), 2019, pp. 1-4.
[31] Y. Chai, X. J. Zeng, Load and Energy Aware Hybrid Routing Protocol for Hybrid Wireless Mesh Networks, in: IEEE 90th Vehicular Technology Conference (VTC2019-Fall), 2019, pp. 1-5.
[32] Y. Chai, X. J. Zeng, An effective routing with delay minimization for multi-hop wireless mesh network, in: IEEE Global Communications Conference (GLOBECOM), 2019, pp. 1-6.
[33] S. Kumar, S. Dalal, V. Dixit, The OSI model: Overview on the seven layers of computer networks, International Journal of Computer Science and Information

Technology Research. 2(3) (2014) 461-466.
[34] A. U. Chaudhry, R. H. Hafez, O. Aboul-Magd, S. A. Mahmoud, Throughput improvement in multi-radio multi-channel 802.11 a-based wireless mesh networks, in: IEEE Global Telecommunications Conference (GLOBECOM), 2010, pp. 1-5.
[35] M. Tsai, Path-loss and shadowing (large-scale fading), National Taiwan University. (2011).
[36] G. D. Durgin, T. S. Rappaport, Theory of multipath shape factors for small-scale fading wireless channels, IEEE Transactions on Antennas and Propagation. 48(5) (2000) 682-693.
[37] C. Lozano-Garzon, M. Camelo, P. Vila, Y. Donoso, A multi-objective routing algorithm for wireless mesh network in a smart cities environment, Journal of Networks. 10(1) (2015) 60-69.
[38] R. Morsi, D. S. Michalopoulos, R. Schober, Multiuser scheduling schemes for simultaneous wireless information and power transfer over fading channels, IEEE Transactions on Wireless Communications. 14(4) (2014) 1967-1982.
[39] J. Kim, K. Kim, J. Lee, Energy-efficient relay selection of cooperative HARQ based on the number of transmissions over Rayleigh fading channels, IEEE Transactions on Vehicular Technology. 66(1) (2016) 610-621.
[40] Y. Hu, A. Schmeink, J. Gross, Blocklength-limited performance of relaying under quasi-static Rayleigh channels, IEEE Transactions on Wireless Communications. 15(7) (2016) 4548-4558.
[41] M. Ridwan, M. Abdo, E. Jorswieck, Probability distributions of SIR in a Rayleigh fading channel, in: AFRICON, 2015, pp. 1-4.
[42] C. Pimentel, T. H. Falk, L. Lisbôa, Finite-state Markov modeling of correlated Rician-fading channels, IEEE transactions on vehicular technology. 53(5) (2004) 1491-1501.
[43] F. Cali, M. Conti, E. Gregori, IEEE 802.11 protocol: design and performance evaluation of an adaptive backoff mechanism, IEEE journal on selected areas in communications. 18(9) (2000) 1774-1786.
[44] D. Gu, J. Zhang, QoS enhancement in IEEE 802.11 wireless local area networks, IEEE Communications Magazine. 41(6) (2003) 120-124.
[45] B. P. Crow, I. Widjaja, J. G. Kim, P. T. Sakai, IEEE 802.11 wireless local area networks, IEEE Communications magazine. 35(9) (1997) 116-126.
[46] Y. Cheng, X. Ling, W. Song, L. X. Cai, W. Zhuang, X. Shen, A cross-layer approach for WLAN voice capacity planning, IEEE Journal on Selected Areas in Communications. 25(4) (2007) 678-688.
[47] M. Zhu, J. Cao, D. Pang, Z. He, M. Xu, SDN-based routing for efficient message propagation in VANET, in: International Conference on Wireless Algorithms, Systems, and Applications, 2015, pp. 788-797.
[48] E. Ancillotti, R. Bruno, M. Conti, A. Pinizzotto, Load-aware routing in mesh networks: Models, algorithms and experimentation, Computer Communications. 34(8) (2011) 948-961.
[49] V. Sarasvathi, N. C. S. Iyengar, S. Saha, QoS guaranteed intelligent routing using hybrid PSO-GA in wireless mesh networks, Cybernetics and Information

Technologies. 15(1) (2015) 69-83.
[50] H. Zhou, C. Huang, Y. Cheng, G. Wang, A new multi-metric QoS routing protocol in wireless mesh network, in: International Conference on Networks Security, Wireless Communications and Trusted Computing, 2009, pp. 459-467.
[51] L. Zhao, A. Y. Al-Dubai, G. Min, An efficient neighbourhood load routing metric for wireless mesh networks, Simulation Modelling Practice and Theory. 19(6) (2011) 1415-1426.
[52] Z. Hao, Y. Li, An adaptive load-aware routing algorithm for multi-interface wireless mesh networks, Wireless Networks. 21(2) (2015) 557-564.
[53] I. Ullah, K. Sattar, Z. U. Qamar, W. Sami, A. Ali, Transmissions failures and load-balanced routing metric for Wireless Mesh Networks, in: 8th International Conference on High-capacity Optical Networks and Emerging Technologies, 2011, pp. 159-163.
[54] X. Cheng, P. Mohapatra, S. J. Lee, S. Banerjee, MARIA: Interference-aware admission control and QoS routing in wireless mesh networks, in: IEEE International Conference on Communications (ICC), 2008, pp. 2865-2870.
[55] M. Boushaba, A. Hafid, Y. Sarr, MBP: Routing Metric Based on Probabilities for multi-radio multi-channel wireless mesh networks, in: 7th International Wireless Communications and Mobile Computing Conference, 2011, pp. 53-58.
[56] L. Zhao, Z. Yu, J. Niu, H. Zhang, W. Ding, A hybrid routing protocol for hierarchy wireless mesh networks, in: 6th International Conference on Wireless Communications Networking and Mobile Computing (WiCOM), 2010, pp. 1-4.
[57] Y. Chai, W. Shi, T. Shi, Load-aware cooperative hybrid routing protocol in hybrid wireless mesh networks, AEU-International Journal of Electronics and Communications. 74 (2017) 135-144.
[58] Y. Dong, J. Wang, B. Shim, D. I. Kim, DEARER: A distance-and-energy-aware routing with energy reservation for energy harvesting wireless sensor networks, IEEE Journal on Selected Areas in Communications. 34(12) (2016) 3798-3813.
[59] A. Al-Saadi, R. Setchi, Y. Hicks, S. M. Allen, Routing protocol for heterogeneous wireless mesh networks, IEEE Transactions on Vehicular Technology. 65(12) (2016) 9773-9786.
[60] A. A. Eltahir, R. A. Saeed, A. Mukherjee, M. K. Hasan, Evaluation and analysis of an enhanced hybrid wireless mesh protocol for vehicular ad hoc network, EURASIP Journal on Wireless Communications and Networking. 2016(1) (2016) 1-11.
[61] A. A. Pirzada, M. Portmann, J. Indulska, Aodv-hm: A hybrid mesh ad-hoc on-demand distance vector routing protocol, Journal of Research and Practice in Information Technology. 41(1) (2009) 65-84.
[62] M. Boushaba, A. Hafid, M. Gendreau, Node stability-based routing in wireless mesh networks, Journal of Network and Computer Applications. 93 (2017) 1-12.
[63] A. A. Pirzada, R. Wishart, M. Portmann, Congestion aware routing in hybrid wireless mesh networks, in: 15th IEEE International Conference on Networks, 2007, pp. 513-518.
[64] M. Boushaba, A. Hafid, A. Belbekkouche, Reinforcement learning-based best path to best gateway scheme for wireless mesh networks, in: IEEE 7th International

Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), 2011, pp. 373-379.
[65] M. Boushaba, A. Hafid, A. Belbekkouche, M. Gendreau, Reinforcement learning based routing in wireless mesh networks, Wireless networks. 19(8) (2013) 2079-2091.
[66] M. Chelliah, S. Sankaran, S. Prasad, N. Gopalan, B. Sivaselvan, Routing for wireless mesh networks with multiple constraints using fuzzy logic, International Arab Journal of Information Technology. 9(1) (2012) 1-8.
[67] C. E. Koksal, H. Balakrishnan, Quality-aware routing metrics for time-varying wireless mesh networks, IEEE Journal on selected areas in communications. 24(11) (2006) 1984-1994.
[68] Q. Yao, A. Huang, H. Shan, T. Q. Quek, W. Wang, Delay-aware wireless powered communication networks—Energy balancing and optimization, IEEE transactions on Wireless Communications. 15(8) (2016) 5272-5286.
[69] W. Song, X. Fang, Cross-layer routing with link quality and stability-aware in ITS hybrid wireless mesh networks, in: Sixth International Conference on Advanced Language Processing and Web Information Technology (ALPIT), 2007, pp. 304-308.
[70] F. Li, X. Song, H. Chen, X. Li, Y. Wang, Hierarchical routing for vehicular ad hoc networks via reinforcement learning, IEEE Transactions on Vehicular Technology. 68(2) (2018) 1852-1865.
[71] M. Nazari, A. Oroojlooy, L. V. Snyder, M. Takáč, Reinforcement learning for solving the vehicle routing problem, (2018) arXiv preprint arXiv:1802.04240.
[72] A. A. Pirzada, M. Portmann, High performance AODV routing protocol for hybrid wireless mesh networks, in: Fourth Annual International Conference on Mobile and Ubiquitous Systems: Networking & Services (MobiQuitous), 2007, pp. 1-5. IEEE, Philadelphia, PA, USA.
[73] M. M. ALrayes, N. Tyagi, R. Tripathi, A. K. Misra, Exploiting neighboring relationship for enhancement of AODV in hybrid wireless mesh network, in: 17th IEEE International Conference on Networks, 2011, pp. 71-76.
[74] J. Li, B. N. Silva, M. Diyan, Z. Cao, K. Han, A clustering based routing algorithm in IoT aware Wireless Mesh Networks, Sustainable cities and society. 40 (2018) 657-666.
[75] T. Hendriks, M. Camelo, S. Latré, Q^2-routing: A Qos-aware Q-routing algorithm for wireless ad hoc networks, in: 14th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), 2018, pp. 108-115.
[76] S. Chettibi, S. Chikhi, Adaptive maximum-lifetime routing in mobile ad-hoc networks using temporal difference reinforcement learning, Evolving Systems. 5(2) (2014) 89-108.
[77] P. Deepalakshmi, S. Radhakrishnan, An ant colony based multi objective approach to source-initiated QoS multicasting method for ad hoc networks, Int. J. Advance. Soft Comput. Appl. 3(2) (2011) 1-18.
[78] K. Kwon, S. H. Kim, M. Ha, D. Kim, Traffic-aware stateless multipath routing for fault-tolerance in IEEE 802.15. 4 wireless mesh networks, Wireless networks. 24(5) (2018) 1755-1774.
[79] Z. You, Y. Wang, An efficient and secure routing protocol for a hybrid wireless

mesh network, Journal of Computational Information Systems. 8(21) (2012) 8693-8705.
[80] Y. Yang, J. Wang, R. Kravets, Designing routing metrics for mesh networks. In: IEEE workshop on wireless mesh networks (WiMesh), 2005, pp. 1-9.
[81] F. A. Khasawneh, M. Kadoch, Adaptive transmission rate congestion aware routing algorithm in wireless mesh network, Wireless Personal Communications. 97(3) (2017) 4327-4342.
[82] K. W. Choi, W. S. Jeon, D. G. Jeong, Efficient load-aware routing scheme for wireless mesh networks, IEEE Transactions on Mobile Computing. 9(9) (2010) 1293-1307.
[83] E. Alotaibi, V. Ramamurthi, M. Batayneh, B. Mukherjee, Interference-aware routing for multi-hop wireless mesh networks, Computer Communications. 33(16) (2010) 1961-1971.
[84] R. M. Kortebi, Y. Gourhant, N. Agoulmine, On the use of SINR for interference-aware routing in wireless multi-hop networks, in: Proceedings of the 10th ACM Symposium on Modeling, analysis, and simulation of wireless and mobile systems, 2007, pp. 395-399.
[85] C. Xu, K. Wang, P. Li, R. Xia, S. Guo, M. Guo, Renewable energy-aware big data analytics in geo-distributed data centers with reinforcement learning, IEEE Transactions on Network Science and Engineering. 7(1) (2018) 205-215.
[86] D. G. Zhang, X. Wang, X. D. Song, J. Li, Y. J. Chen, A kind of novel VPF-based energy-balanced routing strategy for wireless mesh network, International Journal of Communication Systems. 30(6) (2017) 1-15.
[87] T. Carvalho, J. J. Júnior, R. Frances, A new cross-layer routing with energy awareness in hybrid mobile ad hoc networks: A fuzzy-based mechanism, Simulation Modelling Practice and Theory. 63 (2016) 1-22.
[88] S. Moad, M. T. Hansen, R. Jurdak, B. Kusy, N. Bouabdallah, WETX: A weighted expected transmission routing metric for diversity in wireless sensor networks, in: IFIP Wireless Days (WD), 2011, pp. 1-7.
[89] H. Mostafaei, Energy-efficient algorithm for reliable routing of wireless sensor networks, IEEE Transactions on Industrial Electronics. 66(7) (2018) 5567-5575.
[90] A. A. A. M. Rahat, R. M. Everson, J. E. Fieldsend, Multi-objective routing optimisation for battery-powered wireless sensor mesh networks, in: Proceedings of the Annual Conference on Genetic and Evolutionary Computation, 2014, pp. 1175-1182.
[91] R. Murugeswari, S. Radhakrishnan, D. Devaraj, A multi-objective evolutionary algorithm based QoS routing in wireless mesh networks, Applied Soft Computing. 40 (2016) 517-525.
[92] N. Gunantara, G. Hendrantoro, Multi-objective cross-layer optimization with Pareto method for relay selection in multihop wireless ad hoc networks, WSEAS Transaction on Communications. 12(3) (2013) 85-95.
[93] C. H. Liu, A. Gkelias, K. K. Leung, A cross-layer framework of QoS routing and distributed scheduling for mesh networks, in: Vehicular Technology Conference (VTC Spring), 2008, pp. 2193-2197.

[94] H. Yetgin, K. T. K. Cheung, L. Hanzo, Multi-objective routing optimization using evolutionary algorithms, in: IEEE Wireless Communications and Networking Conference (WCNC), 2012, pp. 3030-3034.
[95] M. Camelo, C. Omaña, H. Castro, QoS routing algorithm based on multi-objective optimization for wireless mesh networks, in: IEEE Latin-American Conference on Communications, 2010, pp. 1-6.
[96] M. O. de Mello, V. C. Borges, L. D. L. Pinto, K. V. Cardoso, Load balancing routing for path length and overhead controlling in wireless mesh networks, in: IEEE Symposium on Computers and Communications (ISCC), 2014, pp. 1-6.
[97] H. Alwan, A. Agarwal, Multi-objective QoS routing for wireless sensor networks, in: International Conference on Computing, Networking and Communications (ICNC), 2013, pp. 1074-1079.
[98] G. Li, L. Boukhatem, J. Wu, Adaptive quality-of-service-based routing for vehicular ad hoc networks with ant colony optimization, IEEE Transactions on Vehicular Technology. 66(4) (2016) 3249-3264.
[99] N. Magaia, N. Horta, R. Neves, P. R. Pereira, M. Correia, A multi-objective routing algorithm for wireless multimedia sensor networks, Applied Soft Computing. 30 (2015) 104-112.
[100] M. Srinivas, L. M. Patnaik, Genetic algorithms: A survey, computer. 27(6) (1994) 17-26.
[101] Y. Shi, Particle swarm optimization: developments, applications and resources, in: Proceedings of the congress on evolutionary computation, 2001, pp. 81-86.
[102] D. Benyamina, A. Hafid, N. Hallam, M. Gendreau, J. C. Maureira, A hybrid nature-inspired optimizer for wireless mesh networks design, Computer Communications. 35(10) (2012) 1231-1246.
[103] F. Xue, A. Sanderson, R. Graves, Multi-objective routing in wireless sensor networks with a differential evolution algorithm, in: IEEE International Conference on Networking, Sensing and Control, 2006, pp. 880-885.
[104] R. Murugeswari, S. Radhakrishnan, Discrete multi-objective differential evolution algorithm for routing in wireless mesh network, Soft Computing. 20(9) (2016) 3687-3698.
[105] M. Dorigo, M. Birattari, T. Stutzle, Ant colony optimization, IEEE computational intelligence magazine. 1(4) (2006) 28-39.
[106] F. Bokhari, G. Zaruba, On the use of smart ants for efficient routing in Wireless Mesh Networks, arXiv preprint. (2012) arXiv:1209.0550.
[107] S. Karunaratne, H. Gacanin, An overview of machine learning approaches in wireless mesh networks, IEEE Communications Magazine. 57(4) (2019) 102-108.
[108] M. Maleki, V. Hakami, M. Dehghan, A model-based reinforcement learning algorithm for routing in energy harvesting mobile ad-hoc networks, Wireless Personal Communications. 95(3) (2017) 3119-3139.
[109] D. E. Goldberg, Genetic Algorithm in Search, Optimization and Machine Learning, Pearson Education. (2005) Low Price Edition, Delhi.
[110] K. Deb, Multi-objective optimisation using evolutionary algorithms: an introduction, in: Multi-objective evolutionary optimisation for product design and

manufacturing, 2011, pp. 3-34.
[111] H. Jiang, J. Chen, T. Liu, H. Fu, Design of an FBG sensor network based on Pareto multi-objective optimization, IEEE Photonics Technology Letters. 25(15) (2013) 1450-1453.
[112] NS-2. https://www.isi.edu/nsnam/ns/. Accessed September 10, 2021.
[113] M. H. Rehmani, S. Doria, M. R. Senouci, A tutorial on the implementation of Ad-hoc on Demand Distance Vector (AODV) Protocol in Network Simulator (NS-2), arXiv preprint. (2010) arXiv:1007.4065.
[114] D. B. Johnson, D. A. Maltz, J. Broch, DSR: The dynamic source routing protocol for multi-hop wireless ad hoc networks, Ad hoc networking. 5(1) (2001) 139-172.
[115] H. Li, Y. Cheng, C. Zhou, W. Zhuang, Minimizing end-to-end delay: A novel routing metric for multi-radio wireless mesh networks, in: IEEE INFOCOM, 2009, pp. 46-54.
[116] R. F. Ali, A. K. Kiani, A. A. Pirzada, Load dependent dynamic path selection in multi-radio hybrid wireless mesh networks, in: IEEE Wireless Communications and Networking Conference (WCNC), 2014, pp. 2020-2025.
[117] D. W. Kum, A. N. Le, Y. Z. Cho, C. K. Toh, I. S. Lee, An efficient on-demand routing approach with directional flooding for wireless mesh networks, Journal of Communications and Networks. 12(1) (2010) 67-73.
[118] M. Boushaba, A. Hafid, M. Gendreau, Source-based routing in wireless mesh networks, IEEE systems Journal. 10(1) (2014) 262-270.
[119] A. Singh, S. S. Walia, S. Kumar, FW-AODV: An Optimized AODV Routing Protocol for Wireless Mesh Networks, International Journal of Advanced Research in Computer Science. 8(3) (2017) 1131-1135.
[120] S. Khan, J. Loo, Cross layer secure and resource-aware on-demand routing protocol for hybrid wireless mesh networks, Wireless Personal Communications. 62(1) (2012) 201-214.
[121] A. K. Kiani, R. F. Ali, U. Rashid, Energy-load aware routing metric for hybrid wireless mesh networks, in: IEEE 81st Vehicular Technology Conference (VTC Spring), 2015, pp. 1-5.
[122] F. Li, A. Lippman, Interference-aware minimum energy path routing in multi-hop wireless ad hoc networks, in: 5th IEEE Consumer Communications and Networking Conference, 2008, pp. 488-492.
[123] X. Deng, L. He, Q. Liu, X. Li, L. Cai, Z. Chen, EPTR: expected path throughput based routing protocol for wireless mesh network, Wireless Networks. 22(3) (2016) 839-854.
[124] M. Boushaba, A. Hafid, A. Maach, D. Elghanami, SGRL-Selective Gateway and Reinforcement Learning-based routing for WMN, in: IEEE/ACS 12th International Conference of Computer Systems and Applications (AICCSA), 2015, pp. 1-8.
[125] A. A. Pirzada, C. McDonald, A. Datta, Performance comparison of trust-based reactive routing protocols, IEEE transactions on mobile computing. 5(6) (2006) 695-710.

[126] M. Genetzakis, V. A. Siris, A contention-aware routing metric for multi-rate multi-radio mesh networks, in: 5th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, 2008, pp. 242-250.
[127] Y. Yang, J. Wang, R. Kravets, Interference-aware load balancing for multihop wireless networks, Technical Report in University of Illinois. (2005) 1-16.
[128] T. Dargahi, A. masoud Rahmani, A. Khademzadeh, A hybrid of reactive and proactive approaches based on neighbors' conditions of nodes for mobile ad hoc networks, in: 4th International Conference on Information and Automation for Sustainability, 2008, pp. 425-430.
[129] M. S. Kang, D. W. Kum, J. S. Bae, Y. Z. Cho, A. N. Le, Mobility Aware Hybrid Routing protocol for mobile ad hoc network, in: International Conference on Information Network, 2012, pp. 410-414.
[130] H. Bargaoui, N. Mbarek, O. Togni, M. Frikha, Hybrid QoS based routing protocol for inter and intra wireless mesh infrastructure communications, Wireless Networks. 22(7) (2016) 2111-2130.
[131] T. Clausen, P. Jacquet, C. Adjih, A. Laouiti, P. Minet, P. Muhlethaler, A. Qayyum, L. Viennot, Optimized link state routing protocol (OLSR), RFC 3626. (2003).
[132] J. Rust, Dynamic programming, The New Palgrave Dictionary of Economics, (2016) 1-26.
[133] https://www.scopus.com/sources.uri. Accessed September 20, 2021.
[134] https://www.journals.elsevier.com/computer-networks.
Accessed September 20, 2021.
[135] https://www.letpub.com.cn/index.php?page=journalapp.
Accessed September 20, 2021.
[136] https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=4267003.
Accessed September 20, 2021.
[137] https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=4234.
Accessed September 20, 2021.
[138] https://www.journals.elsevier.com/applied-soft-computing.
Accessed September 20, 2021.
[139] X. Deng, J. Luo, L. He, Q. Liu, X. Li, L. Cai, Cooperative channel allocation and scheduling in multi-interface wireless mesh networks, Peer-to-peer Networking and Applications. 12(1) (2019) 1-12.
[140] S. Avallone, A. Banchs, A channel assignment and routing algorithm for energy harvesting multiradio wireless mesh networks, IEEE Journal on Selected Areas in Communications. 34(5) (2016) 1463-1476.
[141] Y. Liu, K. F. Tong, X. Qiu, Y. Liu, X. Ding, Wireless mesh networks in IoT networks, in: International workshop on electromagnetics: applications and student innovation competition, 2017, pp. 183-185.
[142] D. L. C. Dutra, M. Bagaa, T. Taleb, K. Samdanis, Ensuring end-to-end QoS based on multi-paths routing using SDN technology, in: IEEE Global Communications Conference (GLOBECOM), 2017, pp. 1-6.
[143] Y. Peng, L. Guo, Q. Deng, Z. Ning, L. Zhang, A novel hybrid routing forwarding

algorithm in SDN enabled wireless mesh networks, in: IEEE 17th International Conference on High Performance Computing and Communications, 2015, pp. 1806-1811.
[144] M. Bano, S. S. A. Gilani, A. Qayyum, A comparative analysis of hybrid routing schemes for SDN based wireless mesh networks, in: IEEE 20th International Conference on High Performance Computing and Communications, 2018, pp. 1189-1194.
[145] E. Di Pascale, I. Macaluso, A. Nag, M. Kelly, L. Doyle, The network as a computer: A framework for distributed computing over IoT mesh networks, IEEE Internet of Things Journal. 5(3) (2018) 2107-2119.
[146] F. Tang, B. Mao, Z. M. Fadlullah, N. Kato, O. Akashi, T. Inoue, K. Mizutani, On removing routing protocol from future wireless networks: A real-time deep learning approach for intelligent traffic control, IEEE Wireless Communications. 25(1) (2017) 154-160.
[147] S. Chinchali, P. Hu, T. Chu, M. Sharma, M. Bansal, R. Misra, M. Pavone, S. Katti, Cellular network traffic scheduling with deep reinforcement learning, in: Proceedings of the AAAI Conference on Artificial Intelligence, 32(1), 2018, pp. 766-774.
[148] M. L. Bote-Lorenzo, E. Gómez-Sánchez, C. Mediavilla-Pastor, J. I. Asensio-Pérez, Online machine learning algorithms to predict link quality in community wireless mesh networks, Computer Networks. 132 (2018) 68-80.
[149] G. Stampa, M. Arias, D. Sánchez-Charles, V. Muntés-Mulero, A. Cabellos, A deep-reinforcement learning approach for software-defined networking routing optimization, arXiv preprint. (2017) arXiv:1709.07080.

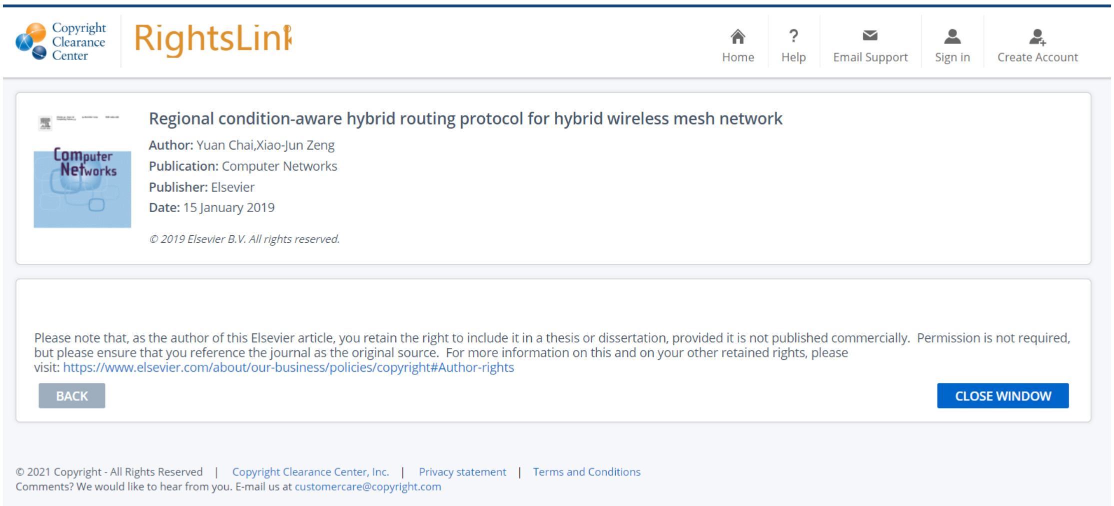
Appendix A

Permission from Publishers

The permission from publishers for reusing the published papers which are included in this thesis is given in this part.

A.1 Permission to Reuse Content from Elsevier Publications

This section shows the permission from Elsevier for reusing the publications [25] and [28] mentioned in section 1.5.



Copyright Clearance Center | RightsLink

Home | Help | Email Support | Sign in | Create Account

Regional condition-aware hybrid routing protocol for hybrid wireless mesh network

Author: Yuan Chai,Xiao-Jun Zeng

Publication: Computer Networks

Publisher: Elsevier

Date: 15 January 2019

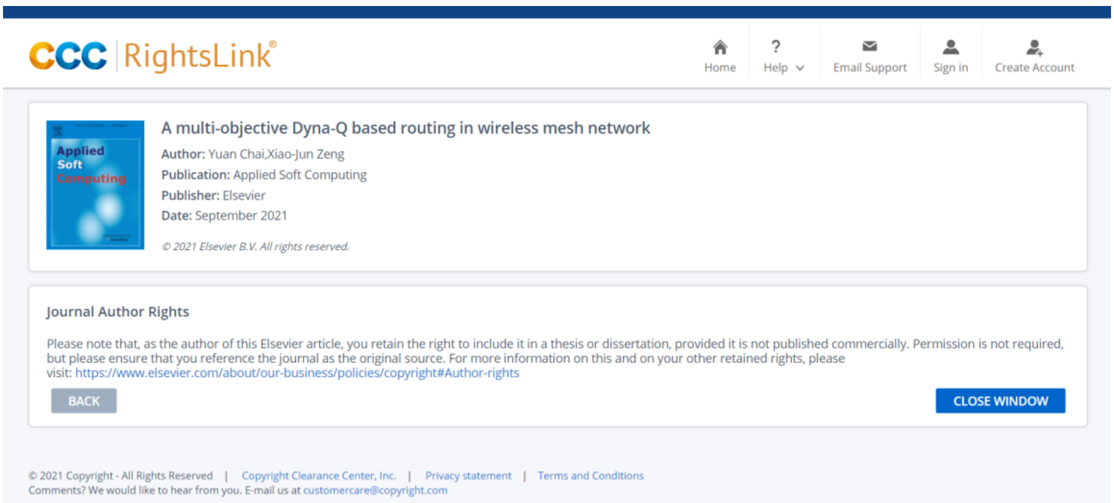
© 2019 Elsevier B.V. All rights reserved.

Please note that, as the author of this Elsevier article, you retain the right to include it in a thesis or dissertation, provided it is not published commercially. Permission is not required, but please ensure that you reference the journal as the original source. For more information on this and on your other retained rights, please visit: https://www.elsevier.com/about/our-business/policies/copyright#Author-rights

BACK | CLOSE WINDOW

© 2021 Copyright - All Rights Reserved | Copyright Clearance Center, Inc. | Privacy statement | Terms and Conditions

Comments? We would like to hear from you. E-mail us at customercare@copyright.com



CCC | RightsLink®

Home | Help | Email Support | Sign in | Create Account

A multi-objective Dyna-Q based routing in wireless mesh network

Author: Yuan Chai,Xiao-Jun Zeng

Publication: Applied Soft Computing

Publisher: Elsevier

Date: September 2021

© 2021 Elsevier B.V. All rights reserved.

Journal Author Rights

Please note that, as the author of this Elsevier article, you retain the right to include it in a thesis or dissertation, provided it is not published commercially. Permission is not required, but please ensure that you reference the journal as the original source. For more information on this and on your other retained rights, please visit: https://www.elsevier.com/about/our-business/policies/copyright#Author-rights

BACK | CLOSE WINDOW

© 2021 Copyright - All Rights Reserved | Copyright Clearance Center, Inc. | Privacy statement | Terms and Conditions

Comments? We would like to hear from you. E-mail us at customercare@copyright.com

A.2 Permission to Reuse Content from IEEE Publications

This section shows the permission from IEEE for reusing the publications [26] and [27] mentioned in section 1.5.

Copyright Clearance Center RightsLink

Home | Help | Email Support | Xiao-Jun Zeng

IEEE Requesting permission to reuse content from an IEEE publication

Delay- and Interference-Aware Routing for Wireless Mesh Network

Author: Yuan Chai
Publication: IEEE Systems Journal
Publisher: IEEE
Date: Sept. 2020

Thesis / Dissertation Reuse

The IEEE does not require individuals working on a thesis to obtain a formal reuse license, however, you may print out this statement to be used as a permission grant:

Requirements to be followed when using any portion (e.g., figure, graph, table, or textual material) of an IEEE copyrighted paper in a thesis:

1) In the case of textual material (e.g., using short quotes or referring to the work within these papers) users must give full credit to the original source (author, paper, publication) followed by the IEEE copyright line © 2011 IEEE.
2) In the case of illustrations or tabular material, we require that the copyright line © [Year of original publication] IEEE appear prominently with each reprinted figure and/or table.
3) If a substantial portion of the original paper is to be used, and if you are not the senior author, also obtain the senior author's approval.

Requirements to be followed when using an entire IEEE copyrighted paper in a thesis:

1) The following IEEE copyright/ credit notice should be placed prominently in the references: © [year of original publication] IEEE. Reprinted, with permission, from [author names, paper title, IEEE publication title, and month/year of publication]
2) Only the accepted version of an IEEE copyrighted paper can be used when posting the paper or your thesis on-line.
3) In placing the thesis on the author's university website, please display the following message in a prominent place on the website: In reference to IEEE copyrighted material which is used with permission in this thesis, the IEEE does not endorse any of [university/educational entity's name goes here]'s products or services. Internal or personal use of this material is permitted. If interested in reprinting/republishing IEEE copyrighted material for advertising or promotional purposes or for creating new collective works for resale or redistribution, please go to http://www.ieee.org/publications_standards/publications/rights/rights_link.html to learn how to obtain a License from RightsLink.

If applicable, University Microfilms and/or ProQuest Library, or the Archives of Canada may supply single copies of the dissertation.

BACK | CLOSE WINDOW

Copyright Clearance Center RightsLink

Home | Help | Email Support | Xiao-Jun Zeng

IEEE Requesting permission to reuse content from an IEEE publication

Load Balancing Routing for Wireless Mesh Network With Energy Harvesting

Author: Yuan Chai
Publication: IEEE Communications Letters
Publisher: IEEE
Date: April 2020

Thesis / Dissertation Reuse

The IEEE does not require individuals working on a thesis to obtain a formal reuse license, however, you may print out this statement to be used as a permission grant:

Requirements to be followed when using any portion (e.g., figure, graph, table, or textual material) of an IEEE copyrighted paper in a thesis:

1) In the case of textual material (e.g., using short quotes or referring to the work within these papers) users must give full credit to the original source (author, paper, publication) followed by the IEEE copyright line © 2011 IEEE.
2) In the case of illustrations or tabular material, we require that the copyright line © [Year of original publication] IEEE appear prominently with each reprinted figure and/or table.
3) If a substantial portion of the original paper is to be used, and if you are not the senior author, also obtain the senior author's approval.

Requirements to be followed when using an entire IEEE copyrighted paper in a thesis:

1) The following IEEE copyright/ credit notice should be placed prominently in the references: © [year of original publication] IEEE. Reprinted, with permission, from [author names, paper title, IEEE publication title, and month/year of publication]
2) Only the accepted version of an IEEE copyrighted paper can be used when posting the paper or your thesis on-line.
3) In placing the thesis on the author's university website, please display the following message in a prominent place on the website: In reference to IEEE copyrighted material which is used with permission in this thesis, the IEEE does not endorse any of [university/educational entity's name goes here]'s products or services. Internal or personal use of this material is permitted. If interested in reprinting/republishing IEEE copyrighted material for advertising or promotional purposes or for creating new collective works for resale or redistribution, please go to http://www.ieee.org/publications_standards/publications/rights/rights_link.html to learn how to obtain a License from RightsLink.

If applicable, University Microfilms and/or ProQuest Library, or the Archives of Canada may supply single copies of the dissertation.

BACK | CLOSE WINDOW