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Contributions to Communication and
Networking for the Internet of Things
Environments

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Ning Li

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To my beloved family.

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Abstract

Due to the advantages of the IoT, the applications of IoT have been widely used and development in recent years. The IoT will be the new revolution of the Internet. The IoT applications have been widely used in forest monitoring, the disaster management, the home automation, the factory automation, smart city, etc. For the IoT applications, one of the important issues is the efficiency of the data transmission, which is important to the Quality of Services (QoS). The efficiency of the data transmission includes the reliability, the energy consumption, the transmission delay, etc. of the network.

For different layer, there have different approaches to improving the efficiency of the data transmission. In this thesis, we mainly focus on the network layer. In the network layer, for improving the efficiency of the data transmission is to design the routing algorithm carefully. There are two different routing technologies: the deterministic routing and the opportunistic routing. During the data transmission, the deterministic routing choose one of its neighbor node as the next hop relay node; however, in opportunistic routing, the sender chooses a set of neighbors as the next hop relay nodes to improving the packet delivery ratio. In this thesis, we mainly focus on the opportunistic routing.

However, to the opportunistic routing, even the packet delivery ratio is high compare to the deterministic routing, the transmission delay and the redundant transmission are serious than that in deterministic routing. For solving this issue, we propose the concept of sub relaying network; the sender chooses the next hop relay nodes based on the sub relaying network. This approach can reduce the transmission delay and redundant transmission greatly without reducing the packet delivery ratio of the opportunistic routing. During the data relaying in the candidate relay set, the nodes in the candidate relay set should be set with relaying priorities. For improving the fairness when determining the relaying priorities of the relay nodes, we propose a fuzzy logic based relaying priority determining algorithm. This algorithm can take as many as performance metrics into account during the relay priority determining without increasing the computation complexity. Moreover, in this thesis, we applied these two algorithms into the underwater environment and terrestrial environment.

Not only the routing algorithms, the topology control is also popular and effective on improve the efficiency of data transmission. Firstly, in this thesis, we investigate the relationship between interference optimal and energy efficient by adjusting the transmission power of node. We concluded that for most cause, when the network is interference optimal by adjusting the transmission power, then it is also energy efficient near 100%. Secondly, for reducing the control cost, in this thesis, we propose two approaches; in the first approach, the

nodes are divided into different categories based on some performance metrics, such as the residual energy, the node degree, etc.; the nodes in different categories have different transmission power adjust probabilities; in the second approach, we introduce the Pareto optimal into the topology control to reduce the control cost. Moreover, we also introduce the topology control technology into the opportunistic routing to stable the packet delivery ratio. Finally, in this thesis, we evaluate all the proposed algorithms by simulation. The simulation results have been shown in this paper. These results demonstrate that the proposed algorithm in this thesis are effective and have better performance than the previous works.

Key words: Internet of Things, Opportunistic routing, Packet delivery ratio, Interference, Topology control, Fuzzy logic, Optimal theory.

Resumen

Debido a las ventajas del IoT, las aplicaciones de IoT se han utilizado y desarrollado ampliamente en los últimos años. El IoT será la nueva revolución de Internet. Las aplicaciones de IoT se han utilizado ampliamente en el monitoreo forestal, la gestión de desastres, la domótica, la automatización de fábricas, la ciudad inteligente, etc. Para las aplicaciones de IoT, uno de los problemas importantes es la eficiencia de la transmisión de datos, que es importante para la calidad de los servicios (QoS). La eficiencia de la transmisión de datos incluye la fiabilidad, el consumo de energía, el retardo de transmisión, etc. de la red.

Para capa diferente, existen diferentes enfoques para mejorar la eficiencia de la transmisión de datos. En esta tesis, nos enfocamos principalmente en la capa de red. En la capa de red, para mejorar la eficiencia de la transmisión de datos, es necesario diseñar el algoritmo de enrutamiento con cuidado. Hay dos tecnologías de enrutamiento diferentes: el enrutamiento determinista y el enrutamiento oportunista. Durante la transmisión de datos, el enrutamiento determinístico elige uno de sus nodos vecinos como nodo de retransmisión del próximo salto; sin embargo, en el enrutamiento oportunista, el emisor elige un conjunto de vecinos como nodos de relevo del siguiente salto para mejorar la proporción de entrega de paquetes. En esta tesis, nos centramos principalmente en el enrutamiento oportunista.

Sin embargo, para el enrutamiento oportunista, incluso la relación de entrega de paquetes es alta en comparación con el enrutamiento determinista, el retardo de transmisión y la transmisión redundante son serios que en el enrutamiento determinista. Para resolver este problema, proponemos el concepto de red secundaria de retransmisión; el emisor elige los nodos de relevo del siguiente salto en función de la red de retransmisión secundaria. Este enfoque puede reducir en gran medida el retardo de transmisión y la transmisión redundante sin reducir la proporción de entrega de paquetes del enrutamiento oportunista. Durante la transmisión de datos en el conjunto de relés candidatos, los nodos en el conjunto de relés candidatos deben configurarse con prioridades de retransmisión. Para mejorar la equidad al determinar las prioridades de retransmisión de los nodos de retransmisión, proponemos un algoritmo de determinación de prioridad de retransmisión basado en lógica difusa. Este algoritmo puede tomar tantas medidas de rendimiento en cuenta durante la determinación de prioridad de retransmisión sin aumentar la complejidad del cálculo. Además, en esta tesis, aplicamos estos dos algoritmos en el ambiente submarino y el ambiente terrestre.

No solo los algoritmos de enrutamiento, el control de topología también es popular y eficaz para mejorar la eficiencia de la transmisión de datos. En primer lugar, en esta tesis, investigamos la relación entre la interferencia óptima y la eficiencia energética mediante el

ajuste de la potencia de transmisión del nodo. Llegamos a la conclusión de que, por la mayoría de las causas, cuando la red es la interferencia óptima mediante el ajuste de la potencia de transmisión, entonces también es eficiente en energía cerca del 100%. En segundo lugar, para reducir el costo de control, en esta tesis, proponemos dos enfoques; en el primer enfoque, los nodos se dividen en diferentes categorías en función de algunas medidas de rendimiento, como la energía residual, el grado del nodo, etc.; los nodos en diferentes categorías tienen diferentes probabilidades de ajuste de potencia de transmisión; En el segundo enfoque, introducimos el óptimo de Pareto en el control de topología para reducir el costo de control. Además, también introducimos la tecnología de control de topología en el enrutamiento oportunista para establecer la relación de entrega de paquetes.

Finalmente, en esta tesis, evaluamos todos los algoritmos propuestos por simulación. Los resultados de la simulación se han mostrado en este documento. Estos resultados demuestran que el algoritmo propuesto en esta tesis es efectivo y tiene un mejor rendimiento que los trabajos anteriores.

Palabras clave: Internet de las cosas, Enrutamiento oportunista, Proporción de entrega de paquetes, Interferencia, Control de topología, Lógica difusa, Teoría óptima.

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Chapter 1

Introduction

In this chapter, the motivations and objectives of this thesis are introduced, and the contributions for the investigated problems are present. This chapter ends with the listing the structure of this thesis.

1.1 Motivation

In nowadays, the Internet of Things (IoT) [1-2] promotes a huge number of novel applications, which is boosting the world economy and improving people's lives. As the evaluation and revolution of the current internet network, the IoT is not only the networks consist by computers or mobile phones, but also the networks made up by devices of all types and sizes, such as the vehicular, the robot, the household appliances, etc. All of these devices are defined as "Things" (or, "nodes" as the same argument). These years, the IoT becomes one of the most active research topics in academia and industry, which benefits from the development of the communication technology, the big data, and the artificial intelligence. The applications, such as the forest monitoring, the disaster management, the home automation, the smart city, the medical and health care, etc., are on rise. The IoT will become one of the most important industrial for the world economy in the near future.

As defined by the European Research Cluster (IERC) [3], the IoT is: "Internet of Things: A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies." The IoT is inherently multi-disciplinary. Enabling technologies cover a huge scope of disciplines, for instance, wireless sensor networks [4-5], RFID, M2M, mobile internet, ad hoc networks, vehicular ad hoc networks, 2G/3G/4G, artificial intelligent, etc.

Since the IoT is mainly used for information collection and exchanging, so it puts a significant amount of emphasis on the quality of network information transmission. The goal of the IoT is to enable things can communicate with each other at anytime, anywhere, with anything and anyone ideally using any path/network and any service [6]. This goal motivated the study of this thesis. Since for achieving the goals introduced above, the reliable and effective data

transmission network is necessary for the IoT. However, on one hand, due to the mobility of many IoT applications, the unexpected node failures, the harsh environment, or the malicious attacks, the communication links and the connection between the nodes are unreliable and easy to break. On the other hand, the communication resources in IoT applications are always limited, such as the energy, the computing capability, or the storage space, etc., so how to improving the network performance as much as possible under such limitation is also an important issue in the IoT; moreover, it can be predicted that this issue will be always existed during the development of the IoT. For instance, in many applications, the nodes are power by battery which is easy to be exhausted, so how to reduce the energy consumption of nodes while not reduce the quality of service (QoS) of IoT is an important issue. Finally, for IoT applications, the scenario environments are also different; for the different application environment, the network resource also has great difference; for instance, the transmission rate and bandwidth between the underwater environment and the terrestrial environment. So the design of the algorithms of the IoT applications should take these constrains into account.

For guaranteeing the reliable and efficient data transmission between different nodes, one of the important issues is the routing technology. Routing is defined as the process of selecting a path for data transmission from source node to destination node in the network. The routing guarantees the data packet can be transmitted between any nodes and is divided into two different categories: the deterministic routing and the opportunistic routing [7]. In deterministic routing, the source node chooses one one-hop neighbor as the next hop relay node during the data packet transmission based on some principles, such as the distance, the residual energy, the memory space, etc.; however, in opportunistic routing, when the source node want to send data packet to the destination node, a set of one-hop neighbors will be chosen and consist of the candidate relay set (CRS) [8-11]; all the nodes in this set involve in the data packet transmission to the next hop data transmission. Our research is developed based on the opportunistic routing. The most important advantage of the opportunistic routing compares with the deterministic routing is that it improves the packet delivery ratio (PRO) greatly, because more than one neighbor takes part in the data packet transmission to the next hop [8-11]. The high packet delivery ratio means high reliability and effectiveness of the routing algorithm. However, due to the strategy of the opportunistic routing, i.e., all the nodes in CRS take part in the data transmission, the redundant transmission, the network interference in opportunistic routing are much more serious than that in deterministic routing. Moreover, the transmission delay in opportunistic routing that caused by the disadvantages introduced above is also higher than that in the deterministic routing [11]. There, how to reducing the transmission delay, the redundant transmission, and the network interference is one of the key points to improving the performance of opportunistic routing in the IoT applications, in which the network resources are always limited.

For improving the reliability and effectiveness of the data transmission, not only the routing should be carefully designed and optimized but also the network topology should be controlled based on the network condition, such as the energy consumption, the connectivity, etc. There are many different kinds of topology control technologies [12-13], such as the transmission power control, the graph theory, the power model management [25-26], the clustering approach [27], etc. In this thesis, the topology control approach is mainly the transmission power control. In this method, the network topology is controlled by adjusting the transmission

power of node in a distribution manner according to the network parameters dynamically. This method can improve the network connectivity, and reduce the energy consumption and network interference. As shown in the previous works, the larger transmission power of node, the higher network connectivity (i.e., the more reliable of the communication link); however, the large transmission power causes high energy consumption and network interference, which will deteriorate the network performance in turn [13]. So the transmission power control should be able to find a tradeoff between the QoS and the network resource consumption. On other hand, for some scenario environments, such as the underwater environment, in which the bandwidth is much narrower than that in the terrestrial environment, so for this kind of application, the cost caused by the topology control should be reduced as much as possible. As mentioned in the previous works, in opportunistic routing, the more nodes in the CRS, the higher packet delivery ratio is; however, if there are too many nodes in CRS, the network interference and the redundant transmission will be serious; if too less nodes in the CRS, the packet delivery ratio during the data packet transmission cannot be guaranteed [11, 14-15]. Therefore, one of the important research topics in the opportunistic routing is the CRS filtering and optimizing, which means that removed some nodes from CRS or added some nodes into the CRS based on some principles to improve the performance of the opportunistic routing. This mission is extremely suitable for the topology control technologies. So introducing the topology control technology into the opportunistic routing is an attractive research topic, and investigating the effect of topology control on opportunistic routing can provide guidelines for the routing design in the future.

1.2 Problem Statement

In the previous works, the opportunistic routing and the topology control have been investigated and applied in many applications. Many excellent algorithms have been proposed for different application scenarios. However, the already exist algorithms cannot meet the rapid QoS requirements growing of the IoT applications, in which the QoS requirements and the resource demand are more rigorous than before. On one hand, the routing algorithms and the topology control algorithms are highly application related, so for different application scenarios, the algorithms will be different. On the other hand, with the development of the artificial intelligence, the virtual reality, the 5G technologies, etc., the QoS requirements and the resource demand are more and more rigorous. The traditional routing algorithms and the topology control algorithms have difficult on meeting these requirements anymore; moreover, the performance of these applications will be limited by the development of routing and topology control technologies. So improving the existed routing and topology control strategies or proposing the new strategies for the IoT applications is necessary and urgent.

As introduced above, the opportunistic routing can improve the packet delivery ratio greatly at the cost of high redundant transmission and delay. For solving these issues, the nodes in the CRS should be filtered and optimized carefully; there are many CRS optimization and filtering algorithms have been proposed. The most commonly used filtering approach is to remove the candidates that are worse than the sender according to a specific metric. However, this simple filtering policy cannot guarantee optimal performance [11]. Therefore, other considerations such as connectivity, duplicate likelihood and node contribution have been taken into consideration later in the literature [16-21]. For instance, the works in [17] and [18]

require that the candidate relays in the candidate relay set are connected in a mesh fashion so that they can hear one another and avoid redundant transmission. An alternative approach consists in filtering out the bad candidates based on their duplicate forwarding probability. In [21], this probability was derived using a discrete time Markov model. Finally, the third method removes the candidate relays with low contribution in traffic forwarding [16, 20-21]. For example, in MORE [16] and CCACK [20], each candidate is given a predicted number of transmissions for a flow. If a candidate does not perform at least 10% of the overall predicted transmissions, it is pruned. In addition to these filtering techniques, another approach of CRS construction is adopted in some prior works. This approach consists in running optimization algorithms that can directly determine the optimal CRS for each node without having to apply any filtering technique [22-24]. On the other hand, in LCAR [22], based on generalization of the Bellman-Ford algorithm, the authors introduce a shortest any path algorithm capable of finding optimal forward sets. However, these works do not address the problem of duplicate transmissions caused by node deafness; instead they assume an ideal underlying MAC protocol. Overall, candidate relay ordering and filtering are done separately in these works. Thus the outcome of this phase is not necessarily optimal [11]. For example, filtering based on the connectivity criterion removes candidates that trigger duplicate transmissions. However, these filtered candidates may be the best in terms of the routing metric and may bring the highest expected performance. Therefore, it is necessary to jointly consider the node contribution and its duplicate probability, in future candidate relay set selection schemes design.

In Opportunistic routing, when determining the relay priority for each node in CRS, the more performance metrics are taken into account, the more accuracy and balanced of the result is. In the previous works, the number of the performance metrics is always limited, so the results are biased inevitably. However, when taking more performance metrics into account, the computation complexity will increase seriously. So the best choice is to find a paradigm which can take as many metrics into account as possible while does not increase the computation complexity obviously.

The topology control is mainly used to improve the network connectivity and reduce the energy consumption and network interference. The effect of the topology control on the network connectivity has been investigated in depth in the past decades. In this thesis, we mainly focus on the effect on the energy consumption and network interference. The transmission power control method always tend to use the short communication links to replace the long communication links for reducing the energy consumption and network interference while keeping the network connectivity. However, does the short communication link is more effective than the long communication link on reducing the energy consumption and network interference has not been investigated in detail. The [28] and [29] have proved that short communication links does not means lower network interference. However, the relationship between energy consumption and network interference when controlling the transmission power has not been learned by the previous works. Moreover, in the previous works, once the current transmission power does not equal to the optimal one, the transmission power need to be adjusted. This strategy is effective when the network is static; however, when the nodes in the network are mobile, the network topology will change frequently. This means that the transmission power needed to be adjusted frequently and the control cost is high.

1.3 Contributions

Based on the issues that we mentioned above, in this thesis, we propose some algorithms and paradigms to solve them. The contributions of this thesis can be summarized as follows:

1. In this thesis, based on the issue that the transmission redundant and delay are serious in the opportunistic routing, we propose the delay based duplicate transmission avoid coordination scheme for the opportunistic routing. In this algorithm, the nodes in the relay node set are divided into different sub networks which are fully connected; for each sub network, the node utility which used to decide the relay priority and the transmission delay of the network are taken into account to determine the network utility of each sub network. Then the sub network which has highest network utility will be chosen as the final relay node set.
2. Except the coordination scheme, in this thesis, we also propose a relay node priority algorithm for the opportunistic routing. In this algorithm, for improving the accuracy and the balance when determine the relay priority of each relay node in the relay node set, we introduce the fuzzy logic into this algorithm, which is good at deal with this kind of issue. In this algorithm, for getting the most accuracy and balance result on determining the relay priority for each node, many cross layer parameters are taken into account. However, the computation complexity of the traditional fuzzy logic algorithm increases exponentially with the increase of the input parameters. So in this algorithm, the parameters are not inputted into the fuzzy logic system directly, the variance of each parameter are the input of the fuzzy logic; the output of the fuzzy logic system is the weight of each parameter; then the utility of each node are determined based on the weight based approach in multi attribution utility theory.
3. According to the relay node priority determine algorithm and the coordination scheme proposed above, we propose a fuzzy logic based opportunistic routing for the underwater cooperation robot networks. In this algorithms, the residual energy, the link lifetime, the node distance, the ETX, the queue length, and the node delay are taken into account to determine the relay priority of each node.
4. Not only in the underwater environment, but also the terrestrial environment, we evaluate the proposed coordination scheme. In this section, the delay based redundant transmission avoid algorithm are evaluated in VANETs. In the VANETs, the most serious problem is that the speed of the vehicular is high, so the network topology changes greatly. For providing more accuracy information to the source node during the relay priority determining, in this algorithm, we propose a probability prediction algorithm based on the proposed coordination scheme. In this algorithm, before determine the relay priority of each vehicular, the source node predicts the probability that after a period of time, the SINR of the neighbors are still larger than the threshold and the probability that the queue length of the packet is smaller than the maximum allowed value. Then based on these two parameters and the coordination scheme, the relay nodes and the relay priorities of these nodes are determined based on the weight based approach in multi attribution utility theory.
5. In this thesis, we investigate the relationship between the energy consumption and interference optimal under controlling the transmission power of the nodes. Based on the analysis, we conclude that reduce the transmission power of nodes cannot guarantee low

energy network interference and energy consumption. When the network is interference optimal, then this network equals to that energy effective.

6. Based on the conclusions by the analysis the relationship between the energy consumption and interference optimal, we propose an energy effective topology control algorithm for the wireless sensor network. In this algorithm, for reducing the energy consumption, the $0.85r$ and the node degree of nodes are taken into account to set the transmission range of node, where r is the initial transmission range of node.
7. As that shown in the routing algorithms, not only in the terrestrial environment, we also investigate the effect of the topology control for the underwater cooperation robot network. For the underwater network, since the acoustic channel is narrower than the communication channel in the terrestrial environment, so the control cost in the underwater environment should be reduced as much as possible. Based on this analysis, we propose the probabilistic topology control for the underwater cooperation robot network. In this algorithm, when the transmission power does not equal to the optimal one, then the nodes change their transmission power probabilistic. The probability can be calculated based on the degree that parameters of nodes departure the optimal value or the threshold. The large deviation, the high adjustment probability is. Based on this, the control cost of the network reduces and the performance of the network is guaranteed.
8. For the opportunistic routing, one of the important issues is the number of nodes in the relay set. As introduced in the last section, if too many nodes in the relay set, the redundant transmission and network interference will be serious; however, if too less nodes in the relay set, then the packet delivery ratio of the opportunistic routing cannot be guaranteed. In this algorithm, we investigate how to combine the transmission power control with the opportunistic routing together to improve the performance of opportunistic routing. Based on the fact that the transmission power and the node degree are related; if optimizing the transmission power and the node degree separately, the results will not be accuracy. So based on the Pareto optimization method, in this algorithm, we optimize the transmission power with the node degree together to find the best combination of the transmission power and the node degree. Then all the nodes that covered by the transmission range of source node will be chosen as the candidate relay nodes; then the DDA algorithm is applied to optimized the relay node set.
9. As introduce in 7, in some applications, for reducing the control cost will guarantee the network performance, we divide the node into different categories based on the node degree of this node. The nodes are divided into healthy node and unhealthy node based on their node degree. If the number of nodes in the relay node set cannot meet the requirements of the packet delivery ratio, then the node is unhealthy; otherwise, the node is healthy. During the transmission power control, only the unhealthy nodes need to adjust their transmission power; the healthy nodes do not need to adjust their transmission power. When the relay node set has been chosen, then the source node optimizes the relay node set based on DDA algorithm.

1.4 Thesis structure

Before ending this chapter, the outline of this thesis is made as follows. The rest of this thesis consists of chapters:

1. Chapter 2 introduces the state-of-the-art related to this work, and discusses the models and the techniques which employed in this thesis.
2. Chapter 3 develops a mathematical model to analyze the properties of the stochastic network. In this chapter, the numerical analysis prove the effectiveness and the correctness of the mathematical model.
3. Based on the mathematical model and the analysis in Chapter 3, Chapter 4 presents a set of routing algorithms for both the underwater scenario and the terrestrial scenario.
4. Based on the mathematical model and the analysis in Chapter 3, Chapter 5 presents a set of topology control algorithms for both the underwater scenario and the terrestrial scenario.
5. Chapter 6 shows the experimental results of the proposed routing algorithms and topology control algorithms. In this chapter, both the theory analysis and the numerical analysis are presented. Moreover, the numerical analysis is proved the effectiveness of these algorithms and the correctness of the theory analysis.
6. Chapter 7 concludes this work, and points out the remaining challenges, which would be our future work.

Chapter 2

Related Works

This chapter provides a survey concerning the design of the routing algorithm and the topology control algorithm perceptively; moreover, the related mathematic methodologies are also introduced in detail in this chapter. Firstly, the network models and definitions that used for both the routing algorithms and topology control algorithms are presented; after that, the principles of the opportunistic routing and the transmission power control are introduced; finally, the optimal algorithms which will be used in the design of the routing algorithms and the topology control algorithms are introduced; these optimal algorithms include the fuzzy logic algorithm, the Pareto optimization, and the multi-attribute utility theory.

This chapter is also part of the contributions in this thesis, since it provides a reference for those researches who want to design the routing algorithm and topology control algorithm for both theoretical study and practical application point of view.

2.1 Network Models and Definitions

In the routing algorithms design and topology control algorithms design, there are some basic definitions and network models need to be introduced before the introduction of the proposed algorithms. In the following of this chapter, we will introduce them in detail.

In general, there are three models can express the connection mode between nodes, which are shown in Figure 2.1 [30]. Figure 2.1(a) illustrates the k nearest neighbor model; each node in this model has constant node degree and maintains the node degree by changing transmission power dynamically. Figure 2.1(b) illustrates the disc model; in this model, the transmission power is modeled as a disk with radius r ; the nodes connect with other nodes that fall into its communication range. Figure 2.1(c) illustrates the Erdos-Renyi random graph that connects any two nodes by the same probability. Disc model is more plausible in wireless network since obtaining k neighbors is not always feasible due to the communication range limitation [30]. Therefore, in this thesis, we only interested in the Disc model.

Figure 2.1. Different network models: (a) k nearest neighbor model; (b) disc model; and (c) Erdos-Renyi random graph.

There are two different kinds of Disc model: the Homogenous model and the Heterogeneous model, which are shown in Figure 2.2. The nodes in Homogenous model have the same transmission ranges while the nodes in the Heterogeneous model have different transmission ranges.

Figure 2.2. Different Disc Models: (a) Homogeneous Disc Model; (b) Heterogeneous Disc Model.

The transmission range of node relates to its transmission power. The receiving power of node at distance d when the transmission power is p_t can be expressed as:

$$p_{r,d} = \frac{G_t G_r \lambda^2 p_t}{(4\pi)^2 d^\alpha} \quad (2.1)$$

where p_t is the transmission power; G_t and G_r are the antenna gains of sender and receiver; λ is the wavelength; α is the path loss exponent and $2 \leq \alpha \leq 5$ depends on the geometry of propagation environment [31], i.e., when $\alpha = 2$, it means free space, when $2.7 \leq \alpha \leq 3.5$, it represents the urban area cellular radio, when $3 \leq \alpha \leq 5$, it represents the shadowed urban cellular radio, etc.

Based on (2.1), the transmission range of node when knowing the transmission power and the receiving power can be calculated as:

$$d = \left(\frac{G_t G_r \lambda^2 p_t}{(4\pi)^2 p_{r,d}} \right)^{1/\alpha} \quad (2.2)$$

Let $G = \frac{G_t G_r \lambda^2}{(4\pi)^2}$ is constant, then if the transmission power is changed, the transmission range also changed with fixed proportion; therefore, in this thesis, the transmission power and the transmission range are used exchangeable.

Based on Figure 2.1 and Figure 2.2, the transmission range of node is a circle. As shown in Figure 2.3, if node a can send data packet to node b , then the node b should located in the

transmission range of node a . In Figure 2.3, the node a can send data packet to node b ; however, node b cannot send data packet to node a ; node a and node c can send data packet to each other, since they are covered by the transmission ranges of each other. If node a and node c can communicate with each other, then the following constraints should be satisfied: $r_a \geq d_{ac}$ and $r_c \geq d_{ac}$. In the following, we defined the bi-direction communication link.

Figure 2.3. The communication links between different nodes

Definition 2.1. The bi-direction communication link between two nodes is defined as the communication link which can guarantee these two nodes can communicate with each other successfully, i.e., they are covered by the transmission ranges of each other, such as the communication link between node a and node c .

Based on Definition 2.1, assuming that the receiving threshold (the receiving threshold is the minimum receiving power which can guarantee correct decoding at the receiver) is P_{ths} , then the minimum energy $P_{t,min}$ required to transmit data packet from node a to node c is defined

$$\text{as } \frac{P_{ths}}{G} d^\alpha.$$

Definition 2.2. The one-hop neighbor nodes of node a are the nodes whose distances to node a are smaller than node a 's transmission range.

As shown in Figure 2.3, according to the definition of the one-hop neighbors, if node c is the neighbor of node a , then the node a is also the neighbor of node c . In Figure 2.3, even the node b locates in the communication range of node a , but it cannot send packet to node a due to the limitation of its transmission range, so node b is not the neighbor of node a . Node c is the neighbor node of node a , since node a also locates in the transmission range of node c .

Definition 2.3. The node degree of node a is defined as the number of one-hop neighbor nodes of node a . For instance, in Figure 2.3, the node degree of node a is 10.

Definition 2.4. The interference at node a is defined as the summary of the receiving power of its neighbor nodes at node a , which can be calculated as:

$$I_a = N + \sum_{i=1}^n \frac{G_t G_r \lambda^2 p_{i,t}}{(4\pi)^2 d_i^\alpha} \quad (2.3)$$

where N is the white Gaussian noise, n is the number of neighbors, $p_{i,t}$ is the transmission power of neighbor i , d_i is the distance between node a and neighbor i .

2.2 The opportunistic routing

Since the opportunistic routing has been proposed by Sanjit Biswas and Robert Morris [32], many opportunistic routing algorithms have been developed in recent years. In [32], the S. Biswas and R. Morris first proposed the concept of opportunistic routing, named ExOR. In ExOR, the routing protocol and the MAC layer operations are integrated together. The source node broadcasts a batch of packets to a list of nodes which can potentially forward these packets. Each neighbor in the forwarding list waits for its turn to transmit the received packets by using the same transmission strategy as source node. In [33], the authors propose a relaying node selection algorithm for 1-D wireless sensor network, named energy saving via opportunistic routing (ENS_OR). The ENS_OR selects the candidate relays set and prioritizes the nodes in it based on their virtual optimal transmission distance and residual energy level. The nodes which are closer to the energy equivalent nodes and have more residual energy than the source node will be selected as the relaying nodes. In [34], the authors propose two accurate energy consumption based objective functions, which exploit the knowledge of both the frame error ratio within the physical layer, the maximum number of retransmissions in the medium access control (MAC), and the number of relays in the network layer. Based on the objective functions, the routing algorithm is designed for opportunistic routing, which employs the objective functions to prioritize the nodes in the candidate relays set. The authors in [35] exploit the geographic opportunistic routing (GOR) for Quality of Services (QoS) provisioning with both the end to end reliability and delay constraints in wireless sensor networks (WSNs); moreover, the authors also define the problem of efficient GOR for multiconstrained QoS provisioning in WSNs. Based on these conclusions, the authors propose the Efficient QoS-aware GOR protocol for the WSNs, in which the energy efficiency, latency, and the time complexity are taken into account to select the relaying nodes. The authors in [36] propose a distributed optimal community-aware opportunistic routing algorithm, in which the home-aware community model is proposed. In this algorithm, first, the routing between lots of nodes are turned to the routing between a few community homes; then the algorithm maintains an optimal candidate relays set for each home. Each home only forwards its message to the node in its optimal candidate relays set. More opportunistic routings can be found in [37], [38] and [11]; especially in [11], the author reviews the opportunistic routing algorithms in recent years and identifies and discusses the future research directions related to the opportunistic routing design, optimization, and deployment. More opportunistic routing algorithms can be found in [39-42].

The principle of the opportunistic routing can be explained by Figure 2.4. Different with the deterministic routing, in opportunistic routing, when the source node s want to send data packet to the receiver node r , the node s will select a set of relay nodes (i.e., node1, node2, node3, node6) rather than only one relay node to improve the packet delivery ratio. These relay nodes is defined as the candidate relay set, denoted as CRS. The number of nodes in CRS (shown in Figure 2.4) is defined as relay node degree (RND), denoted by n_{rel} . As shown in Figure 2.4, the relay node degree of node s is 4.

The source node s selects and priorities the nodes in CRS based on the specific principles, such as the residual energy, the link life time between the source node and the relay node, the residual memory space, etc. When the nodes in the CRS are prioritized, the source node s sends the data packet to all the nodes in CRS, and these relay nodes will relay the data packet to the next hop relay node based on the coordination schemes [11]. According to the previous works,

the packet delivery ratio can be defined as follows.

Definition 2.5. The packet delivery ratio (PDR) for one hop transmission in opportunistic routing is defined as the data packet send by the sender can be received successfully by at least one relay node in CRS, which can be calculated as:

$$P = 1 - \prod_{i=1}^n (1 - P_i) \quad (2.4)$$

where P is the one hop PDR between sender and CRS; P_i is the packet delivery ratio between sender and node i ($1 \leq i \leq n$) in CRS, which can be measured by periodically beacon packet; n is the number of nodes in CRS. From (4), we can find that the more nodes in CRS, the higher P is; moreover, if the number of nodes in CRS is fixed, then the higher P_i of the relay nodes, the higher P is. So for improving the PDR, we can increase the number of nodes in CRS or choose the nodes which have high P_i as candidate relay nodes. However, too many nodes in CRS will cause high redundant transmission and transmission delay, and the nodes whose P_i are low have little contributions on improving the PDR, so the number of nodes and kinds of nodes in CRS should be optimized and filtered.

The forwarding process of the opportunistic routing can be consisted by four main steps [11]: 1) candidate relays set selection; 2) data broadcast to candidate relays; 3) best relay selection using a coordination scheme; 4) data forwarding.

Figure 2.4. The principle of opportunistic routing

2.2.1 Candidate relays set (CRS) selection

In opportunistic routing, each node broadcasts a packet to multiple next hop relay nodes simultaneously. So, if the transmission between the sender and one of its neighbors fails, then the other neighbors that received this packet can forward it to the next hop nodes. As we introduced in the last section, the number of the candidates in CRS should be limited; too many or too less candidates in CRS are not suitable. Since more than one candidate relay nodes receive the same packet when a packet is broadcasted to the CRS, so to avoid duplicate forwarding, only one of these candidates should be selected to carry on the packet forwarding. In the CRS, each node is assigned a relaying priority which is used to be computed based on a predefined metric. This means the node which has the highest priority in CRS receives the packet successfully will forward it to the next hop nodes. Otherwise, the node with the second highest priority forwards the packet, and so on. Therefore, the CRS selection can be divided into four main components: (1) candidate relays discovery; (2) prioritization metric computation, (3) candidate relays selection and prioritization, and (4) candidate relays

filtering.

1. The candidate relays discovery

The candidate relays discovery is also known as neighbor discovery. In this stage, the sender sends the period or non-period packet to discovery the neighbors which are reachable, i.e., the nodes that locate in its transmission range. Since the wireless communication link is highly variable and unstable, so in this stage, both the physical proximity and the quality of the communication link are taken into account. All the nodes that discovered by the sender are the candidate relay nodes. These nodes will be optimized future by delating some nodes based on the optimal algorithms.

2. Prioritization metric computation

For the candidate relays nodes in CRS, they are needed to be prioritized based on the candidate relays prioritization metrics. The priority metrics are chosen depends on the routing application requirements and objectives. There are many different kinds of prioritization metrics used in the opportunistic routing, such as the ETX [8, 16-18, 43], the ETT [44-46], the EAX [22-23, 47-48], the EATT [24], etc. For different scenarios, the prioritization metrics are also different; for instance, in the emergency recovery application, the location information is important, so the GOR is used in the candidate relays prioritization; in the fire detection application, which is delay sensitive, the EDC and DFD are used.

3. Candidate relays set optimization

As introduced in Chapter 1, although including more candidates in the CRS provides higher resiliency, for reducing the energy consumption, the interference, and the duplicate transmission, the number of nodes in the CRS should be limited [14-15]. On the other hand, if there are too many candidate relays in the CRS, the number of nodes that cannot hear one another increases. As demonstrated in [11], the candidate relays prioritization and filtering are done separately in the prior works. So the outcome of this phased is not necessarily optimal. Thus, it is necessary to jointly consider the node contribution and its duplicate probability in the CRS selection schemes design.

2.2.2. *Best relay selection and announcement*

Since in each hop, only one node in CRS can relay the data packet to the next hop node, so the sender chooses one available path to reach the destination on the fly. Which path is chosen is based on which node in the CRS receives the data packet successfully. So for the same sender and receiver, for different data packet, the path may different.

The most important process in this stage is that when the node in CRS receives the data packet successfully and relays the data packet to the next hop nodes, how it can inform the rest candidate nodes to avoid duplicate transmission. This is the relay announcement, which is also called the coordination method. The coordination scheme is used to find the appropriate candidate relaying nodes for packet transmission. In the past decades, many coordination schemes for the opportunistic routing algorithm have been proposed. These coordination schemes can select the best relaying node while incurring the smallest cost (in terms of the relaying delay, the duplicated transmission, etc.) and can be classified into four main classes: contention-based coordination [50][51][19], time-based coordination [32][17], token-based coordination [52][18], and random coordination [53]. In the following of this section, we will introduce the algorithms relate to these four schemes briefly.

In [17] and [32], the time-based coordination schemes are used. In [32], the concept of opportunistic routing is proposed. The source node prioritizes and chooses the candidate relaying nodes based on the values of nodes' estimated transmission count (ETX) to the destination node. The node which the ETX is small will be set with high priority to relay the packet. When the source node sends the packet, the relaying nodes relay in the order in which they appear in the forwarding list, highest priority first. Low priority relaying nodes drop the packet when they receive the ACK from the high priority relaying nodes during the waiting time; otherwise, relaying the packet. Similar to [32], in [17], the coordination scheme is the same as that introduced in [32]; moreover, in this algorithm the waiting timer is set to 45ms. For reducing the transmission delay in time-based coordination schemes, some algorithms introduce the network coding into the routing algorithm, such as in [16], [20], [54], and [55]. The network coding improves the network throughput and reduces the overhead; however, the issue of deciding when and how often to generate coded packets is still not solved in these researches [11].

The contention-based coordination scheme is used in [19], [50], and [51]. In [50], the source node sends RTF (Request to Forward) packet, the neighbors who receive this RTF packet will reply CTF (clear to forward) packet to the source node. These CTF packets' transmission is competitive with each other. The neighbor which the CTF packet is received by the source node will be the next hop relaying node. The forwarding scheme used in [51] is the similar contention-based scheme with that used in [50]. The coordination approach used in [19] is different with that shown in [50] and [51]. In [19], when the candidate relaying nodes receive the packet transmitted from the source node, they will contend the same transmission channel to relay the packet to the next hop relaying nodes; the candidate relaying node which competes to the communication channel will transmit the packet to the next hop relaying nodes.

In the token-based coordination schemes, such as [18] and [52], since only the node which holds the token can transmit packets, so the duplicate transmission is reduced greatly. However, in the token-based coordination scheme, the control cost is pretty high. When the source node transmits the packet to the candidate relaying nodes, the relaying nodes receive and store the packet. The relaying node is allowed to relay the packet only it receives the tokens. The tokens include the acknowledgement information and are passed from high priority relaying node to low priority node. The candidate relaying nodes receive the tokens and can only transmit the unacknowledgement packet. Similar to the time-based coordination scheme, in the token-based coordination scheme, the candidate relaying nodes should also be fully connected.

For reducing the waiting delay in the above coordination schemes, in [53], the authors propose the random selection coordination scheme. In this scheme, each candidate relaying node decides whether to continue forwarding the packet to the destination or not probabilistically, so the relaying delay that caused by the waiting timer is reduced greatly. However, in this scheme, since the candidate relaying nodes decide whether forwarding or not probabilistically, so the duplication transmission is serious.

In this thesis, the coordination method is the time based coordination method. The time based coordination scheme can be found in Figure 2.5.

Figure 2.5. The time based coordination scheme

As shown in Figure 2.5, when the source node s has send the data packet to the relay node set, the nodes in the CRS which receive the data packet will check the relay node list. If the node is in the relay node list, then it will acquire its relaying priority and set the waiting time as that shown in Figure 2.5 accords to its relaying priority. The waiting time can be set based on Figure 2.5, which is:

$$t_i = (i - 1)T \quad (2.5)$$

where t_i is the waiting time of the relaying node whose relaying priority is i th in CRS, i is the relaying priority of the relaying node, and T is the interval of the time slot. If the relaying nodes receive the acknowledgement from the higher priority relaying nodes during its waiting time, then the node will drop the data packet directly; otherwise, if the relaying nodes do not receive the acknowledgement from the higher priority relaying nodes in its waiting time, then at the end of the waiting time, the relaying node will relay the data packet to the next hop relay nodes. This process will be repeated until the data packet is received by the final receiver. Therefore, the transmission delay in this coordination scheme can be defined as follows.

Definition 2.6. One hop transmission delay in opportunistic routing based on the time based coordination scheme is defined as the time needed for transmitting data packet from sender to the CRS, which can be calculated as:

$$DT = (\sum_{i=1}^{n-1} i P_{i+1} \prod_{j=1}^i (1 - P_j) + n \prod_{i=1}^n (1 - P_i))T \quad (2.6)$$

where i is the relaying priority of the relay nodes in CRS; n is the number of relaying nodes in CRS; T is the interval between two time slots.

2.2. 3 Data forwarding and acknowledgment

Once the data packet is forwarded by the selected relay node, for providing reliable transmission, the ARQ mechanisms will be needed at the network layer and link layer. There are two different kinds of acknowledgment mechanisms: the end-to-end approach that generated by the final destination [8][17][20] and the hop-by-hop approach that generated by the forwarders in CRS [56][57]. The end-to-end approach can reduce the packet overhead at the cost of high transmission delay since the forwarding progress depends on the acknowledgements generated by the destination. The hop-by-hop approach has small transmission delay; however, the extra overhead in this approach is high. In this thesis, we use

the hop-by-hop acknowledgment approach in the opportunistic routing.

2.3 Topology control

In this section, we will introduce the principle of the topology control technologies used in IoT applications briefly; moreover, a review of the topology control algorithms in recent years has been presented.

2.3.1 Overview of the topology control

Topology control is an important technique used in wireless network to achieve energy conservation and improve network reliability without affecting the important network performance such as connectivity and throughput. The idea of topology control is to grant nodes a sense of control over certain parameters such that these parameters can be manipulated in a way that benefits the network [12]. In particular, wireless nodes have the capacity to adjust their transmission power, switch to the various operation modes or even decide on the eligibility of the nodes joining the network backbone. These features are the parameters that are exploited in enforcing a reduced topology to achieve energy saving and improve network reliability.

In wireless network, a topology provides information about a set of nodes and connectivity (links) between a pair of nodes in the network. To construct a network topology, each node discovers its neighbors and relative links using its maximum transmission power. Based on the information gathered, the node can build a network. The disadvantage of this approach is that the network created might be either too dense (which is vulnerable to excessive interference) or too sparse (which is highly susceptible to network partitioning) [58]. To avoid this problem, a proper topology control should be employed to eliminate the unnecessary links in the dense network without sacrificing the network performance.

The main objectives of topology control are two-fold. The first objective is to save energy and reducing the network interference. Topology control offers a mechanism that allows nodes to vary their transmission power which potentially reduces the energy consumption during transmission. As a result, the long distance communication links are dropped while the short distance communication links are chosen. From the perspective of energy consumption and interference, a direct communication over short distance is more energy efficient than the long distance communication [59]. Therefore, reducing the transmission power will eliminate the long distance links which waste energy. The second objective is to overcome collisions. Other than discarding the inefficient links, the use of minimal transmission power successfully removes the long distance links, thus resulting in a sparse network. The effects of this include a reduction in the packet retransmissions and interference, and an improvement in the network capacity.

Topology control can be implemented in three ways: 1) minimizing the energy consumption during transmission by means of adjusting the transmission power of nodes, which is a common approach adopted; 2) reducing the energy consumption by adjusting the operation model of nodes; this approach can provide a substantial energy saving since the energy consumption in idle mode is quite significant in comparison with the energy consumed during the sleep mode [60]; 3) topology control can be performed through a clustering approach; based on selection criteria, nodes select a set of neighbors to form a cluster, which provides

control over the topology to achieve energy saving and permits a structured hierarchical network architecture; the potential selection criteria are residual energy, the number of neighboring nodes or the node identifier; in clustering, data forwarding and aggregation are dedicated to the nodes in the set to restrict the number of packet retransmission and maximize energy resources.

In recent years, many topology control algorithms have been proposed for different scenarios and applications. The purposes of these algorithms are different, and the methods used in these algorithms are also different. In the following of this section, we will review these algorithms briefly. The latest surveys of network topology control algorithms can be found in [74-75, 83-84]. The primary goals of topology control are to guarantee the network connectivity and reliability, and reduce the energy consumption and network interference as far as possible.

For improving the connectivity and the reliability of WSNs, in [61], the authors proposed a novel fuzzy-logic topology control (FTC) algorithm to achieve any desired average node degree by adaptively changing the nodes' transmission power. The FTC algorithm does not rely on location information of neighbors and is constructed from the training data set to facilitate the design process. In [62], for reducing energy consumption and end to end delay of WSNs, the authors proposed an optimization problem for energy consumption in WSNs, in which the topology control and the network-coding based multi-cast are combined together. This optimization problem is transformed into a convex problem which offers numerous theoretical and conceptual advantages. In this algorithm, the Karush-Kuhn-Tucker optimality conditions are presented to derive analytical expressions of the globally optimal solution. By these innovations, the performance of energy consumption and end to end delay was improved. In [63], the authors investigated a dynamic topology control scheme to improve the network lifetime for WSNs in the presence of selfish sensors, and propose a non-cooperative game-aided topology control approach to design energy-efficient and energy balanced network topologies dynamically. The nodes in the topology control game try to minimize their unwillingness to construct a connected network according to their residual energy and transmission power. In [64], considering the lossy links which can only provide probabilistic connectivity in network, the authors propose the probabilistic topology control (PTC). In PTC, the network connectivity is metered by network reachability and is defined as the minimal upper limit of the end-to-end delivery ratio between any pair of nodes in network. The PTC algorithm can find a minimal transmission power for each node while the network reachability is above a given application-specified threshold. Moreover, in [64], due to the lossy links in the real environment (which can provide only probabilistic connection), the authors propose a novel probabilistic network model, in which the network connectivity is metered by the network reachability. The authors explore the minimal transmission power for each node when the network reachability is above a given threshold. Based on the conclusion, the authors propose BRASP algorithm to improve the energy efficiency and reduce the average node degree. The adaptive disjoint path vector (ADPV) algorithm has been proposed for heterogeneous WSNs in [65]. In ADPV, the algorithm is divided into two phases: single initialization phase and restoration phase. The restoration phase utilizes the alternative routes that are computed in the initialization phase with the help of a novel optimization algorithm which is based on the well-known set-packing problem. The simulation results demonstrate

that the ADPV is superior in preserving super node connectivity. The authors in [66] consider that topology control has never achieved breakthroughs in real world deployment; moreover, the authors identify five practical obstacles of topology control algorithms at present. To address these obstacles, the authors propose a re-usable framework for implementation and evaluation of topology control. In [67] the authors propose the concept of a disjoint path vector (DPV) algorithm for a heterogeneous network in which the large number of sensor nodes has limited energy and computing capability and there are several supernodes with limited energy and unlimited computing capability. The DPV algorithm addresses the k -degree any-cast topology control problem where the main objective is to assign each sensor's transmission range such that each node has at least k -vertex-disjoint paths to super nodes and the total power consumption is minimized. The resulting topologies are tolerant up to $k-1$ node failures in the worst case. In [68], to enhance the energy efficiency and reduce the radio interference in WSNs, the authors propose a new distributed topology control algorithm. In this algorithm, each node makes local decisions about its transmission power and the culmination of these local decisions produces a network topology that preserves global connectivity. The main idea of this topology control algorithm is the novel Smart Boundary Yao Gabriel Graph (SBYaoGG) and the appropriate optimizations to ensure that all links in network are symmetric and energy efficient. The more recent researches on topology control can be found in [69–73]. Moreover, detailed introductions and comparisons between different topology control algorithms can be found in reviews, such as [74–76].

There are also many heuristic topology control algorithms have been proposed, such as, Local Minimum Spanning Tree (LMST) [85], Local Tree-based Reliable Topology (LTRT) [86], A1 [87], Poly [88], Centralized Robust Topology Control Algorithm (CRTCA) [89], Cooperative topology control scheme with Opportunistic Interference Cancellation (COIC) [90], Local Mean Neighbor (LMN) [91], Local Mean Algorithm (LMA) [91], etc. Almost all of these protocols regard topology control as a technique in which nodes dynamically change their transmission ranges to gain energy efficient and network connection. In [85], each node builds its own LMST independently and only on-tree nodes that one-hop away are kept in the final topology. Considering the fact that the LMST always constructs one-connected network in the final topology, in [86], the authors propose LTRT algorithm, which combines the idea of LMST and Tree-based Reliable Topology (TRT) together to guarantee k -edge connectivity in the resulting topology. LTRT can maintain the network connection at low computational cost and energy consumption. A1 assumes the network topology as a connected network and finds a set of active nodes to form connected dominating set (CDS) [87]. This algorithm can form a reduced topology while keeping the network connection and coverage at the same time. In addition, A1 forms the CDS which comprising high energy nodes in a single phase construction process and a set of active nodes for energy efficiency and better sensing coverage, respectively. Similarly with A1, Poly [88] is also the algorithm based on CDS. In Poly, the network is modeled as a connected graph. The protocol can turn off the unnecessary node and keep the network connection and coverage at the same time. LMN and LMA are the two typical power adjustment topology control algorithms [91]. In LMA, all the nodes can get their node degree. The algorithm sets the minimum threshold and maximum threshold for this number; if the node degree is less than the minimum threshold, the transmission range will be increased; otherwise, transmission range will be reduced. The principle of LMN is similar

with LMA, but LMN does not set the maximum and minimum thresholds for the node degree. In LMN, the nodes use the mean neighbors' node degree as the threshold to adjust the transmission ranges.

For reducing the interference in wireless network, a large number of researches have been implemented. In [28-29], first, the authors show that reducing the transmission range cannot guarantee low network interference; then they propose several algorithms to construct topologies in which the maximum link interference is minimized while the network is still connected. In [92], the authors have discussed different methods which are used to measure network interference and proposed a new topology control algorithm to describe the interference of the entire network. The new algorithm minimizes the network interference and successfully maintains the spanner properties of the original network. The work in [93] studies the interference in WSNs and proposes several algorithms to construct topologies such that the maximum node interference and the average node interference are minimized. In [94], the authors propose an interference-based topology control algorithm for the delay constrained mobile ad hoc network (ITCD). In this algorithm, the impact of node mobility on ITCD is investigated. Moreover, the transmission delay, the contention delay, and the queuing delay are taken into account to remove the unstable communication links. For reducing the link interference in co-channel wireless ad hoc and sensor networks, in [95], the authors propose a new link interference model. Based on this model, a centralized topology control algorithm is designed to construct an interference-optimal network. The new interference model can also be found in [96]. This interference model can not only reflect the fact that interference occurs when the node is receiving a message, but also demonstrates robustness when adding or removing nodes from the network. In [97], the authors investigate how to minimize the average interference when a node is receiving message. In this paper, the 1-D (1-Dimensional) and 2-D (2-Dimensional) networks are studied; and two exact algorithms are proposed to minimize the average interference of 1-D and 2-D networks, respectively. Based on the PRR-SINR (Packet Reception Ratio versus Signal to Interference Plus Noise Ratio) model, in [98], the authors propose an accuracy-aware algorithm for interference modeling and measurement in WSNs. This accuracy-aware algorithm can characterize the accuracy of the PRR-SINR model and enforce a specified accuracy bound by adaptively controlling the measurement process during the run time. In [99], the authors define an explicit notion for network interference and propose an interference model based on the current network traffic. The work in [100] models the interference with physical signal and noise ratio, and defines the concept of scheduling complexity for the wireless network connectivity. In [101], the authors present a comprehensive survey on the interference models for wireless ad hoc networks. The survey emphasizes the domains of the application and illustrates them with examples. There are also many research papers which are devoted to measuring the interference in WSNs, such as [102–105]. In [102], the authors take the shadowing and fading effects into account to determine the interference range of the link. The link interference is determined by the interference number which is calculated based on the real coverage region. The interference measurement algorithms also can be found in [103] and [104]. In [103], a passive interference measurement approach which is derived from the actual physical model has been presented. In [104], the authors propose SoNIC (Sensor Network Interference Classification) to detect interference in an 802.15.4 sensor network which shares 2.4 GHz

with other Bluetooth and Wi-Fi devices. The authors in [105] investigate interference prediction in MANETs (Mobile Ad Hoc Networks) (in which the node number is finite) by using a general-order linear model.

The topology control algorithms of underwater WSNs are not as extensively investigated as that of the terrestrial WSNs. In [77], considering the signal irregularity phenomenon can affect network performance, especially in underwater environments, the authors constructed an authentic signal irregularity model which can easily be degenerated into a variety of special cases. Based on this model, three representative topology control objectives are concluded in this work. In [78], two topology control algorithms are proposed for underwater WSNs: improved Distributed Topology Control (iDTC) and Power Adjustment Distributed Topology Control (PADTC). These two algorithms can increase network throughput while conserving energy at the same time. The algorithms guarantee the delivery of data by dealing with the communication void problem in geographic opportunistic routing. In [79], the authors investigate scale-free underwater WSNs. The algorithm begins with a scale-free network model for calculating the edge probability, which is used to generate an initial topology randomly. Subsequently, a topology control strategy based on complex network theory is put forward to construct a double clustering structure, where there are two kinds of cluster-heads to ensure connectivity and coverage. Considering that using the Global Positioning System (GPS) may not be feasible in adverse underwater environments and the anchored sensor nodes towed by wires are prone to offset around their static positions which causes each node to move within a spherical crown surface, in [80], the authors propose a mobility model for underwater WSNs and three representative topology control objectives are attained. Based on these objectives, the authors design a distributed radius determination algorithm for the mobility-based topology control problem. Due to the fact the coverage requirements in different regions are probably different in underwater environments, in [81], the authors proposed two algorithms for different coverage problems in underwater WSNs: a Traversal Algorithm for Different Coverage (TADC) and a Radius Increment Algorithm for Different Coverage (RIADC). The TADC adjusts the sensing radii at each round and the RIADC sets the sensing radii of nodes incrementally at each round. In [82], the authors illuminated network topology modeling from a routing viewpoint. The probabilistic multipath routing behavior which is driven by opportunistic routing protocols in underwater WSNs are modeled in this paper. Based on these models, the authors proposed the PCen centrality metric to measure the importance of underwater sensor nodes to the data transmission through opportunistic routing, which is aimed at identifying critical nodes that can be used to guide topology control solutions.

2.3.2 Definitions of topology control in wireless network

The phrase topology control has been interchangeably used with transmission power control and its concept is defined in many contexts. In this thesis, we define topology control as a technique that uses any controlled network parameter to generate and maintain a topology for the benefits of reducing energy consumption and achieving a desired property for an entire network. The possible controlled parameters that can be modified to gain a desired topology are transmission power, operation model of nodes, and role of nodes.

In this thesis, we use the definition of topology control that defined in [12], which is more

comprehensive and accuracy than the previous definitions [28, 59, 106-110]. The [12] considers that the techniques use any controlled parameter to configure the network topology for achieving energy saving can be regarded as topology control. Another definition for topology control used popularly is transmission power control [111-113]. Paolo [114] describes power control as a technique in which nodes adjust the transmission power to achieve energy efficient.

In this thesis, the topology control algorithms are mainly based on the transmission power control technology. For the transmission power control based approach, each node in the network maintains the network connection, the energy consumption, or the network interference by adjusting the transmission power of nodes dynamically based on the network condition. So in the following, we define the transmission power adjustment ratio for the transmission power control method.

Definition 2.7. The transmission power adjustment ratio (TAR) is defined as the ratio of the number of nodes which adjust their transmission power to the number of nodes in the whole

network, which can be expressed as: $C_{TAR} = \frac{\text{nodes adjust the transmission power}}{\text{total nodes in the network}}$.

As introduced in Section 2.1, the transmission range of node relates to its transmission power. The number of nodes in the coverage area of node is not fixed, it relates to nodes' distribution in the network. There are many different distribution models for the wireless network applications. For instance, many researches regard the nodes in WSNs are distributed uniformly; in the vehicular ad hoc network (VANETs), the vehicles can only move along the street, so the network distribution and topology are quite different with that in the traditional mobile ad hoc networks (MANETs). For the uniform distribution network, the relationship between the number of nodes in the coverage area and the transmission power can be expressed by the probability function defined as follows.

Definition 2.8. For the uniform distribution, if the transmission power is p , then the probability that there are n nodes in its coverage area can be calculated as: $P(n) =$

$\frac{(\rho\pi d^2)^n}{n!} e^{-\rho\pi d^2}$, where d can be calculated based on (2.2).

2.4 The mathematic methods

In this section, we will introduce the mathematic methods used in this thesis. The mathematic methods used in this thesis include the fuzzy logic, the multi-attribution utility theory, and the Pareto optimal. In the following of this section, we will introduce these mathematic methods briefly.

2.4.1 Fuzzy logic

A. Overview of fuzzy logic

Fuzzy logic is a form of many-valued logic in which the truth values of variables may be any real number between 0 and 1. It is employed to handle the concept of partial truth, where the truth value may range between completely true and completely false [115]. By contrast, in Boolean logic, the truth values of variables may only be the integer values of 0 or 1. Fuzzy logic has been applied in many fields, from control theory to artificial intelligence.

In fuzzy logic, the input value might have several separate membership functions that used to

define the particular value range of the input to control the system properly. Each function maps the same input to a truth value between 0 and 1. These truth values can then be used to determine how the system should be acted or controlled. In fuzzy logic, the non-numeric values are used to facilitate the expression of rules and facts [116]. For instance, a linguistic variable such as age may accept values such as young and its antonym old. Since natural languages do not contain enough value terms to express a fuzzy value scale, it is common practice to modify linguistic values with some pacific words; for instance, the hedges rather and somewhat to construct the additional values rather old or somewhat young.

The fuzzy logic becomes popular recently in many research areas, such as the artificial intelligence, the optimal theory, the decision making theory, etc. For the wireless network, many fuzzy logic based routing algorithms and topology control algorithms have been proposed. In [117], the authors propose an energy-effective cross-layer routing protocol for wireless sensor networks based on fuzzy logic. In this protocol, for minimizing the consumed energy and maximizing the network lifetime, the algorithm takes the remaining battery reserve capacity, the link quality, and the transmission power of the neighbor nodes into consideration to select the next hop relay nodes, dynamically. In [118], for reducing the average end-to-end delay of the mobile *ad hoc* network, the authors propose a fuzzy logic-based adaptive cross-layer routing protocol for the delay-sensitive applications. In this algorithm, each node can switch between reactive routing mode and proactive routing mode based on the current node status separately. The algorithm uses the fuzzy logic controller to decide the routing model of each node. The inputs of the fuzzy logic controller are the number of link breaks, the interface queue length, and the type of application for each node. In [119], the authors introduce a new routing algorithm for the wireless sensor network to extend the network lifetime and balance the energy consumption by combining the fuzzy approach and the A-star algorithm together. In this algorithm, the remaining battery power, the number of hops to the destination node, and the traffic loads are taken into consideration to determine an optimal routing path from the source node to the destination node. In [120], to prolong the lifetime of the wireless sensor network, a fuzzy logic-based energy-optimization routing protocol is proposed. In this algorithm, the social welfare function is used to predict inequality of residual energy of neighbor nodes after selecting different next hop nodes. The algorithm computes the degree of energy balance based on the energy inequality. The fuzzy logic system uses the degree of node closeness to the shortest path, the degree of node closeness to sink, and the degree of energy balance to achieve the routing decision. Additionally, in [121], the node density, the delay, and the number of dead nodes are the inputs of the fuzzy logic system to select the next hop relay node to achieve the balanced energy consumption across all of the sensor nodes with minimum delay. In [126], the authors propose an energy-effective cross-layer routing protocol for WSNs based on fuzzy logic. In this protocol, for minimizing the energy consumption and maximizing the network lifetime, the algorithm takes the remaining battery reserve capacity, the link quality, and the transmission power of the neighbor nodes into account to select the next hop relaying nodes. In [127], for reducing the average end-to-end delay of the MANETs, the authors propose a fuzzy logic based adaptive cross-layer routing protocol for the delay-sensitive applications. In this algorithm, each node can switch between reactive routing mode and proactive routing mode based on the current node status separately. The algorithm uses the fuzzy logic

controller to decide the routing mode of each node. In [128], the authors propose a routing algorithm for WSNs which can extend the network lifetime and balance the energy consumption by combining the fuzzy approach and the A-star algorithm together. The remaining battery power, the number of hops to the destination node, and the traffic loads are taken into consideration to determine the optimal routing path from the source node to the destination node. Similar in [129], to prolong the network lifetime, a fuzzy logic based energy-optimization routing protocol is proposed, in which the social welfare function is used to predict inequality of residual energy of neighbor nodes. The algorithm computes the degree of energy balance based on the energy inequality. The fuzzy logic system uses the degree of node closeness to the shortest path, the degree of node closeness to sink, and the degree of energy balance to achieve the routing decision. Additionally, in [130], the node density, the delay, and the number of dead nodes are used as inputs of the fuzzy logic system to select the next hop relaying node for achieving the balanced energy consumption of all the nodes with minimum delay. More related works about the fuzzy logic based routing algorithms can also be found in [122–125] and [131–134].

B. The principle of fuzzy logic

As shown in Figure 2.6, the fuzzy logic system is composed by three modules: fuzzification, fuzzy logic inference, and defuzzification [135][136].

Figure 2.6. The process of fuzzy logic system

In fuzzification module, the input universes are mapped to fuzzy set based on the linguistic variables and membership functions. Assuming that the input universe is U and the fuzzy set of universe U is A ; μ_A is the membership function which maps universe U to fuzzy set A . The membership function represents the membership between universe U and fuzzy set A : $\mu_A: U \rightarrow A \in [0,1]$. The fuzzy set A can be expressed as: $A = \{(u_i, \mu_A(u_i)) | u_i \in U\}$, where u_i is the element of universe U . The general definition of membership function is:

$$\begin{cases} \mu_A(u_i) = 1: \mu_i \text{ belongs to } A \text{ Complete;} \\ \mu_A(u_i) = 0: \mu_i \text{ does not belong to } A \text{ Complete;} \\ 0 < \mu_A(u_i) < 1: \mu_i \text{ belongs to } A \text{ partly;} \end{cases} \quad (2.7)$$

The fuzzy set A is the input of the fuzzy inference module which will be used to calculate the output fuzzy set B . The core part of the fuzzy inference system is the *if-then* rules (fuzzy rules). The *if-then* rules determine the relationship between the inputs (fuzzy set A) and outputs (fuzzy set B). The form of the fuzzy rule is generally expressed as:

$$\text{If } A \text{ (input) then } B \text{ (output)} \quad (2.8)$$

where A and B are the fuzzy sets of universe X (input) and Y (output), respectively. The membership functions are $\mu_A(x_i)$ and $\mu_B(x_i)$, where $x_i \in X$, $y_i \in Y$. Thus, according to the fuzzy mathematic theory (Mamdani fuzzy inference algorithm), the membership function between fuzzy set A and fuzzy set B can be decided by:

$$\mu_{A \rightarrow B}(x, y) = \mu_R(x, y) \triangleq \mu_A(x) \wedge \mu_B(y) \quad (2.9)$$

where R represents the fuzzy relationship between universe X and universe Y , i.e., $R = A \rightarrow B$; “ $\wedge$ ” is the conjunction operator in discrete mathematics. By (2.9), the fuzzy result can be got.

However, for taking more cross-layer performance metrics into account, the fuzzy rules will be much more complex than that shown in (2.8), which is a multi-inputs-single-output fuzzy system. In this scenario, the fuzzy rules will be:

$$\text{If } A_1, A_2, A_3, \dots, A_n \text{ then } B \quad (2.10)$$

where $A_1, A_2, A_3, \dots, A_n$ (inputs) and B (output) are the fuzzy sets of universes $U_1, U_2, U_3, \dots, U_n$ (inputs) and U (output), respectively. The membership functions are $\mu_A(u_1), \mu_A(u_2), \mu_A(u_3), \dots, \mu_A(u_n), \mu_B(u)$, where $u_1 \in U_1, u_2 \in U_2, u_3 \in U_3, \dots, u_n \in U_n$, and $u \in U$. So the membership function can be expressed as:

$$\begin{aligned} \mu_{\{A_1, A_2, A_3, \dots, A_n\} \rightarrow B}(u_1, u_2, u_3, \dots, u_n, u) &= \mu_R(u_1, u_2, u_3, \dots, u_n, u) \\ &\triangleq \mu_{A_1}(u_1) \wedge \mu_{A_2}(u_2) \cdots \mu_{A_n}(u_n) \wedge \mu_B(u) \end{aligned} \quad (2.11)$$

where $R = \{A_1, A_2, A_3, \dots, A_n\} \rightarrow B$ is the fuzzy relationship between universe $U_1, U_2, U_3, \dots, U_n$ and U .

As shown in (2.11), in multi-inputs-single-output fuzzy system, the number of the permutation and combination between the fuzzy sets are huge. The (2.11) illustrates that with the increasing of the fuzzy set, the calculation complexity of the fuzzy logic system increases seriously. Moreover, if we take the number of linguistic variables into account, the calculation is too complexity to be accepted. For instance, if the number of linguistic variables for each fuzzy set is n and the number of fuzzy sets is m , then according to (2.11), the total number of the fuzzy rules is n^m . This means that with the increasing of either the fuzzy set or the linguistic variables, the number of the fuzzy rules will increase exponential. The large number of fuzzy rules needs large memory space of nodes, which is always impractical in wireless networks.

2.4.2. The multi-attribute decision making

A. Overview of the multi attribute decision making (MADM)

In the decision theory, a multi-attribute utility function is used to represent the preferences of an agent over kinds of choices either under conditions of certainty about the results of any potential choice, or under conditions of uncertainty [137]. The MADM is an economic terms, and the decision of MADM is based on the attributes of two or more options. For instance, a person has to select between two employment options: option A gives 12K per month and 20 days of vacation, while option B gives 15K per month and only 10 days of vacation. The person has to decide between (12K,20) and (15K,10). Different people may have different preferences. Under certain conditions, a person's preference can be represented by a numeric function. According to these properties, we can find that MADM is very suitable for the relay priority determination in opportunistic routing.

The mathematic principle can be explained by the multi-attribute utility theory (MAUT) as follows [137]. The goal of MAUT is to calculate a utility function $u(x_1, x_2, \dots, x_n)$ which

represents the person's preferences on different options, i.e., option i is preferred over option j if and only if the utility function u_i is higher than u_j :

$$u_i(x_1, x_2, \dots, x_n) > u_j(x_1, x_2, \dots, x_n) \quad (2.12)$$

B. The principle of MADM [138][139]

The model of the multi-attribute decision making can be expressed as: $\max_{a \in A} U(a)$, where a is the decision variable, A is the set of all the decision variables and $A = \{a_1, a_2, \dots, a_n\}$. The utility function $U(a)$ is consistent by n single utility functions $u_i(a)$ ($i = 1, 2, \dots, n$) and $U(a) = [u_1(a), u_2(a), \dots, u_n(a)]^T$. A multi attribute decision making issue can be expressed by a matrix $D = (u_{ij})_{m \times n}$, in which u_{ij} means the utility of a_i under j . The u_{ij}

can be quantitative values or qualitative value. The $i \in I = \{1, 2, \dots, m\}$ is the set of choices; $j \in J = \{1, 2, \dots, n\}$ is the set of attributes. Then $u_i = (u_{i1}, u_{i2}, \dots, u_{in})$ is the utility of a_i under different attributes; $u_j = (u_{1j}, u_{2j}, \dots, u_{mj})$ is the set of utilities under the same attribute.

The objective of MADM is to find the best scheme or rank the schemes. Since it is difficult to find a scheme which is the best on all aspects, so there are many MADM approaches and algorithms are proposed. These algorithms include the Simple linear weighting algorithm (SWA), WP algorithm, TOPSIS algorithm, AHP algorithm, ELECTRE algorithm, and PROMETHEE algorithm. The SWA algorithm is used in this thesis, which is easy to be understood and accepted, and is widely used in many areas.

In the SWA algorithm, first, the decision maker (in this thesis, it is the node who want to transmission data packet) decides the weights for each attributes and normalizes the attributes; then the decision maker calculates the utilities of each schemes based on the linear weight method; then the priorities of each schemes are determined based on their utilities. The process of the SWA algorithm can be demonstrated as follows.

1. The decision maker decides the weights for each attributes based on some criterions. Assuming the set of weights is $\omega = (\omega_1, \omega_2, \dots, \omega_n)$, then all these weights should satisfies $\omega_i \in [0, 1]$ and $\sum_{i=1}^n \omega_i = 1$;
2. Normalizing the decision matrix, which is $D' = (u'_{ij})_{m \times n}$, where D' and u'_{ij} are the decision matrix and utility after normalized, respectively;
3. Calculating the utility of each scheme via the linear weight method, which is: $U_i = \sum_{j=1}^n \omega_j u'_{ij}$, $i \in I = \{1, 2, \dots, m\}$.
4. Based on the value of U_i , $i \in I = \{1, 2, \dots, m\}$, the schemes are ranked.

Whether this utility function is suitable enough to evaluate different scheme can be proved based on the MAUT which is introduce in next section.

C. Sensitivity analysis [138][139]

In MADM, the final utility is calculated based on some decision factors, such as the attribute, the weight, etc. So the sensitivity analysis of the MADM is to analyze when these factors are changed, and how the final utility and the rank of the schemes change. If the changing of the attribute or the weight makes the utility changes greatly, even can affect the rank of the schemes, then we called the sensitive is high, i.e., the robustness is poor; otherwise, the

sensitive is low and the robustness is good. The common method to evaluate the sensitive of the algorithm is the perturbation method; the idea of perturbation method is changing the value of attribute or weight slightly and finding out how the final utility changes.

Assuming that the utilities of schemes $s_1, s_2, \dots, s_n$ and the weights of attributes $f_1, f_2, \dots, f_n$ are $w_1, w_2, \dots, w_n$, respectively. Let $s_i = (a_{i1}, a_{i2}, \dots, a_{im})$, $i = 1, 2, \dots, n$, where a_{ij} is the value of s_i under attribute f_j , then the decision matrix will be $A = (a_{ij})_{m \times n}$.

Assuming the norm of decision matrix is $\|A\|$, then the $\|A\|$ can be calculated as: $\|A\| = \max\{|a_{ij}| | i = 1, 2, \dots, m; j = 1, 2, \dots, n\}$. The norm of the weight matrix $w = \{w_1, w_2, \dots, w_n\}$ is $\|w\|$ and can be calculated as: $\|w\| = \max\{|w_i| | i = 1, 2, \dots, m\}$. For the SWA algorithm, the utility of scheme s_i can be calculated as:

$$u_i = \sum_{j=1}^n a_{ij}w_j, \quad i = 1, 2, \dots, m \quad (2.13)$$

Let $h = \min\{|u_i - u_j|; i \neq j; i, j = 1, 2, \dots, m\}$; then if the weight w_i has a small disturbance Δw_i (the set of disturbance is $\Delta w = \{\Delta w_1, \Delta w_2, \dots, \Delta w_n\}$), then the variable of the utility u_i (the set of the variable is $\Delta u = \{\Delta u_1, \Delta u_2, \dots, \Delta u_n\}$) can be calculated as:

$$\Delta u_i = \sum_{j=1}^n a_{ij}\Delta w_j \quad i = 1, 2, \dots, m \quad (2.14)$$

Then $\Delta u_i = \sum_{j=1}^n a_{ij}\Delta w_j \leq \sum_{j=1}^n |a_{ij}||\Delta w_j| \leq \sum_{j=1}^n \|A\|\|\Delta w\| = n\|A\|\|\Delta w\|$. Since if

$|\Delta d_i| < h$, then the results of the decision is stable, i.e., if $\|\Delta w\| < \frac{h}{n\|A\|}$, then the result of

decision is unchanged. Then the following corollary can be got.

Corollary 2.1. For the SWA algorithm, if the disturbance of the weight satisfy the condition

$\|\Delta w\| < \frac{h}{n\|A\|}$, then the decision result is stable during the disturbance.

In the following, we will investigate the effect of the disturbance of a_{ij} on the decision. The disturbance of a_{ij} is $\Delta A = (\Delta a_{ij})_{m \times n}$. According to (2.14), the disturbance of u_i can be

calculated as: $|\Delta u_i| = |\sum_{j=1}^n \Delta a_{ij}w_j| \leq \sum_{j=1}^n |\Delta a_{ij}||w_j| \leq \sum_{j=1}^n \|\Delta A\|\|w\| \leq n\|\Delta A\|\|w\|$.

Since if $|\Delta d_i| < h$, then the decision is stable, so we can conclude that when $\|\Delta A\| < \frac{h}{n\|w\|}$

the decision is stable. Thus, we have the following corollary.

Corollary 2.2. For the SWA algorithm, if the disturbance of the attribute Δa_{ij} satisfy that

$\|\Delta A\| < \frac{h}{n\|w\|}$, then the decision is stable.

Based on the conclusions above, we can conclude that if the disturbance of the attribute or weight is small enough, i.e., smaller than the tolerance range, then the decision will not change. Moreover, from Corollary 2.1 and Corollary 2.2, we can find that the value of h is important to the sensitive of SWA; when the h is large, then the algorithm has low sensitivity; otherwise, the algorithm has high sensitivity.

2.4.3. Pareto optimal

The Pareto optimality [140-142] is used to determine whether an allocation is optimal or not. An allocation is not Pareto optimal if there is an alternative allocation where improvements

can be made to at least one participant's beneficial without reducing any other participant's beneficial. If there is a transfer that satisfies this condition, the reallocation is called a Pareto improvement; otherwise, the allocation is a Pareto optimal. The Pareto optimal can be defined as follows.

Definition 2.3 [142]. For the allocation $\{x_1, x_2, \dots, x_n\}$ is Pareto optimal if there is no other feasible allocation $\{x'_1, x'_2, \dots, x'_n\}$, for each utility u_i and i , $u_i(x'_i) \geq u_i(x_i)$ for all $i \in (1, 2, \dots, n)$ with $u_i(x'_i) > u_i(x_i)$ for some i .

Based on the definition of Pareto optimal, we can conclude that for an optimal issue, the Pareto optimal solutions may not single; all the Pareto optimal solutions consistent the Pareto optimal set. Compared with other Pareto optimal solutions in Pareto optimal set, it can improve the performance of the optimal issue in some aspects and reduce the performance in other aspects. For the solutions which are not in the Pareto optimal set, the performance of the optimal issue under Pareto optimal solutions is much better than that are not in Pareto solution set.

Table 2.1. An example for Pareto Optimal

Solutions	A	B	C	D	E	F
Transmission power	1	2	3	4	5	6
SINR	0.5	0.6	1.2	1.8	1.3	0.9
Energy consumption	10	12	13	11	12.5	15
Link lifetime	2	3	4.5	5	6.5	8

For instance, as shown in Table 2.1, the transmission power is the control variable; the SINR, the energy consumption, and the link lifetime are the optimal variables. Based on the definition of the Pareto optimal, solution B and solution C are not Pareto optimal solutions, since all the optimal variables in D are better than that in B and C; however, the (A, D, E, F) is the Pareto optimal set, since in these four solutions, if improving the performance in one aspect, then the performance will be damaged in other aspect.

2.5 Summary

In this chapter, we introduce the basic network model and definitions that will be used in this thesis. Based on these models, we introduce the principle of opportunistic routing and transmission power control based topology control method. For clearly understanding the proposed algorithms in this thesis, we also introduce the mathematic methods that used in this thesis, including the fuzzy logic, the multi attribute decision making and multi attribute utility theory, and the Pareto optimal. In the next chapter, we will introduce the proposed opportunistic routing algorithms in detail.

Chapter 3

Routing algorithms improve efficiency and reliability for IoT

In this chapter, the routing algorithms which aim to improve the efficiency and reliability of data packet transmission in Internet of Things (IoT) are presented. The routing architecture can be divided into deterministic routing and the opportunistic routing. In this thesis, the routing architecture is opportunistic routing.

For improving the efficiency of the opportunistic routing, we propose a fuzzy logic based relay priority determining algorithm for opportunistic routing; for reducing the redundant transmission and relaying delay, we propose the delay based redundant transmission avoid coordinate scheme. Moreover, we apply these two algorithms in both the underwater environment and terrestrial environment, and two high quality opportunistic routing algorithms for both the underwater environment and terrestrial environment are proposed.

3.1 The fuzzy logic based cross-layer relay priority determining algorithm for opportunistic routing

As introduced in Chapter 2, one of the important issues in opportunistic routing algorithm is how to determine the relaying priorities for the nodes in CRS. In traditional opportunistic routing algorithms, the source node chooses the relay node set based one or two performance metrics, which cannot reflect the comprehensive characteristic of the network. For instance, in the mobile ad hoc networks (MANETs), when the source node chooses the ETX as the performance metric to select and prioritize the relay nodes, the nodes whose ETX are small will be chosen and set with high relaying priorities; however, the problem is that in MANETs, when the nodes move slowly, the nodes whose ETX are small will be used again and again to relay data packets, so the energy of this node will be exhausted soon. Moreover, if more than one adjacent source nodes choose the similar CRS, there will have serious collision between these relay nodes, and the relaying delay increases. On the other hand, considering the parameters in MAC layer, link layer, or physic layer, the nodes which the ETXs are small do not represent that the other performance metrics are optimized either. For solving this issue, the more network parameters are taken into account, the more balance and accuracy result is. However, since

find the optimal solutions for multiple performance metrics are always NP-hard, such as reduce energy consumption and increase network connection, increase SINR and reducing the transmission delay, etc., so the priority determining algorithm should be able to find the tradeoff between these performance metrics.

The fuzzy logic has great advantages on dealing with multi-objective optimal issues [143], which has been widely used in routing algorithm and topology control algorithm design. Many excellent fuzzy logic based algorithms for wireless network have been proposed, such as in [143], [144], [145], [146], and [147]. The principle of fuzzy logic has been introduced in detail in last chapter. However, the main disadvantage of the fuzzy logic is that with the increasing of the inputs' number, the number of fuzzy rules increases exponential. This means the fuzzy logic algorithm cannot handle too many cross-layer performance metrics at the same time. In general, this number is no larger than 3. So this will limit the further performance improvement of the fuzzy logic based cross-layer routing algorithm.

Due to the issues mentioned above, we propose a fuzzy logic based cross-layer relaying priority determining algorithm for the opportunistic routing, in which far more than 3 cross-layer performance metrics are taken into account; however, the number of the fuzzy rules in this algorithm does not increase with the increase of the inputs' number. The new algorithm is named scatter based fuzzy logic algorithm, shorted as SBFL.

Table 3.1. Performance metrics and priorities

	node1	node2	node3	V	rv
Metric_1	1001	1002	1003	0.667	6.64×10^{-6}
Metric_2	0.5	0.8	0.1	0.0822	0.377
Metric_3	1000	2000	3000	666667	0.167

In SBFL algorithm, assuming that there are n input universes, which are $U = [U_1, U_2, \dots, U_n]$;

for each universe, there are m elements, i.e., $U_i = [U_i^1, U_i^2, \dots, U_i^m]^T$; therefore, U is a $m \times n$

$$\text{matrix: } \begin{bmatrix} U_1^1, U_2^1, \dots, U_n^1 \\ U_1^2, U_2^2, \dots, U_n^2 \\ \vdots \\ U_1^m, U_2^m, \dots, U_n^m \end{bmatrix}.$$

For evaluating the variation rate of each metric, one of the available metric is the variance. However, as shown in Table 3.1, the variance is affected seriously by the value of the metric. In Table 3.1, the variance of Metric_1 is larger than that of Metric_2; however, taking the metric's value into account, the variation rate of Metric_1 is smaller than that of Metric_2 in fact. So a new metric should be developed to reflect the accurate variation rate of the performance metrics; in SBFL, the relative variance (rv), which takes the average value of the metrics into account, is used to evaluate the variation rate of the metric, shown as:

$$D_i = \frac{1}{m} \sum_{j=1}^m \left(\frac{U_i^j - \bar{U}_i}{\bar{U}_i} \right)^2, i \in [1, n] \quad (3.1)$$

where U_i^j means the j th element of universe U_i ; $\bar{U}_i$ is the mean value of the parameters in U_i and can be calculated as:

$$\bar{U}_i = \frac{1}{m} \sum_{j=1}^m U_i^j, i \in [1, n] \quad (3.2)$$

In (3.1), the relative variance (rv) is not affected by the metric's value, which can be found in Table 3.1. In Table 3.1, even the variance of Metric_1 is larger than that of Metric_2, the rv of Metric_1 is much smaller than that of the Metric_2, which can reflect the variation rate of the metric more accurate than variance.

In SBFL, the input universes $U_1, U_2, \dots, U_n$ are replaced by the relative variance D as the input of the fuzzy inference system. The fuzzy set A_D can be expressed as:

$$A_D = \{(d, d_A(d_i)) | d_i \in D\} = [d_A(d_1), d_A(d_2), \dots, d_A(d_n)] \quad (3.3)$$

where $d_A(d_i)$ is the membership function between relative variance D and fuzzy set A_D . Since D is a $1 \times n$ matrix, so the fuzzy rules shown in (2.10) can be rewritten as: *If A_D then B* . Therefore, the membership function between A_D and B will be:

$$\mu_{D \rightarrow B}(z, y) = \mu_R(z, y) \triangleq \mu_D(z) \wedge \mu_B(y) \quad (3.4)$$

As shown in (3.4), the membership function is much simpler than that in (2.10). By using the concept of relative variance, the number of fuzzy set has been reduced from n to 1, so the calculation complexity is reduced. Moreover, the number of fuzzy rules in SBFL does not increase when the number of fuzzy set and the linguistic variables increase. Additionally, as shown in Figure 3.1, the complexity caused by the increase of the number of inputs has been isolated from the fuzzy inference system successfully. This means no matter how many different universes are inputted into SBFL, the number of input is only one. Therefore, the SBFL algorithm can take as many cross-layer metrics into account as possible to figure out the most efficient solution without increasing the computation complexity.

Figure 3.1. (a) The principle of traditional fuzzy logic system; (b) The principle of SBFL algorithm.

Since for each node, there are more than one performance metrics are taken into account during the relaying priority determination, so we introduce the weight based multi-attribute utility approach [148] into the SBFL algorithm. For the weight based multi-attribute utility approach, two important issues are: 1) calculating the weight for each metric; 2) parameter normalization. We use the SBFL algorithm to calculate the weight for each parameter. As discussed before, the relative variance D_i will be used as the inputs of the fuzzy logic inference system, and the outputs are the weights of each cross-layer parameters. The weights relate to the effect of different cross-layer performance metrics on the relaying priority determination.

As discussed in Chapter 2, the rv set D includes the different relative variances of the cross-layer parameters. For each scatter D_i , there will have a set of linguistic variables to fuzzification the rv D_i . The number of the fuzzy rules is n^m , in which n is the number of the linguistic variables and m is the number of the fuzzy sets. In the traditional fuzzy logic

inference system, due to the number of the fuzzy rules increases sharply with the increase of the linguistic variables, the number of the linguistic variables should not too large, even the fact that the more linguistic variables are, the more accurate the fuzzy logic system is. This will be improved in SBFL. In SBFL, due to the number of the fuzzy set is fixed to 1, so the number of the fuzzy rules is n which is equal to the number of the linguistic variables. Consequently, when the number of the linguistic variables increases, the number of the fuzzy rules increase slowly compare with the traditional fuzzy logic system. This means that the number of linguistic variables in SBFL can be set as large as possible, which means the result can be as accurate as possible. In SBFL, the number of the linguistic variables is set to 7. The fuzzy linguistic variables and the fuzzy rules are shown in Table 3.2. The membership functions are shown in Figure 3.2.

Table 3.2. Fuzzy logic rules

IF Input (D)	THEN Output (ω)
very small	very small
medium small	medium small
small	small
medium	medium
large	large
medium large	medium large
very large	very large

Figure 3.2. The membership function of input and output

During the weight decision, a fact need to be taken into account is that the parameter which the rv is large will have great effect on the relaying priority determination. This means that for the parameters which the relative variances are small, which node is chosen will have small effect on the routing performance; however, to the parameter which the rv is large, we always hope to select the node which has better performance on this performance metric. For instance, for the parameters shown in Table 3.3, since the rv of the parameter2 is much larger than parameter1, so for the point of view of parameter1, which node is chosen has small effect on the routing performance; however, to the parameter2, this will have great effect on the routing performance. Therefore, in this algorithm, the large rv will has large parameter weight. This is why the fuzzy rules are designed in Table 3.2. Moreover, as shown in Table 3.3 and Table 3.4

(the parameters in Table 3.4 are the parameters of Table 3.3 after normalization), after parameter normalization, the scatter of each parameter is unchanged; however, the variances of these parameters change greatly. The outputs of SBFL are the weights of the cross-layer metrics:

$$\omega = [\omega_1, \omega_2, \omega_3, \dots, \omega_m] \quad (3.5)$$

When the weight of each cross-layer metric has been gotten, the ω and U will be used to calculate the nodes' utilities in CRS:

$$\psi = \omega \times U = [\psi_1, \psi_2, \psi_3, \dots, \psi_n] = [\sum_{j=1}^m \omega_j U_i^j, \sum_{j=1}^m \omega_j U_2^j, \dots, \sum_{j=1}^m \omega_j U_n^j] \quad (3.6)$$

The utilities will be used to decide the relaying priorities of the relay nodes. The relaying priority determination principle is: *the higher utility, the higher relaying priority is.*

Table 3.3. Cross-layer performance metrics

	node1	node2	node3	scatter	variance
parameter1	1001	1002	1003	0.0007	0.66667
parameter2	0.8	0.5	0.1	0.5238	0.08222
parameter3	27	49	15	0.4103	198.222

Table 3.4. Performance metrics after normalization

	node1	node2	node3	scatter	variance
parameter1	0.1	0.2	0.3	0.0007	7×10^{-9}
parameter2	0.8	0.5	0.1	0.5238	0.08222
parameter3	0.27	0.49	0.15	0.4103	0.01982

The process of SBFL based relaying priority determination algorithm is shown as follows:

Algorithm 3.1. The proposed SBFL based relaying priority determination algorithm

Input:

β_n^i : The cross-layer parameters from node i ;

β_{th} : The threshold of the cross-layer parameters;

Output:

NR: The rank of the neighbor node to be the next hop relay node;

Function:

Dispersion(β_n^i): The function to calculate the dispersion of the cross-layer parameters;

Fuzzylogic(D_n): The fuzzy logic inference function to calculate the weight of each cross-layer parameters;

Utility(β_n^i, α_n): The function to calculate the utility of each node;

Probability(U_n): The function to decide the rank of the neighbor node to be the next hop relay node;

Initialization:

Routediscovery=0;

Nodestatus==false;

Main:

While Routediscovery=1 do

```

Broad hello message to neighbor nodes;
For cross-layer parameters received from other nodes, store these parameters;
if ( $\beta_n^i \geq \beta_{th}$ )
  Nodestatus  $\leftarrow$  true;
else if ( $\beta_n^i < \beta_{th}$ )
  Nodestatus  $\leftarrow$  false;
end if
while Nodestatus==true do
   $D_n \leftarrow$  Dispersion( $\beta_n^i$ );
   $\alpha_n \leftarrow$  Fuzzylogic( $D_n$ );
   $U_n \leftarrow$  Utility( $\beta_n^i, \alpha_n$ );
   $NR \leftarrow$  Probability( $U_n$ );
end while
end while

```

3.2 Delay based redundant transmission avoid CRS optimal algorithm for opportunistic routing [214]

As mentioned in Chapter 1, the opportunistic routing can improve the packet delivery ratio greatly at the cost of high redundant transmission and delay. For solving these issues, the nodes in the CRS should be filtered and optimized carefully; there are many CRS optimization and filtering algorithms have been proposed. The most commonly used is to remove the candidates that are worse than the sender according to a specific metric. However, this simple filtering policy cannot guarantee optimal performance [11]; moreover, the candidate relay ordering and filtering are done separately in prior works. Thus the outcome of this phase is not necessarily optimal [11]. For example, filtering based on the connectivity criterion removes candidates that trigger duplicate transmissions. However, these filtered candidates may be the best in terms of the routing metric and may bring the highest expected performance. Therefore, it is necessary to jointly consider the node contribution and its duplicate probability, in future candidate relay set selection schemes design.

The opportunistic routing can be divided into two stages: 1) the sender chooses the candidate relay nodes and prioritizes these nodes based on some performance metrics (such as, the distance to the destination node, the ETX, the residual energy, etc.); in this stage, the node utility, denoted as U , is calculated based on the performance metrics; 2) the CRS is optimized and filtered, and the nodes in CRS relay the data packet to the next hop relaying nodes based on the coordination schemes. The second stage is important to the routing performance, since for improving the efficiency of the routing algorithm, the CRS is optimized and filtered in this stage; moreover, the transmission delay and the redundant transmission are mainly caused by this stage. In this stage, when the CRS receive the data packet, which node is the first one to transmit the data packet to the next hop relaying nodes and how they notify the other relaying nodes that the data packet has been relayed to the next hop are decided. This is determined based on the time-based coordination scheme in this algorithm.

The principle of the time-based coordination scheme has been introduced in detail in [17], [32], and [11]. The main issue with the time-based solution is that it is based on packet overhearing, thereby leading to high duplicate transmissions and transmission delay [11]. These latter occur

when some candidates do not overhear the selected relay's reply. This is the case especially in sparse networks, where candidate relays are placed further apart. In order to mitigate this problem, one possible solution consists in removing some nodes from the candidate relay set so that only fully connected candidate relays are kept.

Figure 3.3. The candidate relaying networks of opportunistic routing.

Unfortunately, in the previous researches, how to construct and judge the fully connected relaying network has not been investigated sufficiently. Based on the conclusion in [11], it is necessary to jointly consider the node contribution and the duplicate transmission. As shown in Figure 3.3, to the nodes in the candidate relaying set, more than one fully connected relaying networks can be constructed; the topologies and the nodes in these networks are different, such as the network (1,2,3,7) and network (4,5,8), etc. For the candidate relaying set shown in Figure 3.3, many different relaying networks can be constructed; since the nodes and topologies in these relaying networks are different, so the properties (such as the relaying delay, the packet delivery ratio, etc.) of these networks are different; for example, the packet delivery ratio and the relaying delay of networks (1,2,3,7) and network (4,5,8) are different. Therefore, how to evaluate the performance of these relaying networks and select the most appropriate relaying network for the opportunistic routing are also the main contents of this algorithm.

Moreover, for reducing the transmission delay, the node which the packet delivery ratio is high should have high relaying priority (this will be proved in the following). As the viewpoints proposed in [7] and [149], the packet delivery ratios of the nodes in the communication link from the source node to the destination node have different effect on the routing performance. For instance, the packet delivery ratio of the node at the end of the link have great effect on the energy consumption and transmission delay [149]; the ETX relates to all the packet delivery ratios of nodes in the communication link from the source node to the destination node [7]. In this section, we will prove that the routing performance, such as the transmission delay, is also affected greatly by the first node's packet delivery ratio in the communication link. Therefore, the effect of the packet delivery ratios of the candidate relaying nodes on the routing performance will be investigated in detail.

Motivated by these, we propose the delay based duplicate transmission avoid (DDA) CRS optimization algorithm. In the following, we will introduce this algorithm in detail. The main objectives of this algorithm can be summarized as: 1) how to recognize the fully connected

relaying networks that constructed by the candidate relaying nodes; and 2) how to chosen the most suitable relaying network from these networks.

3.2.1. Network Model and Calculation Model

A. Network model

Figure 3.4. The network model for opportunistic routing: (a) the network of the candidate relaying nodes; (b) the independent sub-networks of the original network; (c) the dependent sub-networks of Fig. 2(b.1)

As shown in the Figure 3.4(a), in opportunistic routing, when the sender wants to send data packet, first, a set of neighbor nodes are chosen as the candidate relaying nodes based on the performance metrics (such as, ETX, distance, etc.), and the sender relays the data packet to all the nodes in the CRS $\mathbb{R}$. For instance, in Figure 3.4(a), $\mathbb{R} = \{1, 2, 3, 4, 5, 6, 7, 8\}$. The network that constructed by the nodes in $\mathbb{R}$ is denoted as $G(V_{\mathbb{R}}, E_{\mathbb{R}})$, where $V_{\mathbb{R}}$ represents the set of nodes in $\mathbb{R}$ and $E_{\mathbb{R}}$ represents the set of bi-directional communication links in the network. Second, the candidate relaying nodes relay the data packet to the next hop candidate relaying nodes with the same process as the sender. In the second step, the CRS need to be filtered and optimized. For instance, in the time-based coordination scheme, the relaying nodes should be able to communicate directly with each other, i.e., the network constructed by these nodes should be fully connected. The fully connected network means that between any two nodes in this network there exists a bi-directional communication link; otherwise, the network is not fully connected. However, as shown in Figure 3.4(a), the $G(V_{\mathbb{R}}, E_{\mathbb{R}})$ may not the fully

connected network. For instance, node_3 and node_6 are not connected directly. The feasible approach is to keep the fully connected candidate relaying node set $\mathbb{R}^*$ and remove the un-fully connected nodes, where $\mathbb{R}^*$ is the subset of $\mathbb{R}$. For instance, the nodes in $\mathbb{R}^* = \{1,2,3,7\}$, which is shown in Figure 3.4(b), are fully connected. To $\mathbb{R}$, there are many different subsets $\mathbb{R}^*$, which means that to $G(V_{\mathbb{R}}, E_{\mathbb{R}})$, there are many fully connected sub-networks $G(V_{\mathbb{R}^*}, E_{\mathbb{R}^*})$ can be constructed by the nodes in $\mathbb{R}^*$. For example, the networks are shown in Figure 3.4(b) and Figure 3.4(c) are all the fully connected sub-networks of Figure 3.4(a). Since these fully connected networks are different, so for investigating the differences between these networks and jointing the node contributions into the CRS optimized, some definitions are presented as follows.

In the fully connected networks, there must have bi-directional links between any two nodes, so we can simplify the expression of the fully connected network by only showing the nodes in

this network; such as, for $G((2,6,7), (\overline{26}, \overline{27}, \overline{67}))$ which is shown in Figure 3.4(b.2), we can

simplify the expression as $G(2,6,7)$. Since in the time-based coordination scheme, the relaying networks that constituted by the candidate relaying nodes should be fully connected, so we define the relaying network as follows.

Definition 3.1: The fully connected sub-networks $G(V_{\mathbb{R}^*})$ of $G(V_{\mathbb{R}})$ are defined as the relaying networks of candidate relaying set $\mathbb{R}$.

For instance, in Figure 3.4(a), $G(2,6,7)$ is one of the relaying networks. Since there are more than one relaying networks and the nodes in these relaying networks are different, such as the relaying networks $G(2,6,7)$ and $G(1,2,3,7)$, so for distinguishing these networks, we define the network degree in Definition 3.2.

Definition 3.2: The degree of the relaying network is defined as the number of nodes in the relaying networks, denoted as d_G .

For instance, in Figure 3.4(b), the network degree of Figure 3.4(b.1) is 4. Notice the fact that in the relaying networks, the small degree relaying networks may be the sub-network of the large degree relaying networks (it is not always true); so we define the relevant and irrelevant for the relaying networks in Definition 3.3.

Definition 3.3: For any two relaying networks $G(V_{\mathbb{R}_1^*})$ and $G(V_{\mathbb{R}_2^*})$, in which $V_{\mathbb{R}_1^*} \not\subseteq V_{\mathbb{R}_2^*}$ and $V_{\mathbb{R}_2^*} \not\subseteq V_{\mathbb{R}_1^*}$, if $G(V_{\mathbb{R}_1^*} + V_{\mathbb{R}_2^*})$ is still the relaying network, then these two relaying networks are relevant; otherwise, these two relaying networks are irrelevant.

Based on Definition 3.3, we can give the Definition 3.4 as follows.

Definition 3.4: For the relaying network $G(V_{\mathbb{R}_i^*})$, if there exist relaying network $G(V_{\mathbb{R}_j^*})$

which relevant with $G(V_{\mathbb{R}_i^*})$, then $G(V_{\mathbb{R}_j^*})$ is called *s-network*; otherwise, $G(V_{\mathbb{R}_i^*})$ is called *o-network*.

For instance, the $G(1,2,3,7)$ shown in Figure 3.4(b) is an *o-network*; the $G(1,2,3)$ shown in Figure 3.4(c) is a *s-network* of $G(1,2,3,7)$. The *s-network* can be derived from the *o-network*. To each *o-network*, there are more than one *s-networks* can be derived from this *o-network*; the degree of these *s-networks* are smaller than that of the *o-network*. For instance, the relaying networks shown in Figure 3.4(c) are all *s-networks* that derived from the *o-network* shown in Figure 3.4(b.1). Moreover, since the network degree of Figure 3.4(b.1) is 4, so the *s-networks*

that derived from Figure 3.4(b.1) will be 2-degree and 3-degree, respectively. Note that if the network degree is 1-degree, then the algorithm will be the same as the deterministic routing, so we do not consider the 1-degree networks.

B. The calculation model of network relaying delay and packet delivery ratio

For investigating the performance of the relaying networks, in this section, we will introduce the calculation model of relaying delay and packet delivery ratio of the relaying network. For the time-based coordination scheme, the relaying delay is mainly caused by overhearing the high priority node's ACK message. For better understanding the relaying delay of the time-based coordination scheme, in the following, we introduce the principle of the time-based coordination scheme in detail. The principle can be found in Figure 3.5.

Figure 3.5. The principle of the time-based coordination scheme

As shown in Figure 3.5, in time-based coordination scheme, the high priority node has high priority to relay data packet to the next hop relaying nodes, the low priority nodes overhear the ACK messages from the high priority nodes. The node priority is determined based on the node utility U which is calculated in the first stage of opportunistic routing algorithm (the different stages of opportunistic routing is introduce in last section). After the sender sends the data packet to the candidate relaying nodes, the first priority node will check if it receives the data packet. If yes, this node will be the new sender immediately and broadcasts the ACK message to other candidate relaying nodes; the candidate relaying nodes which receive this message will drop the data packet that received from the sender. If the first priority node fails to receive the data packet, then after time T (which is called the waiting time, in [17], this time is set to 45ms), the second priority relaying node begins the same process as the first priority node. This process will be repeated until one of the candidate relaying nodes receives the data packet or none of the node receives the data packet. So the average one-hop relaying delay after one transmission try can be calculated as:

$$DT_{G(1,2,\dots,n)} = (\sum_{i=1}^{n-1} i P_{i+1} \prod_{j=1}^i (1-P_j) + n \prod_{i=1}^n (1-P_i)) T \quad (3.7)$$

where n is the degree of the relaying network, i is the priority of each node in the relaying network, P_i is the packet delivery ratio of the i th priority node in $\mathbb{R}^*$ and $0 < P_i < 1$, T is the

waiting period. The second term in (3.7) represents that none of the node receives the data packet transmitted from the sender. Based on the average one-hop relaying delay introduced in (3.7), we can conclude that to the same relaying network, the network relaying delay will be the smallest when the node priorities are determined based on the packet delivery ratio of node (this can be got easily from (3.7)). The packet deliver ratio of the relaying network used in this algorithm is defined as the probability that the data packet sent by the sender can be received by at least one node in $\mathbb{R}^*$. So the packet delivery ratio of the relaying network $G(1,2,\dots,n)$ can be calculated as [7]:

$$P_{G(1,2,\dots,n)} = 1 - \prod_{i=1}^n (1 - P_i) \quad (3.8)$$

Note that P_i is different with $P_{G(1,2,\dots,n)}$, since P_i is the probability that the i th priority node in $\mathbb{R}^*$ can receive the data packet from sender, and $P_{G(1,2,\dots,n)}$ is the probability that the data packet sent by the sender can be received by at least one node in $\mathbb{R}^*$. From (3.7) and (3.8), we can conclude that even the s -networks can be derived from the o -networks, the relaying delay and the network packet delivery ratios of these two kinds of networks are different. In the next section, we will investigate the properties of the relaying networks in detail.

3.2.2. Properties of the Relaying Networks

In this section, based on the calculation model of network relaying delay and packet delivery ratio that proposed in the last section, we investigate the properties of the relaying network in detail. The properties are divided into in-network properties and inter-network properties. These network properties can be used during the relaying network selection. In the opportunistic routing, for determining the priorities of the candidate relaying nodes, some different performance metrics are used based on different application purposes. These metrics can be divided into two different categories: 1) the packet delivery ratio based metrics, such as the ETX [7], the link correlation [17], etc.; and 2) not the packet delivery ration based metrics, such as the distance to the destination nodes, the residual energy, the interference, etc. The network relaying delay of these two different routing algorithms have great difference, since the network relaying delay is affected seriously by the packet delivery ratio of the candidate relaying nodes and their relaying priorities, which will be proved in the following of this section. As shown in (3.7), the network relaying delay will be different when the node priorities are different to the same network; however, as shown in (3.8), to the same relaying network, the packet delivery ratio of this relaying network is the same even the node priorities are changed.

A. Inter-network properties

The inter-network properties represent the properties of the whole relaying network, i.e., the relaying network is regarded as an entirety.

Corollary 3.1: If the $G(V, E)$ is a relaying network, then $E = \frac{V(V-1)}{2}$; otherwise, $E < \frac{V(V-1)}{2}$.

Proof. See Appendix A.

For each $\mathbb{R}$, in which the number of candidate relaying nodes is n , the number of relaying networks (including the s -networks and the o -networks) can be calculated as:

$$num = \sum_{i=2}^{n-1} C_n^i \quad (3.9)$$

In (3.9), C_n^i is the number of i -degree relaying networks. In this algorithm, the 1-degree network has been ignored, since the 1-degree network is equal to the deterministic routing.

B. In-network properties

In the relaying networks, different node parameters, including the packet delivery ratio and the node priority, have different effect on the network performance. For investigating the effect of the node parameter (including the packet delivery ratio and the node priority) on the network performance, in this section, we investigate the in-network properties of the relaying network.

Definition 3.5: To the relaying network $G(1,2,\dots,n)$, the effect of P_i on the network relaying delay is defined as when P_i changes while the packet delivery ratios of the other nodes keep constant, the variation of $DT_{G(1,2,\dots,n)}$, denoted as $\Delta DT_{G(1,2,\dots,n)}^i$.

According to the Definition 3.5 and (3.7), the $\Delta DT_{G(1,2,\dots,n)}^i$ (where $1 \leq i \leq n$ and n is the degree of the relaying network) can be calculated as:

$$\begin{aligned} \Delta DT_{G(1,2,\dots,n)}^i &= (\sum_{i=1}^{n-1} i P_{i+1} \prod_{j=1}^i (1 - (P_i + \Delta P)) + n \prod_{i=1}^n (1 - (P_i + \Delta P))) T \\ &= \begin{cases} (1 - P_2) [\sum_{j=1}^{n-1} j P_{j+1} \prod_{j=3}^{n-1} (1 - P_j) + n \prod_{j=3}^n (1 - P_j)] \Delta P \cdot T, i = 1 \\ (\prod_{j=1}^n (1 - P_j)) \cdot [\sum_{j=1}^{n-1} j P_{j+1} \prod_{j=i+1}^{n-1} (1 - P_j) \\ + n \prod_{j=i+1}^n (1 - P_j) - (i - 1)] \Delta P \cdot T, 1 < i < n \end{cases} \end{aligned} \quad (3.10)$$

where P_j represents the packet delivery ratio of the j th relaying node in $G(1,2,\dots,n)$; n is the degree of $G(1,2,\dots,n)$; ΔP is the variation of the packet delivery ratio P_i . Note that the j used in (3.10) does not the node relaying priority in $\mathbb{R}$, it is the relaying priority in $\mathbb{R}^*$. For instance, if the relaying network is $G(2,6,7)$, then the P_1 , P_2 , and P_3 in (3.10) represent P_2 , P_6 , and P_7 , respectively. The coefficient of each term in (3.10) does not change for the same relaying network. Based on (3.10), we can calculate the difference of the relaying delay variation between two adjacent relaying nodes $\Delta DT_{G(1,2,\dots,n)}^i$ and $\Delta DT_{G(1,2,\dots,n)}^{i+1}$, which is denoted as

$\Delta DT_{G(1,2,\dots,n)}^{(i,i+1)}$. The $\Delta DT_{G(1,2,\dots,n)}^{(i,i+1)}$ can be calculated as follows:

$$\begin{aligned} \Delta DT_{G(1,2,\dots,n)}^{(i,i+1)} &= \Delta DT_{G(1,2,\dots,n)}^i - \Delta DT_{G(1,2,\dots,n)}^{i+1} \\ &= (\prod_{j=1}^n (1 - P_j)) \cdot [1 + (P_i - P_{i+1}) \cdot [1 + (1 - P_{i+2}) \\ &\quad \cdot (1 + (1 - P_{i+3}) \cdots 1 + (1 - P_{n-1})(2 - P_n) \overbrace{\cdots}^{n-i-2})]] \Delta P \cdot T \end{aligned} \quad (3.11)$$

Based on (3.11), we can get the difference of the relaying delay variation between any two relaying nodes, denoted as $\Delta DT_{G(1,2,\dots,n)}^{(i,j)}$, which can be calculated as:

$$\begin{aligned} \Delta DT_{G(1,2,\dots,n)}^{(i,j)} &= \sum_{k=i}^{j-1} \Delta DT_{G(1,2,\dots,n)}^{(k,k+1)} \\ &= (\prod_{j=1}^n (1 - P_j)) \cdot [1 + (1 - P_{i+1}) \end{aligned}$$

$$\cdot \left(1 + (1 - P_{i+2}) \cdots 1 + (P_i - P_j)(2 - P_n) \overbrace{\cdots}^{j-i-2} \right) \Delta P \cdot T \quad (3.12)$$

For instance, for the relaying network $G(1,2,3,7)$, $\Delta DT_{G(1,2,3,7)}^{(1,3)}$ represents the difference of the relaying delay variation between $\Delta DT_{G(1,2,3,7)}^1$ and $\Delta DT_{G(1,2,3,7)}^3$.

Corollary 3.2: To the relaying networks which the priority of the relaying nodes are determined based on the packet delivery ratio based metrics, the higher relaying priorities (i.e., the packet delivery ratio is high), the higher effect on the network relaying delay; i.e., if $i >$

j , then $\Delta DT_{G(1,2,\dots,n)}^{(i,j)} > 0$; and if $(i-j) > (i-k)$, then $\Delta DT_{G(1,2,\dots,n)}^{(i,j)} > \Delta DT_{G(1,2,\dots,n)}^{(i,k)}$.

Proof. This can be proved directly by (3.10), (3.11), and (3.12).

The Corollary 3.2 demonstrates that the packet delivery ratios of the high priority relaying nodes have greater effect on the network performance than that of the low priority relaying nodes. Based on (3.10) and (3.11), we can derive the Corollary 3.3 and Corollary 3.4 as follows.

Corollary 3.3: To the relaying networks which the relaying priorities of the candidate relaying nodes are decided based on the packet delivery ratio based metrics, with the increasing of the network degree, the effect of the same P_i becomes more and more serious, which means if $n >$

m , then $\Delta DT_{G(1,2,\dots,n)}^i > \Delta DT_{G(1,2,\dots,m)}^{(i,j)}$ and $\Delta DT_{G(1,2,\dots,n)}^{(i,j)} > \Delta DT_{G(1,2,\dots,m)}^{(i,j)}$.

Proof. This can be proved directly by (3.10), (3.11), and (3.12).

For instance, based on Corollary 3.3, for the relaying networks $G(1,2,3)$ and $G(1,2,3,7)$, the $\Delta DT_{G(1,2,3)}^{(1,3)}$ is smaller than $\Delta DT_{G(1,2,3,7)}^{(1,3)}$ and the $\Delta DT_{G(1,2,3)}^1$ is smaller than $\Delta DT_{G(1,2,3,7)}^1$.

Corollary 3.4: To the relaying network $G(1,2,\dots,n)$ which the priorities of the candidate relaying nodes are decided based on the packet delivery ratio based metrics, with the decreasing

of the relaying priority, if $n \rightarrow \infty$, then $\Delta DT_{G(1,2,\dots,n)}^{(i,i+1)} \rightarrow 0$ and $\Delta DT_{G(1,2,\dots,n)}^i \rightarrow 0$.

Proof. See Appendix B.

The Corollary 3.4 demonstrates that the effect of the low priority relaying node on the network performance becomes smaller and smaller when the number of node in the relaying network increases.

For the relaying networks which the node relaying priorities are not decided based on the packet delivery ratio relevant metrics, the properties are the same with that of the relaying networks which the node relaying priorities are decided based on the packet delivery ratio. Before investigating the properties of this kind of relaying network, according to (3.11) and (3.12), we propose Corollary 3.5 first.

Corollary 3.5: To the relaying network $G(1,2,\dots,n)$ which the relaying priorities of the candidate relaying nodes are not decided based on the packet delivery ratio based metrics, if P_i

$< P_j$, then the condition that $\Delta DT_{G(1,2,\dots,n)}^{(i,j)} < 0$ is shown as follows:

$$(P_j - P_i) > \frac{1 + (2 - P_{j-1}) \prod_{k=i+1}^{j-2} (1 - P_k)}{(2 - P_{j-1}) \prod_{k=i+1}^{j-1} (1 - P_k)} = \varphi(i, j) > 1 \quad (3.13)$$

Proof. See Appendix C.

As shown in (3.13), since P_i and P_j are all smaller than 1, so the $(P_j - P_i)$ is smaller than 1, too. Thus, the (3.13) will not hold. The conclusion in Corollary 3.5 means that even $P_i < P_j$, then

$\Delta DT_{G(1,2,\dots,n)}^{(i,j)} > 0$. Moreover, the Corollary 3.5 also illustrates that not only the packet delivery

ratio but also the relaying priority can affect the network relaying delay.

Based on Corollary 3.5, we can conclude that to the relaying networks which the priorities of the candidate relaying nodes are decided based on the packet delivery ratio irrelevant metrics, with the decreasing of the relaying priority, the effect of the node packet delivery ratio on the network relaying delay decreases. This means that in the network which the nodes are prioritized based on the packet delivery ratio irrelevant metrics, we can get the same corollaries as that shown in Corollary 3.2, Corollary 3.3, and Corollary 3.4.

According to the properties of the relaying network, the parameters of node which the relaying priority is high, has greater effect on the transmission delay than that of the node which the priority is low. So for reducing the transmission delay, the high priority relaying nodes should have higher packet delivery ratios than that of the low priority relaying nodes. This conclusion is similar to the conclusions in [7] and [149]. In [149], the authors illustrate that the node's packet delivery ratio which is at the end of the communication link has great effect on the energy consumption; the communication link which this packet delivery ratio is low will deteriorate the routing performance greatly. The authors in [7] use the ETX which relates to all the packet delivery ratios in the communication link to evaluate the effect on the routing performance. In this algorithm, we prove that the packet delivery ratio of the high priority relaying nodes can affect the transmission delay greatly.

Since for reducing the transmission delay, the high priority relaying node should have higher packet delivery ratio than that of the low priority relaying nodes, however, this is not always hold in the algorithms which the node priority is not determined based on the packet delivery ratio based metrics. In these algorithms, the high relaying priority does not mean small packet delivery ratio. For instance, when the performance metric is residual energy, the node which has large residual energy may not have higher packet delivery ratio than the nodes which have small residual energy. Therefore, for reducing the relaying delay, one approach is re-setting the relaying priority based on the packet delivery ratio. However, this will deteriorate the routing performance, because the node which the residual energy is large may have low relaying priority that determined based on the packet delivery ratio. So to these algorithms, for taking both the node contributions and the packet delivery ratio into account, the node priority needs to be re-calculated.

Assuming that the utility of i th candidate relaying node which calculated in the first stage of the opportunistic routing is U_i (U_i does not take the packet delivery ratio into account), and the packet delivery ratio of this node is P_i ; according to the definition of ETX in [7], we define the one-hop ETX for each relaying nodes, denoted as $ETX_{one-hop}$, as follows: $ETX_{one-hop} = 1 / P_i$. Therefore, when taking the packet delivery ratio into consideration, the utilities of the candidate relaying nodes that calculated in the first stage of the opportunistic routing will deteriorate; the lower of the packet deliver ratio, the more serious deterioration is. So the new utility which has taken the packet delivery ratio into account can be calculated as:

$$U_i^* = \frac{U_i}{\text{ETX}_{\text{one-hop}}} = U_i \cdot P_i \quad (3.14)$$

The (3.14) demonstrates that when taking the packet delivery ratio into account, the utility of relaying node i deduces to U_i^* from U_i . The new priorities of the candidate relaying nodes will be determined based on the value of U_i^* . An example can be found in Table 3.5. As shown in Table 3.5, when taking both the packet delivery ratio and the residual energy into account, node b has better performance than node a and node c . In Table 3.5, we can find that the high priority node determined by (3.14) has both high packet delivery ratio and residual energy.

Table 3.5. An Example

node	a	b	c	d	e
residual energy (%)	0.9	0.87	0.83	0.79	0.75
packet delivery ratio (%)	0.65	0.78	0.8	0.69	0.57
priority decided by residual energy	1	2	3	4	5
priority decided by packet delivery ratio	4	2	1	3	5
priority decided by (3.14)	3	1	2	4	5

3.2.3. Delay based Redundant Transmission Avoid Coordination Scheme

In this section, based on the conclusions in Section 3.2.1 and Section 3.2.2, we propose the relaying network recognition algorithm (RNR) and delay based redundant transmission avoid (DDA) coordination scheme for the opportunistic routing.

A. Relaying network recognition algorithm

In Section 3.2.1, we introduce the definition of the relaying network, which is the fully connected sub-network of $G(V_R, E_R)$. The relaying networks include the s -networks and o -networks; moreover, the s -networks can be derived from the o -networks. However, how to judge whether the nodes in $\mathbb{R}^*$ can construct a relaying network or not has not been investigated sufficiently. In this section, based on the conclusion in Corollary 3.1, we propose a relaying network recognition algorithm (RNR) to estimate whether any n nodes can constitute a relaying network or not and distinguish the relaying network is s -network or o -network.

Before introducing RNR, we first define the neighbor matrix for each candidate relaying node. Assuming that there are m nodes in $\mathbb{R}$, for node i , the neighbor matrix can be expressed as:

$$\text{neib}_i = \begin{bmatrix} 1 & 2 & 3 & 4 & \dots & i & \dots & m \\ 0 & 0 & 0 & 0 & \dots & 1 & \dots & 1 \end{bmatrix} \quad (3.15)$$

In (3.15), if the node j has bi-directional communication link with node i , then the j th value in neib_i will be “1”; otherwise, this value will be “0”. In RNR, we regard that node i is a neighbor of itself. For estimating the existence of the relaying network, we define a sum operator between any two neighbor matrixes as follows.

Definition 3.6: For two neighbor matrixes which only contain “0” and “1”, the “+” between two neighbor matrixes neib_i and neib_j is defined as:

$$D_{(i,j)} = \text{neib}_i + \text{neib}_j = \sum_{k=1}^m (\text{neib}_i(k) \wedge \text{neib}_j(k)) \quad (3.16)$$

where “ $\wedge$ ” is the “and” operator in Boolean algebra. For instance, to the matrixes $[1 \ 0 \ 0 \ 1 \ 1 \ 1]$ and $[0 \ 1 \ 0 \ 1 \ 1 \ 0]$, based on (3.16), the summary of these two matrixes will be 2. According to

Definition 3.6, we can estimate whether any n -degree network is the relaying network or not.

Corollary 3.6: For any network $G(V_R, E_R)$ which the network degree is n , if $D_{G(V_R, E_R)} \geq n$, then the network is the relaying network; otherwise, the network is not the relaying network.

Proof. See Appendix D.

Figure 3.6. The neighbor matrixes of the candidate relaying nodes in Figure 3.4(a)

For instance, the neighbor matrixes of the candidate relaying nodes in Figure 3.4(a) are shown in Figure 3.6. As shown in Figure 3.6, according to the Definition 3.6, $D_{(1,2,3)}=4$, which is larger than the network degree of $G(1,2,3)$, so based on the Corollary 3.6, we can conclude that $G(1,2,3)$ is a relaying network. However, since $D_{(2,5,6)}=1$, which is smaller than the network degree of $G(2,5,6)$, so $G(2,5,6)$ is not a relaying network. The rest of the relaying networks can be gotten by the same process based on the conclusions of Definition 3.6 and Corollary 3.6. Note that the relaying networks gotten from Corollary 3.6 include both the s -networks and the o -networks. The Corollary 3.6 is only the algorithm to estimate whether the network is a relaying network or not; it cannot distinguish the relaying network is s -network or o -network. Therefore, we propose the Corollary 3.7 which can be used to distinguish different kinds of relaying networks.

Corollary 3.7: For any relaying network $G(V_{R^*})$ which the network degree is n , if $D_{G(V_{R^*})} =$

n , then the network $G(V_{R^*})$ is an o -network; otherwise, if $D_{G(V_{R^*})} = n > m$, where m is the degree of $G(V_{R^*})$, then $G(V_{R^*})$ is a s -network, and the degree of the o -network that $G(V_{R^*})$ is derived from is n ; moreover, based on (3.9), the number of the relevant m -degree s -network is c_n^m .

Proof. See Appendix D.

For instance, in Figure 3.6, $D_{(1,2,3)}=4$ and the degree of $G(1,2,3)$ is 3, so $G(1,2,3)$ is s -network and derived from an o -network which the network degree is 4. Additionally, the number of 3-degree relevant s -network of $G(1,2,3)$ is 4. In Figure 3.6, since $D_{(1,2,3,7)}=4$ which is equal to its network degree, so the network $G(1,2,3,7)$ is an o -network.

The relaying network recognition algorithm is shown as follows.

Algorithm 3.2: The Relaying Network Recognition (RNR) Algorithm

1. candidate relaying node i calculates the neighbor matrix $neib_i$;
2. if $D_{G(V_{R^*})} = n \rightarrow G(V_{R^*})_n$ is the o -network;
3. if $D_{G(V_{R^*})} = n > m \rightarrow G(V_{R^*})_n$ is the s -network;
4. if $G(V_{R^*})_n < n \rightarrow G(V_{R^*})_n$ is not the relaying network.

B. Delay based duplicate transmission avoid (DDA) coordination scheme

After the recognition of the relaying network, we need to decide which relaying network is the most appropriate one as the final relaying network. The nodes in the selected relaying network will be the final relaying nodes and the other nodes in $\mathbb{R}$ will be deleted.

For improving the performance of the opportunistic routing, during the relaying network selection, the following properties of the relaying network should be met as much as possible: 1) the relaying delay of the relaying network should be as small as possible; 2) the packet delivery ratio of the relaying network should be as large as possible; 3) the network in which the node utilities (i.e., the utility is calculated in the first stage of the opportunistic routing) are high should be selected as much as possible for guaranteeing high network performance. Therefore, in the relaying network selection, not only the network packet delivery ratio and the network relaying delay, but also the node contributions in the relaying network should be taken into account [11].

Based on (3.7) and (3.8), the network relaying delay and network packet delivery ratio can be calculated, respectively. Similar to the Expect Transmission Count (ETX) of relaying node which is defined in [7], according to the network packet delivery ratio, we define the one-hop ETX of the relaying network $G(1,2,\dots,n)$, which can be expressed as:

$$t_{G(1,2,\dots,n)} = \frac{1}{P_{G(1,2,\dots,n)}} = \frac{1}{1 - \sum_{i=1}^n (1 - P_i)} \quad (3.17)$$

where P_i is the packet delivery ratio of node i in the relaying network. When takes the network ETX into account, the network relaying delay deteriorates, so the network relaying delay which takes the network ETX into account can be calculated as:

$$DT_{G(1,2,\dots,n)}^* = DT_{G(1,2,\dots,n)} = \frac{\left(\sum_{i=1}^{n-1} i P_{i+1} \prod_{j=1}^i (1 - P_j) + n \sum_{i=1}^n (1 - P_i) \right) T}{1 - \sum_{i=1}^n (1 - P_i)} \quad (3.18)$$

Similarly to the analysis in Section 3.2.3, during the relaying network selection, the relaying network which has good performance on both the network relaying delay and the node utilities should have high priority to be selected as final relaying network. For evaluating the effect of the node utilities on the network performance, we define and calculate the network utility $U_{G(1,2,\dots,n)}$ as follows.

For the relaying network $G(1,2,\dots,n)$, considering the packet delivery ratios and utilities of nodes in the relaying network, which is calculated in the first stage of opportunistic routing, the network utility $U_{G(1,2,\dots,n)}$ varies; this can be expressed in (3.19):

$$U_{G(1,2,\dots,n)} = \begin{cases} U_1, \text{ the probability is } P_1 \\ U_2, \text{ the probability is } (1 - P_1)P_2 \\ \vdots \\ U_n, \text{ the probability is } \sum_{i=1}^{n-1} (1 - P_i)P_n \\ 0, \text{ the probability is } \sum_{i=1}^n (1 - P_i) \end{cases} \quad (3.19)$$

where U_i means the utility of i th relaying nodes that calculated in the first stage of opportunistic routing (demonstrate in Section I). Therefore, for a relaying network which the network degree is n , the average network utility can be calculated as:

$$\bar{U}_{G(1,2,\dots,n)} = U_1 \cdot P_1 + \sum_{i=2}^n (U_i \prod_{j=1}^{i-1} (1 - P_j) P_i) \quad (3.20)$$

The (3.20) is the average network utility of network $G(1,2,\dots,n)$ on one transmission try. Similar to the network relaying delay, when taking the network ETX which calculated in (3.17) into account, this utility deteriorates. According to (3.18), the network utility which takes the network ETX into account can be calculated as:

$$U_{G(1,2,\dots,n)}^* = \frac{\bar{U}_{G(1,2,\dots,n)}}{t_{G(1,2,\dots,n)}} = (U_1 \cdot P_1 + \sum_{i=2}^n (U_i \prod_{j=1}^{i-1} (1 - P_j) P_i)) (1 - \prod_{i=1}^n (1 - P_i)) \quad (3.21)$$

Based on (3.18) and (3.21), we can find that for each relaying network, two network parameters should be taken into account during the relaying network selection: (1) the network relaying delay $DT_{G(1,2,\dots,n)}^*$ which takes the network ETX into account and (2) the network utility $U_{G(1,2,\dots,n)}^*$ which takes the node utility and network ETX into account. The selected relaying network should have high quality performance on both of these two metrics.

In this thesis, for achieving this purpose, we introduce the weight based multi-objective making decision approach into the final network utility calculation, which can be expressed as:

$$U_{G(1,2,\dots,n)}^F = \omega_{DT} \cdot DT_{G(1,2,\dots,n)}^* + \omega_U \cdot U_{G(1,2,\dots,n)}^* \quad (3.22)$$

where ω_{DT} is the weight of $DT_{G(1,2,\dots,n)}^*$, ω_U is the weight of $U_{G(1,2,\dots,n)}^*$.

For the weight based algorithm, the first important issue is to determine the weights for each performance metrics. To the metrics of the relaying network, there is a fact that the metric (i.e., $DT_{G(1,2,\dots,n)}^*$ and $U_{G(1,2,\dots,n)}^*$) which the variation rate is larger has greater effect on the network performance than the metric which the variation rate is smaller. For instance, as the parameters shown in Table 3.6, since the values of $U_{G(1,2,\dots,n)}^*$ between different relaying networks are similar, so which $U_{G(1,2,\dots,n)}^*$ is chosen as the final relaying network has small effect on the network performance. However, for different relaying networks, the values of $DT_{G(1,2,\dots,n)}^*$ are quite different, so which $DT_{G(1,2,\dots,n)}^*$ is chosen has great effect on the network performance. Based on this conclusion, one of the feasible approaches is to use the variances of $DT_{G(1,2,\dots,n)}^*$ and $U_{G(1,2,\dots,n)}^*$ as the weights in (3.22).

However, as shown in [143], if we use the values of $DT_{G(1,2,\dots,n)}^*$ and $U_{G(1,2,\dots,n)}^*$ that calculated in (3.18) and (3.21), and the variances of $DT_{G(1,2,\dots,n)}^*$ and $U_{G(1,2,\dots,n)}^*$ in (3.22) directly, there may have problems. Because: 1) the final network utility will be mainly decided by the metric which its value is large; for instance, in Table 3.6, since the value of $DT_{G(1,2,\dots,n)}^*$

is much larger than $U_{G(1,2,\dots,n)}^*$, so the value of $U_{G(1,2,\dots,n)}^F$ will be mainly decided by $DT_{G(1,2,\dots,n)}^*$; 2) the variance is affected seriously by the value of the metric, so it can not reflect the practical variation rate of the metric; for instance, as shown in Table 3.6, the variance of

$U_{G(1,2,...,n)}^*$ is larger than that of $DT_{G(1,2,...,n)}^*$; however, when taking the values of the metrics into account, the variation rate of $U_{G(1,2,...,n)}^*$ is smaller than that of $DT_{G(1,2,...,n)}^*$ in fact. So when we choose the next hop relaying network, the $DT_{G(1,2,...,n)}^*$ should has greater effect on the routing performance than that of the $U_{G(1,2,...,n)}^*$. This is because the variance is the absolute difference between different parameters, so it is affected seriously by the values of the parameters. Therefore, for investigating the effect of different metrics on the routing performance, we use the relative variance (rv) which takes the average of the parameter into account and use the relative variance as the weight shown in (3.22).

Table 3.6. An Example

network	a	b	c	variance	rv
$U_{G(1,2,...,n)}^*$	51	52	53	0.67	0.00074
$DT_{G(1,2,...,n)}^*$	0.27	0.68	0.49	0.028	0.366

The relative variance is defined as:

$$v_{rx} = \frac{1}{n} \sum_{i=1}^n \left(\frac{x_i - \bar{x}}{\bar{x}} \right)^2 \quad (3.23)$$

where x represents $DT_{G(1,2,...,n)}^*$ and $U_{G(1,2,...,n)}^*$, $\bar{x}$ is the average of x , n is the number of relaying networks. In the relative variance, the value of (3.23) can reflect the effect of different parameters on the routing performance accurately. This can be found in Table 3.6. In Table 3.6, even the variance of $U_{G(1,2,...,n)}^*$ is larger than that of $DT_{G(1,2,...,n)}^*$, the relative variance of $DT_{G(1,2,...,n)}^*$ is larger than that of $U_{G(1,2,...,n)}^*$, which is consist with the effect of the metric on the routing performance.

For evaluating the difference between the relative variances of these two metrics, we define the parameter resolution ratio ξ as:

$$\xi = \begin{cases} \frac{v_{rDT}}{v_{rU}}, & v_{rDT} > v_{rU} \\ 1, & v_{rDT} = v_{rU} \\ \frac{v_{rU}}{v_{rDT}}, & v_{rDT} < v_{rU} \end{cases} \quad (3.24)$$

From (3.24), we can find that $\xi \geq 1$, the larger ξ is, the larger difference between the relative variances of these two parameters. For the network utility calculated in (3.22), with the increase of ξ , the effect of the metric which the relative variance is large on the network utility increases, and the effect of the parameter which the variance is small decreases. When the ξ is small, the effect of these two parameters on the network utility is similar.

For the first issue, if we use the values of metrics directly in the network utility calculation, then there will have some mistakes. For instance, as the metrics shown in Table 3.6, since the relative variance of Metric_1 is smaller than that of the Metric_2, so according to the analysis above, the network utility should be affected mainly by the Metric_2; however, the fact is that the network utilities are decided mainly by Metric_1, i.e., the network which the value of Metric_1 is the largest will have the highest network utility. According to the network utility defined in (3.22), the priorities of the network utilities are: $network_c \rightarrow network_b \rightarrow network_a$, which is the same as the priorities of Metric_1. This is not consistent with the analysis above. The reason is that the value of Metric_1 is much larger than that of the Metric_2. When the difference between Metric_1 and Metric_2 is too large, it will cover up the effect of Metric_2

on the relaying network selection. For solving this issue, in [143], the authors map the different order of magnitudes parameters to the same order of magnitude; in this paper, considering the fact that for each performance metric, there has an order number relates to each relaying network, so we introduce the order number of the relaying network into the network utility calculation. For instance, as the values of Metric_2 shown in Table 4, the order numbers of the relaying networks relate to Metric_2 are: $network_a \rightarrow 1$, $network_b \rightarrow 3$, and $network_c \rightarrow 2$, respectively. The large order number means that the related metric's value is large in the relaying network, vice versa. So in this paper, the value of parameter shown in (3.22) will be replaced by the order number of each relaying network, which can be expressed as:

$$U_{G(1,2,\dots,n)}^F = v_{rDT} \cdot n_{DT_{G(1,2,\dots,n)}}^i + v_{rU} \cdot n_{U_{G(1,2,\dots,n)}}^i \quad (3.25)$$

where $n_{DT_{G(1,2,\dots,n)}}^i$ is the order number of $G(1,2,\dots,n)$ relates to DT , $n_{U_{G(1,2,\dots,n)}}^i$ is the order number of $G(1,2,\dots,n)$ relates to U . The network utility will be decided by (3.25), which can be found in Table 3.7. In Table 3.7, the network utility of network_b is larger than that of network_c, which is consistent with the analysis above. In Table 4, we also present the network utilities that calculated based on the algorithm proposed in [143] which is the weight based algorithm and [150] which is the fuzzy logic based algorithm. From Table 4, we can find that the priorities of the relaying networks that calculated by (19) are the same as that calculated by [143] and [150].

Table 3.7. An Example

network	a	b	c	rv
Metric_1	29	45	63	0.0925
Order number of Metric_1	1	2	3	
Metric_2	0.27	0.68	0.49	0.122
Order number of Metric_2	1	3	2	
Utility calculated by (3.22)	2.72	4.25	5.89	
Utility calculated by (3.25)	0.3365	0.551	0.3995	
Utility calculated by [143]	0.06	0.125	0.118	
Utility calculated by [150]	0.448	0.529	0.517	

Based on (3.24) and (3.25), we can derive the property of this algorithm as follows. The network utility calculated by (3.25) relates to both the weight of the metric and the priority of the relaying network. Assuming that there are two relaying networks, for the network_1, the order number based on DT is n_i and the order number based on U is n_j ; for the network_2, the order numbers relate to these two Metrics are n_m and n_k , respectively. Let $\Delta_{DT}^n = |n_i - n_j|$, $\Delta_U^n = |n_m - n_k|$, $\xi = \alpha$, and $v_{rDT} > v_{rU}$, then we can derive the property of this algorithm as follows.

Corollary 3.8. If $\frac{\Delta_U^n}{\Delta_{DT}^n} < \alpha$, the utility will be decided mainly by DT , and if $\frac{\Delta_U^n}{\Delta_{DT}^n} > \alpha$, then the utility will be decided mainly by U ; vice versa.

Proof. See Appendix E.

An example can be found in Figure 3.7. The values of the metrics in Figure 3.7 are the same as

that shown in Table 3. As shown in Figure 3.7(a), for the network_2 and network_3, since $\Delta_{DT} = 1$ and $\Delta_U = 1$, so $\frac{\Delta_U^n}{\Delta_{DT}^n} = 1$; since $\xi = 1.32 > \frac{\Delta_U^n}{\Delta_{DT}^n}$, so in Figure 3.7(a), the network utility will be decided mainly by the value of DT . Therefore, in Figure 3.7(a), the relaying priority of network_2 is 1 and the priority of network_3 is 2, which is the same as the order of DT . However, as shown in Figure 3.7(b), for network_2 and network_3, since $\frac{\Delta_U^n}{\Delta_{DT}^n} = 2$ which is larger than ξ , so the network utility will be decided mainly by the value of U . Therefore, in Figure 3.7(b), the relaying priorities of network_2 and network_3 are 2 and 1, respectively; this is the same as the order of U . The relaying priorities of network_2 and network_3 are opposite in these two figures.

Figure 3.7. An example of the relaying network prioritize and selection algorithm

When the relaying network is selected by the algorithm introduced above, the nodes in the relaying network will relay the data packet based on the relaying priority that calculated in Section 3.2.1. The relaying is time-based, which has been introduced in [7], [17], and [11] in detailed; the waiting timer is set to $45ms$, which is the same as that shown in [17]. When the node in the relaying network relays the data packet to the next hop relaying network, the processes are the same as that shown above until the data packet is received by the destination node. The process of the DDA can be found below.

Algorithm 3.3: DDA coordination scheme

1. each relaying network calculated the network ETX based on (3.17);
 2. based on (3.18) and (3.21), the network relaying delay $DT_{G(1,2,...,n)}^*$ and network utility $U_{G(1,2,...,n)}^*$ are calculated;
 3. the source node calculate the variances of network relaying delay and network utility, i.e.,
-

$\xi_{DT_{G(1,2,\dots,n)}^*}$ and $\xi_{U_{G(1,2,\dots,n)}^*}$, respectively;

4. applying the Corollary 3.2, Corollary 3.3, and Corollary 3.4 to pre-select the relaying network;
 5. based on (3.25), the final network utility $U_{G(1,2,\dots,n)}^F$ is calculated;
 6. the relaying network which has highest final network utility will be chosen as the relaying network.
-

3.3 Cross layer balanced relaying priority determining algorithm based opportunistic routing for underwater ad hoc networks [136]

Based on the cross layer balanced relaying priority determining algorithm and DDA algorithm that introduced in Section 3.1 and Section 3.2, we proposed the opportunistic routing algorithm which combines these two algorithms for the underwater ad hoc networks. This routing algorithm is designed for the underwater detection, inspection and traction of plumes, which is one of the scenarios of the SWARMs project.

3.3.1 Network Model

The architecture of communication network used in SWARMs project can be found in Figure 3.8. In SWARMs project, the communication network has been divided into five different categories: 1) Overwater RF wireless communication network; 2) Satellite communication network; 3) Cabled communication network; 4) Underwater Acoustic MF communication network; 5) Acoustic HF communication network. In this algorithm, we mainly focus on the underwater Acoustic MF communication network. Based on the architecture of communication network, there are many use cases have been proposed in SWARMs project; for instance, Corrosion Prevention in offshore installation, Monitoring of chemical pollution, Detection, inspection and traction of plumes, Berm building, and Seabed mapping, which can be found at <http://swarms.eu/usecases.html>. This routing algorithm is designed for the detection, inspection and traction of plumes, see Figure 3.9.

In the use case shown in Figure 3.9, there are two different kinds of movement patterns of AUVs: 1) all AUVs in network move in group with the same movement pattern of plumes; 2) in the interior of network, the AUVs move freely in the area where the plumes exists; moreover, for guaranteeing this area can be covered by AUVs' transmission area, the movement of AUVs should be able to guarantee that the AUVs are approximately uniformly distributed in the area where the plumes exist. These two kinds of movement are different. To the first kind of movement, since the moving of plumes is randomly, so the AUVs must be able to detect the movement of plumes and tracing them; for most cases, the movement of plumes under the water can be regarded as the group mobility and many mobility models can be used to describe this kind of movement, such as the Reference point group mobility model [151], the Nomadic community mobility model [152], the Reference velocity group mobility model [153], etc. So the first kind of movement of AUVs is similar to the movement of plumes. However, to the second movement, which is the inner-network movement, the AUVs can move in the area where the plumes exists freely; moreover, for guaranteeing this area can be covered by AUVs' transmission area, the AUVs should uniformly distributed in this area.

Figure 3.8. The architecture of the communication network in SWARMs project

Figure 3.9. Use case of detection, inspection and traction of plumes in SWARMs project: (a) AUVs tracking and detecting the plume; (b) AUVs sharing the information between each other

A. The parameters of the underwater environment

Considering the fact that different hydrological parameters have different effects on the communication performance of underwater cooperation AUVs network, so we present the hydrological parameters of the test location in this section. These hydrological parameters, including the water temperature, water salinity, and sound speed, are the average values in past decades of the test location.

Figure 3.10 and Figure 3.11 are the average temperature and salinity in a year with water depth is 10m, respectively. Figure 3.12 and Figure 3.13 are the average temperature and salinity in different water depths and months. Figure 3.14 illustrates the average sound speed in different month with different water depths.

Figure 3.10. Average temperature in a year

Figure 3.11. Average salinity in a year

Figure 3.12. Average temperature with different water depths

Figure 3.13. Average salinity with different water depths

Figure 3.13. Average sound speed with different water depths

B. Parameters of hardware

In underwater cooperation AUVs network, the communication modules are equipped on underwater AUVs to allow the AUVs to communicate with each other. There are three different kinds of AUVs used in SWARMs project, and the parameters of these AUVs can be found in the table below.

Table 3.8. Parameters of AUVs used in SWARMS project

	length (<i>m</i>)	width (<i>m</i>) (circular)	height (<i>m</i>) (circular)	weight (<i>Kg</i>)
ALISTER 9	2	0.22	0.22	70
IXN	1.9	0.5	0.3	150
Naiad	0.84	0.6	0.25	30

The communication modules used in SWARMS project include MF (medium frequency) module and HF (high frequency) module. The MF communication module used for data exchanging between different AUVs; the HF communication module used for P2P communication between different AUVs and ROVs. This routing algorithm is mainly designed for MF communication network. The MF communication module used in SWARMS project is the S2CR communication module. The module operated in the frequency band 18-34 kHz around the central frequency is 25 kHz with the efficient frequency bandwidth is 16 kHz. Sweep-spread carrier is used for data encoding in S2CR module. The detail of this communication module can be found in Table 3.9. These parameters will be used in simulation.

Table 3.9. Parameters of S2CR communication module

Items	Parameters
operating depth	200 <i>m</i> to 2000 <i>m</i> depending on housing material; 6000 <i>m</i> titanium
operating range	3500 <i>m</i>
frequency band	18-34 kHz
transducer beam pattern	horizontally omnidirectional
acoustic connection	1) burst data mode: up to 13.9 kbit/s in good channel condition; 2.2-3.2 kbit/s in complex channel conditions shallow water; 2) instant message mode: 1 kbit/s
bit error rate	less than 10^{-10}
power	stand-by mode: 2.5 <i>mW</i> ; listen mode: 5-285 <i>mW</i> ; receive mode: $\leq$ 1.3 <i>W</i> ; transmission mode: 2.8 <i>W</i> (1000 <i>m</i>), 8 <i>W</i> (2000 <i>m</i>), 35 <i>W</i> (3500 <i>m</i>), 80 <i>W</i> (max available)
power supply	external 24VDC; internal rechargeable battery
dimensions	diameter 110 <i>mm</i> ; total length 265 <i>mm</i>

C. The sweep-spread carrier model

The S2CR module shown in Table 3.9 is built upon the sweep-spread carrier (S2C) technology [154]. In the following, we will introduce this technology under multipath environment and *Doppler* spreading environment briefly.

1. Digital signal with sweep spread carrier

Assuming that the sweep spread carrier (S2-carrier) consist of a succession of sweeps with frequency variation from ω_L to ω_H within a time interval T_{SW} , and all the sweeps be uniformly produced in linear manner with rapid frequency variation following each other successively without any gap between them. Then the S2-carrier can be expressed as:

$$c(t) = A_c e^{j\left(\omega_L\left(t - \left\lfloor \frac{t}{T_{SW}} \right\rfloor T_{SW}\right) + m\left(t - \left\lfloor \frac{t}{T_{SW}} \right\rfloor T_{SW}\right)^2\right)} \quad (3.26)$$

where A_c is the amplitude; $m = \frac{\omega_H - \omega_L}{2T_{SW}}$ is a coefficient denoting the frequency variation rate; ω_L and ω_H denote the lowest and highest angular frequencies, respectively; T_{SW} is the sweep duration; the term $\left\lfloor \frac{t}{T_{SW}} \right\rfloor$ denotes the operand for truncating the value to the nearest least integer, which is defined as:

$$\left(t - \left\lfloor \frac{t}{T_{SW}} \right\rfloor T_{SW} \right) = \left\{ \frac{t}{T_{SW}} \right\} T_{SW} \quad (3.27)$$

The (3.27) can be interpreted in Equation (3.26) as an actual cycle time with the cycle duration T_{SW} .

2. Signal with sweep spread carrier under multipath channel

Based on the conclusions in (3.26) and (3.27), the signal with S2C in multipath channel can be calculated. Let $s(t)$ symbols be phase encoded data. The symbols are modulated onto the S2C, which is $x(t) = s(t) \cdot c(t)$. The signal is transmitted over dispersive underwater channel. The part of the model which represents the water medium consists of a number of delay elements τ_i which denotes time intervals between two successive multipath arrivals, and a number of multiplication elements V_i which takes possible attenuations on interfering multipath arrivals into account.

If both $c(t)$ and $s(t)$ have unit amplitudes, and every coefficient V_i and delay element τ_i keep constant during the entire transmission time, then after propagation along different paths in underwater medium, the signals received by receiver can be calculated as:

$$y(t) = V_0 x(t) + \sum_i V_i x(t - \tau_i) + n(t) \quad (3.28)$$

where $x(t)$ is defined above, $x(t - \tau_i)$ can be expressed as:

$$x(t - \tau_i) = s(t - \tau_i) \cdot e^{j\left(\omega_L \left(t - \left\lfloor \frac{t}{T_{SW}} \right\rfloor T_{SW}\right) + m \left(t - \left\lfloor \frac{t}{T_{SW}} \right\rfloor T_{SW}\right)^2\right)} \quad (3.29)$$

where $n(t)$ is the white noise. It is evident that:

$$\left\{ \frac{t - \tau_i}{T_{SW}} \right\} T_{SW} = \begin{cases} t_c - \tau_{ci}, & t_c \geq \tau_{ci} \\ T_{SW} + t_c - \tau_{ci}, & t_c < \tau_{ci} \end{cases} \quad (3.30)$$

where $t_c = \left\{ \frac{t}{T_{SW}} \right\} T_{SW}$ is the cycle time defined in (3.27), and $\tau_{ci} = \left\{ \frac{\tau_i}{T_{SW}} \right\} T_{SW}$ is a fractional part of time delay related to sweep duration T_{SW} . Thus, every delayed arrival represented in the second member of (3.28) can be rewritten as:

$$x(t - \tau_i) = \begin{cases} s(t - \tau_i) \cdot e^{j(\omega_L(t_c - \tau_{ci}) + m(t_c - \tau_{ci})^2)}, & t_c \geq \tau_{ci} \\ s(t - \tau_i) \cdot e^{j(\omega_L(T_{SW} + t_c - \tau_{ci}) + m(T_{SW} + t_c - \tau_{ci})^2)}, & t_c < \tau_{ci} \end{cases} \quad (3.31)$$

After transformation of (3.31), each delayed arrival can be written as:

$$x(t - \tau_i) = s(t - \tau_i) \cdot e^{j(\omega_L t_c + m t_c^2 - \Delta\omega_i t_c + \phi_i)} \quad (3.32)$$

where $\Delta\omega_i = \begin{cases} 2m\tau_{ci}, & t_c \geq \tau_{ci} \\ -2m(T_{SW} - \tau_{ci}), & t_c < \tau_{ci} \end{cases}$ is the frequency deviation of i th multipath arrival

caused by delay τ_i , and $\phi_i = \begin{cases} (m\tau_{ci} - \omega_L)\tau_{ci}, & t_c \geq \tau_{ci} \\ (\omega_H + \omega_L - 2m\tau_{ci}) \frac{T_{SW} - \tau_{ci}}{2}, & t_c < \tau_{ci} \end{cases}$ is the phase of i th

multipath arrival.

The term with $i = 0$ in (3.28) represents an attenuated version of the original signal, and the other term is the multipath diversity of its delayed, attenuated and frequency shifted reproductions. The most important feature of (3.32) is that at any instant all the interfering multipath arrivals have different frequencies spaced by $\Delta\omega_i$ from each other.

3. Signal with sweep spread carrier under Doppler spreading

The same can be shown for time-varying channels. The sweep spread carrier under Doppler spreading can be expressed as [154]:

$$x(t - \tau_i) = s(t - \tau_i) e^{j\left(\omega_L\left(t - \left\lfloor \frac{t}{T_{sw}} \right\rfloor T_{sw}\right) + m\left(t - \left\lfloor \frac{t}{T_{sw}} \right\rfloor T_{sw}\right)^2\right)} e^{j\omega_d^i(t - \tau_i)} \quad (3.33)$$

where ω_d^i is the *Doppler* frequency encountered in *ith* propagation path, which reflects the influence of Doppler effect on the received signal. The last exponent in (3.33) can reflect time-varying phase/frequency. In this case, the ω_d^i is characterized with a time dependent function specific for *ith* path induced. The (3.33) demonstrates that *Doppler* shifts belongs to different paths will not be coupled while the ω_d^i stays within certain boards; so a maximum value ω_{dmax}^i of the time-varying bandwidth enlargement ω_d^i does not extend a half of frequency separation space between respective multipath arrivals (e.g. $\omega_{dmax}^i < \frac{\omega_d^i}{2}$). In this case, every arrival stays within definite frequency range and does not influence another frequency band; no inter-modulation between differently varying Doppler terms belong to different propagation paths takes place.

D. Propagation model

According to the conclusion in [155], the path loss model of underwater acoustic channel over a distance l with signal frequency f is given as:

$$A(l, f) = l^k a(f)^l \quad (3.34)$$

where k is the spreading factor, $a(f)$ is the absorption coefficient. The pass loss model shown in (3.34) can be expressed by *dB*, which is:

$$10 \log A(l, f) = k \cdot 10 \log l + l \cdot 10 \log a(f) \quad (3.35)$$

where $k \cdot 10 \log l$ is the spreading loss; $10 \log a(f)^l$ means the absorption loss. The k is the spreading factor which describes the geometry of propagation and the values are: 1) $k = 2$ for spherical spreading; 2) $k = 1$ for cylindrical spreading; 3) $k = 1.5$ for practical spreading.

The absorption coefficient $a(f)$ can be expressed by using the Thorp's formula, which is an empirical formula; the $a(f)$ can be expressed as:

$$10 \log a(f) = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f^2} + 2.75 \times 10^{-4} f^2 + 0.003 \quad (3.36)$$

The (3.36) is used for frequencies above a few hundred Hz. If the frequencies are low, then the (3.36) can be rewritten as:

$$10 \log a(f) = 0.11 \frac{f^2}{1+f^2} + 0.011 f^2 + 0.002 \quad (3.37)$$

Therefore, when the transmission power is P , the received signal power will be:

$$P_r = \frac{P}{A(l, f)} = \frac{P}{l^k a(f)^l} \quad (3.38)$$

According to Equation (3.38), when the received signal power is equal to the receive threshold

P_{r-th} , the transmission range r of this AUV can be calculated based on Equation (3.38).

For the scenario shown in Figure 3.8, since the underwater AUVs move freely in a 2-dimensional plane, so one of the important issues for this kind of network is the link lifetime, which is crucial to the performance of the routing algorithm. Therefore, in the next section, we propose the link lifetime predication algorithm for the scenario shown in Figure 3.8 first.

3.3.2. Link lifetime predication algorithm

The routing performance is affected by the mobility of AUV. Due to the mobility of AUV, the network topology changes frequently, so the router easily to be broken and cannot last a long time [156]. The node mobility includes the moving speed and moving direction of AUV. Both the moving speed and moving direction can affect the link lifetime. However, in the previous researches, the effect of the moving direction on the link lifetime has not been fully investigated. In this section, this issue will be investigated in detail.

The link lifetime prediction is difficult in underwater cooperation AUVs network because the AUVs can move freely [156]. During the calculation, we assume that the link connections are unstable and can only last a short period of time. Moreover, in the underwater network, each AUV knows other AUVs' location and only the sender's neighbors whose distances to the destination AUV are smaller than that of the sender will be considered as the candidate relaying AUVs. As shown in Figure 3.15, when the AUVs locate in the red area (which is defined as the survival area, the survival area means that in this area, the link connection can be guaranteed), the link lifetimes are larger than 0. The value of the link lifetime relates to the sender s , the relaying AUV r , and the destination AUV d . Due to the mobility of the sender s and the destination AUV d , the survival area changes continuously. In addition, considering the mobility of the relaying AUV r , the communication link will be broken when the AUV r moves out of the survival area. Therefore, the relative velocity of AUV r relative to AUV s and AUV d need to be calculated. The calculation of the relative velocity is shown in Figure 3.16.

Figure 3.15. Geographic based relay node selection

Figure 3.16. The principle of the velocity vector operation

In Figure 3.16, the moving velocities of AUV s , AUV r , and AUV d are $\vec{v}_s$ (the moving speed is v_s and the moving direction is θ_s), $\vec{v}_r$ (the moving speed is v_r and the moving direction is θ_r), and $\vec{v}_d$ (the moving speed is v_d and the moving direction is θ_d), respectively. If the destination AUV d is chosen as the reference frame, then the relative velocity of sender s relative to AUV d is given by: $\vec{v}_{sd} = \vec{v}_s - \vec{v}_d$. According to the vector synthesis theory, the relative moving speed and moving direction of $\vec{v}_{sd}$ can be given by: $v_{sd} = \sqrt{v_{xsd}^2 + v_{ysd}^2}$, $\theta_{sd} = \arctan(v_{xsd}/v_{ysd})$, $v_{xsd} = v_s \cos \theta_s + v_d \cos \theta_d$, and $v_{ysd} = v_s \sin \theta_s + v_d \sin \theta_d$; where v_{xsd} is the moving speed of v_{sd} in x -axis and v_{ysd} is the moving speed of v_{sd} in y -axis. Therefore, the relative velocity of relay AUV r relatives to $\vec{v}_{sd}$ can be calculated as: $\vec{v}_{sdr} = \vec{v}_r - \vec{v}_{sd}$. Similarly with that shown above, the relative moving speed and moving direction of $\vec{v}_{sdr}$ can be got from: $v_{sdr} = \sqrt{v_{xsdr}^2 + v_{ysdr}^2}$, $\theta_{sdr} = \arctan(v_{xsdr}/v_{ysdr})$, $v_{xsdr} = v_r \cos \theta_r + v_{sd} \cos \theta_{sd}$, and $v_{ysdr} = v_r \sin \theta_r + v_{sd} \sin \theta_{sd}$, where v_{xsdr} is the speed of v_{sdr} in x -axis and v_{ysdr} is the speed of v_{sdr} in y -axis.

As shown in Figure 3.17, AUV r moves with velocity $\vec{v}_{sdr}$. Assuming that the AUV r moves out of the survival area at time t , according to Figure 3.17, there are two different scenarios about this issue: (1) the relaying AUV moves toward to the destination AUV; (2) the relaying AUV moves far away from the destination AUV. For solving this problem, we need calculate the relative velocity angle of r .

Figure 3.17. The principle of the residual link lifetime calculation

As shown in Figure 3.16, assuming the coordinate of s is (x_s, y_s) and the coordinate of d is (x_d, y_d) , then the angle of $\vec{sd}$ relative to the x -axis can be got from: $\theta_{\vec{sd}x} = \arctan\left(\frac{y_s - y_d}{x_s - x_d}\right)$. According to $\theta_{sdr} = \arctan(v_{xsdr}/v_{ysdr})$ and the triangle geometry theory, the velocity angle of r relates to $\vec{sd}$ is: $\theta_{rel} = \theta_{sdr} - \theta_{\vec{sd}x}$. Therefore, if $\theta_{rel} \in \left[0, \frac{\pi}{2}\right] \cup \left[\frac{3\pi}{2}, \pi\right]$, the AUV r moves close to the destination AUV in x -axis or y -axis; otherwise, when $\theta_{rel} \in \left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$, the AUV r moves far away from the destination AUV in both x -axis and y -axis. So the link lifetime prediction should be divided into two different parts.

1. When $\theta_{rel} \in \left[0, \frac{\pi}{2}\right] \cup \left[\frac{3\pi}{2}, \pi\right]$

In this scenario, the relay AUV r moves toward to the destination AUV d in x -axis or y -axis. According to Figure 3.15 and the law of cosines, in triangle srd we can get the function as follows:

$$d_{dr}^2 = d_0^2 + d_{ds}^2 - 2d_0d_{ds}\cos\phi_3 \quad (3.39)$$

where d_{dr} is the distance between relay AUV r and destination AUV d ; d_0 is the distance between sender s and relay AUV r at time t_0 ; d_{ds} is the distance between sender s and destination AUV d . Since the values of d_{dr} , d_0 , and d_{ds} can be calculated based on the coordinates of these AUVs, so the value of ϕ_3 can be got from (3.39). Therefore, ϕ_2 can be calculated as: $\phi_2 = \pi - \phi_3$.

Additionally, in triangle srC , θ_{rel} and ϕ_3 are all known, so the angle α can be calculated: $\alpha = \pi - \phi_3 - \theta_{rel}$. In triangle srA , according to the law of cosines, we can get:

$$R^2 = d_0^2 + [v_{sdr}(t - t_0)]^2 - 2d_0v_{sdr}(t - t_0)\cos\alpha \quad (3.40)$$

where R is the transmission range of sender s . Therefore, the t can be calculated by (3.41).

Thus in this scenario, the residual link lifetime is:

$$T_r = t - t_0 \quad (3.41)$$

2. When $\theta_{rel} \in \left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$

When $\theta_{rel} \in \left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$, the link lifetime predication is similar to that when $\theta_{rel} \in \left[0, \frac{\pi}{2}\right] \cup \left[\frac{3\pi}{2}, \pi\right]$. The distance between the destination AUV d and relay AUV r at time t_0 is d_{dr} and the length of line dD is equal to d_{ds} . Moreover, in triangle drD , the $\angle drD$ can be calculated as:

$$\angle drD = \phi_5 = \pi - (\phi_2 - \phi_1) \quad (3.42)$$

Additionally, in triangle srd , according to the law of cosines we can get:

$$d_{ds}^2 = d_0^2 + d_{dr}^2 - 2d_0d_{dr}\cos\phi_1 \quad (3.43)$$

$$\phi_1 = \pi - \phi_4 \quad (3.44)$$

In (3.42), the ϕ_2 can be calculated by $\phi_2 = \pi - \phi_3$ and ϕ_1 can be calculated by (3.43) and (3.44), so in triangle drD , we have:

$$d_{ds}^2 = d_{dr}^2 + [v_{sdr}(t - t_0)]^2 - 2d_{dr}v_{sdr}(t - t_0)\cos\phi_5 \quad (3.45)$$

In (3.45), the t can be calculated. So the residual link lifetime in this scenario can be calculated by (3.41).

3.3.3. The SBFL based relay node selection and priority algorithm

Considering the disadvantages of the traditional opportunistic algorithms, and based on the SBFL algorithm introduced in last chapter, in this section, we propose the SBFL based relay node selection and prioritization algorithm for underwater opportunistic routing.

In SBFL, we assume that each node know the locations of the other nodes in the network; the neighbors whose distances to the destination node are larger than the source node will not be considered as the candidate relay node. If the source node want send packet to the destination node, first, it will broadcast the RREQ to its neighbors. The neighbors are the nodes who have one-hop bi-directional communication links with the source node. The RREQ includes the location of the source node and the destination node. The neighbors who receive this message

will calculate the distances to the destination node. The neighbor nodes whose distances to the destination node are larger than that of the source node will drop the RREQ packet directly. Only the neighbor nodes whose distances to the destination node are smaller than the source node will reply the RREP message to the source node. In the RREP packet, the residual energy of the node, the ETX of the communication link, the packet queue length in the relay node, the delay of the relay node, the distance to the destination node, the moving speed, and the moving direction will be included.

When the source node receives the RREP packet, first, the source node will extract the cross-layer parameters from the RREP packets; then according (3.1), the source node will calculate the relative variance D_i for each cross-layer parameters that from different neighbor nodes. Since for each underwater node, there are more than one parameter are taken into account during the relaying node selection, so in this algorithm, we introduce the weight based multi-attribute utility approach [148] into the SBFL algorithm. For the weight based multi-attribute utility approach, two important issues are: 1) calculating the weight for each parameter; 2) parameter normalization. We use the SBFL algorithm introduced in Chapter 2 to calculate the weight for each parameter. As discussed before, the rv D_i are the inputs of the fuzzy logic inference system, and the outputs are the weights of each cross-layer parameters. The weights relate to the effect of different cross-layer parameters on the relay node selection. When the weights of each cross layer parameters are got, then the SBFL algorithm that introduced in Section 3.1 will be used to decide the relaying priority for each node in the CRS.

When the relaying priority of each node is determined, then the source node will call the DDA coordination algorithm that proposed in Section 3.2 to optimize the CRS to guarantee the complete connection and reduce the transmission delay and redundant transmission.

The process of the SBFL based relay node selection and prioritization algorithm is shown as follows:

Algorithm 3.4. SBFL based relay node selection and prioritization algorithm

Function:

$S(U_i^j)$: calculate the scatter of the cross-layer parameters;

$fu_lo(D_i)$: fuzzy logic calculate the weight of each parameters;

$U(U_i^j, \omega_i)$: calculate the utility of each AUV;

$r(\psi)$: decide the rank of the neighbor AUV in the relay node set;

Main:

while Route_discovery=1 do

 sender broad RREQ to neighbor AUVs;

 if(distance(AUV_i, destination_AUV)<distance(sender, destination_ AUV))

 AUV_i sends RREP to sender;

 end if

 sender extract cross layer parameters from RREP;

 if ($U_i^j \geq U_i^{th}$)

```
AUV_status  $\leftarrow$  true;
else if ( $U_i^j < U_i^{th}$ )
AUV_status  $\leftarrow$  false;
end if
while AUV_status == true do
call SBFL algorithm;
call DDA algorithm
end while
sender send data packet to the relay AUVs with the rank list;
relay AUVs relay the data packet according the priority in the rank list;
end while
```

3.4 Probability Prediction based reliable and efficient opportunistic routing algorithm for VANETs [215]

Except the underwater cooperation AUVs network, based on the DDA algorithm, we also investigate the properties of this coordinate scheme in terrestrial environment. Since for the mobile wireless networks, the mobility pattern in the VANETs is more accuracy to predict, so we apply the delay based duplicate transmission avoid coordination scheme in the vehicular ad hoc networks (VANETs).

To the wireless network, one of the crucial parameters which can affect the network performance is the Signal to Interference plus Noise Ratio (SINR). The receiver can receive the data packet that transmitted from the sender correctly only when the SINR at the receiver is larger than the receiving threshold [157][158][159]. The SINR in wireless network has been investigated in-depth and many high quality SINR based routing algorithms have been proposed, such as [158], [159], [160], and [161]. However, in these algorithms, the calculation of the SINR is not sufficient to reflect the dynamic of the network; especially the VANETs, in which the network parameters change frequently and the information that the sender maintains may outdate due to the high mobility of vehicles [149, 162].

Not only the SINR, but also the packet queue length (PQL) in the buffer space of the vehicle has great effect on the PDR [149]. For instance, assuming that the SINR of the receiver is larger than the receiving threshold but the residual buffer space is not enough to store the coming packets, the packets will be dropped. Moreover, the data traffic may be aggregated at some vehicles through improper routing, which incurs long PQL (i.e., long one-hop delay), even worse may induce buffer overflow and packet loss in network layer. This reduces the packet delivery ratio and increases the transmission delay. So the PQL of the receiver should be taken into account during the relaying node selection. Similar to the calculation of SINR, the calculation of PQL in VANETs should also be able to aware of the high network dynamic of VANETs.

Thus, for improving the routing performance of VANETs, the routing algorithms should be able to predict the variation of the network parameters before data packet transmission [149, 162-165], such as the SINR, the PQL, the link availability, the movement, etc. The network parameters in VANETs are predictable because the vehicles move on a road network. The prediction of the link availability and movement has been investigated in [149, 162-165].

3.4.1. Network Model

The network model used in this algorithm is different with that shown in Chapter 2, which is shown in Figure 3.18. In VANETs, the vehicles can only move along the streets. Each vehicle uses the same transmission power to communicate with other vehicles, i.e., the transmission ranges of different vehicles are the same. At the intersections, only one road is unblocked. Between different roads, there are some buildings. The velocity variation follows a truncated Gaussian distribution as that shown in [166]; moreover, the *Wiener process* is utilized to model the movement of vehicles [167][168]. On each road, there are two moving directions. Assuming that the length of the road between two adjacent intersections is much longer than the transmission range of vehicle, so the vehicles which locate at different intersections of the same road cannot communicate with each other directly; for instance, as shown in Figure 3.18, the vehicle a and vehicle b cannot communicate with each other directly. The vehicles equip GPS devices and can acquire their locations [162].

Figure 3.18. Network model

For a transmission pair $\langle s, d \rangle$, the sender s can move close to or far away from the destination d . In this algorithm, the sender vehicle s moves close to the destination vehicle d means that after Δt , the Euclidean distance between s and d reduces. Based on Figure 3.18, the vehicle s moves close to vehicle d can be divided into two directions: horizontal direction and vertical direction. For instance, to the transmission pair $\langle s, d \rangle$ (the d has been shown in Figure 3.18), the moving directions of s towards to d are: 1) upward movement along Road B or Road C; 2) moving to the right along Road A.

3.4.2. Probability Prediction Algorithm

Based on the mobility model of the vehicles in VANETs [166][167][168], the sender vehicle can predict the parameter variation of its neighbor vehicles. The probability prediction algorithms of the distance and the link availability have been learned in previous works, such as [162], [167], [168], [169], [170], and [149]; so the main content in this section is to investigate the probability prediction algorithms of SINR and PQL in VANETs, which have not been proposed in the previous works.

For predicting the distances variation between vehicle s and its neighbors, the moving pattern

introduced in [166] is referenced in [149]. The velocity variation of vehicle s is calculated as [149]:

$$\Delta v_{s,t_{12}} = v_{s,t_1} - v_{s,t_2} = \sigma_s \sqrt{t_2 - t_1} \quad (3.46)$$

where v_{s,t_1} and v_{s,t_2} are the velocities of vehicle s at t_1 and t_2 , respectively; $\Delta v_{s,t_{12}}$ is the velocity changing of s during $[t_1, t_2]$; σ_s follows a standard Gaussian distribution. Additionally, Δv has an independent increment in different time intervals. So the relative distance changing between vehicles s and r during $[t_1, t_2]$ can be expressed as:

$$\Delta d(s, r)_{\Delta t} = (v_{s,t_1} - v_{r,t_1} + \Delta v_{s,t_{12}} - \Delta v_{r,t_{12}}) \cdot \Delta t \quad (3.47)$$

where $\Delta t = t_2 - t_1$. The value of $\Delta d(s, r)_{\Delta t}$ relates to v_{s,t_1} , v_{r,t_1} , $\Delta v_{s,t_{12}}$, and $\Delta v_{r,t_{12}}$. According to different values of v_{s,t_1} , v_{r,t_1} , $\Delta v_{s,t_{12}}$, and $\Delta v_{r,t_{12}}$, the $\Delta d(s, r)_{\Delta t}$ could larger or smaller than zero, which means the vehicles could close to or far away from each other. In [149], the authors has proved that $\Delta v_{s,t_{12}}$, $\Delta v_{r,t_{12}}$, and $\Delta v_s - \Delta v_r$ are all independent variables and follow zero-mean Gaussian distribution. Moreover, after Δt , the probability that the vehicle s and r can communicate with each other directly, i.e., the link reliability [162], can be calculated as [149]:

$$\begin{aligned} P_{sr}^d(\Delta t) &= p\{\Delta d(s, r)_{\Delta t} < R - d_{sr,t_1}\} \\ &= F\left(\Delta v_{s,t_{12}} - \Delta v_{r,t_{12}} < \frac{R - d_{sr,t_1} - (v_{s,t_1} - v_{r,t_1})\Delta t}{\Delta t}\right) \\ &= \int_{-\infty}^{\frac{R - d_{sr,t_1} - (v_{s,t_1} - v_{r,t_1})\Delta t}{\Delta t}} f(\Delta v_{s,t_{12}} - \Delta v_{r,t_{12}}) d(\Delta v_{s,t_{12}} - \Delta v_{r,t_{12}}) \end{aligned} \quad (3.48)$$

where $\Delta v_s \sim N(0, \sigma_s^2 \Delta t)$, $\Delta v_r \sim N(0, \sigma_r^2 \Delta t)$, and $\Delta v_s - \Delta v_r \sim N(0, \sigma_s^2 \Delta t + \sigma_r^2 \Delta t)$. Since $\Delta v_s - \Delta v_r \sim N(0, \sigma_s^2 \Delta t + \sigma_r^2 \Delta t)$, so the probability density function (PDF) $f(\Delta v_{s,t_{12}} - \Delta v_{r,t_{12}})$ follows Gaussian distribution; $F(\Delta v_{s,t_{12}} - \Delta v_{r,t_{12}})$ is the accumulative distribution function of $f(\Delta v_{s,t_{12}} - \Delta v_{r,t_{12}})$.

Based on the conclusions and assumptions introduced above, we propose the prediction algorithms for SINR and PQL in the following of this section.

A. Prediction algorithm of SINR

The SINR at the receiver can be calculated according to the conclusions in [171]. When the vehicle s sends data packet to vehicle r , the interference of vehicle r at t_1 can be calculated based on the long-distance path loss model [172][173], which is:

$$I_{r,t_1} = N + \sum_{i=1}^{n_{int-r,t_1}} \xi(d_{ir,t_1}) = N + \sum_{i=1}^{n_{int-r,t_1}} \frac{G_t G_r \lambda^2 P_t}{(4\pi)^2 d_{ir,t_1}^\alpha} \quad (3.49)$$

where n_{int-r,t_1} is the number of interference vehicles of r at t_1 ; N is the additive white Gaussian noise (AWGN); P_t is the transmission power; G_t and G_r are the antenna gains of sender and receiver; λ is the wavelength; α is the path loss exponent and $2 \leq \alpha \leq 5$ depends on the geometry of propagation environment [170], i.e., when $\alpha = 2$, it means free space, when $2.7 \leq \alpha \leq 3.5$, it represents the urban area cellular radio, when $3 \leq \alpha \leq 5$, it represents the shadowed urban cellular radio, etc. Without losing of generality, let $G = \frac{G_t G_r \lambda^2}{(4\pi)^2}$,

then (3.49) can be rewritten as:

$$I_{r,t_1} = N + G \sum_{i=1}^{n_{int-r,t_1}} P_t / d_{ir,t_1}^\alpha \quad (3.50)$$

If the vehicle r can receive the data packet that transmitted from vehicle s successfully, the

SINR at vehicle r should satisfy the constraint as follows:

$$SINR_{r,t_1} = \frac{GP_t/d_{sr,t_1}^\alpha}{N+G\sum_{i=1,i\neq s}^{n_{int-r,t_1}} P_t/d_{ir,t_1}^\alpha} = \frac{d_{sr,t_1}^{-\alpha}}{N/P_t G + \sum_{i=1,i\neq s}^{n_{int-r,t_1}} d_{ir,t_1}^{-\alpha}} \geq \beta \quad (3.51)$$

In (3.51), as the assumptions in Section 3.4.1, all the vehicles have the same transmission power P_t ; d_{sr,t_1} is the Euclidean distance between s and r at t_1 ; $d_{ir,t_1}, (i = 1, 2, \dots, n_{int-r,t_1})$ is the Euclidean distance between the receiver r and its interference vehicle i at t_1 (the interference vehicle is defined as the vehicle which the transmission range covers r); β is the receiving threshold which can guarantee successful data packet decoding at the receiver.

According to the conclusions in [149] and (3.47), the distance variation between the sender vehicle s and the receiver vehicle r after Δt can be calculated as:

$$d_{sr,t_1+\Delta t} = d_{sr,t_1} + \Delta d(s,r)_{\Delta t} \quad (3.52)$$

The distance variation between the receiver r and its interference vehicles after Δt can be expressed as:

$$d_{ir,t_1+\Delta t} = d_{ir,t_1} + \Delta d(i,r)_{\Delta t}, \quad i = 1, 2, \dots, n_{int-r,t_1+\Delta t} \quad (3.53)$$

As shown in (3.52), when the distance between the sender vehicle s and the receiver vehicle r is d_{sr,t_1} at t_1 , then it will be $d_{sr,t_1+\Delta t}$ after Δt . Additionally, since $\Delta v_s \sim N(0, \sigma_s^2 \Delta t)$, $\Delta v_r \sim N(0, \sigma_r^2 \Delta t)$, and $\Delta v_s - \Delta v_r \sim N(0, \sigma_s^2 \Delta t + \sigma_r^2 \Delta t)$ [149], so based on the principle of linear combination of Gaussian variables, the distance variation during Δt which is shown in (3.47) follows the Gaussian distribution as follows:

$$\Delta d(s,r)_{\Delta t} \sim N(0, (\sigma_s^2 + \sigma_r^2) \Delta t^3) \quad (3.54)$$

According to (3.52) and (3.54), since the d_{sr,t_1} is constant during Δt , so the $d_{sr,t_1+\Delta t}$ shown in (3.54) also follows the Gaussian distribution, which is:

$$d_{sr,t_1+\Delta t} \sim N(d_{sr,t_1}, (\sigma_s^2 + \sigma_r^2) \Delta t^3) \quad (3.55)$$

Therefore, according to (3.51), (3.52) and (3.53), the SINR of vehicle r at $t_1 + \Delta t$ can be expressed as:

$$SINR_{r,t_1+\Delta t} = \frac{(d_{sr,t_1} + \Delta d(s,r)_{\Delta t})^{-\alpha}}{N' + \sum_{i=1,i\neq s}^{n_{int-r,t_1+\Delta t}} (d_{ir,t_1} + \Delta d(i,r)_{\Delta t})^{-\alpha}} \quad (3.56)$$

where $N' = N/P_t G$. Then the probability that after Δt , the SINR at the receiver vehicle r is larger than the receiving threshold β can be calculated as:

$$Pr_{sr}^{SINR}(\Delta t) = p \left\{ \frac{(d_{sr,t_1} + \Delta d(s,r)_{\Delta t})^{-\alpha}}{N' + \sum_{i=1,i\neq s}^{n_{int-r,t_1+\Delta t}} (d_{ir,t_1} + \Delta d(i,r)_{\Delta t})^{-\alpha}} \geq \beta \right\} \quad (3.57)$$

As shown in (3.57), two parameters can affect the probability prediction of SINR: 1) the distances between vehicle r and its interference vehicles; 2) the number of the interference vehicles of r , i.e., the value of n_{int-r} . With the time goes on, these two parameters change. On one hand, the interference vehicles of r at t_1 may not the interference vehicles at $t_1 + \Delta t$, and the vehicles which are not the interference vehicles of r at t_1 may be the interference vehicles at $t_1 + \Delta t$. As shown in Figure 3.19, at t_1 , the interference vehicles of r are vehicles A, B, C , and D ; at $t_1 + \Delta t$, the interference vehicles are C, D, E, F , and G . On the other hand, the distances between vehicle r and its interference vehicles change with the vehicles' movement. Therefore, during the SINR prediction, both these two parameters need to be taken into account.

Figure 3.19. Network topology variation

1. The effect of the distances between r and its interference vehicles

For calculating the probability shown in (3.57), we need to know the PDF of $(d_{sr,t_1} + \Delta d(s,r)_{\Delta t})^{-\alpha}$ and $N' + \sum_{i=1, i \neq s}^{n_{int-r,t_1+\Delta t}} (d_{ir,t_1} + \Delta d(s,r)_{\Delta t})^{-\alpha}$, respectively. Here we propose three corollaries as follows to calculate the PDF of $(d_{sr,t_1} + \Delta d(s,r)_{\Delta t})^{-\alpha}$ and $N' + \sum_{i=1, i \neq s}^{n_{int-v,t_1+\Delta t}} (d_{ir,t_1} + \Delta d(s,r)_{\Delta t})^{-\alpha}$.

Corollary 3.9. For $x \sim N(\mu, \sigma^2)$, the PDF of $y = x^{-\alpha}$ is: $f_Y(y) = y^{-\frac{1+\alpha}{\alpha}} \frac{1}{\sqrt{2\pi}\alpha} e^{-\frac{(y^{-1/\alpha}-\mu)^2}{2}}$.

Proof. See Appendix F.

Corollary 3.10. For $x \sim N(\mu, \sigma^2)$, the PDF of $z = N + \sum_{i=1}^m x_i^{-\alpha}$ is:

$$f_z(z) = p(N) + \underbrace{\int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty}}_m (z - \sum_{i=2}^m y_i)^{-\frac{1+\alpha}{\alpha}} \frac{1}{\sqrt{2\pi}\alpha} e^{-\frac{\left((z - \sum_{i=2}^m y_i)^{-\frac{1}{\alpha}} - \mu\right)^2}{2}} \\ \cdot \prod_{i=2}^m y_i^{-\frac{1+\alpha}{\alpha}} \frac{1}{\sqrt{2\pi}\alpha} e^{-\frac{\left(y_i^{-\frac{1}{\alpha}} - \mu\right)^2}{2}} dy_2 \dots dy_m.$$

Proof. See Appendix G.

Corollary 3.11. For $x \sim N(\mu, \sigma^2)$, $y = x^{-\alpha}$ and $z = N + \sum_{i=1}^m x_i^{-\alpha}$, the probability density

function of $w = y/z$ is: $f_w(w) = \int_{-\infty}^{\infty} |z| (wz)^{-\frac{1+\alpha}{\alpha}} \frac{1}{\sqrt{2\pi}\alpha} e^{-\frac{\left((wz)^{-\frac{1}{\alpha}} - \mu\right)^2}{2}} \cdot f_z(z) dz$, where

$f_z(z)$ can be calculated by Corollary 3.10.

Proof. See Appendix H.

As shown in this section, the PDF of $d_{sr,t_1+\Delta t}$ can be calculated by (3.55); moreover, $d_{ir,t_1+\Delta t}$ follows the similar distribution as $d_{sr,t_1+\Delta t}$, which is $d_{ir,t_1+\Delta t} \sim N(d_{ir,t_1}, (\sigma_i^2 + \sigma_r^2)\Delta t^3)$. Therefore, according to Corollary 3.9, Corollary 3.10, and Corollary 3.11, the $Pr_{sr}^{SINR}(w)$ shown in (3.57) can be calculated as:

$$Pr_{sr}^{SINR}(w) = p \left\{ \frac{(d_{sr,t_1+\Delta t}(s,r)_{\Delta t})^{-\alpha}}{N' + \sum_{i=1, i \neq s}^{n_{int-r,t_1+\Delta t}} (d_{ir,t_1+\Delta t}(i,r)_{\Delta t})^{-\alpha}} \geq \beta \right\}$$

$$\begin{aligned}
&= 1 - p \left\{ \frac{(d_{sr,t_1} + \Delta d(s,r)_{\Delta t})^{-\alpha}}{N' + \sum_{i=1, i \neq s}^{n_{int-r,t_1+\Delta t}} (d_{ir,t_1} + \Delta d(i,r)_{\Delta t})^{-\alpha}} < \beta \right\} \\
&= 1 - \int_{-\infty}^{\infty} |z| (wz)^{-\frac{1+\alpha}{\alpha}} \frac{1}{\sqrt{2\pi}\alpha} e^{-\left((wz)^{-\frac{1}{\alpha}-\mu}\right)^2/2} \cdot f_z(z) dz
\end{aligned} \tag{3.58}$$

where $z = N' + \sum_{i=1, i \neq s}^{n_{int-r,t_1+\Delta t}} (d_{ir,t_1} + \Delta d(i,r)_{\Delta t})^{-\alpha}$ $f_z(z)$ can be calculated by Corollary 3.10.

However, the probability shown in (3.58) does not take the variation of n_{int-r} into account. Due to the high mobility of vehicles, the n_{int-r} changes greatly (as shown in Figure 3.18), which can affect the SINR seriously. In the following, we will calculate the effect of the number of interference vehicles on the probability prediction of SINR.

2. The effect of the number of interference vehicles

The value of n_{int-r} relates to the distances between the receiver r and its interference vehicles. After Δt , the probability that the vehicle r locates in the transmission range of vehicle s is denoted as $P_{sr}^d(\Delta t)$, which can be calculated by (3.48). Therefore, assuming that there are n vehicles in the network, then at $t_1 + \Delta t$, the average of n_{int-r} can be calculated as:

$$\bar{n}_{int-r,t_1+\Delta t} = \sum_{i=1}^n P_{ir}^d(\Delta t) \tag{3.59}$$

According to Corollary 3.10 and (3.59), after Δt , the PDF of the interference at receiver r can be calculated as:

$$\begin{aligned}
f_z(z) &= p(N) + \underbrace{\int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty}}_{\bar{n}_{int-r,t_1+\Delta t}} \left(z - \sum_{i=2}^{\bar{n}_{int-r,t_1+\Delta t}} x_i \right)^{-\frac{1+\alpha}{\alpha}} \cdot \frac{1}{\sqrt{2\pi}\alpha} e^{-\frac{\left(\left(z - \sum_{i=2}^{\bar{n}_{int-r,t_1+\Delta t}} x_i \right)^{-\frac{1}{\alpha}-\mu} \right)^2}{2}} \\
&\quad \cdot \prod_{i=2}^{\bar{n}_{int-r,t_1+\Delta t}} x_i^{-\frac{1+\alpha}{\alpha}} \frac{1}{\sqrt{2\pi}\alpha} e^{-\frac{\left(x_i^{-\frac{1}{\alpha}-\mu} \right)^2}{2}} dx_2 \dots dx_{\bar{n}_{int-r,t_1+\Delta t}}
\end{aligned} \tag{3.60}$$

Then the probability $Pr_{sr}^{SINR}(w)$ can be calculated based on (3.58) and (3.60). Note that in this calculation, the value of $f_z(z)$ has changed. In (3.60), both the value of n_{int-r} and the distances between vehicle r and its interference vehicles are taken into account.

B. Prediction algorithm of PQL

From the viewpoint of PQL, if the sender vehicle s can send data packet to the receiver vehicle r successfully, the receiver vehicle r should have enough memory space to store the data packet that transmitted from the sender vehicle s , which means that the PQL at the receiver r much smaller than the maximum allowed value.

Assuming that there are n_{int-r,t_1} neighbor vehicles of receiver r at t_1 ; then after Δt , this number can be calculated by (3.60). However, both the neighbors at t_1 and $t_1 + \Delta t$ can send data packet to vehicle r , so there are two kinds of neighbor vehicles: 1) the vehicles which locate in the transmission range of receiver r at t_1 , such as vehicles A, B, C , and D in Figure 3.19; 2) the vehicles which do not locate in the transmission area of r but move into it during Δt , such as the vehicles E, F , and G in Figure 3.19. The PQL prediction should take these two

kinds of neighbor vehicles into account.

Since the probability that a vehicle has data packet need to be transmitted relates to the MAC protocols and different MAC protocols have different generation probabilities (which is not the main research topic of this thesis), therefore, without loss of generality, we use p_0 to represent the data packet generation probability. The detail of how the MAC protocols determine the packet generation probability of vehicles can be found in [174].

Based on these assumptions, we assume that the data generation probability of vehicle is p_0 ; the time interval is Δt ; the transmission interval in the MAC protocol is t_m ; therefore, the number of transmission interval is $n_{inter} = \Delta t/t_m$. The maximum allowed PQL is M and the PQL is a at t_1 ; so the remaining available PQL is $b = M - a$. In each transmission interval, only one vehicle can transmit one data packet; the transmitter could be the receiver vehicle r or its neighbor vehicles. When the sender is the neighbor vehicle of r , the PQL in r increases; otherwise, if the sender is r , then the PQL decreases. If the receiver r can receive the data packet transmitted by sender s after Δt , the PQL in r should smaller than the maximum PQL. In each transmission interval, there are three different situations: 1) the neighbor vehicles of r send data packet; 2) the r sends the data packet; 3) both the neighbor vehicles and r do not send data packet, which can be found in Figure 3.20.

Figure 3.20. Different transmission situations during the transmission interval

For the first situation, assuming that there are $n_{int-r,t_1+\Delta t_j}$ neighbor vehicles of r in the j th transmission interval, then the probability that there is at least one neighbor vehicle generates data packet can be calculated as:

$$p_{nei} = 1 - (1 - p_0)^{n_{int-r,t_1+\Delta t_j}} \quad (3.61)$$

Similarly, the probability of situation 2 p_{rec} and situation 3 p_{nons} can be calculated as:

$$p_{rec} = p_0 \quad (3.62)$$

$$p_{nons} = (1 - p_0)^{n_{int-r,t_1+\Delta t_j}+1} \quad (3.63)$$

The average number of neighbors at j th transmission interval can be calculated based on (3.59), which is:

$$\bar{n}_{int-r,t_1+\Delta t_j} = \sum_{i=1}^n P_{ir}^d(t_1 + \Delta t_j), \quad j = 1, 2, \dots, n_{inter} \quad (3.64)$$

So the average number of neighbors during Δt is:

$$\bar{n}_{\Delta t} = \frac{1}{n_{inter}} \sum_{j=1}^{n_{inter}} \sum_{i=1}^n P_{ir}^d(t_1 + \Delta t_j) \quad (3.65)$$

As shown in Figure 3.19, since in some transmission intervals, there may have no vehicles send

data packet, so the average number of transmission intervals in which there have a data packet need to be transmitted can be calculated as:

$$\bar{n}_{inter} = n_{inter} - \sum_{j=1}^{n_{inter}} (1 - p_0)^{\bar{n}_{\Delta t} + 1} \quad (3.66)$$

where $\sum_{j=1}^{n_{inter}} (1 - p_0)^{\bar{n}_{\Delta t} + 1}$ is the average number of transmission intervals in which there have no data packet needed to be transmitted. According to (3.66), during Δt , the number of received data packets x and the sent data packets y by r should meet the requirements as follows:

$$\begin{cases} x + y = \bar{n}_{inter} \\ x - y \leq b \end{cases} \quad (3.67)$$

where b is the remaining available PQL. According to (3.67), we can conclude that the maximum and minimum number of data packets that can be transmitted by the neighbor vehicles of r are $x_{max} = \frac{(\bar{n}_{inter} + b)}{2}$ and $x_{min} = \frac{(\bar{n}_{inter} - b)}{2}$, respectively. Therefore, the probability that after Δt , the packet queue length of r is smaller than the maximum allowed value can be calculated as:

$$Pr_r^Q(\Delta t) = \sum_{i=0}^{\frac{(\bar{n}_{inter} + b)}{2}} C_{\bar{n}_{inter}}^i (1 - (1 - p_0)^{\bar{n}_{\Delta t}})^i \cdot (1 - p_0)^{\bar{n}_{\Delta t} - i} \quad (3.68)$$

Based on the probability prediction models introduced above, after Δt , the probability that the SINR of the receiver is larger than the receiving threshold and the probability that the PQL of the receiver is smaller than the maximum allowed value can be calculated. The next step is to select the relaying vehicles in CRS for each sender based on these predicted probabilities.

3.4.3. Probability Prediction based Efficient and Reliable Opportunistic Routing

In this section, we propose the probability prediction based reliable and efficient opportunistic routing (PRO) algorithm based on the conclusions in Section IV. Since the PRO algorithm is geographic based, so only the neighbor vehicles which the distances to the destination vehicle are smaller than that of the sender and move toward to the destination can be chosen as the candidate relaying vehicles. The set of the candidate relaying vehicles is defined as the candidate set.

A. Vehicle utility calculation algorithm

When the sender gets $Pr_{sr}^{SINR}(w)$ and $Pr_r^Q(\Delta t)$ of the candidate relaying vehicles, then the utilities of these relaying vehicles are determined based on these two parameters. In the CRS, each relaying vehicle can be expressed by $Pr_{sr}^{SINR}(w)$ and $Pr_r^Q(\Delta t)$, i.e., $node_i = \{Pr_{sr(i)}^{SINR}(w), Pr_{r(i)}^Q(\Delta t)\}$. Assuming that there are n candidate relaying vehicles, so the set of

$$Pr_{sr(i)}^{SINR}(w) \quad (i \in n) \quad \text{and} \quad Pr_{r(i)}^Q(\Delta t) \quad (i \in n) \quad \text{are}$$

$$P_{SINR}(n) = \{Pr_{sr(1)}^{SINR}(w), Pr_{sr(2)}^{SINR}(w), \dots, Pr_{sr(n)}^{SINR}(w)\} \quad \text{and} \quad P_Q(n) =$$

$$\{Pr_{r(1)}^Q(w), Pr_{r(2)}^Q(w), \dots, Pr_{r(n)}^Q(w)\}, \text{ respectively.}$$

When calculating the utilities of the relaying vehicles, the ideal situation is that the relaying vehicle which the utility is the highest has highest $Pr_{sr}^{SINR}(w)$ and $Pr_r^Q(\Delta t)$; the vehicle which the utility is the second highest has the second highest $Pr_{sr}^{SINR}(w)$ and $Pr_r^Q(\Delta t)$, and so on. However, this is not always feasible. The most common situation is that the relaying vehicle has excellent performance at one aspect and ordinary performance on the other aspect, which can be found in Figure 3.21. For instance, in Figure 3.21, the first parameter in node 2 is high while the second parameter is low.

Figure 3.21. The parameters of the relaying vehicles in opportunistic routing

Therefore, during calculating the utilities of the relaying vehicles, both of these two parameters should be taken into account. There is a fact that for the parameter $Pr_{sr}^{SINR}(w)$ and $Pr_r^Q(\Delta t)$, the effect of these two parameters on the routing performance is not same. The parameter which the variance is large has greater effect on the routing performance than the parameter which the variance is small. For the parameter which the variance is large, to different relaying vehicles, the routing performance changes greatly; for the parameter which the variance is small, this changing is slight. For instance, in Table 3.10, the variance of $Pr_{sr}^{SINR}(w)$ is much larger than that of $Pr_r^Q(\Delta t)$; therefore, during the relaying vehicle selection, for $Pr_r^Q(\Delta t)$, which vehicle is chosen has small effect on the routing performance, since the difference between these four nodes are quite small; however, to $Pr_{sr}^{SINR}(w)$, which vehicle is chosen as the first relaying vehicle has great effect on the routing performance. For example, for node 3 and node 4, even the $Pr_r^Q(\Delta t)$ of node 4 is larger than that of node 3, the utility of node 3 should larger than that of node 4, since the $Pr_{sr}^{SINR}(w)$ (which the variance is much larger than that of $Pr_r^Q(\Delta t)$) of node 3 is much larger than that of node 4.

Table 3.10. Parameters with different variances

	node 1	node 2	node 3	node 4	variance
$Pr_{sr}^{SINR}(w)$	0.11	0.34	0.67	0.49	0.056
$Pr_r^Q(\Delta t)$	0.81	0.83	0.815	0.824	8.2×10^{-5}

Since there are two parameters relates to the performance of each vehicle, i.e., $Pr_{sr}^{SINR}(w)$ and $Pr_r^Q(\Delta t)$, so we introduce the weight based approach in multi-attribute utility theory (MAUT) into the calculation of the vehicle's utility [175]. The weights represent the effect of the parameters on the routing performance. Since the parameter which the variance is larger has greater effect on the routing performance than that of the smaller one, so we use the variances of

$P_{SINR}(n)$ and $P_Q(n)$ as the weights to calculate the vehicle's utility, which is defined as:

$$U = v_{SINR} \cdot Pr_{sr}^{SINR}(w) + v_Q \cdot Pr_r^Q(\Delta t) \quad (3.69)$$

where v_{SINR} is the variance of $P_{SINR}(n)$ and v_Q is the variance of $P_Q(n)$; moreover, v_{SINR} and v_Q are the weights of $P_{SINR}(n)$ and $P_Q(n)$, respectively. For evaluating the difference between the variances of these two parameters, we define the parameter resolution ratio ξ as:

$$\xi = \begin{cases} v_{SINR}/v_Q, & v_{SINR} > v_Q \\ 1, & v_{SINR} = v_Q \\ v_Q/v_{SINR}, & v_{SINR} < v_Q \end{cases} \quad (3.70)$$

From (3.70), we can find that $\xi \geq 1$, the larger ξ is, the larger difference between the variances of these two parameters. In the following, we will investigate the effectiveness of the utility function U based on the MAUT and the parameter resolution ratio ξ . For the utility function shown in (3.69), with the increasing of ξ , the effect of the parameter which the variance is large on the vehicle's utility increases, and the effect of the parameter which the variance is small decreases.

Figure 3.22. Vehicle's utility and relaying priority when the ξ is large

Figure 3.23. Vehicle's utility and relaying priority when the ξ is small.

For instance, as the parameters shown in Figure 3.22, the parameter resolution ratio is $\xi = 6.61$, which is much larger than 1. So the utility of vehicle 1 (in which the $Pr_r^Q(\Delta t)$ is the largest) is larger than that of vehicle 3 and vehicle 2. However, when ξ is small, the situation is much more complex than that when ξ is large. As shown in Figure 3.23, in which $\xi = 1.1$, the results are different. The results shown in Figure 3.23 demonstrate that when the ξ is small, even the $v_{SINR} > v_Q$, the relaying priorities of the vehicles are not determined by the parameter which the variance is large, i.e., the $Pr_{sr}^{SINR}(w)$. This is because that when the parameter resolution ratio ξ is small, (i.e., near to 1), the utility not only relates to the variance of the parameter, but also the values of the parameters. We use the parameters in Figure 3.23 to explain this clearly, which is shown in Table 3.11.

Table 3.11. Parameter in Figure 3.23

	node1	node2	node3	variance	ξ
$Pr_{sr}^{SINR}(w)$	0.1	0.2	0.3	0.0067	1.1
$Pr_r^Q(\Delta t)$	0.57	0.68	0.49	0.006	
U	4.13×10^{-3}	5.45×10^{-3}	4.98×10^{-3}	-	

In Table 3.11, even the variance of $Pr_{sr}^{SINR}(w)$ is larger than that of $Pr_r^Q(\Delta t)$, the utility of node2 is larger than that of node3. This is because when the ξ is small (i.e., the variances of $Pr_{sr}^{SINR}(w)$ and $Pr_r^Q(\Delta t)$ are similar), then the vehicle's utility relates to not only the variances of the parameters but also the values of the parameters. In Table 3.11, the difference of $Pr_{sr}^{SINR}(w)$ (which the variance is larger) between node2 and node3 is smaller than that of $Pr_r^Q(\Delta t)$. This means that for the parameters in node2 and node3, the variance of $Pr_r^Q(\Delta t)$ is larger than that of $Pr_{sr}^{SINR}(w)$, which is defined as the local parameter variance. As we talked before, the parameter which the variance is larger has greater effect on the routing performance than that of the smaller one, so when the ξ is small, the calculating of the utility should take the local parameter variance into account.

Based on the ξ and the local parameter variance, we define the preference rules in MAUT as follows:

Preference rules (when $v_{SINR} > v_Q$)

1. If $v_{SINR} > v_Q$ and $\xi > \frac{|Pr_{r1}^Q(\Delta t) - Pr_{r2}^Q(\Delta t)|}{|Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)|}$
 2. If $Pr_{sr1}^{SINR}(w) > Pr_{sr2}^{SINR}(w)$
 3. $(Pr_{sr1}^{SINR}(w), Pr_{r1}^Q(\Delta t)) \succcurlyeq (Pr_{sr2}^{SINR}(w), Pr_{r2}^Q(\Delta t))$
 4. Else if $Pr_{sr1}^{SINR}(w) < Pr_{sr2}^{SINR}(w)$
 5. $(Pr_{sr1}^{SINR}(w), Pr_{r1}^Q(\Delta t)) \preccurlyeq (Pr_{sr2}^{SINR}(w), Pr_{r2}^Q(\Delta t))$
 6. End if
 7. End if
 8. If $v_{SINR} > v_Q$ and $1 \leq \xi \leq \frac{|Pr_{r1}^Q(\Delta t) - Pr_{r2}^Q(\Delta t)|}{|Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)|}$
 9. If $Pr_{r1}^Q(\Delta t) > Pr_{r2}^Q(\Delta t)$
 10. $(Pr_{sr1}^{SINR}(w), Pr_{r1}^Q(\Delta t)) \succcurlyeq (Pr_{sr2}^{SINR}(w), Pr_{r2}^Q(\Delta t))$
 11. Else if $Pr_{r1}^Q(\Delta t) < Pr_{r2}^Q(\Delta t)$
 12. $(Pr_{sr1}^{SINR}(w), Pr_{r1}^Q(\Delta t)) \preccurlyeq (Pr_{sr2}^{SINR}(w), Pr_{r2}^Q(\Delta t))$
 13. End if
 14. End if
-

Based on the MAUT, the “ $\succcurlyeq$ ” in the preference rules means “better than”; the “ $\preccurlyeq$ ” means “worse than”. Since the $Pr_{sr}^{SINR}(w)$ and $Pr_r^Q(\Delta t)$ are dual, so when $v_{SINR} < v_Q$, the preference rules can be inferred from the rules when $v_{SINR} > v_Q$ and are similar to the rules

shown above.

In the following, we will prove the effectiveness of the utility function and the preference rules.

Corollary 3.12. The utility function and the preference rules are effective.

Proof. Based on the definition in MAUT [175], if the 2-attribute utility function can be expressed as that shown in (3.69), then the following constraint must be satisfied: $(x_1, y_1) \succcurlyeq (x_2, y_2) \Leftrightarrow U(x_1, y_1) \geq U(x_2, y_2)$, $\forall x \in X$ and $\forall y \in Y$, where x is $Pr_{sr2}^{SINR}(w)$, y is $Pr_{r2}^Q(\Delta t)$, X is $P_{SINR}(n)$, and Y is $P_{SINR}(n)$.

Based on the preference rules, when $v_{SINR} > v_Q$, if

$(Pr_{sr1}^{SINR}(w), Pr_{r1}^Q(\Delta t)) \succcurlyeq (Pr_{sr2}^{SINR}(w), Pr_{r2}^Q(\Delta t))$, then there are two different situations: 1)

$$\xi > \frac{|Pr_{r1}^Q(\Delta t) - Pr_{r2}^Q(\Delta t)|}{|Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)|} \text{ and } Pr_{sr1}^{SINR}(w) > Pr_{sr2}^{SINR}(w); \text{ 2) } 1 \leq \xi \leq \frac{|Pr_{r1}^Q(\Delta t) - Pr_{r2}^Q(\Delta t)|}{|Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)|}$$

and $Pr_{r1}^Q(\Delta t) > Pr_{r2}^Q(\Delta t)$. For situation 1, there are also two different cases: 1) $Pr_{sr1}^{SINR}(w) > Pr_{sr2}^{SINR}(w)$ and $Pr_{r1}^Q(\Delta t) > Pr_{r2}^Q(\Delta t)$, denoted as s_1 ; 2) $Pr_{sr1}^{SINR}(w) > Pr_{sr2}^{SINR}(w)$ and

$Pr_{r1}^Q(\Delta t) < Pr_{r2}^Q(\Delta t)$, denoted as s_2 . For s_1 , it is obviously that $U(Pr_{sr1}^{SINR}(w), Pr_{r1}^Q(\Delta t)) \geq$

$U(Pr_{sr2}^{SINR}(w), Pr_{r2}^Q(\Delta t))$. For s_2 , since $\xi = \frac{v_{SINR}}{v_Q} > \frac{|Pr_{r1}^Q(\Delta t) - Pr_{r2}^Q(\Delta t)|}{|Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)|}$, and

$Pr_{sr1}^{SINR}(w) > Pr_{sr2}^{SINR}(w)$ and $Pr_{r1}^Q(\Delta t) < Pr_{r2}^Q(\Delta t)$, so $v_{SINR}|Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)| >$

$v_Q|Pr_{r1}^Q(\Delta t) - Pr_{r2}^Q(\Delta t)|$ equals to $v_{SINR}(Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)) > v_Q(Pr_{r2}^Q(\Delta t) -$

$Pr_{r1}^Q(\Delta t))$, which also equals to $U(Pr_{sr1}^{SINR}(w), Pr_{r1}^Q(\Delta t)) \geq U(Pr_{sr2}^{SINR}(w), Pr_{r2}^Q(\Delta t))$.

For situation 2, there are also two different cases: 1) $Pr_{sr1}^{SINR}(w) > Pr_{sr2}^{SINR}(w)$ and $Pr_{r1}^Q(\Delta t) > Pr_{r2}^Q(\Delta t)$, denoted as f_1 ; 2) $Pr_{sr1}^{SINR}(w) < Pr_{sr2}^{SINR}(w)$ and $Pr_{r1}^Q(\Delta t) > Pr_{r2}^Q(\Delta t)$,

denoted as f_2 . Since the f_1 is equals to s_1 , so f_1 holds. In f_2 , since $1 < \xi = \frac{v_{SINR}}{v_Q} <$

$$\frac{|Pr_{r1}^Q(\Delta t) - Pr_{r2}^Q(\Delta t)|}{|Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)|}, \text{ and } Pr_{sr1}^{SINR}(w) < Pr_{sr2}^{SINR}(w) \text{ and } Pr_{r1}^Q(\Delta t) > Pr_{r2}^Q(\Delta t), \text{ so}$$

$v_{SINR}|Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)| < v_Q|Pr_{r1}^Q(\Delta t) - Pr_{r2}^Q(\Delta t)|$ equals to $v_{SINR}(Pr_{sr2}^{SINR}(w) -$

$Pr_{sr1}^{SINR}(w)) < v_Q(Pr_{r2}^Q(\Delta t) - Pr_{r1}^Q(\Delta t))$, which also equals to $U(Pr_{sr1}^{SINR}(w), Pr_{r1}^Q(\Delta t)) \geq$

$U(Pr_{sr2}^{SINR}(w), Pr_{r2}^Q(\Delta t))$.

When $v_{SINR} < v_Q$, the proof is the same as that shown above, so we can conclude that

$$(x_1, y_1) \succcurlyeq (x_2, y_2) \Rightarrow U(x_1, y_1) \geq U(x_2, y_2), \forall x \in X \text{ and } \forall y \in Y.$$

Based on the utility function, when $U(Pr_{sr1}^{SINR}(w), Pr_{r1}^Q(\Delta t)) \geq U(Pr_{sr2}^{SINR}(w), Pr_{r2}^Q(\Delta t))$, it

equals to $v_{SINR}(Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)) > v_Q(Pr_{r2}^Q(\Delta t) - Pr_{r1}^Q(\Delta t))$. So, if

$Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w) > 0$ and $Pr_{r2}^Q(\Delta t) - Pr_{r1}^Q(\Delta t) < 0$, it holds obviously. This equals to that $Pr_{sr1}^{SINR}(w) > Pr_{sr2}^{SINR}(w)$ and $Pr_{r1}^Q(\Delta t) > Pr_{r2}^Q(\Delta t)$; which means that

$(Pr_{sr1}^{SINR}(w), Pr_{r1}^Q(\Delta t)) \succcurlyeq (Pr_{sr2}^{SINR}(w), Pr_{sr2}^Q(\Delta t))$. If $Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w) > 0$ and $Pr_{r2}^Q(\Delta t) - Pr_{r1}^Q(\Delta t) > 0$, when $v_{SINR}(Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)) > v_Q(Pr_{r2}^Q(\Delta t) - Pr_{r1}^Q(\Delta t))$ holds, then $\xi = \frac{v_{SINR}}{v_Q} > \frac{(Pr_{r2}^Q(\Delta t) - Pr_{r1}^Q(\Delta t))}{(Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w))} = \frac{|Pr_{r1}^Q(\Delta t) - Pr_{r2}^Q(\Delta t)|}{|Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)|}$; as talked in the preference rules, when $\xi > \frac{|Pr_{r1}^Q(\Delta t) - Pr_{r2}^Q(\Delta t)|}{|Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)|}$ and $Pr_{sr1}^{SINR}(w) > Pr_{sr2}^{SINR}(w)$, then $(Pr_{sr1}^{SINR}(w), Pr_{r1}^Q(\Delta t)) \succcurlyeq (Pr_{sr2}^{SINR}(w), Pr_{sr2}^Q(\Delta t))$ holds. If $Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w) < 0$ and $Pr_{r2}^Q(\Delta t) - Pr_{r1}^Q(\Delta t) < 0$, the $v_{SINR}(Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)) > v_Q(Pr_{r2}^Q(\Delta t) - Pr_{r1}^Q(\Delta t))$ equals to $Pr_{sr1}^{SINR}(w) < Pr_{sr2}^{SINR}(w)$ and $Pr_{r1}^Q(\Delta t) > Pr_{r2}^Q(\Delta t)$. So $\xi = \frac{v_{SINR}}{v_Q} < \frac{(Pr_{r2}^Q(\Delta t) - Pr_{r1}^Q(\Delta t))}{(Pr_{sr2}^{SINR}(w) - Pr_{sr1}^{SINR}(w))} = \frac{|Pr_{r1}^Q(\Delta t) - Pr_{r2}^Q(\Delta t)|}{|Pr_{sr1}^{SINR}(w) - Pr_{sr2}^{SINR}(w)|}$; moreover, since $Pr_{r1}^Q(\Delta t) > Pr_{r2}^Q(\Delta t)$, so

according to the preference rules, the $(Pr_{sr1}^{SINR}(w), Pr_{r1}^Q(\Delta t)) \succcurlyeq (Pr_{sr2}^{SINR}(w), Pr_{sr2}^Q(\Delta t))$ holds. Thus, we can conclude that $(x_1, y_1) \succcurlyeq (x_2, y_2) \iff U(x_1, y_1) \geq U(x_2, y_2)$, $\forall x \in X$ and $\forall y \in Y$.

Since the $Pr_{sr}^{SINR}(w)$ and $Pr_r^Q(\Delta t)$ are dual, so we can get the same conclusion when $v_{SINR} < v_Q$. Therefore, the Corollary 3.12 holds.

B. Computation complexity

In this section, we will investigate the computation complexity of this algorithm. According to the utility function shown in (3.69), the computation complexity is caused by the calculation of $Pr_{sr}^{SINR}(w)$ and $Pr_r^Q(\Delta t)$. As shown in last section, the calculation of $Pr_r^Q(\Delta t)$ is much simpler than that of $Pr_{sr}^{SINR}(w)$, so the complexity of this algorithm is mainly caused by the calculation of $Pr_{sr}^{SINR}(w)$. As shown in (3.58), the computation complexity of $Pr_{sr}^{SINR}(w)$ relates to the calculation of $f_z(z)$ and $f_w(w)$. In the following, we will investigate the computation complexity of $Pr_{sr}^{SINR}(w)$.

For $f_z(z)$, there are $\bar{n}_{int-r, t_1+\Delta t} - 1$ multiple integrals. Since the *Newton-Leibniz formula* cannot be used for calculating the integral in $f_z(z)$, so we introduce the *Simpson's rule* into the calculation of the integral in $f_z(z)$ [176]. According to the *Simpson's rule*, for $f(x)$, $x \in [a, b]$, the $S = \int_a^b f(x)dx$ can be calculated as: $S = \frac{b-a}{6n} \{f(x_0) + 4f(x_1) + 2f(x_2) + \dots +$

$4f(x_{2n-1}) + 2f(x_{2n})\}$, where $x_i = a + ih$, $i = 0, 1, 2, \dots, 2n$, and $h = \frac{b-a}{2n}$; $2n$ means that

the interval $[a, b]$ is divided into $2n$ equal parts; h is the step-size. Based on the *Simpson's rule*, the calculation complexity for each integral is $O(2n)$. For the $\bar{n}_{int-r, t_1+\Delta t} - 1$ multiple integrals in $f_z(z)$, only one variable is calculated in each integral, which is:

$$f(x_n) = (z - x_n - X)^{-\frac{1+\alpha}{\alpha}} \cdot \frac{1}{\sqrt{2\pi\alpha}} e^{-\frac{\left((z-x_n-X)^{-\frac{1}{\alpha}-\mu}\right)^2}{2}}$$

$$\cdot \prod_{i=2}^{\bar{n}_{int-r,t_1+\Delta t}} (x_n + X)^{-\frac{1+\alpha}{\alpha}} \frac{1}{\sqrt{2\pi\alpha}} e^{-\frac{\left((x_n+X)^{-\frac{1}{\alpha}-\mu}\right)^2}{2}}$$

where $X = \sum_{i=2, i \neq n}^{\bar{n}_{int-r,t_1+\Delta t}} x_i$. So the computation complexity of each integral is also $O(2n)$.

Since there are $\bar{n}_{int-r,t_1+\Delta t} - 1$ multiple integral in the calculation of $f_z(z)$, so the computation complexity is $O(2(\bar{n}_{int-r,t_1+\Delta t} - 1)n)$.

For the $f_w(w)$ shown in Corollary 3.12, according to the *Simpson's rule* and the computation complexity of $f_z(z)$, the computation complexity of $f_w(w)$ is $O(4(\bar{n}_{int-r,t_1+\Delta t} - 1)n^2)$. Note that in this analysis, the interval $[a, b]$ is divided into $2n$ parts; however, for improving the accuracy of the *Simpson's rule*, the interval can be divided into kn equal parts, where k is integer and larger than 2; then the computation complexity of this algorithm will be $O((\bar{n}_{int-r,t_1+\Delta t} - 1)(kn)^2)$.

C. Routing process

When the sender vehicle want to send data packet, first, it selects the candidate set based on the geographic information of its neighbors; only the neighbors which the distances to the destination vehicle are smaller than that of the sender vehicle can be chosen as the candidate relaying vehicles. The sender vehicle predicts the $Pr_{sr}^{SINR}(w)$ and $Pr_r^Q(\Delta t)$ for each vehicle in the candidate set and calculates the utilities of the candidate relaying vehicles based on the algorithm proposed in this section. Based on the candidate set optimization algorithm DDA that introduced in Section 3.2, the candidate set is optimized. Then the sender vehicle broadcasts the data packet to all the relaying vehicles in the CRS which has been optimized. This data packet includes the CRS and the relaying priorities of the relaying vehicles in this set. When the relaying vehicles receive the data packet transmitted from the sender vehicle, then the relaying priority based relaying algorithm introduced in [17] will be applied. In the relaying priority based relaying algorithm, each neighbor vehicle monitors the packet transmitted from the sender vehicle. When the neighbor vehicle receives the data packet, first it checks if it is included in the candidate set. If not, it discards the packet directly. Otherwise, it sets its forwarding timer as follows. The i th relaying vehicle on the candidate set sets its forwarding timer to $(i - 1)T$, where i is the relaying priority of the relaying vehicles in the candidate set and starts from 1. In this way, the vehicle with larger utility forwards the packet earlier, and other nodes hear its forwarding will cancel their forwarding timer and remove the packet from their packet queue, thereby avoiding duplicate forwarding. In [17], the waiting time T is set to 45ms, which is appropriate for bulk transfer, targeted by all opportunistic routing; so in this algorithm, we use the same waiting time as [17].

The process of the PRO routing algorithm can be expressed below.

Algorithm 3.5: Probability prediction based reliable opportunistic routing (PRO) algorithm

Notations:

s: The sender vehicle;

Packet(i): The *i*th packet in the sender *s*;
d_{node(s)}: the distance of sender vehicle *s* to the destination node;
d_{node(i)}: the distance of the *i*th neighbor of sender *s* to the destination node;
 $\mathbb{R}_s$: the candidate relaying set;
 $\mathbb{R}_s^*$: the optimized relaying set;
node(i): the *i*th relaying nodes in $\mathbb{R}_s$;
move(i): the moving direction of *i*th candidate relaying node;
direction(d): the direction of the destination node *d*;
U_i: the node utility of *i*th relaying nodes in $\mathbb{R}_s$;
T_{node(i)}: the timer of relaying node *i*;
T_{wait_{node(i)}}: the waiting time of relaying node *i* before receiving the ACK from the higher priority relaying node;

1. **for** *Packet(i)* **do**
2. **if** $d_{node(i)} \leq d_{node(s)}$ && $move(i) == direction(d)$ **then**
3. $\mathbb{R}_s \leftarrow node(i)$;
4. **end if**
5. Predicating the $Pr_{sr}^{SINR}(w)$ and $Pr_r^Q(\Delta t)$ for each node in $\mathbb{R}_s$;
6. Calculating the v_{SINR} and v_Q of $P_{SINR}(n)$ and $P_Q(n)$;
7. Calculating the node utility U_i for each node in $\mathbb{R}_s$ based on (24);
8. Assigning the priorities to the nodes in $\mathbb{R}_s$ based on U_i ;
9. Call DDA algorithm to optimized the candidate relay set;
10. Updating the relaying node set as $\mathbb{R}_s^*$;
11. The sender node broadcasts the data packet with the relaying priority list $L(s)$ to the nodes in $\mathbb{R}_s^*$;
12. **if** $node(i) \in L(s)$ **then**
13. *node(i)* receive the data packet;
14. $T_{node(i)} = (k-1)T$;
15. **else**
16. *node(i)* drop the data packet;
17. **end if**
18. **if** $T_{wait_{node(i)}} = T_{node(i)}$ **then**
19. node *i* relaying the data packet to the next hop relaying nodes the same as the Step 1 to Step 16;
20. **else if** $T_{wait_{node(i)}} < T_{node(i)}$ **then**
21. node *i* drop the data packet;
22. **end if**
23. **end for**.

3.5 Summary

In this chapter, first we propose the fuzzy logic based balanced relay node priority algorithm and the delay based duplicate transmission avoid coordinate scheme for opportunistic routing; then based on these two algorithms, we proposed two opportunistic routing algorithms for the underwater environment and terrestrial environment, respectively. In the opportunistic routing algorithm for the underwater environment, the fuzzy logic based relay node priority algorithm

and the DDA coordinate scheme are applied; for the terrestrial environment, i.e., the vehicular ad hoc network, we proposed the SINR and PQL prediction algorithm for the vehicle and applied the DDA coordinate scheme into this kind of network.

Chapter 4

Topology control algorithms improving reliability and efficiency for IoT

As mentioned in the previous chapters, for improving the reliability and efficiency of the wireless network, one of the effective approaches is topology control. Through controlling the transmission power of the nodes in the network, the reliability, the energy consumption, the network interference can be improved successfully. In this chapter, first, we investigate the relationship between the energy consumption and network interference based on the transmission power control. Then we propose the topology control algorithms for both the underwater cooperation robot network and the wireless sensor network, respectively.

4.1. Probability analysis for energy efficient and interference optimal [216]

One of the aims of topology control is to improve the network connection and reduce the energy consumption [12-13]. Many researches have been implemented and many remarkable topology control algorithms have been proposed, such as [28-29, 92-104, 177]. The transmission power control method always tend to use the short communication links to replace the long communication links for reducing the energy consumption and network interference while keeping the network connectivity. However, based on the conclusions in [28] and [29], reducing the transmission power cannot guarantee low network interference and small transmission range does not mean small network interference. Does the short communication link is more effective than the long communication link on reducing the energy consumption and network interference has not been investigated in detail. The topology control algorithms which reduce the network interference by adjusting the transmission power of node are probabilistic. This property is important and necessary to be taken into account on designing the interference optimization topology control algorithm. So, in this section, the following issues will be investigated in detail.

- What is the probability that the network interference is reduced by adjusting the transmission power of node;
- What are the properties of this probability, such as how the probability changes when the network topology changes or the transmission power changes, etc.;

- If the network topology is fixed, what value of the transmission power has highest probability of optimal interference;
- What is the relationship between the interference optimization and the energy efficient, i.e., the probability that the requirements of interference optimization and energy efficient can be met at the same time.

4.1.1 Network Model

In [28] and [29], the authors propose the interference model for wireless sensor network. In this model, the network interference is defined. As shown in Figure 4.1, node s and node r can communicate with each other, so node s and node r can affect all the nodes that locate in the area that node s and node r covered. The definition of interference is the cardinality of nodes covered by node s and node r with the transmission ranges that are chosen, which is:

$$Int(s, r) = int(s, R_s) \cup int(r, R_r) \quad (4.1)$$

where $Int(s, r)$ is the interference of edge (s, r) , $int(s, R_s)$ means the interference of node s with transmission range R_s .

Figure 4.1. Interference before adjusting the transmission range.

Figure 4.2. Interference after adjusting the transmission range.

Due to the different node deployment scenarios (which are shown in Figure 2.2), there are two different probabilities: the Homogenous probability and the Heterogeneous probability.

As discussed in (4.1) and Figure 4.1, the interference of edge (u, v) is defined as the number of nodes that locate in the coverage area of node u and node v . As shown in Figure 4.2, when the transmission ranges are reduced, node u and node v cannot communicate with each other directly; node n will be chosen as the relay node. The node n can communicate with node u and node v , respectively. So the interference of link (u, n, v) will be:

$$Int(s, n, r) = int(s, R_s) \cup int(n, R_n) \cup int(r, R_r) \quad (4.2)$$

where R_s , R_n , and R_r are the transmission ranges of s , n , and r , respectively.

In [178], the authors have proved that for the uniformly distributed sensor network, the number of nodes that locate in the coverage area of a node (the coverage area of node is πR^2 , R is the transmission range of node) has Poisson distribution. Therefore, the probability that a node has N neighbor nodes is:

$$P(N) = \frac{(\rho\pi R^2)^N}{N!} e^{-\rho\pi R^2} \quad (4.3)$$

where ρ is the node density and $\rho = n/A$; n is the node number in network and A is the area that the nodes are deployed. Due to the fact that the number of nodes that a node covered is

stochastic and decided by both the transmission range R and the node density ρ , so we consider the mean value of the node number. Since the node is uniformly distributed, the mathematical expectation of the node number that a node covered is:

$$E(N) = \rho\pi R^2 \quad (4.4)$$

The (4.4) indicates that in wireless sensor network, the expectation of the node number that a node covered is $\rho\pi R^2$. Therefore, when the node density is constant, the node number will be decided by the area that the node covered. Based on this conclusion, the issue of interference can be abstracted as the issue of the node's coverage area.

4.1.2. Homogenous node deployment probability analysis

In homogenous wireless sensor network, all the nodes have the same transmission ranges and the transmission ranges are circle.

Corollary 4.1. In homogenous wireless sensor network, the relationship between the overlapping coverage area s and the node distance d_{sr} is approximately linear, which is $s = \pi R^2 - 1.93Rd_{sr}$.

Figure 4.3. The overlapping coverage area in homogeneous network

Proof. As shown in Figure 4.3, the distance between node s and node r is d_{sr} ; the intersection points of the overlapping coverage area are A and B , respectively. Thus the acreage of the shade area in Figure 4.3 can be calculated as:

$$s = 2R^2 \left(\arccos \frac{d_{sr}}{2R} \right) - d_{sr} \sqrt{R^2 - \frac{d_{sr}^2}{4}} \quad (4.5)$$

where R is the transmission radius. Based on the Taylor Formula, the Taylor Expansion of (4.5) is:

$$s_t = \pi R^2 - (R + 1)d_{sr} + O \left[\left(\frac{d_{sr}}{2R} \right)^3 \right] \quad (4.6)$$

where $\frac{d_{sr}}{2R} \in (0, \frac{1}{2})$; since the $O \left[\left(\frac{d_{sr}}{2R} \right)^3 \right]$ is small during the calculation of s ; therefore, the relationship between the overlapping coverage area s and the node distance d_{sr} is approximately linear according (4.6). For simplifying the calculation of (4.5), we assume:

$$f = \pi R^2 - kRd_{sr} \quad (4.7)$$

Additionally, we define the difference between s and f is:

$$y = s - f = 2R^2 \left(\arccos \frac{d_{sr}}{2R} \right) - d_{sr} \sqrt{R^2 - \frac{d_{sr}^2}{4}} - (\pi R^2 - kRd_{sr}) \quad (4.8)$$

The variance of the difference y is:

$$D(y) = E(y^2) - (E(y))^2 \quad (4.9)$$

$$D(y)|'_k = E(y^2)|'_k - (E(y))^2|'_k \quad (4.10)$$

where $E(\cdot)$ is the operator of mathematical expectation. In (4.10), when $0 < k < 1.93$, $D(y)|'_k < 0$; when $k > 1.93$, $D(y)|'_k > 0$, which also can be found in Figure 4.4. Therefore, when $k = 1.93$, the $D(y)$ can get the minimum value.

Therefore, the linear function of two nodes' overlapping coverage area is:

$$f = \pi R^2 - 1.93 R d_{sr} \quad (4.11)$$

For investigating the evaluation error between s and f , we define the evaluation error as:

$$e = \frac{y}{s} = 1 - \frac{f}{s} \quad (4.12)$$

Figure 4.4 and Figure 4.5 show the variance of y and the evaluation error between s and f , respectively. In this simulation, $R=100$.

Figure 4.4. The variance of the difference between s and f under different value of k Figure 4.5. The evaluation error between s and f

From Figure 4.4, we can conclude that with the increase of k , the variance will get the minimum value when k is 1.93, which is consistent with the theoretical analysis in (4.10). Figure 4.5 indicates that when the value of k is 1.93, the error between s and f is smaller than 0.015, which is small enough to be ignored. In addition, when $k = 1.93$, the variance and the evaluation error are minimal simultaneous. Therefore, the function $f = \pi R^2 - 1.93 R d_{sr}$ can be used to evaluate two nodes' overlapping coverage area.

The results of (4.5) and (4.11) can be found in Figure 4.6. In Figure 4.6, the (4.5) and (4.11) are fitted with small evaluation error, which indicates that in homogenous wireless sensor network, the relationship of the overlapping coverage area and the node distance is approximately linear.

Figure 4.6. The fitting results of (4.5) and (4.11)

Even this conclusion is got under the assumption that $R=100$, however, when the value of R changes, we can get the same conclusion as (4.11).

Corollary 4.2: In homogeneous network, the probability that when reducing the transmission range, the interference is reduced is:

$$p_{hom} = \int_0^{0.85R} \left(e^{-\pi\rho(R-R_s)^2} - e^{-\pi\rho\left(0.19\left(\sqrt{R_s^2+27.67R^2}-R\right)\right)^2} \right) dR_s \\ + \int_{0.85R}^R \left(e^{-\pi\rho(R-R_s)^2} - e^{-\pi\rho\left(2.63\left(\frac{R^2}{R_s}-R_s\right)\right)^2} \right) dR_s .$$

Proof. Considering the conclusion of Corollary 4.1, the acreage of the coverage area before transmission range adjusting (shown in Figure 4.1) is:

$$s_R = \pi R^2 + \pi R^2 - (\pi R^2 - 1.93Rd_{sr}) = \pi R^2 + 1.93Rd_{sr} \quad (4.13)$$

where R is the original transmission range, d_{sr} is the distance between two nodes.

When the transmission ranges are reduced, the network topology is shown in Figure 4.2. In Figure 4.2, the distance (s, n) is d_{sn} and the distance (n, r) is d_{rn} , therefore the coverage area of node n , node s , and node r can be calculated as:

$$s_{R_s} = \pi R_s^2 + \pi R_s^2 - (\pi R_s^2 - 1.93R_s d_{sn}) + \pi R_s^2 - (\pi R_s^2 - 1.93R_s d_{rn}) \\ = \pi R_s^2 + 1.93R_s(d_{sn} + d_{rn}) \quad (4.14)$$

In (4.14), there are three parts: (1) πR_s^2 is the area of circle s ; (2) $\pi R_s^2 - (\pi R_s^2 - 1.93R_s d_{sn})$ means the area of circle n after removing the overlapping area of circle s and circle n ; (3) $\pi R_s^2 - (\pi R_s^2 - 1.93R_s d_{rn})$ is the area of circle r after removing the overlapping area of circle n and circle r . Moreover, in (4.14), since the d_{sn} and d_{rn} are all variables, for simplifying the calculation, we assume that the distance d_{sn} is equal to the transmission range of source node s , i.e., $R = d_{sn}$. This assumption is reasonable, since the distance equal to the transmission range means the node which is farthest from the source node will be chosen as the relay node. For instance, as shown in Figure 4.2, when the node s transmits data packet to node r , the source node s will choose node n which is in the boundary of the coverage area as the relay node, therefore the transmission range is equal to the distance (s, n), i.e., the distance (s, n) is the maximum value among all the neighbors' distances to the source node. Therefore, when the transmission ranges are reduced, the coverage area can be rewritten as:

$$\begin{aligned} s_{R_1} &= \pi R_s^2 + \pi R_s^2 - (\pi R_s^2 - 1.93R_s d_{sn}) + \pi R_s^2 - (\pi R_s^2 - 1.93R_s d_{rn}) \\ &= 5.07R_s^2 + 1.93R_s d_{rn} \end{aligned} \quad (4.15)$$

Additionally, in (4.15), R_s is the transmission range after being reduced and equal to the maximum value between distance (s, n) and distance (n, r) . For instance, as shown in Figure 4.2, the distance (s, n) is larger than the distance (n, r) , and d_{rn} is the distance between node n and node r ; so R_s is equal to the node distance (s, n) , and larger than d_{rn} (the situation that R_s is smaller than d_{rn} will be investigated following). In this scenario, the transmission ranges of node s , node r , and node n are the same and equal to R_s .

Based on the principle of linear programming, the boundary condition of this issue is $\rho_{S_R} = \rho_{S_{R_s}}$ (as shown in the last section, the interference of the node can be calculated by (4.4), the boundary condition means that the interference before transmission range adjustment is equal to the interference that after the node transmission range adjustment), which can be expressed as:

$$d_{rn} = 2.63 \left(\frac{R^2}{R_s} - R_s \right) \quad (4.16)$$

In addition, when the transmission ranges are reduced, for guaranteeing the network connection, the value of R_s and d_{rn} should satisfy the constraints as follows:

$$\begin{cases} 0 < R_s < R \\ 0 < d_{rn} < R \\ R_s > d_{rn} \\ R_s + d_{rn} > R \end{cases} \quad (4.17)$$

In the calculation of the coverage area, we assume that R_s is larger than d_{rn} , i.e., $0 < d_{rn} < R_s$, so based on the (4.16) and (4.17), the feasible region when $0 < d_{rn} < R_s$ is the triangle DBC in Figure 4.7.

Figure 4.7. The feasible region in homogeneous network

However, in the coverage area calculation, since $R_s = d_{sn}$ and the role of d_{sn} and d_{rn} are equal in (4.14), i.e., d_{sn} and d_{rn} can be replaced by each other in (4.14), Therefore, when the distance (s, n) is smaller than distance (n, r) , i.e., $R_s < d_{rn}$, the feasible region should be symmetrical with DBC based on the line $R_s = d_{rn}$. So, according to (4.16), when R_s is smaller than d_{rn} , then $R_s = d_{rn}$, the boundary will be $d_{rn} = 0.19 \left(\sqrt{R_s^2 + 27.67R^2} - R \right)$ (this

boundary condition can be got by variable swap between R_s and d_{rn} in (4.16)). In this situation, the feasible region is DBA in Figure 4.7. The whole feasible region is triangle ABC

which can be found in the shade area of Figure 4.7.

In Figure 4.7, when R_s and d_{rn} equal to the values in the shade area, the network interference will decrease; otherwise, the interference will increase. In addition, the coordinate of B is $(0.85R, 0.85R)$, so when $0 < R_s < 0.85R$, the value range of d_{rn} is $\left(R - R_s, 0.19\left(\sqrt{R_s^2 + 27.67R^2} - R\right)\right)$; when $0.85R < R_s < R$, the value range is $\left(R - R_s, 2.63\left(\frac{R^2}{R_s} - R_s\right)\right)$, where AC represents the line $R - R_s$ in Figure 4.7.

In [26], the authors have proved that when the nodes in the network are uniformly distributed, the probability density function of the neighbor distance is Rayleigh Distribution:

$$f(d) = 2\pi\rho d \cdot e^{-\pi\rho d^2} \quad (4.18)$$

where d is the distance between two nodes, and ρ is the node density. Thus the probability that the neighbors' distances are smaller than a and larger than b can be calculated as:

$$P(a \leq R \leq b) = \int_a^b f(x)dx = e^{-\pi\rho b^2} - e^{-\pi\rho a^2} \quad (4.19)$$

As shown in Figure 4.7, the probability that the distance between two nodes is R_s can be calculated by (4.18). Under specific R_s , the probability that the value of d_{rn} satisfy the constrains shown in Figure 4.7 can be calculated by (4.19). Then the probability that the network interference is reduced by adjusting the transmission range is:

$$\begin{aligned} p_{hom} &= \int_0^{0.85R} p\left(R - R_s \leq d_{rn} \leq 0.19\left(\sqrt{R_s^2 + 27.67R^2} - R\right)\right) \\ &\quad + \int_{0.85R}^R p\left(R - R_s \leq d_{rn} \leq 2.63\left(\frac{R^2}{R_s} - R_s\right)\right) \\ &= \int_0^{0.85R} \left(e^{-\pi\rho(R-R_s)^2} - e^{-\pi\rho\left(0.19\left(\sqrt{R_s^2 + 27.67R^2} - R\right)\right)^2} \right) dR_s \\ &\quad + \int_{0.85R}^R \left(e^{-\pi\rho(R-R_s)^2} - e^{-\pi\rho\left(2.63\left(\frac{R^2}{R_s} - R_s\right)\right)^2} \right) dR_s \quad (4.20) \end{aligned}$$

The (4.20) indicates that the probability relates to not only the original transmission range r but also the node density ρ . The properties of this probability under different r and ρ will be investigated in the simulation part in detail.

However, the probability shown in (4.20) is just a general probability. This probability means that to the different original transmission range, when the transmission range is reduced, the possibility that there exists an optimal solution for the network interference. However, the probability of interference optimization under specific transmission range is different with that in (4.20).

Corollary 4.3: In homogeneous network, the probability that the network interference is optimal under the specific transmission range is:

$$P_{homs} = \begin{cases} \int_{R-R_s}^{0.19(\sqrt{R_s^2+27.67R^2}-R)} 2\pi\rho d_{rn} \cdot e^{-\pi\rho d_{rn}^2} dd_{rn}, & (0 < R_s < 0.85R) \\ \int_{R-R_s}^{2.63(\frac{R^2}{R_s}-R_s)} 2\pi\rho d_{rn} \cdot e^{-\pi\rho d_{rn}^2} dd_{rn}, & (0.85R < R_s < R) \end{cases}.$$

Proof. As shown in Figure 4.7, when $0 < R_s < 0.85R$, the value range of d_{rn} is $(R - R_s, 0.19(\sqrt{R_s^2 + 27.67R^2} - R))$; when $0.85R < R_s < R$, the value range is $(R - R_s, 2.63(\frac{R^2}{R_s} - R_s))$. According the probability density function (PDF) (4.18), the integral of the PDF shown in (4.18) on value range of d_{rn} represents the probability of interference optimization under the specific transmission range R_s , which can be calculated as:

$$P_{homs} = \begin{cases} \int_{R-R_s}^{0.19(\sqrt{R_s^2+27.67R^2}-R)} 2\pi\rho d_{rn} \cdot e^{-\pi\rho d_{rn}^2} dd_{rn}, & (0 < R_s < 0.85R) \\ \int_{R-R_s}^{2.63(\frac{R^2}{R_s}-R_s)} 2\pi\rho d_{rn} \cdot e^{-\pi\rho d_{rn}^2} dd_{rn}, & (0.85R < R_s < R) \end{cases} \quad (4.21)$$

This probability means that under specific transmission range R_s , the possibility that the network interference is optimal.

Corollary 4.4: In homogeneous network, when the transmission range is $0.85R$, the probability that the network interference is optimal will get the maximal value.

Proof. To the (4.21), when $0 < R_s < 0.85R$, $P'_{homs} > 0$, and when $0.85R < R_s < R$, $P'_{homs} < 0$, therefore, if $d_{rn} = 0.85R$, P_{homs} can get the maximum value, i.e., if the transmission range is $0.85R$, the probability that the network is interference optimization is maximal.

4.1.3 Heterogeneous node deployment probability analysis

In last section, the obtained asymptotic results are based on the assumption that each node has the same transmission range which is often not the case in practice. In this section, we will analyze the probability under the assumption that the communication ranges are different in the network.

Figure 4.8. Different node positions in heterogeneous network: (a) $R_s/2 \leq d_{sr} \leq R_s$; (b) $0 \leq d_{sr} \leq R_s/2$.

As shown in Figure 4.8, we assume that the transmission range of node s is larger than node r . So there are two different positions of node r : (1) the distance between node s and node r is smaller than R_s and larger than $R_s/2$, i.e., $R_s/2 \leq d_{sr} \leq R_s$; which is shown in Figure 4.8(a). In this scenario, node r locates in the coverage area of node s , and the overlapping area is part of node r 's coverage area; (2) The distance between node s and node r is smaller than $R_s/2$, i.e., $0 \leq d_{sr} \leq R_s/2$, as shown in Figure 4.8(b). In this scenario, the whole coverage area of node r will be included by node s . The coverage area calculation will different in these two scenarios.

A. The node distance is $R_s/2 \leq d_{sr} \leq R_s$

Corollary 4.5. In the heterogeneous wireless sensor network, when the distance between node s and node r is smaller than R_s and larger than $R_s/2$, the relationship between the overlapping coverage area s and the node distance d_{sr} is $s = -1.57d_{sr}^2 + 3.23R_sd_{sr} - 0.44R_s^2$, approximately, which is quadratic equation.

Proof. As shown in Figure 4.8(a), when the transmission ranges of two nodes are different, the overlapping coverage area can be calculated as:

$$s = R_s^2 \arccos \frac{R_s}{2d_{sr}} + 2d_{sr}^2 \arcsin \frac{R_s}{2d_{sr}} - R_s \sqrt{d_{sr}^2 - \left(\frac{R_s}{2}\right)^2} \quad (4.22)$$

where R_s is the transmission range of node s , and d_{sr} is the distance between two nodes. Based on the *Taylor Formula*, the Taylor Expansion of (4.22) is:

$$s_t = \frac{\pi d_{sr}^2}{2} - \frac{d_{sr}}{2R_s} + o\left[\left(\frac{d_{sr}}{2R_s}\right)^3\right] \quad (4.23)$$

where $\frac{d_{sr}}{2R_s} \in \left(\frac{1}{4}, \frac{1}{2}\right)$; since the $o\left[\left(\frac{d_{sr}}{2R_s}\right)^3\right]$ is small during the calculation of s , the relationship between the overlapping coverage area s and the node distance d_{sr} is approximately quadratic; so for simplifying the calculation of (4.22), we assume:

$$f = ad_{sr}^2 + bR_sd_{sr} + cR_s^2 \quad (4.24)$$

Additionally, we define the difference between s and f is:

$$y = s - f \\ = R_s^2 \arccos \frac{R_s}{2d_{sr}} + 2d_{sr}^2 \arcsin \frac{R_s}{2d_{sr}} - R_s \sqrt{d_{sr}^2 - \left(\frac{R_s}{2}\right)^2} - (ad_{sr}^2 + bR_sd_{sr} + cR_s^2) \quad (4.25)$$

The variance of the difference y is:

$$D(y) = E(y^2) - (E(y))^2 \quad (4.26)$$

$$D(y)|'_a = E(y^2)|'_a - E(y)^2|'_a \quad (4.27)$$

In (4.27), with the help of the value $(R_s/2, s_1)$ and (R_s, s_2) (which can be got from (4.22)), we can confirm the relationship between a , b and c . The values of s_1 and s_2 are:

$$\begin{cases} s_1 = \pi d_{sr}^2 \\ s_2 = \left(\frac{\pi}{3} - \frac{\sqrt{3}}{2}\right) R_s^2 + \frac{\pi}{3} d_{sr}^2 \end{cases} \quad (4.28)$$

In (4.27), when $-\infty < a < -1.57$, $D(y)|'_a < 0$; when $-1.57 < a < \infty$, $D(y)|'_a > 0$. Therefore, when $a = -1.57$, the variance of y is minimum. This is also can be found in Figure 4.9. Therefore, the function of two nodes' overlapping coverage area in heterogeneous network can be evaluated approximately as:

$$f = -1.57d_{sr}^2 + 3.23R_sd_{sr} - 0.44R_s^2 \quad (4.29)$$

For investigating the evaluation error between s and f , we define the evaluation error as:

$$e = \frac{y}{s} = 1 - \frac{f}{s} \quad (4.30)$$

The error between s and f is shown in Figure 4.10. In Figure 4.10, we can conclude that the maximum error between s and f is only 0.025 and the mean absolute value of the error is only 0.0139. This means that the error between s and f can be omitted during the calculation of the overlapping coverage area in heterogeneous network, i.e., the (4.29) can be used to calculate the overlapping coverage area approximately. The results of s and f are shown in Figure 4.11. In Figure 4.11, the curve of s and f can be matched in small error. Thus in the calculation of the overlapping coverage area when the transmission ranges are different, the (4.22) can be replaced by the quadratic function approximately.

Figure 4.9. The variance of difference between s and f under different value of a Figure 4.10. The evaluation error between s and f

Figure 4.11. The fitting results of (4.22) and (4.29)

Based on Corollary 4.1, the coverage area before reducing the transmission range is:

$$s_{R_s} = 2\pi R_s^2 - (\pi R_s^2 - 1.93R_s^2) = 5.07R_s^2 \quad (4.31)$$

As shown in Figure 4.2, based on Corollary 4.5, the coverage area after reducing the transmission ranges is:

$$s_{R_{s1}} = \pi R_{s1}^2 + \pi d_{sn}^2 - (3.23R_{s1}d_{sn} - 1.57R_{s1}^2 - 0.44d_{sn}^2) + \pi d_{rn}^2 - (3.23d_{rn}d_{sn} - 1.57d_{rn}^2 - 0.44d_{sn}^2) \quad (4.32)$$

In (4.32), there are three parts: (1) πR_{s1}^2 is the area of circle s ; (2) $\pi d_{sn}^2 - (3.23R_{s1}d_{sn} - 1.57R_{s1}^2 - 0.44d_{sn}^2)$ means the area of circle n after removing the overlapping area of circle s and circle n ; (3) $\pi d_{rn}^2 - (3.23d_{rn}d_{sn} - 1.57d_{rn}^2 - 0.44d_{sn}^2)$ is the area of circle r after removing the overlapping area of circle n and circle r . In (4.32), since the d_{sn} and d_{rn} are all

variables, for simplifying the calculation, we assume that the distance d_{sn} is equal to the transmission range of source node s , i.e., $R_{s1} = d_{sn}$. This assumption is reasonable, since the distance equal to the transmission range means node which is farthest from the source node will be chosen as the relay node. For instance, as shown in Figure 4.2, when the node s transmission data packet to node r , then the source node s will choose node n which is in the boundary of the coverage area as the relay node, therefore the transmission range is equal to the distance (s,n) , i.e., the distance (s,n) is the maximum value among all the neighbors' distances. Therefore, when the transmission ranges are reduced, the coverage area can be rewritten as:

$$\begin{aligned} s_{R_{s1}} &= \pi R_{s1}^2 + \pi R_{s1}^2 - (3.23R_{s1}^2 - 1.57R_{s1}^2 - 0.44R_{s1}^2) \\ &\quad + \pi d_{rn}^2 - (3.23R_{s1}d_{rn} - 1.57d_{rn}^2 - 0.44R_{s1}^2) \\ &= 4.62R_{s1}^2 - 3.23R_{s1}d_{rn} + 4.71d_{rn}^2 \end{aligned} \quad (4.33)$$

Similar with the analysis in last section, the boundary condition is $\rho s_{R_s} = \rho s_{R_{s1}}$, which can be expressed as:

$$d_{rn} = 0.343R_{s1} + \sqrt{R_s^2 - R_{s1}^2} \quad (4.34)$$

The transmission range R_{s1} and node distance d_{rn} should satisfy the constraints shown in (4.17). In addition, in (4.33), R_{s1} is the node's transmission range that after adjustment and equal to the maximum value between distance (s, n) and distance (n, r) . For instance, as shown in Figure 4.2, the distance (s, n) is larger than the distance (n, r) , and d_{rn} is the distance between node n and node r ; so R_{s1} equals to the node distance (s, n) , and larger than d_{rn} (the situation that the R_{s1} is smaller than d_{rn} will be investigated following). Moreover, in this scenario, we assume that $R_{s1}/2 \leq d_{rn} \leq R_{s1}$, so the constraints are shown as follows:

$$\begin{cases} 0 < R_{s1} < R_s \\ 0 < d_{rn} < R_s \\ R_{s1}/2 \leq d_{rn} \leq R_{s1} \\ R_{s1} + d_{rn} > R_s \end{cases} \quad (4.35)$$

In Figure 4.12, the constraint $R_{s1}/2 \leq d_{rn} \leq R_{s1}$ in (4.35) is between the line OF and OA ; the line OF represents $d_{rn} = R_{s1}/2$ and the line OA represents $d_{rn} = R_{s1}$; therefore, the feasible region when $d_{rn} < R_{s1}$ is $KHBA$ in Figure 4.12. As discussed in last section, the role of R_{s1} and d_{rn} are equal in (4.33) and (4.34). So when the node distance (n, r) is larger than the node distance (s, n) , the feasible region should symmetrical with $KHBA$ based on the line $d_{rn} = R_{s1}$ (line OA), which is $IKEA$ in Figure 4.12. According (4.34), when $d_{rn} > R_{s1}$, the transmission range will equal to d_{rn} , then the constraint $R_{s1}/2 \leq d_{rn} \leq R_{s1}$ in (4.34) will be $d_{rn}/2 \leq R_{s1} \leq d_{rn}$, which is between the line OD and line OA ; moreover, according (4.34), the boundary condition is $d_{rn} = 0.445\sqrt{4.5R_s^2 - 4R_{s1}^2} + 0.31R_{s1}$ for feasible region $IKEA$ in Figure 4.12. Thus the whole feasible region in this scenario is $EIHB$ which is shown in Figure 4.12.

Figure 4.12. The feasible region in Heterogeneous network

The coordinate of the points in Figure 4.12 are shown in Table 4.1.

Table 4.1. The coordinates of the points in Figure 4.12

Points	A	B	C	D	E	F	G
Coord.	$(0.84r, 0.84r)$	$(0.99r, 0.495r)$	$(r, 0.343r)$	$(r, 0.5r)$	$(0.495r, 0.99r)$	$(0.5r, r)$	$(0.343r, r)$

B. The node distance is $0 \leq d_{sr} \leq R_s/2$

As shown in Figure 4.8, when the transmission range of node r is smaller than $R_s/2$, the whole coverage area of node r will be included by node s . So when the transmission range is smaller than $R_s/2$, the overlapping coverage area is πd_{sr}^2 , which is also the quadratic function. According Figure 4.1, in this scenario, when the transmission ranges are reduced, the probability of network interference is reduced. Similar with the analysis in the first part of this section, the feasible regions have been shown in Figure 4.12 (IFY and HDX).

As shown in Figure 4.12 and Table 4.1, the coordinate of point B is $(0.99R_s, 0.495R_s)$, the coordinates of point D and point C are $(R_s, 0.5R_s)$ and $(R_s, 0.343R_s)$, respectively. Thus the area of HBX and HDX are similar; this means we can use HBX to represent HDX to simplify the probability calculation of heterogeneous network. The relationship between IFY and IEY is similar with that between HBX and HDX .

Corollary 4.6: In heterogeneous network, the probability that when adjusting the transmission ranges, the network interference is optimal is:

$$\begin{aligned}
 p_{het} = & \int_{0.343R_s}^{0.84R_s} \left(e^{-\pi\rho(R_s-R_{s1})^2} - e^{-\pi\rho\left(0.445\sqrt{4.5R_s^2-4R_{s1}^2}+0.31R_{s1}\right)^2} \right) dR_{s1} \\
 & + \int_{0.84R_s}^{R_s} \left(e^{-\pi\rho(R_s-R_{s1})^2} - e^{-\pi\rho\left(\sqrt{R_s^2-R_{s1}^2}+0.343R_{s1}\right)^2} \right) dR_{s1} \\
 & + \int_0^{0.343R_s} (e^{-\pi\rho(R_s-R_{s1})^2} - e^{-\pi\rho R_{s1}^2}) dR_{s1}.
 \end{aligned}$$

Proof. In last section, we investigate the constraints of reducing the network interference by adjusting the transmission ranges in heterogeneous network. The whole feasible region is shown in Figure 4.12 (the shade area). As shown in Figure 4.12, when $0 < R_{s1} < 0.343R_s$, the

value range of d_{rn} is $(R_s - R_{s1}, R_s)$; when $0.343R_s < R_{s1} < 0.84R_s$, the value range is $(R_s - R_{s1}, 0.445\sqrt{4.5R_s^2 - 4R_{s1}^2} + 0.31R_{s1})$; when $0.84R_s < R_{s1} < R_s$, this will be $(R_s - R_{s1}, \sqrt{R_s^2 - R_{s1}^2} + 0.343R_{s1})$. Therefore, similar with the analysis in last section and according to the probability distribution function (4.19), the probability of interference optimization by adjusting the transmission range can be calculated as:

$$\begin{aligned}
 p_{het} = & \int_{0.343R_s}^{0.84R_s} \left(e^{-\pi\rho(R_s - R_{s1})^2} - e^{-\pi\rho\left(0.445\sqrt{4.5R_s^2 - 4R_{s1}^2} + 0.31R_{s1}\right)^2} \right) dR_{s1} \\
 & + \int_{0.84R_s}^{R_s} \left(e^{-\pi\rho(R_s - R_{s1})^2} - e^{-\pi\rho\left(\sqrt{R_s^2 - R_{s1}^2} + 0.343R_{s1}\right)^2} \right) dR_{s1} \\
 & + \int_0^{0.343R_s} \left(e^{-\pi\rho(R_s - R_{s1})^2} - e^{-\pi\rho R_{s1}^2} \right) dR_{s1} \quad (4.36)
 \end{aligned}$$

In (4.36), the probability relates to both the original transmission range and the node density of the wireless sensor network. The properties of this probability under different R_s and ρ will be investigated in the simulation part in detail.

Similar with the probability in (4.20), the probability that shown in (4.36) is just a general probability under different original transmission ranges. This probability means that to the different original transmission range, when the transmission range is reduced, the possibility that there exist an optimal solution for the network interference. However, the probability of interference optimization under specific transmission range is different with that in (4.36).

Corollary 4.7: In heterogeneous network, the probability that the network interference is optimal under the specific transmission range is:

$$p_{hets} = \begin{cases} \int_{R_s - R_{s1}}^{R_s} 2\pi\rho R_{s1} e^{-\pi\rho R_{s1}^2} dR_{s1}, & (0 < R_{s1} < 0.343R_s) \\ \int_{R_s - R_{s1}}^{0.445\sqrt{4.5R_s^2 - 4R_{s1}^2} + 0.31R_{s1}} 2\pi\rho R_{s1} e^{-\pi\rho R_{s1}^2} dR_{s1}, & (0.343R_s < R_{s1} < 0.84R_s) \\ \int_{R_s - R_{s1}}^{\sqrt{R_s^2 - R_{s1}^2} + 0.343R_{s1}} 2\pi\rho R_{s1} e^{-\pi\rho R_{s1}^2} dR_{s1}, & (0.84R_s < R_{s1} < R_s) \end{cases}$$

Proof. As shown in Figure 4.12, when $0 < R_{s1} < 0.343R_s$, the value range of d_{rn} is $(R_s - R_{s1}, R_s)$; when $0.343R_s < R_{s1} < 0.84R_s$, the value range is $(R_s - R_{s1}, 0.445\sqrt{4.5R_s^2 - 4R_{s1}^2} + 0.31R_{s1})$; when $0.84R_s < R_{s1} < R_s$, this will be $(R_s - R_{s1}, \sqrt{R_s^2 - R_{s1}^2} + 0.343R_{s1})$. Therefore, according to the probability density function (PDF) (4.18), the integral of the PDF shown in (4.18) on value range of d_{rn} represents the probability of interference optimization under the specific transmission range R_{s1} , which can be calculated as:

$$p_{hets} = \begin{cases} \int_{R_s - R_{s1}}^{R_s} 2\pi\rho R_{s1} e^{-\pi\rho R_{s1}^2} dR_{s1}, (0 < R_{s1} < 0.343R_s) \\ \int_{R_s - R_{s1}}^{0.445\sqrt{4.5R_s^2 - 4R_{s1}^2} + 0.31R_{s1}} 2\pi\rho R_{s1} e^{-\pi\rho R_{s1}^2} dR_{s1}, (0.343R_s < R_{s1} < 0.84R_s) \\ \int_{R_s - R_{s1}}^{\sqrt{R_s^2 - R_{s1}^2} + 0.343R_{s1}} 2\pi\rho R_{s1} e^{-\pi\rho R_{s1}^2} dR_{s1}, (0.84R_s < R_{s1} < R_s) \end{cases} \quad (4.37)$$

Corollary 4.8: In heterogeneous network, when the transmission range is $0.84R_s$, the probability that the network interference is optimal will get the maximal value.

Proof. As shown in Equation (4.37), when $0 < R_{s1} < 0.84R_s$, $p'_{hets} > 0$; when $0.84R_s < R_{s1} < R_s$, $p'_{hets} < 0$. So when $R_{s1} = 0.84R_s$, the probability of interference optimization for the heterogeneous wireless sensor network will get the maximal value.

4.1.4 The probability of energy efficient by adjusting the transmission power [69]

Corollary 4.9. After the transmission range adjustment, the probability that the energy consumption is less than the previous one is $\rho = \frac{2}{d^2} \int_0^d (d^\alpha - x^\alpha)^{1/\alpha} dx - 1$.

Proof. In WSN, supposing that node r is the neighbor of node s . when node s transmits packet to node r , the energy consumption is related to the distance between two nodes, which can be expressed as:

$$P_{sr1} = Gd_{sr}^\alpha \quad (4.38)$$

where d_{sr} is the Euclidean distance between node s and node r , α is the distance-power gradient that depending on the characteristics of the communication medium ($2 \leq \alpha \leq 4$, $\alpha \geq 2$ for outdoor propagation modes [170][179]); P_{sr1} is the power needed for link between node s and node r ; $G = \frac{G_t G_r \lambda^2}{(4\pi)^2}$, where G_t and G_r are the antenna gains of sender and receiver; λ is the wavelength.

If the transmission ranges of node s and node r are reduced based on the topology control algorithm, and node s and node r cannot communicate directly, which is shown in Figure 4.2. As a result, node n will be chosen as the relay node, where node n is the neighbor of both node s and node r . Thus, the energy needed to transmit packets from node u to node v will be:

$$P_{sr2} = Gd_{sn}^\alpha + Gd_{rn}^\alpha \quad (4.39)$$

where d_{sn} is the Euclidean distance between node s and node n , d_{rn} is the Euclidean distance between node n and node r ; P_{sr2} is the power needed for communicating between node s and node r by using relay node n .

Therefore, the issues we need to investigate are when P_{sr2} is smaller than P_{sr1} and what is the probability that P_{sr2} smaller than P_{sr1} . For exploring these issues, we define the Energy efficient Dominating Sets (EDS) as follows:

$$\begin{cases} P_{sr1} \geq P_{sr2} \\ d_{sn} + d_{rn} \geq r \\ 0 < d_{sn} \leq r \\ 0 < d_{rn} \leq r \end{cases} \quad (4.40)$$

where the first constraint means the energy consumption after power adjustment is smaller than the previous one; the second constraint make sure node s still can communication with node r by using a relay node; the third and the fourth constraints guarantee the transmission ranges of

each nodes are smaller than the previous. The EDS is shown in Figure 4.13.

Figure 4.13. The Energy efficient Dominating Sets (EDS) shown in (4.40).

According the definition of EDS and the principle of linear programming, the EDS is the shadow area in Figure 4.13. The area ABC means the whole values which satisfy the second, third, and fourth constraints in Equation (4.40); the area $\widehat{AB}$ is the set that the energy consumption is smaller than the previous. Therefore, the probability that the energy consumption is less than the previous one is the proportion of area $\widehat{AB}$ in area ABC , which can be calculated as:

$$\rho = \frac{2}{d_{sr}^2} \int_0^{d_{sr}} (d_{sr}^\alpha - x^\alpha)^{1/\alpha} dx - 1 \quad (4.41)$$

where x is the transmission range of nodes and $0 < x < d_{sr}$.

Corollary 4.10. With the increasing of α ($2 \leq \alpha \leq 4$), the probability ρ increases from 0.5708 to 0.8541.

Proof. Considering the first derivative function of ρ on α :

$$\rho'_\alpha = \frac{d \left[\frac{2}{d_{sr}^2} \int_0^{d_{sr}} (d_{sr}^\alpha - x^\alpha)^{1/\alpha} dx - 1 \right]}{d\alpha} \quad (4.42)$$

In order to simplify the denotation, we define:

$$f(\alpha) = (d_{sr}^\alpha - x^\alpha)^{1/\alpha} \quad (4.43)$$

Therefore, the (4.42) can be rewritten as:

$$\rho'_\alpha = \frac{d \left[\frac{2}{d_{sr}^2} \int_0^{d_{sr}} f(\alpha) dx - 1 \right]}{d\alpha} \quad (4.44)$$

Since $0 < x < d_{sr}$, so if we can prove $f(\alpha)$ is an increasing function, then we can conclude that $\rho(\alpha)$ is also the increasing function with α . The first derivative function of $f(\alpha)$ on α is:

$$f'(\alpha) = e^{\frac{(d_{sr}^\alpha - x^\alpha)}{\alpha}} \cdot \frac{\frac{\alpha}{d_{sr}^\alpha - x^\alpha} (d_{sr}^\alpha \ln d_{sr} - x^\alpha \ln x) - \ln(d_{sr}^\alpha - x^\alpha)}{\alpha^2} > e^{\frac{(d_{sr}^\alpha - x^\alpha)}{\alpha}} \cdot \frac{\ln d_{sr}^\alpha - \ln(d_{sr}^\alpha - x^\alpha)}{\alpha^2} > 0 \quad (4.45)$$

As $f'(\alpha) > 0$, so $f(\alpha)$ is an increasing function. Thus, the probability ρ will increase with the increase of α . In addition, the maximum and minimum values of ρ are as follows: $\rho_{min} = \rho_2 = 0.5708$, and $\rho_{max} = \rho_4 = 0.8541$. This can also be found in Figure 4.14.

As shown in Figure 4.14, with the increasing of α , the probability ρ increases. The maximum value of ρ is 0.8741 and the minimum value is only 0.5708. This demonstrates that the algorithm which reduces the energy consumption by adjusting the transmission range is probabilistic, i.e., short transmission range does not mean small energy consumption. The reason why the probability increases with the increasing of α is that with the increasing of α ,

the energy consumption is more and more seriously effected by the distance between two nodes, which can be concluded from (4.38); so if the transmission range changes, the energy consumption will be changed obviously.

Figure 4.14. The relationship between α and ρ .

Corollary 4.11. With constant α , the probability ρ will keep constant with the variation of the initial transmission range r .

Proof. We can prove this conclusion by simulation. The result can be found in Figure 4.14.

Figure 4.15. Relationship between R and ρ for α .

Figure 4.15 illustrates that with the increasing of R , the probability ρ will keep constant. In addition, when α increases, the probability increases, too; and the bigger the α , the small increasing rate is, which is consistent with the conclusion of Corollary 4.10 (shown in Figure 4.14). The Corollary 4.11 indicates that the probability is nothing to do with the initial transmission range, i.e., no matter what R is, with constant α , the probability will be the same.

Corollary 4.12. With fixed value of α , when the transmission range is $(1/2)^{\frac{1}{\alpha}}R$, the probability ρ_e can get the maximum value.

Proof. When applying the power adjustment topology control algorithm, the EDS of d_{sn} and d_{rn} are shown in (4.40) and Figure 4.13. Thus, similar with the definition of EDS, the Un-EDS of d_{sn} and d_{rn} can be shown as follows:

$$\begin{cases} P_{sr1} \leq P_{sr2} \\ d_{sn} + d_{rn} \geq r \\ 0 < d_{sn} \leq r \\ 0 < d_{rn} \leq r \end{cases} \quad (4.46)$$

The meanings of each constraint are similar with Equation (4.40). The values which satisfy Un-EDS mean that the energy consumption of WSN does not decrease after reducing the transmission range. Therefore, how to reduce the size of Un-EDS is an effective method to increase the probability of energy efficient. A possible way is to eliminate some values of d_{sn} and d_{rn} from Un-EDS. Therefore, the new probability of energy efficient will be:

$$\rho_e = \frac{\int_0^{d_{sr}} (d_{sr}^\alpha - x^\alpha)^{1/\alpha} dx - d_{sr}^2/2}{d_{sr}^2/2 - (d_{sr} - d_{sn})(d_{sr} - d_{rn})} \quad (4.47)$$

where $s = (d_{sr} - d_{sn})(d_{sr} - d_{rn})$ is the eliminated Un-EDS.

According to the principle of linear programming, when d_{sn} and d_{rn} are in the boundary of Un-EDS, the eliminated Un-EDS s can get the maximum value, i.e., the probability ρ_e can get the maximum value, which can be found in (4.47). This means that d_{sn} and d_{rn} should satisfy the constraint as follows:

$$d_{rn} = (d_{sr}^\alpha - d_{sn}^\alpha)^{1/\alpha} \quad (4.48)$$

The first derivative function of s and d_{rn} on d_{sn} can be expressed as:

$$s'_{d_{sn}} = \frac{ds}{dd_{sn}} = d_{rn} - d_{sr} + (d_{sn} - d_{sr})d'_{rn d_{sn}} \quad (4.49)$$

$$d'_{rn d_{sn}} = \frac{dd_{rn}}{dd_{sn}} = -d_{sn}^{\alpha-1} (d_{sr}^\alpha - d_{sn}^\alpha)^{\frac{1-\alpha}{\alpha}} \quad (4.50)$$

Substitute (4.50) into (4.49), when $s'_{d_{sn}} = 0$, the eliminated Un-EDS s can get the extremum value when $d_{sn} = (1/2)^{1/\alpha} d_{sr}$. Furthermore, when $0 < d_{sn} < (1/2)^{1/\alpha} d_{sr}$, then $s'_{d_{sn}} > 0$;

when $(1/2)^{1/\alpha} d_{sr} < d_{sn} < d_{sr}$, then $s'_{d_{sn}} < 0$; so $s((1/2)^{1/\alpha} d_{sr})$ is the maximum value of s . This conclusion also can be found in Figure 4.18. In Figure 4.18, we set the initial transmission range r to 1, i.e., $d_{sr} = 1$ in this simulation.

Figure 4.16. Relationship between r and ρ_e for α .

When the probability ρ_e get the maximum value, the values of d_{sn} are $0.7r$, $0.8r$, and $0.85r$ when $\alpha = 2$, $\alpha = 3$, and $\alpha = 4$, respectively. The maximum value of ρ_e in Figure 4.16 is

consistent with the conclusion in Table 4.2, which are got from Equation (4.41) and Equation (4.47).

Table 4.2. Probabilities before and after optimizing.

Value of α	Probabilities		
	d_{sn}	ρ_e	ρ
$\alpha = 2$	0.7071	0.689	0.5708
$\alpha = 3$	0.7937	0.8379	0.7666
$\alpha = 4$	0.8409	0.8996	0.8541

From Table 4.2, we can find that after eliminating some values from the Un-EDS, the probabilities of energy efficient increase obviously: 11% when $\alpha = 2$, 7% when $\alpha = 3$, and 5% when $\alpha = 4$.

4.1.5. The relationship between energy efficient and interference optimal by adjusting the transmission power of node

A. Homogenous node deployment mode

Corollary 4.13: In the homogeneous network, when the network is energy efficiency, the probabilities that the network is also interference optimization are from 0.972 to 0.998.

Proof. As discussed in section 4.1.2, in the homogeneous network, the feasible region of interference optimization is shown in Figure 4.7. Considering the (4.40) and (4.17), the feasible region of both energy efficient and network interference optimization can be found in Figure 4.17. In Figure 4.17, the boundary conditions of energy efficient and interference optimization are shown in (4.51) and (4.52), respectively:

$$b_e = (d_{sr}^\alpha - d_{sn}^\alpha)^{1/\alpha} \quad (4.51)$$

$$b_i = \begin{cases} 0.19 \left(\sqrt{d_{sn}^2 + 27.67 d_{sr}^2} - d_{sr} \right), & (0 < d_{sn} < 0.85 d_{sr}) \\ 2.63 (d_{sr}^2 / d_{sn} - d_{sn}), & (0.85 d_{sr} < d_{sn} < d_{sr}) \end{cases} \quad (4.52)$$

Figure 4.17. The feasible region of energy efficient and interference optimization in homogeneous network

Figure 4.18. The boundary of energy efficient and interference optimization in homogeneous network

Figure 4.18 indicates the relationship between the energy efficient and the network interference optimization. From Figure 4.17 and Figure 4.18, we can find that with the increase of the distance-power gradient α , the feasible region of energy efficient will be larger and larger.

However, the probability that the values cannot meet the network interference optimization and energy efficient simultaneous will increase with the increase of α , too. The coordinates of E , F and H in Figure 4.17 are shown in Table 4.3.

Table 4.3. The coordinates of E , F and H

	F	E	H
$\alpha = 2$	$(0.94r, 0.36r)$	$(0.36r, 0.94r)$	$(0.71r, 0.71r)$
$\alpha = 3$	$(0.88r, 0.68r)$	$(0.68r, 0.88r)$	$(0.79r, 0.79r)$
$\alpha = 4$	$(0.86r, 0.83r)$	$(0.83r, 0.86r)$	$(0.84r, 0.84r)$

Therefore, as shown in Figure 4.17, when the network is energy efficient, the probability that the network is not interference optimization at the same time is the region between line AE and $\widehat{AE}$ and the region between line FC and $\widehat{FC}$, moreover, these two regions are equal since these two regions are symmetry with line OB ; therefore, the probability can be calculated as:

(1) The minimum probability is when $\alpha = 2$:

$$p_{min} = 2 \int_0^{0.36d_{sr}} \left(e^{-\pi\rho(d_{sr}^2 - d_{sn}^2)} - e^{-\pi\rho\left(0.19\left(\sqrt{d_{sn}^2 + 27.67d_{sr}^2} - d_{sr}\right)\right)^2} \right) \cdot 2\pi\rho d_{sn} e^{-\pi\rho d_{sn}^2} dd_{sn} = 0.002 \quad (4.53)$$

(2) The maximum probability is when $\alpha = 4$:

$$p_{max} = 2 \int_0^{0.83d_{sr}} \left(e^{-\pi\rho(d_{sr}^4 - d_{sn}^4)^{1/2}} - e^{-\pi\rho\left(0.19\left(\sqrt{d_{sn}^2 + 27.67d_{sr}^2} - d_{sr}\right)\right)^2} \right) \cdot 2\pi\rho d_{sn} e^{-\pi\rho d_{sn}^2} dd_{sn} = 0.028 \quad (4.54)$$

According (4.53) and (4.54), when the network is energy efficiency, the probabilities that the network is also interference optimization are from 0.972 to 0.998, which are pretty high. So in most case, we can regard that the energy efficient network is an interference optimization network approximately.

B. Heterogeneous node deployment mode

Corollary 4.14: In the heterogeneous network, when the network is energy efficiency, the probability that the network is also interference optimization is approximately 1.

In section 4.1.3, when the transmission ranges of nodes are different in the network, the feasible region of interference optimization is shown in Figure 4.12. Considering (4.40), the feasible region of energy efficient and interference optimization is shown in Figure 4.19 and Figure 4.20.

Figure 4.19. The feasible region of energy efficient and interference optimization in heterogeneous network

Figure 4.20. The boundary of energy efficient and interference optimization in heterogeneous network

Figure 4.21. The error between the boundaries of energy efficient and interference optimization

Similar with Figure 4.18, in Figure 4.20, when $\alpha = 4$, the feasible region of energy efficient is the biggest and equal to the feasible region of interference optimization approximately. The evaluation error can be found in Figure 4.21. In Figure 4.21, when $\alpha = 4$, the evaluation error between the feasible region of energy efficient and interference optimization is only 0.65×10^{-3} which is small enough to be omitted; therefore, we can regard that the probability that when the network is energy efficient, then the network is interference optimization at the same time is approximately equal to 1. Consequently, we can conclude that in heterogeneous wireless sensor network, when the network is energy efficient, the network interference is optimal, not vice versa.

According the conclusion in this section, on one hand, in the heterogeneous wireless sensor network, when the network is energy efficient, then the network interference is optimal with probability 1; on the other hand, in the real scenario, since the transmission ranges of node are always heterogeneous, therefore, we can regard that the energy efficient means the interference optimization in practice.

4.2 Energy Efficient and Reliable Topology Control Protocol [69]

In this section, based on the analysis in Section 4.1, we propose an energy efficient topology control algorithm for the wireless sensor network.

Definition 4.1. R -range of the node is defined as the optimal transmission range which has high probability of energy efficient.

Like the definition of k -connection for the network reliability and considering the probability of

reducing the energy consumption by adjusting the transmission range, if the nodes can maintain the optimal transmission range, i.e., R -range, the probability of energy efficient will be high. In Section 4.1.4, we proved that the optimal transmission range for getting high probability of energy efficient is $(1/2)^{1/\alpha}r$. In this section, we propose an energy efficient and reliable topology control algorithm based on this conclusion. Moreover, in Section 4.1.4, we have explored the probability of energy efficient by reducing the transmission range in power adjustment based topology control algorithm. For guaranteeing the network connection, we introduce the conclusions in [180] into our algorithm as the constraints of network reliable. In [180], the authors prove that when every node connects to its nearest $5.774 \log n$ neighbors, the network is asymptotic connectivity (the asymptotic connectivity means that when the number of neighbor nodes is larger than m , then the probability that the network is connected is asymptotic to 1); when each node connects to less than $0.074 \log n$ nearest neighbors, the network is asymptotic disconnectivity (the asymptotic disconnectivity means that when the number of neighbor nodes is smaller than k , then the probability that the network is disconnected is asymptotic to 1). The simulation result also shows that if the number of neighbors larger than $1.5 \log n$, the probability of connectedness increases rapidly to 1 for a modest number of nodes (e.g., $n \approx 30$). Therefore, in ERTC, $1.5 \log n$ will be used as the lower limitation of the neighbors number, i.e., the node degree. There are two stages in the energy efficient and reliable topology control algorithm: (1) neighbor information collection; (2) transmission range adjustment.

A. Neighbor Information Collection

In this section, node i broadcast HELLO message m_i using initial transmission range r_i to calculate the node degree and the distances to the neighbor nodes. As shown in Section 4.1, the transmission range is a circle, but may not same for each node. The HELLO message m_i includes the transmission power P_i , the source node ID I_i , and the version number vs_i which is used to decide whether the received HELLO message is a new one or not. When the neighbor nodes receive this HELLO message, firstly, comparing the node ID I_i in the HELLO message m_i with the node IDs that in the neighbors-list; if the node ID already exist, then check the version number vs_i to find out whether this HELLO message is a new one or not; if not, the HELLO message will be dropped immediately; otherwise, updating the neighbor-list; in case the node ID I_i does not exist in the neighbors-list, then adding the node ID to the neighbors-list. The distances d_{ij} between two nodes are calculated when the node i receives the HELLO message m_j from the neighbor nodes by using received signal strength indicator (RSSI) [181-182]. When the node i receive the HELLO message m_j from other nodes, they will update the neighbors-list based on the same principle which described above and calculate the node degree N_{1i} .

As shown in Corollary 4.12, the optimal transmission range for node i is $(1/2)^{1/\alpha}r_i$, when the source node i receive the HELLO message m_j from the neighbor nodes, it will compare the distance d_{ij} with $(1/2)^{1/\alpha}r_i$; the number of neighbor nodes whose distances to the source node i are smaller than $(1/2)^{1/\alpha}r_i$ will be the node degree of node i with transmission range $(1/2)^{1/\alpha}r_i$, which is N_{2i} .

B. Transmission Range Adjustment

In this stage, the node i adjusts its transmission range according to the node degree N_{1i} and N_{2i} . As discussed in Section 4.1.4, the optimal transmission range for energy efficient is $(1/2)^{1/\alpha} r_i$ and for guaranteeing the network connection, the lower limitation of the neighbors number is $1.5 \log n$; therefore, for meeting the requirements of both the energy efficient and the network reliability, the node degree N_{1i} and N_{2i} should be compared with $1.5 \log n$ for deciding the transmission range of node i . There are three kinds of relationships between the node degree and the lower limitation of neighbor numbers in ERTC: (1) $N_{2i} \geq 1.5 \log n$; (2) $N_{2i} \leq 1.5 \log n \leq N_{1i}$; and (3) $N_{1i} \leq 1.5 \log n$; different relationships have different transmission range adjustment strategies:

- (i) when $N_{2i} \geq 1.5 \log n$, it means that when the transmission range of node i is $(1/2)^{1/\alpha} r_i$, it has the highest probability to satisfy the requirements of both the energy efficient and network connection. Therefore, the transmission range of node i is reduced to $(1/2)^{1/\alpha} r_i$, which is reasonable.
- (ii) when $N_{2i} \leq 1.5 \log n \leq N_{1i}$, this means that when the transmission range of node i is r_i , the network connection can be satisfied; however, when the transmission range is $(1/2)^{1/\alpha} r_i$, it can not meet the requirement of network connection. As shown in Figure 4.18, when the transmission range is close to $(1/2)^{1/\alpha} r_i$, the probability is close to the highest probability, too. In addition, considering the node in ERTC is uniform distributed, so the node degree n_i is proportional with the coverage area πr_i^2 ; therefore, the transmission range in this situation can be set to $\left(\frac{1.5 \log n}{N_{2i}}\right)^{1/2} \cdot \left(\frac{1}{2}\right)^{1/\alpha} r_i$.
- (iii) when $N_{1i} \leq 1.5 \log n$, this means the initial transmission range of node i r_i can not meet the requirement of network connection. Therefore, the transmission range should be increased. Similar with the reason in (ii), the transmission range closer to $(1/2)^{1/\alpha} r_i$ has higher probability of energy efficient than that far from $(1/2)^{1/\alpha} r_i$ and considering the node distribution in ERTC is uniform, so the transmission range in this range can be set to $\left(\frac{1.5 \log n}{N_{1i}}\right)^{1/2} \cdot r_i$.

The process of the energy efficient and reliable topology control algorithm is:

Algorithm 4.1. Energy Efficient and Reliable Topology Control Algorithm (ERTC)

Input:

1. The length of the configuration area, *Border_length*;
2. The number of the nodes in the network, n ;
3. The value of distance-power gradient, α ;

Ensure:

4. Broadcast the HELLO message m_i with initial transmission range r_i ;
 5. Receive the HELLO message m_j ;
 6. Update the neighbors-list;
 7. Calculate the node degree N_{1i} ;
 8. Compare the distance between node i and the neighbor nodes with $(1/2)^{1/\alpha} r_i$;
 9. Calculate the node degree N_{2i} ;
 10. **if** $N_{2i} \geq 1.5 \log n$ **then**
 $TR = (1/2)^{1/\alpha} r_i$;
-

11. **else if** $N_{2i} \leq 1.5 \log n \leq N_{1i}$ **then**

$$TR = \left(\frac{1.5 \log n}{N_{2i}} \right)^{1/2} \cdot \left(\frac{1}{2} \right)^{1/\alpha} r_i;$$

12. **else**

$$TR = \left(\frac{1.5 \log n}{N_{1i}} \right)^{1/2} \cdot r_i;$$

13. **end if**

14. $r_i = TR$;

As shown in the table above, the runtime complexity for ERTC is $O(n)$, which is the same as the runtime complexity of LMA and LMN [91]. Therefore, the ERTC can improve the network performance without increasing the algorithm complexity seriously.

4.3. Probabilistic and High Efficient Topology Control Algorithm for Underwater Cooperation AUVs Network [217]

For the topology control algorithm presented in Section 4.2, it is effective for the terrestrial wireless sensor network; however, for the underwater environment, in which the node moves frequently and the network topology changes frequently, the traditional topology control algorithm will be executed again and again, which will consume a lot of network resource. Moreover, since the acoustic wave is used in the underwater environment, so the bandwidth is much more narrow than that of the terrestrial environment; this means that the extra bandwidth consume should be reduced as much as possible, such as the control packet. So in this section, we propose the probabilistic topology control algorithm for the underwater cooperation AUVs network. The network model of the underwater cooperation AUVs network and the detail of the SWARMs project have been introduced in last chapter.

Since the radio frequency (RF) wave is seriously attenuated in underwater environment [183], so the underwater AUVs use acoustic wave rather than RF wave to communicate with each other [184]. In SWARMs, for providing efficient and reliable communication network to mission execution, one of the important and necessary issues is the topology control of underwater cooperation AUVs network. The reasons are: 1) for achieving the missions, the underwater AUVs keep moving along the pre-defined paths, in which case, the topology of underwater cooperation AUVs network changes frequently; 2) since the transmission speed of acoustic wave is much smaller than that of RF wave, so the transmission delay in underwater cooperation AUVs network (UCAN) is more critical than that in traditional RF-based WSNs [185-186]; 3) due to the bandwidth of underwater acoustic channel is very limited, so the congestion in such kind of channel could be severe [187], which means the control messages of underwater cooperation AUVs network should be reduced as much as possible; 4) the multipath interference and the *Doppler* spreading are serious in underwater environment. Although there are many topology control algorithms have been proposed for conventional WSNs, considering the control cost, these topology control algorithms are not efficient in underwater cooperation AUVs network where the AUVs move frequently. For instance, in traditional topology control algorithms, once the current transmission power does not equal to the optimal one which is calculated based on optimal algorithms (such as [61-62], [65], [68]), then the nodes need to adjust their transmission power. In the network which the network topology changes slightly or the network resources are abundant, the above mentioned

approach is effective. However, to the UCAN, in which the network resources are limited and the network topology changes frequently, this approach is not as efficient as that in static network. The heavy control cost caused by AUVs' mobility will deteriorate the network performance greatly. Therefore, it is necessary to investigate how to reduce the control cost in order to improve the network performance of underwater cooperation AUVs network.

Additionally, for underwater cooperation AUVs network, once the current transmission power of AUV does not equal to the optimal transmission power which is calculated based on optimal algorithms (such as interference based, transmission delay based, energy consumption based, etc.), considering the other parameters in AUV, adjusting the transmission power may not a good strategy to improve the network performance. This means it is necessary to find a tradeoff between improving the network performance on one aspect and keeping the functionality of network (such as, network connection). For instance, when the optimal transmission power of AUV is P^* and the current transmission power is P , if $P \approx P^*$ (which means the difference between P and P^* is small enough), then even the current transmission power does not equal to the optimal one, the optimization rules do not need to be applied when takes energy consumption and network congestion into account. This tradeoff is worthy to underwater cooperation AUVs network. Moreover, in underwater cooperation AUVs network, whether the transmission power need to be adjusted or not also relates to other network parameters. For example, if $P \ll P^*$, but the residual energy of this AUV is small, in this case, it is better to not increase the transmission power in order to prolong the lifetime of this AUV.

Motivated by these, we propose a new topology control algorithm for underwater cooperation AUVs network, which is based on the value of AUV's residual energy, packet queue length, current transmission power, and number of neighbors to determine the transmission power adjustment probability of AUV, denominated as probabilistic topology control (PTC) algorithm.

4.3.1 Probabilistic topology control algorithm

In this section, we will introduce the probabilistic topology control algorithm in detail. Note that although the name of this algorithm is the same as that shown in [68], these two topology control algorithms are totally different.

A. Parameter deviation calculation

In underwater cooperation AUVs network, the underwater AUVs are always powered by battery. Moreover, once the energy is exhausted, the AUVs are non-functional, which has great effect on network performance. Similarly to the energy, the buffer space of the underwater AUV is limited, too. Thus, in case the memory space is occupied completely, the node cannot handle the incoming data packets, which makes the packet loss ratio increase. The occupation of the buffer space can be evaluated by packet queue length (in this paper, the queue length is defined as the number of data packets to be transmitted in AUV's buffer space). Therefore, in PTC, the residual energy, the packet queue length, the transmission power, and the AUV's degree will be taken into account to determine the transmission power adjustment probability for each AUV.

Firstly, we define the parameter deviation in Definition 4.2. The deviation of a parameter relates to the optimal solution or the constraint.

Definition 4.2. The deviation of parameter x which relates to its optimal solution or constraint x^* is defined as the ratio of the difference between these two values to the value of the optimal solution or the constraint, which can be expressed as:

$$D = \frac{|x - x^*|}{x^*} \quad (4.55)$$

According to Definition 4.2, to transmission power, when the optimal transmission power of AUV s is P_s^* which is calculated by the optimization algorithm, the deviation of transmission power can be calculated as:

$$D_{P_s} = \frac{|P_s - P_s^*|}{P_s^*} \quad (4.56)$$

Similarly to the transmission power, for the packet queue length, assuming that the maximum queue length allowed in AUV is Q_s^* , and the current queue length of AUV s is Q_s , then according to (4.55), the deviation of queue length is expressed as:

$$D_{Q_s} = \frac{|Q_s - Q_s^*|}{Q_s^*} \quad (4.57)$$

The total energy of AUV is E_s^* and the residual energy of AUV s is E_s , then the deviation of residual energy is:

$$D_{E_s} = \frac{|E_s - E_s^*|}{E_s^*} \quad (4.58)$$

Assuming that the needed degree of AUV for guaranteeing network connection is n_s^* and the current degree of AUV is n_s , then the deviation of AUV's degree can be calculated as:

$$D_{n_s} = \frac{|n_s - n_s^*|}{n_s^*} \quad (4.59)$$

Note that in (4.59), the needed degree of AUV for guaranteeing network connection can be calculated based on the conclusion in [180]. In [180], the authors have proved that for wireless network, if the number of neighbors of a node is larger than $5.1774 \log n$, then the network will be connected with probability 1; where n is the total number of nodes in network. So considering the energy consumption, we choose $n_s^* = 5.1774 \log n$ as the needed degree of AUV.

B. Transmission power adjustment probability calculation

When the parameter deviations have been determined, the transmission range adjustment probability can be calculated based on these deviations. The transmission range adjustment probability is defined in Definition 4.3.

Definition 4.3. In underwater cooperation AUVs network, considering the tradeoff between improving the network performance on one aspect and keeping the function of AUVs, the AUV, in which the current transmission power does not equal to the optimal transmission power that is calculated based on optimal algorithms, does not must to adjust their transmission power; the AUVs change their transmission power probabilistic. This probability is called the transmission power adjustment probability.

The calculation of transmission power adjustment probability is based on the value of parameter deviations. The larger deviation, the larger probability is. Since the mathematical relationship between the transmission power adjustment probability and the parameter deviation cannot be defined clearly, so we use the fuzzy logic algorithm to calculate the

transmission power adjustment probability. The input of the fuzzy logic system is the value of parameter deviation, and the output is the transmission power adjustment probability of each parameters. As introduced in the last chapter, the core part of fuzzy logic system is the fuzzy rules design, which decides the accuracy of the output. The more fuzzy rules are applied, the more accurate outputs are. Therefore, similarly to last chapter, the number of fuzzy rules used in this paper is set to 7, which are shown in Table 3.2. The membership functions of inputs and outputs are shown in Figure 3.2.

The outputs of the fuzzy logic system are the transmission power adjustment probabilities of different parameters, which are ρ_P , ρ_Q , ρ_E , and ρ_n , respectively. However, considering the fact that for one AUV, there is only one transmission power adjustment probability, therefore, the actual transmission power adjustment probability should be determined based on these four probabilities. Moreover, for guaranteeing the network performance, the transmission power adjustment probability should be determined by the parameter in which the performance is the worst (i.e., the parameter which the deviation is the largest); this is called the *Cask Principle*. For instance, for ρ_P , ρ_Q , ρ_E , and ρ_n , assuming that ρ_Q is the largest in these four probabilities, which means that the packet queue length is large in AUV; if the AUV choose the probability which is smaller than ρ_Q as the transmission power adjustment probability, then the performance of packet queue length cannot be guaranteed. Therefore, the approach used to decide the transmission power adjustment probability is setting the maximum probability of these four probabilities as the actual transmission power adjustment probability of AUV, which can be expressed as:

$$\rho_s = \max\{\rho_P, \rho_Q, \rho_E, \rho_n\} \quad (4.60)$$

The (4.60) means that the probability will be decided by the parameter in which the performance is the worst. This approach is efficient. On one hand, the ratio of the AUVs which need to adjust their transmission power is reduced, so the control cost of the network reduces, too; on the other hand, since the transmission power adjustment probability is decided by the parameter in which the performance is the worst, so the network performance can be guaranteed. When the transmission power adjustment probability has been calculated, the AUVs adjust their transmission power according to this probability.

For evaluating the effectiveness of the PTC algorithm, we define the transmission power adjustment ratio for underwater cooperation AUVs network as follows.

Definition 4.4. The transmission power adjustment ratio is defined as the ratio of the number of AUVs which adjust their transmission power to the total number of AUVs in network, which

can be expressed as: $R_p = \frac{\text{AUVs adjust the transmission power}}{\text{total AUVs in the network}}$.

According to the PTC algorithm, not all the AUVs change their transmission power when the current transmission power does not equal to the optimal one. Therefore, we have the Corollary 4.15 as follows.

Corollary 4.15. The PTC algorithm can reduce the transmission power adjustment ratio.

Proof. According to (4.60), in PTC algorithm, the transmission power adjustment probability of AUV s is ρ_s . Assuming that there are n AUVs in network and the number of AUVs which the transmission power does not equal to the optimal one is n_s ; therefore, the average number of AUVs which adjust their transmission power can be calculated as: $E(n_s) = \sum_{i=1}^{n_s} \rho_i$. Then according to Definition 4.4, the transmission power adjustment ratio of the PTC algorithm can

be calculated as:

$$R_P = \frac{E(n_s)}{n} = \frac{\sum_{i=1}^{n_s} \rho_i}{n} \quad (4.61)$$

However, in traditional topology control algorithms, once the transmission power does not equal to the optimal one, the AUVs need to adjust their transmission power. Since the number of AUVs which the transmission power does not equal to the optimal one is n_s , the transmission power adjustment ratio of the traditional topology control algorithm can be calculated as:

$$R_P = \frac{n_s}{n} \quad (4.62)$$

Since $\rho_i < 1$, so the R_P in (4.62) is larger than that in (4.61); moreover, the smaller ρ_s , the smaller R_P is. Therefore, the transmission power adjustment ratio in PTC algorithm is smaller than that in traditional topology control algorithm.

C. PTC based FTC algorithm

Based on last two sections, the transmission power adjustment probability of AUV can be calculated. After that, the AUVs will adjust their transmission power according to this probability.

Since many transmission power allocation algorithms have been proposed in the past decades, so the transmission power allocation algorithm is not the main research topic of this thesis. In this thesis, the calculation of the optimal transmission power is based on the FTC algorithm which is proposed by [61]. The FTC algorithm is the learning based fuzzy logic control algorithm for topology control. In the following, we will introduce this algorithm briefly.

Figure 10 shows the system structure of FTC. Adjusting the communication power is a very common capability of many AUVs. The output of FTC is the transmission power (TP). The target of FTC is to reach a specific degree of AUVs. Therefore, the input is the desired AUV's degree, denoted by ND_{ref} . On the other hand, according to the conclusion in [179], the probability that AUV's degree is n is shown in (4.63). So the probability that an AUV has n neighbors is another fuzzy logic controller input, denoted by $Prob$. In practice, ND_{ref} is integer and the transmission power has an upper bound P_{max} , i.e. $ND_{ref} > 0$ and $0 \leq P < P_{max}$.

Figure 4.22. The Fuzzy-Logic topology control (FTC)

$$P(ND \geq k) = f(k, P) = 1 - \sum_{n=0}^{k-1} \frac{(\rho \pi r^2)^n}{n!} e^{-\rho \pi r^2} \quad (4.63)$$

The training data set is provided by (4.63); the fuzzy controller can be obtained through the neuro-adaptive learning algorithm. In (4.63), the transmission range can be calculated based on

(3.38). The parameters of the membership function are automatically tuned through a back propagation algorithm individually or in combination with a least square method. The generation of the training data set can be shown as follows. As illustrated in Figure 4.24 and (4.63), the inputs are ND_{ref} and $Prob$, and the output is the transmission power. Given ρ , $ND \in (k_1, k_2, \dots, k_m)$ and $TP \in (p_1, p_2, \dots, p_m)$, $Prob = f(ND, TP)$ can be calculated from (4.63). The training data set T is a $s \times 3$ matrix in the form of $[ND, Prob, TP]$, where $s = m \times j$. For instance, one element in the training data set is $[3, 0.9, 0.25]$; this means that the transmission power is set to 0.25 if the probability that $ND \geq 3$ is 0.9, where the transmission power is normalized (i.e., the maximum transmission power is 1). Since ND is characterized by probability, it is necessary to adjust the AUV's degree if an AUV does not reach ND . For instance if $TP=0.25$ cannot lead to actual $k=ND$, then next step is to adjust $Prob$ to a higher value according to the AUV's degree error e_{ND} . There is an integral controller outside the fuzzy control to adaptively change $Prob$ (Figure 4.24). From the control theory point of view, the system properties are controlled by parameter $Prob_0$ and K . If e_{ND} is less than 0, K is configured to be half of its initial value. Therefore, according to the FTC algorithm, the process of the PTC based FTC algorithm can be expressed in the table below.

Algorithm 4.2. PTC based FTC algorithm

Inputs:

1. Training data set, $T = [k, Prob, TP]$;
2. Maximum transmission power, P_{max} ;
3. Reference degree of AUV, ND_{ref} ;
4. Initial probability, $Prob_0$;
5. Initial K , K_0 ;
6. The maximum queue length, Q ;
7. The maximum residual energy, E ;

Algorithm:

8. $TP_i \Leftarrow P_{max}$;
 9. $Prob \Leftarrow Prob_0$;
 10. Broadcast HELLO message with current TP_i ;
 11. For messages received from other AUVs, store the ID of its neighbor AUVs;
 12. Calculate the number of neighbors ND in the neighbor list;
 13. Calculate $e_{ND} = ND - ND_{ref}$;
 14. if $e_{ND} < 0$ then
 15. $K = K_0$;
 16. else
 17. $K = \frac{K_0}{2}$;
 18. end if
 19. $Prob \Leftarrow Prob_0 - Ke_{ND}$;
 20. $TP_i \Leftarrow FTC(ND_{ref}, Prob)$;
 21. Calculate the deviations D_p , D_Q , D_E , D_n ;
 22. Input the deviations into the fuzzy logic system to calculate the transmission power adjustment probability ρ_P , ρ_Q , ρ_E , and ρ_n ;
-

23. $\rho_s \leftarrow \max\{\rho_P, \rho_Q, \rho_E, \rho_n\}$;

24. Adjust the transmission power according to ρ_s (random decision based on the probability value).

Note that in this section, the PTC algorithm is combined with the FTC algorithm; however, in practice, the PTC algorithm can combine with other topology control algorithms to improve the performance and reduce the transmission power adjustment ratio.

4.4. Summary

In this chapter, first we investigate the probability of reducing network interference and energy consumption by adjusting the transmission power of node, respectively; then we investigate the relationship between interference optimal and energy effective by adjusting transmission power. Moreover, based on the probability of energy consumption by adjusting the transmission power, we proposed an effective power control algorithm for the wireless sensor network. Finally, for reducing the control cost in the underwater environment, we propose a probabilistic transmission power control algorithm for the underwater as hoc network.

Chapter 5

Integrating the opportunistic routing with the topology control to improve the performance of IoT

In wireless network, the opportunistic routing can improve the network capability successfully compared with the deterministic routing, especially the packet delivery ratio between the sender and the CRS (PDRsc). The PDRsc is defined as the probability that the data packet sent by sender can be received by at least one relay node in CRS. In previous works, such as [9-10, 34, 40-42, 188-189], the PDRsc has been utilized in routing algorithm design. However, in the wireless sensor networks, the PDRsc changes when the network topology changes; how to control and improve the PDRsc and how the PDRsc affects the routing performance have not been investigated in detail. Since there are two parameters can affect the performance of PDRsc in opportunistic routing (the number of node in relay node set and the packet delivery ratio between sender and one of node in CRS (PDRsn)) [9][189], so for improving the routing performance, the opportunistic routing algorithm should be able to aware and control: 1) number of relay nodes in CRS: in opportunistic routing, the larger number of relay nodes means higher PDRsc; however, the energy consumption and interference increase when the number of relay nodes is large; so the number of relay nodes in opportunistic routing should in an appropriate level [11]; 2) link availability: whether the transmitted data packet can be received by receiver successfully relates to not only the transmission power loss but also the interference of receiver [190]; so for improving the PDRsc, the algorithm should be able to adaptive the changing of transmission power loss and interference. So in this thesis, we introduce the topology control, which is effective on dealing with this kind of issue, into the opportunistic routing to improve the routing performance.

Recently, more and more researchers consider that integrate the topology control and routing algorithm in wireless sensor network or ad hoc network is an effective way to improve the network performance. In [191], the authors proposed three alternative mathematical models for integrating topology control and routing decisions so as to prolong the lifetime of sensors. For reducing the effect of primary user (PU) activities and node mobility to the stability of

links in mobile cognitive networks, in [192], the authors proposed a primary user activity prediction based joint topology control and stable routing protocol (PP-JTCSR), which can quantitatively capture channel utilization patterns of PUs. By topology control in PP-JTCSR, the most stable and shortest path can be found. In [193], the authors investigate the impact of two topology control methods for resolving the problem of void/isolated nodes appeared in geographic routing protocols, which can reduce the number of void/isolated nodes significantly. In [194], the authors have shown that joint topology control and routing assignment as an optimization problem is a NP-hard problem. For solving this problem, in this paper, the author proposed TORA (joint topology control and routing assignment) which seeks to jointly optimize topology and routing for DMesh (directional antennas in wireless mesh networks). There are also many researches that integrate the routing design with the topology control, which can be found in [195], [196], [197], and [198].

5.1. Network model

In this chapter, the two proposed algorithms are all geography based. This means that the nodes in network equip GPS device and can exchange their location periodically. In these two algorithms, only the neighbor nodes whose distances to destination node are smaller than the source node have chance to be selected as relay nodes. This means that not all the neighbor nodes can be selected as relay nodes. So we define the candidate relay area as follows.

Figure 5.1. The network model for opportunistic routing.

Definition 5.1: The candidate relay area of node s for transmitting data packet to destination node d is defined as the intersection area of two circles $C(s, r_s)$ and $C(d, ||ds||)$, which is shown in Figure 5.1 (the red area). $C(d, ||ds||)$ means the circle which the center is destination node d and the radius is $||ds||$.

Only the node in candidate relay area can be selected as the relay node, and the RND denoted by n_{rel} . In Figure 5.1, the transmission range of sender s is r_s and the distance between sender s and destination d is $||ds||$. The candidate relay area is the intersection area of two circles: $C(s, r_s)$ and $C(d, ||ds||)$. So the length of line da shown in Figure 5.1 equals to $||ds||$. The triangle sda is an isosceles triangle. Therefore, the angle of θ_{dsa} can be calculated as:

$$\theta_{dsa} = \arccos\left(\frac{r_s}{2||ds||}\right) \quad (5.1)$$

And the candidate relay area Δ can be calculated by:

$$\Delta = s_1 + s_2 + s_3 \quad (5.2)$$

where s_3 is the area of sector sba shown in Figure 5.1; s_1 is the area of the shadow area; s_2 equals to s_1 . Since the angle of θ_{dsa} has been calculated in (5.1), so the area of sector sba can be calculated as:

$$\theta_{dsa} = r_s^2 \cdot \arccos\left(\frac{r_s}{2\|ds\|}\right) \quad (5.3)$$

The value of s_1 equals to the area of sector dsa minus the area of triangle dsa , which can be expressed as:

$$s_1 = \frac{\|ds\|^2}{2} \left[\left(\pi - 2\arccos\left(\frac{r_s}{2\|ds\|}\right) \right) - \sin\left(\pi - 2\arccos\left(\frac{r_s}{2\|ds\|}\right)\right) \right] \quad (5.4)$$

Since $s_1 = s_2$, so the candidate relay area Δ can be calculated as:

$$\begin{aligned} \Delta = & r_s^2 \cdot \arccos\left(\frac{r_s}{2\|ds\|}\right) \\ & + \frac{\|ds\|^2}{2} \left[\left(\pi - 2\arccos\left(\frac{r_s}{2\|ds\|}\right) \right) - \sin\left(\pi - 2\arccos\left(\frac{r_s}{2\|ds\|}\right)\right) \right] \end{aligned} \quad (5.5)$$

5.2. Cross-layer Balanced and Reliable Opportunistic Routing algorithm [135]

Based on the SBFL algorithm that proposed in Section 3, we propose the cross-layer and reliable opportunistic routing algorithm (CBRT) for Mobile ad hoc networks (MANETs) in this section. Considering the mobility of the nodes in MANETs, in this section, the topology control algorithm and the link lifetime prediction algorithm which takes both the moving speed and the moving direction into account are developed.

5.2.1. Packet delivery ratio based opportunistic topology control algorithm

In this section, we propose the packet delivery ratio based opportunistic topology control algorithm (OTC). The OTC is inspired by the humoral regulation, in which the feasible solution is a range rather than a single value. In OTC, the transmission range is adjusted dynamically based on the packet delivery ratio to maintain the stability and reliability packet delivery ratio; moreover, the OTC reduces the topology control cost successfully by divided the nodes into different categories. In opportunistic routing algorithm, the packet delivery ratio between the sender and the CRS can be calculated based on Definition 2.5. Specifically, if the packet delivery ratios between sender and anyone neighbor nodes are the same, then the packet delivery ratio can be simplified as [11]:

$$PTP = 1 - (1 - p_i)^n \quad (5.6)$$

where p_i is the packet delivery ratio between sender and one neighbor in CRS; it can be determined by periodically beacon packet exchanging between sender and its neighbors [41][188]; n is the RND of the CRS. According to (5.6), to different RND, the packet delivery ratio varies greatly, especially in MANETs. For getting stable packet delivery ratio, the RND should keep constant in CRS. However, due to the high mobility of MANETs, the network topology changes frequently. So if each node maintains constant RND in CRS, the transmission range needs to be adjusted frequently and the transmission range adjustment ratio is high. The high adjustment ratio makes the communication channel more and more congested. Therefore, for reducing the adjustment ratio, the nodes are divided into different categories in OTC according to their packet delivery ratios. Whether the transmission ranges need to be adjusted or not will be decided by which categories that the nodes belong to. The definitions of different

categories are shown in Definition 5.2.

Definition 5.2. When the packet delivery ratio of node is in the region (P_1, P_2) ; then the node is healthy; otherwise, the node is unhealthy.

The definition is shown in Figure 5.2 and expressed in (5.7).

Figure 5.2. The definition of the different categories

$$\begin{cases} R_H \in (PTP|PTP \in (P_1, P_2)) \\ R_{UH} \in (PTP|PTP \in (0, P_1) \cup (P_2, 1)) \end{cases} \quad (5.7)$$

where P_1 and P_2 are the boundary values of different categories; R_H means the healthy region; R_{UH} means the unhealthy region. To the specific packet delivery ratio, the needed RND of the candidate relays set can be calculated by (5.6). So the (5.7) can also be expressed by RND, which is:

$$\begin{cases} R_H \in (n|n \in (n_1, n_2)) \\ R_{UH} \in (n|n \in (0, n_1) \cup (n_2, N)) \end{cases} \quad (5.8)$$

where n is RND, N is the node number in the network.

The source node calculates the RND in the CRS and adjusts the transmission range according to the value of RND. For reducing the transmission range adjustment ratio, in OTC, the transmission range adjustment probabilities are different in different regions. In health region, this probability is 0; however, in unhealthy region, this probability varies from 0 to 1 based on the value of RND, which is:

$$\begin{cases} p_h = 0, n \in (n_1, n_2) \\ p_u = 1, n \in (0, n_1) \cup (n_2, N) \end{cases} \quad (5.9)$$

where p_h is the transmission range adjustment probability of healthy region; p_u is the probability of unhealthy region.

In unhealthy region, the adjustment probability varies and is decided by the deviation of the RND in unhealthy region relative to that in healthy region. When the RND is far from the healthy region, the adjustment probability should be high to guarantee the network connectivity and reliability, vice versa. So the adjustment probability can be calculated as:

$$p_{si} = \begin{cases} \frac{n_1 - n_i}{n_1}, n_i \in (n_1, n_2) \\ \frac{n_i - n_2}{N - n_2}, n_i \in (n_2, N) \end{cases} \quad (5.10)$$

where n_i is the RND of node i ; p_{si} is the transmission range adjustment probability of node i and $0 \leq p_{si} \leq 1$.

As shown in [179], the probability that the node number is n in the coverage area is Poisson distribution; therefore, the probability that there are n nodes in the survival area is:

$$P(n) = \frac{(\rho\Delta)^n}{n!} e^{-\rho\Delta} \quad (5.11)$$

where Δ is the candidate relay area that shown in Figure 5.2; ρ is the node density of the network; n is the RND in the candidate relays set.

According to (5.11), the probability that the RND is in the region (n_1, n_2) can be calculated as:

$$P(n_1 \leq n \leq n_2) = \sum_{n=n_1}^{n_2} \frac{(\rho\Delta)^n}{n!} e^{-\rho\Delta} \quad (5.12)$$

When $P'(n_1 \leq n \leq n_2)|_{\Delta} = 0$, the (5.12) will get the maximum value, which means the under this assumption the probability that there are n nodes in the survival area Δ is the highest. Moreover:

$$P'(n_1 \leq n \leq n_2)|_{\Delta} = \sum_{n=n_1}^{n_2} \frac{(\rho\Delta)^{n-1}}{n!} (n\rho e^{-\rho\Delta} - \rho^2 \Delta e^{-\rho\Delta}) \quad (5.13)$$

when $P'(n_1 \leq n \leq n_2)|_{\Delta} = 0$, we can get the optimal candidate relay area Δ^* .

The area of the candidate relay area can be calculated by (5.5), so the optimal value of the transmission range can be calculated as:

$$\begin{aligned} \Delta^* = & r_s^2 \cdot \arccos\left(\frac{r_s}{2\|ds\|}\right) \\ & + \frac{\|ds\|^2}{2} \left[\left(\pi - 2\arccos\left(\frac{r_s}{2\|ds\|}\right) \right) - \sin\left(\pi - 2\arccos\left(\frac{r_s}{2\|ds\|}\right) \right) \right] \end{aligned} \quad (5.14)$$

Based on (5.13) and (5.14), we can get the optimal transmission range r^* for the source node. This transmission range has the highest probability to guarantee that the RND in CRS is in the region (n_1, n_2) . Therefore, when the node is in unhealthy region, the node transmission ranges will be adjusted to r^* .

Therefore, according to (5.8) and Definition 5.2, we can calculate the transmission range adjustment ratio of OTC as follows:

$$C_{OTC} = P_u + \frac{1}{N} \sum_{i=1}^{NP_s} p_{si} \quad (5.15)$$

where P_u means the probability that the node is in unhealthy region; p_{si} is the transmission range adjustment probability of node i ; N is the node number in network. According to (5.9) and (5.10), the P_u can be calculated as:

$$\begin{aligned} P_u &= P[(0 \leq n \leq n_1) \cup (n_2 \leq n \leq N)] \\ &= \sum_{n=0}^{n_1-1} \frac{(\rho\Delta^*)^n}{n!} e^{-\rho\Delta^*} + \sum_{n=n_2+1}^N \frac{(\rho\Delta^*)^n}{n!} e^{-\rho\Delta^*} \end{aligned} \quad (5.16)$$

Note that there are two variable application-specific parameters in OTC, which are the boundary values of the healthy region: n_1 and n_2 (i.e., P_1 and P_2). Since different applications have different network parameters and QoS (Quality of Services) requirements, so these two parameters are not fixed; they are different with different applications. For instance, if the application requires that the packet delivery ratio between the sender and the candidate relays set should larger than 0.9, then the healthy region can be decided as $(0.9, 0.99)$, since the probability can not equal to 1; then the RND can be calculated based on these two probabilities and (5.6).

5.2.2. Cross-layer and reliable opportunistic routing algorithm

As introduced in Chapter 3, the mobility of the nodes has great effect on the routing

performance, so the mobility of the nodes is taken into account in this algorithm. The effect of the mobility is expressed by the link lifetime. The link lifetime predication algorithm has been introduced in detail in Chapter 3. Therefore, based on the link lifetime predication algorithm and the OTC algorithm, we propose the cross-layer and reliable opportunistic routing algorithm for MANETs, shorted as CBRT.

In CBRT, each node knows the locations of other nodes in the network. If the source node wants to send data packet to the destination node, first, it will broadcast the RREQ to its neighbors. The neighbors are the nodes who have one-hop bi-directional communication links with the source node. The RREQ includes the locations of the source node and the destination node. The neighbors who receive this message will calculate the distances to the destination node. The neighbor nodes whose distances to the destination node are larger than that of the source node will drop the RREQ packet directly. Only the neighbor nodes whose distances to the destination node are smaller than the source node will reply RREP message to the source node. In RREP, the concerned cross-layer parameters (including the moving speed and moving direction) are included. The number and the kinds of the cross-layer parameters can be decided by the different applications. Different applications have different cross-layer parameters. The CBRT algorithm can adapt to different applications.

When the source node receives the RREP packet, it will calculate the RND in the CRS and decide which region that it belongs to according to the value of RND. The source node adjusts its transmission range by using OTC algorithm. After the transmission range adjustment, the source node will update the CRS. If the optimal transmission range is smaller than the previous one, then the source node deletes the nodes whose distances to the source node are larger than its transmission range from CRS. If the transmission range is larger than the previous one, the source node needs to broadcast RREQ packet again. Only the nodes which are not in the CRS and the distances to the destination node are smaller than the source node reply RREP message to source node. After the CRS updating, the source node extracts the cross-layer parameters from the RREP packets and determines the relaying priorities of the nodes in CRS based on the SBFL algorithm. When the relaying nodes receive the data packet, they will repeat the transmission process that introduced above till the data packet is received by the destination node.

The process of the cross-layer and reliable opportunistic routing algorithm is shown as follows:

Algorithm 5.1. Cross-layer and reliable opportunistic routing algorithm

1. source node broads RREQ to its neighbor nodes;
 2. **if** distance(node_i, destination_node) < distance(source_node, destination_node);
 3. node *i* send RREP to source node;
 4. source node calculates the RND by using OTC algorithm;
 5. **end if**
 6. **if** ($U_i^j \geq U_i^{th}$)
 7. node_status $\leftarrow$ true;
 8. **else if** ($U_i^j < U_i^{th}$)
 9. node_status $\leftarrow$ false;
-

```

10.end if
11.while node_status == true do
12.if  $0 < RND < n_1$  or  $n_2 < RND < N$ 
13.   $p_{si} = P_{si}(RND)$ ;
14.   $r_i \xleftarrow{p_{si}} r^*$ ;
15.else if  $n_1 < RND < n_2$ 
16.   $p_{si} = 0$ ;
17.   $r_i = r_i$ ;
18.end if
19.source node update the candidate relays set;
20.source node extract cross-layer parameters from RREP;
21. $D_i \leftarrow rv(U_i^j)$ ;
22. $\omega_i \leftarrow \text{Fuzzylogic}(D_i)$ ;
23. $\psi \leftarrow \text{Utility}(R_{Metric\_i}^1, \omega_i)$ ;
24.ranking( $\psi$ );
25.end while
26.source node sends data packet to the relaying nodes with the priority list;
27.relaying nodes relay the data packet according the priority in the priority list;
28.The relaying nodes repeat 1-28 till the data packet received by the destination node.

```

5.3 Efficient and Reliable topology control algorithm for opportunistic routing in wireless sensor network [218]

As introduced in Chapter 2 and last section, the number of nodes in CRS should be limited; this number should not too large or too small. For guaranteeing high performance of the opportunistic routing, the numbers of nodes in the CRS should be controlled. The number of nodes in the CRS relates to the transmission range (also transmission power) of nodes, so controlling the transmission power of node also can control the number of node in CRS. However, there is a fact that for different distribution of the nodes in the network, to the same transmission power (i.e., the transmission range), the number of nodes in the coverage range is different; moreover, to the same distribution model of nodes and the same transmission power, the number of nodes in the coverage is also probability and obeys a specify probability model. For instance, for the uniform distribution, for given transmission power, the probability that there are n nodes in the coverage area of this node obeys the probability model shown in Definition 2.8, which can also be found in Figure 5.3.

Figure 5.3. Relationship between node degree and transmission power

As shown in [34], the relationship between transmission power and relay node degree is probabilistic in physical layer, i.e., when the transmission power is P_{Ts} , the relay node degree is n_{rel} with probability $P_{rnd}(P_{Ts}, n_{rel})$, which is shown in Definition 2.8 and Figure 5.3. This means that the optimal solutions (P_{Ts}, n_{rel}) may not exist or exist with low probability in reality, which can be found in Figure 5.3. For instance, when the current relay node degree is 20, then if the transmission power is P1 or P3, then the probability will be very low; however, if the transmission power is P2, then the probability is much higher than that when the transmission power is P1 or P3. So under this assumption, if P1 or P3 is chosen as optimal transmission power, the relay node degree may not 20 with high probability. Another issue needs to be solved during the optimal transmission power and relay node degree selection is that the non-uniqueness of (13), which can be found in Figure 5.3. As shown in Figure 5.3, if the maximum probability of (13) is P , then the solutions (P_{Ts}, n_{rel}) are not uniqueness; for instance, the solutions in the red area of Figure 5.3 have the same probability P . So, in this point of view, the transmission power and the relay node degree should be optimal jointly rather than separately.

5.3.1 Optimization Model

As shown in Chapter 1, two parameters can affect the performance of PDRsc, which are relay node degree and PDRsn. In this section, we will investigate these two parameters in detail. Moreover, since the [10] and [188] shows that the excepted energy cost between sender and candidate set in opportunistic routing also relates to PDRsc, therefore, we also investigate the excepted energy cost under accurate PDRsc in the following of this section.

A. Packet delivery ratio between sender and CRS (PDRsc)

In opportunistic routing, the source node relays the data packet to all the nodes in CRS, and the relay nodes transmit the data packet based on their relaying priorities [188]. There are two different kinds of PDR: 1) the PDR between sender and one relay node in CRS, which can be found in Figure 5.4(a); 2) the PDR between sender and candidate set, which can be found in Figure 5.4(b).

Figure 5.4. Packet delivery ratio: (a) PDRsn; (b) PDRsc

Note that in opportunistic routing, the relay nodes in CRS are all the one-hop neighbors of sender. Since the data packets are transmitted to more than one relay nodes in opportunistic routing, so the probability that the data packet can be received successfully by relay nodes increases comparing with the traditional routing algorithms. The PDRsc can be calculated based on Definition 2.5 and (2.4), which is:

$$PTP(P_{Ts}, n_{rel}) = 1 - \prod_{i=1}^{n_{rel}} (1 - p_i) \quad (5.17)$$

where p_i is PDRsn and shown in Figure 5.1(a); n_{rel} is the relay node degree; P_{Ts} is the transmission power of sender s . According to (5.17), we can conclude that there are two parameters can affect the PDRsc: 1) the relay node degree and 2) the value of PDRsn; in the following of this section, we will investigate the effect of these two parameters on the performance of PDRsc in detail.

1. Packet delivery ratio between source node and relay node (PDRsn)

In wireless network, whether the packet can be received successfully by receiver relates to both the transmission power of sender and the interference of receiver [189]. The interference of receiver is defined as the summation of the interference nodes' transmission power (the interference node is defined as the node whose transmission ranges covers the receiver) [199]. This is the natural properties of wireless communication. The nodes not only can affect their neighbors, but also can be affected by interference nodes. Therefore, the p_i shown in (5.17) is affected by both the transmission power and the interference.

In wireless network, if the receiver can decode the received data packet correctly in fading environment, one of the constraints is that the SINR (signal interference noise ratio) should above a certain threshold level β . According to [171], the probability that the SINR is above the given threshold can be calculated as:

$$\begin{aligned} P_{SINR}(P_{Ts}) &= P \left[\frac{\alpha_0^2}{\frac{1}{G} \sum_{i=1}^m \frac{K \alpha_i^2 P_{Ti}}{(\|ri\|/\|rs\|)^\eta P_{Ts}} + \frac{P_n \|rs\|^\eta}{P_{Ts} K}} \geq \beta \right] \\ &= \int_0^\infty \int_0^\infty \dots \int_0^\infty e^{\left(-\beta \left[\frac{1}{G} \sum_{i=1}^m \frac{K \alpha_i^2 P_{Ti}}{(\|ri\|/\|rs\|)^\eta P_{Ts}} + \frac{P_n \|rs\|^\eta}{P_{Ts} K} \right] \right)} \prod_{i=a}^m e^{-\alpha_i} d\alpha_i \\ &= e^{\left[-\frac{\beta P_n \|rs\|^\eta}{P_{Ts} K} \right]} \prod_{i=a}^m \frac{G (\|ri\|/\|rs\|)^\eta P_{Ts}}{G (\|ri\|/\|rs\|)^\eta P_{Ts} + \beta P_{Ti}} \end{aligned} \quad (5.18)$$

where α^2 is an exponential random variable with unit mean; $\|ri\|$ is the distance between

interference node and receiver; $\|rs\|$ is the distance between sender and receiver ; η is the propagation loss coefficient, where $2 \leq \eta \leq 5$; K is the overall antenna gain and equals to $\frac{(G_t G_r \lambda^2)}{(4\pi)^2 L}$; G_t and G_r are the transmission and reception antenna gain; L is the system loss; λ is the signal wavelength; G is the processing gain; P_n is the noise power at receiver, P_{Ti} is the transmission power of i th interference node (except the sender s).

Additionally, if the data packet sent by sender can be received by receiver successfully, the transmission power of sender at receiver should larger than the receiving threshold. According to the conclusion in [171] and [199], the transmission power of sender at receiver can be calculated as:

$$P_R(P_{Ts}) = \left(\frac{K\alpha^2}{\|ds\|^\eta} P_{Ts} + P_n \right) \quad (5.19)$$

where P_n is AWGN (additive white Gaussian noise) with zero mean and deviation is σ^2 ; $\|ds\|$ is the distance between sender s and receiver d .

Assuming that the receiving threshold which can guarantee correct data decoding at receiver is P_{Thresh} , then the probability that the transmission power of sender received by receiver is equal to or larger than P_{Thresh} can be calculated as [188]:

$$P = Q\left(\frac{1}{\sigma} \cdot \frac{P_{Thresh} \|ds\|^\eta}{P_{Ts} K \alpha^2}\right) \quad (5.20)$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{y^2}{2}} dy$.

Since the probability shown in (5.18) and (5.20) are independent with each other, so according to (5.18) and (5.20), the PDRsn which takes both the transmission power loss and interference into account can be calculated, which is:

$$\begin{aligned} p_i &= P_{SINR}(SINR \geq \beta) \cdot P_R(P_{Ts}) \\ &= Q\left(\frac{1}{\sigma} \cdot \frac{P_{Thresh} \|ds\|^\eta}{P_{Ts} K \alpha^2}\right) \cdot e^{\left[-\frac{\beta P_n \|rs\|^\eta}{P_{Ts} K}\right]} \prod_{i=a}^m \frac{G(\|ri\|/\|rs\|)^\eta P_{Ts}}{G(\|ri\|/\|rs\|)^\eta P_{Ts} + \beta P_{Ti}} \end{aligned} \quad (5.21)$$

2. Relay node degree

As shown in (5.17), one parameter which can affect PDRsc is the relay node degree. The relay node degree has been defined in Definition 3. Moreover, the number of neighbors and the transmission power are relevant [179]. When the nodes are uniformly distributed in the event area, based on Definition 2.8, the probability that the number of neighbors is n for node s can be expressed as [179]:

$$P(n) = \frac{(\rho\Psi)^n}{n!} e^{-\rho\Psi} \quad (5.22)$$

where Ψ is the coverage area of node s and can be calculated by $\Psi = \pi r_s^2$, r_s is the transmission range of node s ; ρ is the node density.

However, in ERTO, not the whole coverage area of sender is taken into account during the relay node selection; the interesting area is the candidate relay area which has been defined in Definition 5.1. So the (5.22) cannot be used directly to calculate the probability of relay node degree under specific transmission power. The area of the candidate relay area can be calculated based on (5.5).

Additionally, the transmission range relates to the transmission power. According to (5.19) and

the transmission power of sender s , the transmission range r_s can be expressed as:

$$r_s = \left(\frac{K\alpha^2(P_{Thresh} - P_n)}{P_{Ts}} \right)^{\frac{1}{\eta}} \quad (5.23)$$

where P_{Thresh} is the reception power threshold for successful data packet reception. Thus, the probability that there are n_{rel} nodes in candidate relay area can be calculated as:

$$P_{rnd}(P_{Ts}, n_{rel}) = \frac{(\rho\Delta)^{n_{rel}}}{n_{rel}!} e^{-\rho\Delta} \quad (5.24)$$

where Δ and r_s can be calculated based on (5.5) and (5.23), respectively. $P_{rnd}(P_{Ts}, n_{rel})$ means the probability that the relay node degree is n_{rel} when the transmission power is P_{Ts} . Therefore, the selected relay node degree and transmission power of sender should make $P_{rnd}(P_{Ts}, n_{rel})$ as large as possible.

B. Expected energy consumption

In this section, we introduce the expected energy consumption of the communication link between sender and CRS. The expected energy cost function between sender and CRS has been proposed in [10] and [188]; however, the functions introduced in [10] and [188] are not accurate, since the authors do not take interference into account. Therefore, in this section, we investigate the expected energy consumption between sender and relay node set based on the conclusions in the last sections.

Considering sender s and its CRS $R_{p_n}(s)$ with transmission power P_{Ts} . Let $\mathbb{C}_s(P_{Ts}, n_{rel})$ denote the one-hop expected energy cost incurred by node s with transmission power P_{Ts} to send data packet which can be received by at least one node in $R_{p_n}(s)$. Therefore, according to [10] and [188], $\mathbb{C}_s(P_{Ts}, n_{rel})$ can be calculated as:

$$\mathbb{C}_s(P_{Ts}, n_{rel}) = \frac{E_s}{P_{sdr}(P_{Ts}, n_{rel})} \quad (5.25)$$

where E_s is the energy that needed by transmitting and receipting the data packet which is transmitted from source node to CRS. Based on the conclusion in [10] and [188], the E_s can be calculated as:

$$E_s = (|R_{P_{Ts}}(s)|E_r + E_{p_n})E\{T_{P_{Ts}}(s)\} \frac{L}{B} \quad (5.26)$$

where E_r is the energy consumption for reception; E_{p_n} is the energy consumption for transmitting at transmission power P_{Ts} ; L is the data packet size and B is the bandwidth. In this paper, for simplifying the calculation, we assume that the L and B keep constant during the calculation. $E\{T_{P_{Ts}}(s)\}$ is the mean energy consumption that the packet transmitted by sender can be received by receiver successfully at $T_{P_{Ts}}(s)$ trying times, which can be calculated as [188]:

$$E\{T_{P_{Ts}}(s)\} = \int_{l=0}^{\infty} l \times P_{tr}\{T_{P_{Ts}}(s) = l\} = \frac{1}{1 - \prod_{i=1}^{n_{rel}} (1 - p_i)} \quad (5.27)$$

where $P_{tr}\{T_{P_{Ts}}(s) = l\}$ is the probability that $T_{P_{Ts}}(s)$ equals to l and can be calculated as: $P_{tr}\{T_{P_{Ts}}(s) = l\} = \prod_{i=1}^{n_{rel}} (1 - p_i) (1 - \prod_{i=1}^{n_{rel}} (1 - p_i))$. Since $P_{sdr}(P_{Ts}, n_{rel})$ has been calculated by (5.21), so according to (5.26) and (5.27), the (5.25) can be rewritten as:

$$\mathbb{C}_s(P_{Ts}, n_{rel}) = \frac{(n_{rel}E_r + \xi P_{Ts})\delta}{(1 - \prod_{i=1}^{n_{rel}} (1 - p_i))^2} \quad (5.28)$$

where $\delta = L/B$; ξ is the consume coefficient for data packet transmission; p_i can be

calculated based on (5.21) which has taken transmission power loss and network interference into account.

5.3.2. Topology control based opportunistic routing

A. Optimal solution calculation

As shown in Section 5.3.1, in opportunistic routing, the PDR_{sc} relates to both the relay node degree and the PDR_{sn}. Since the larger relay node degree, the higher successful packet transmission probability, so the relay node degree should as large as possible. However, large relay node degree needs large transmission power, which consumes more energy than the small transmission power. Unfortunately, the node energy are limited in wireless sensor networks and large transmission power cause more serious interference than the small one, so the transmission power should be minimized as far as possible. These are two opposite optimal objectives, and finding the optimal solutions for this issue has been proved is NP-hard problem [189]. This means that it is impossible to find an optimal solution which can make the relay node degree and PDR_{sc} maximal while the network interference and energy consumption minimal at the same time. Therefore, we introduce the multi-objective optimization into the optimal solution calculation to find the tradeoff between these optimal objectives.

The issues introduced in Section 5.3.2 can be expressed as:

$$\begin{aligned} & \begin{cases} \max(P_{TP}(P_{Ts}, n_{rel}), P_{rnd}(P_{Ts}, n_{rel})) \\ \min(\mathbb{C}_s(P_{Ts}, n_{rel})) \end{cases} \\ \text{st. } & 0 \leq P_{Ts} \leq P_{max} \\ & 0 \leq n_{rel} \leq n \end{aligned} \quad (5.29)$$

According to the multi-objective optimization theory [200][201], the (5.29) can be rewritten as:

$$\min_{\mathbf{x} \in \mathbf{X}^0} \mathbf{f}(\mathbf{x}) = (f_1(\mathbf{x}), f_2(\mathbf{x}), \dots, f_m(\mathbf{x})) \quad (5.30)$$

where $\mathbf{X}^0 = \{\mathbf{x} \in \mathbb{R}^n | g_i(\mathbf{x}) \geq 0, i = 1, 2, \dots, p\}$ is the feasible region; $\mathbf{x} = (x_1, x_2, \dots, x_n)$ are the decision variables; $g_i(\mathbf{x}) \geq 0, i = 1, 2, \dots, p$ are the constraint functions. So according to (5.29), there have:

$$\begin{cases} \mathbf{x} = (P_{Ts}, n_{rel}) \\ x_1 = P_{Ts} \\ x_2 = n_{rel} \end{cases} \quad (5.31)$$

$$\begin{cases} f(\mathbf{x}) = (-PDR_{sc}(P_{Ts}, n_{rel}), -P_{rnd}(P_{Ts}, n_{rel}), \mathbb{C}_s(P_{Ts}, n_{rel})) \\ f_1(\mathbf{x}) = -PDR_{sc}(P_{Ts}, n_{rel}) \\ f_2(\mathbf{x}) = -P_{rnd}(P_{Ts}, n_{rel}) \\ f_3(\mathbf{x}) = \mathbb{C}_s(P_{Ts}, n_{rel}) \end{cases} \quad (5.32)$$

$$\begin{cases} g_1(\mathbf{x}) = P_{max} - P_{Ts} \\ g_2(\mathbf{x}) = n - n_{rel} \end{cases} \quad (5.33)$$

The $f_i(\mathbf{x}), (i = 1, 2, 3)$ in (5.32) can be got according to (5.17), (5.24), and (5.28), respectively. Different with single-objective optimization, the optimal solution is a set rather than a single value in multi-objective optimization [200][201]. This solution set is named Pareto optimal solution set. The optimal solutions in Pareto optimal solution do not mean that they can satisfy all the optimal objectives shown in (5.29) simultaneous; these optimal solutions can improve the optimal objectives on at least one aspect compared with the solutions which are not in Pareto optimal solution set [200][201]. For instance, assuming (P_{Ts}, n_{rel}) is the optimal

solution in Pareto optimal solution set and (P_{Ts}, n_{rel}) is not the optimal solution; if $PTP(P_{Ts1}, n_{rel1}) > PTP(P_{Ts2}, n_{rel2})$, then $P_{rnd}(P_{Ts1}, n_{rel1})$ and $\mathbb{C}_s(P_{Ts1}, n_{rel1})$ are at least not worse than $P_{rnd}(P_{Ts2}, n_{rel2})$ and $\mathbb{C}_s(P_{Ts2}, n_{rel2})$. The optimal solutions in Pareto optimal solution set do not have comparability [200][202][203]. For instance, assuming that (P_{Ts1}, n_{rel1}) and (P_{Ts2}, n_{rel2}) are all optimal solutions in Pareto optimal solution set; if $PTP(P_{Ts1}, n_{rel1}) > PTP(P_{Ts2}, n_{rel2})$, then at least one value of $P_{rnd}(P_{Ts1}, n_{rel1})$ and $\mathbb{C}_s(P_{Ts1}, n_{rel1})$ is worse than that of $P_{rnd}(P_{Ts2}, n_{rel2})$ and $\mathbb{C}_s(P_{Ts2}, n_{rel2})$. According to [200] and [201], the definition of Pareto optimal solutions for this issue is defined as follows:

Definition 5.3. Assuming that $(\bar{P}_{Ts}, \bar{n}_{rel}) \in X^0$, if there is no $(P_{Ts}, n_{rel}) \in X^0$ which can make $f_i(P_{Ts}, n_{rel}) < f_i(\bar{P}_{Ts}, \bar{n}_{rel})$ ($i = 1, 2, 3, 4$) hold, then $(\bar{P}_{Ts}, \bar{n}_{rel})$ is the Pareto Optimal Solution of (18), the set of all Pareto Optimal Solutions is Pareto Optimal Solution Set, denoted as $\mathbf{R}$.

There are two different kinds of algorithms to calculate the Pareto optimal solution set of multi-objective optimization [200]: 1) the traditional algorithm; for instance, method of objective weighting, method of distance functions, min-max formulation, etc.; the drawbacks of traditional algorithms have been introduced in [200]; 2) the intelligent optimization algorithm; the intelligent optimization algorithm includes the evolutionary algorithm, particle swarm optimization, etc. The calculation of Pareto optimal solution set is not the main research item of this paper, so we use the evolutionary algorithm introduced in [201], which is more accuracy and efficiency than traditional algorithm, to calculate the Pareto optimal solution set of this issues. The detail of this algorithm can be found in [201].

According to Definition 5.3, there is more than one solution in Pareto optimal solution set, so the Pareto optimal solution set $\mathbf{R}$ can be expressed as:

$$\mathbf{R} = \{(\bar{P}_{Ts1}, \bar{n}_{rel1}), (\bar{P}_{Ts2}, \bar{n}_{rel2}), \dots, (\bar{P}_{Tsn}, \bar{n}_{reln})\} \quad (5.34)$$

The solutions shown in (5.34) can be chosen as the optimal solution of (5.29).

B. Topology control algorithm

Once the routing process begins, first, each node executes a fully distributed algorithm to collect the required information, which can be utilized to estimate PDRsc and expected energy consumption. The information which is needed can be collected through iterative one-hop beacons. The local information is updated by the latest time-stamp in these collection methods. When nodes get the required information, they will calculate the Pareto optimal solution set for topology control. Based on the algorithm introduced in [201], the Pareto optimal solution set $\mathbf{R}$ of issue (5.29) can be gotten. According to the characteristic of the solutions in Pareto optimal solution set, which has been introduced in last section, any solution in Pareto optimal solution set can be chosen as the optimal solution of nodes. However, in practice, each node only has one transmission power and relay node degree, which means that not all the solutions in $\mathbf{R}$ can be selected. Therefore, according to the Pareto optimal solution set and the current transmission power and relay node degree, there are two different topology control strategies as follows.

1. The current transmission power and relay node degree are not in Pareto optimal solution set $\mathbf{R}$. In this situation, since the current transmission power and relay node degree are not in Pareto optimal solution set $\mathbf{R}$, so the transmission power needs to be adjusted.

As introduced in the beginning of this chapter, the relationship between transmission power and relay node degree is probabilistic in physical layer. This means that the optimal solutions (P_{Ts}, n_{rel}) in $\mathbf{R}$ may not exist or exist with low probability in reality. Moreover, as shown in Figure 5.3, assuming that $(P_{Ts1}, n_{rel1}) \in \mathbf{R}$ can make the PDRsc maximal and the expected energy consumption minimal at the same time, but the value of the probability shown in (5.24) is very low, then if P_{Ts1} is chosen as optimal transmission power, the relay node degree may not n_{rel1} with high probability; so the performance of PDRsc and expected energy consumption will deteriorate. Therefore, we choose the optimal solutions in $\mathbf{R}$ which can make (5.24) get the maximum value as the candidate optimal solutions of (5.29).

As shown in Figure 5.3, if the maximum probability shown in (5.24) that calculated based on the solutions in Pareto optimal solution set is $\mathbf{P}$, then the solutions (P_{Ts}, n_{rel}) are not uniqueness, such as the solutions in the red area of Figure 5.3 have the same probability $\mathbf{P}$. So the optimal transmission power needed to be decided based on the values of PDRsc and expected energy consumption during these solutions. Therefore, we define the optimal feasible solution set as follows.

Definition 5.4. When the maximum probability shown in (5.24) is $\mathbf{P}$ which is calculated based on the solutions in Pareto optimal solution set, then the solutions which can make the probability shown in (5.24) equal to $\mathbf{P}$ are the elements of optimal feasible solution set, noted as $\mathbf{R}^*$. For instance, as shown in Figure 5.3, the solutions in the red area are all the elements of optimal feasible solution set.

According to Definition 5.4, the feasible region has been reduced from Pareto optimal solution set to optimal feasible solution set. The optimal transmission power and relay node degree will be chosen from optimal feasible solution set. Considering the fact that the node performance will be decided by the worst node parameter, which is called the cask theory, so for getting a balanced solution, we propose the balanced optimal solution selection algorithm as follows.

In balanced optimal solution selection algorithm, when the optimal solution is (P_{Ts1}, n_{rel1}) , then the corresponding PDRsc, probability shown in (5.24), and expected energy consumption will be $PTP_i(P_{Tsi}, n_{reli})$, $P_{rmdi}(P_{Tsi}, n_{reli})$, $\mathbb{C}_{si}(P_{Tsi}, n_{reli})$, respectively. For different optimal solutions, these values are different. The optimal feasible solution set is $[(P_{Ts1}, n_{rel1}), (P_{Ts2}, n_{rel2}), \dots, (P_{Tsn}, n_{reln})]$, and the corresponding performance matrix can be expressed as (since the probabilities shown in (5.24) are equal in optimal feasible solution set, so this matrix does not include it): $[(PTP_1, \mathbb{C}_{s1}), (PTP_2, \mathbb{C}_{s2}), \dots, (PTP_m, \mathbb{C}_{sm})]$, where m is the number of solutions in optimal feasible solution set. The variance matrix of PDRsc and expected energy consumption can be expressed as: $v = [v_{PTP}, v_{\mathbb{C}_s}]$. The PDRsc and expected energy consumption which the variance is larger will have greater effect on the optimal solution selection than that of the smaller one.

Since the optimal solutions in Pareto solution set do not have comparability and the probabilities are equal in optima feasible solution set, so the PDRsc and expected energy consumption shown in the performance matrix have properties as follows.

Corollary 5.1. In optimal feasible solution set, if $PTP_i(P_{Tsi}, n_{reli}) > PTP_j(P_{Tsj}, n_{relj})$ or $PTP_i(P_{Tsi}, n_{reli}) < PTP_j(P_{Tsj}, n_{relj})$, then there must exist $\mathbb{C}_{si}(P_{Tsi}, n_{reli}) > \mathbb{C}_{sj}(P_{Tsj}, n_{relj})$ or $\mathbb{C}_{si}(P_{Tsi}, n_{reli}) < \mathbb{C}_{sj}(P_{Tsj}, n_{relj})$, $i, j \in (1, 2, 3, \dots, m)$, respectively; vice versa. Moreover, if $PTP_i(P_{Tsi}, n_{reli}) = PTP_j(P_{Tsj}, n_{relj})$, then there must exist $\mathbb{C}_{si}(P_{Tsi}, n_{reli}) \neq \mathbb{C}_{sj}(P_{Tsj}, n_{relj})$, vice versa.

Proof. As shown in (5.29), the purpose of multi-objective optimization is to get large PDRsc and small expected energy consumption as far as possible. Assuming that (P_{Ts1}, n_{rel1}) and (P_{Ts2}, n_{rel2}) are in optimal feasible solution set, then $P_{rnd1}(P_{Ts1}, n_{rel1})$ equals to $P_{rnd2}(P_{Ts2}, n_{rel2})$. Moreover, since the optimal feasible solution set is a subset of Pareto optimal solution set, so according to Definition 5.3, to $PTP_1(P_{Ts1}, n_{rel1})$, $\mathbb{C}_{s1}(P_{Ts1}, n_{rel1})$, and $P_{rnd1}(P_{Ts1}, n_{rel1})$, at least one of these parameters is better than that of $PTP_2(P_{Ts2}, n_{rel2})$, $\mathbb{C}_{s2}(P_{Ts2}, n_{rel2})$, and $P_{rnd2}(P_{Ts2}, n_{rel2})$; meanwhile, at least one parameter of $PTP_1(P_{Ts1}, n_{rel1})$, $\mathbb{C}_{s1}(P_{Ts1}, n_{rel1})$, and $P_{rnd1}(P_{Ts1}, n_{rel1})$ is worse than that of $PTP_2(P_{Ts2}, n_{rel2})$, $\mathbb{C}_{s2}(P_{Ts2}, n_{rel2})$, and $P_{rnd2}(P_{Ts2}, n_{rel2})$. Since $P_{rnd1}(P_{Ts1}, n_{rel1})$ is equal to $P_{rnd2}(P_{Ts2}, n_{rel2})$, so the conclusion in Corollary 5.1 holds.

According to the conclusion of Corollary 5.1, we can conclude the Corollary 5.2 as follows.

Corollary 5.2. In optimal feasible solution set, the order of PDRsc from large to small is the same as that of the corresponding expected energy consumption.

Proof. The meaning of Corollary 5.2 can be explained as follows: in optimal feasible solution set, when PDRsc is the largest, then the corresponding expected energy consumption is the largest, too; when PDRsc is the second largest, then the corresponding expected energy consumption is the second largest; and so on. For proofing Corollary 5.2, we assume that the second largest PDRsc is $PTP_2(P_{Ts2}, n_{rel2})$ and the corresponding expected energy consumption is $\mathbb{C}_{s2}(P_{Ts2}, n_{rel2})$. If $\mathbb{C}_{s2}(P_{Ts2}, n_{rel2})$ is not the second largest, then according to the properties of Pareto optimal solutions [200], there must exist $PTP_x(P_{Tsx}, n_{relx})$ and $\mathbb{C}_{sx}(P_{Tsx}, n_{relx})$ which satisfy $PTP_2(P_{Ts2}, n_{rel2}) > PTP_x(P_{Tsx}, n_{relx})$ and $\mathbb{C}_{s2}(P_{Ts2}, n_{rel2}) < \mathbb{C}_{sx}(P_{Tsx}, n_{relx})$; this conclusion does not conform the conclusion of Corollary 5.1. So the Corollary 5.2 is proved.

The conclusion of Corollary 5.2 means that in optimal feasible solution set, when PDRsc is large, then the corresponding expected energy consumption is large, too; vice versa. However, our purpose is to find an optimal solution that can make the PDRsc is the largest while the expected energy consumption is the smallest, which is impossible in optimal feasible solution set according to the conclusion of Corollary 5.2. So we need find a tradeoff between PDRsc and expected energy consumption, i.e., the balanced optimal solution.

For getting the balanced optimal solution, based on the conclusion of Corollary 5.2, we choose the intermediate value of PDRsc and corresponding expected energy consumption in optimal feasible solution set as the optimal solution, since these solutions are more balanced than the other solutions in optimal feasible solution set. The intermediate value can be calculated as:

1. when the number of solutions in optimal feasible solution set is odd, then the optimal solution is $\left(P_{Ts\frac{m+1}{2}}, n_{rel\frac{m+1}{2}}\right)$, where m is the number of solutions in optimal feasible solution set;

2. when m is even, two optimal solutions can be gotten: $PTP_{\frac{m}{2}}\left(P_{Ts\frac{m}{2}}, n_{rel\frac{m}{2}}\right)$ and $PTP_{\frac{m+2}{2}}\left(P_{Ts\frac{m+2}{2}}, n_{rel\frac{m+2}{2}}\right)$. According to the fact that the parameter which the variance is larger has greater effect on the optimal solution selection than the smaller parameter, so the parameter which its variance and value are large will be chosen as the optimal solution. For

instance, if $v_{PTP} > v_{\mathbb{C}_s}$ and $PTP_{\frac{m}{2}}(P_{TS\frac{m}{2}}, n_{rel\frac{m}{2}}) > PTP_{\frac{m+2}{2}}(P_{TS\frac{m+2}{2}}, n_{rel\frac{m+2}{2}})$, then $(P_{TS\frac{m}{2}}, n_{rel\frac{m}{2}})$ will be chosen as the optimal solution.

The balanced optimal solution selection algorithm can be found in Algorithm 5.2.

Algorithm 5.2. Balanced optimal solution selection algorithm

1. Calculating the optimal feasible solution set R^* ;
 2. Calculating the v_{PTP} and $v_{\mathbb{C}_s}$ of PDRsc and expected energy consumption in optimal feasible solution set R^* , respectively;
 3. if m is odd
 4. $P \leftarrow P_{TS\frac{m+1}{2}}$ and $n_{rel} \leftarrow n_{rel\frac{m+1}{2}};$
 5. else if m is even
 6. if $v_{PTP} > v_{\mathbb{C}_s}$ and $PTP_{\frac{m}{2}}(P_{TS\frac{m}{2}}, n_{rel\frac{m}{2}}) > PTP_{\frac{m+2}{2}}(P_{TS\frac{m+2}{2}}, n_{rel\frac{m+2}{2}})$
 7. $P \leftarrow P_{TS\frac{m}{2}}$ and $n_{rel} \leftarrow n_{rel\frac{m}{2}};$
 8. else
 9. $P \leftarrow P_{TS\frac{m+2}{2}}$ and $n_{rel} \leftarrow n_{rel\frac{m+2}{2}};$
 10. end if
 11. if $v_{PTP} < v_{\mathbb{C}_s}$ and $\mathbb{C}_{s\frac{m}{2}}(P_{TS\frac{m}{2}}, n_{rel\frac{m}{2}}) > \mathbb{C}_{s\frac{m+2}{2}}(P_{TS\frac{m+2}{2}}, n_{rel\frac{m+2}{2}})$
 12. $P \leftarrow P_{TS\frac{m+2}{2}}$ and $n_{rel} \leftarrow n_{rel\frac{m+2}{2}};$
 13. else
 14. $P \leftarrow P_{TS\frac{m}{2}}$ and $n_{rel} \leftarrow n_{rel\frac{m}{2}};$
 15. end if
 16. end if
-

2. The current transmission power and relay node degree are in Pareto optimal solution set $\mathbf{R}$. In this situation, since the current transmission power and relay node degree are in Pareto optimal solution set $\mathbf{R}$, which are better than the solutions that not in Pareto solution set, so for reducing the control cost, the nodes do not adjust their transmission power.

The reasons that the nodes in this scenario do not adjust their transmission powers are: on one hand, the network topology in wireless sensor network changes frequently due to node mobility or node failure, so the frequent transmission power adjustment will consume large amount of network resource that could have been used by data packet transmission; on the other hand, the current transmission power and relay node degree in Pareto optimal solution set $\mathbf{R}$ means that the current network performance is good. So considering the energy consumption and control cost by controlling the network topology, this tradeoff is worthy.

Based on the conclusions above, the process of transmission power adjustment can be shown as

follows.

Algorithm 5.3. Transmission power adjustment algorithm

1. Source node collects the needed information from neighbor nodes;
 2. Source node calculates the Pareto optimal solution set $\mathbf{R}$ according to these information;
 3. if $(P_{Ts}, n_{rel}) \in \mathbf{R}$
 4. $P \leftarrow P_{Ts}$ and $n_{rel} \leftarrow n_{rel}$;
 5. else if $(P_{Ts}, n_{rel}) \notin \mathbf{R}$
 6. call Algorithm 5.2;
 7. end if
-

5.4. Summary

In this section, for improving the performance of opportunistic routing, we introduce the transmission power control technology into the opportunistic routing to control the number of nodes in the candidate relay set. Then we propose two topology control based opportunistic routing algorithms. For the first algorithm, we propose a probabilistic topology control algorithm to reduce the control cost; the algorithm can control the number of nodes in the candidate relay set based on the packet delivery ratio. For the second algorithm, considering the fact that the transmission power and the relay node degree are related, then we propose that the transmission power and the relay node degree should be jointly; finally, we introduce the Pareto optimal into the algorithm to find the optimal transmission power.

Chapter 6

Theoretical analysis and numerical analysis for the algorithms

In this chapter, we will analyze and evaluate the algorithm proposed in the previous chapters by simulation. Since the proposed routing algorithms and the topology control algorithms are applied in different scenarios, so the simulation parameters will be different in these simulations. In the following of this chapter, we will show the simulation results and the discussion on these simulation results in detail.

6.1 The simulation and analysis for the effectiveness of the SBFL relay node priority algorithm

In this section, we will discuss the properties and the performance of the SBFL algorithm in detail. During the simulation, for more general, we do not specify the cross-layer parameters; we use the random number sequence (from 0 to 1) to represent the value of the cross-layer parameters. In section 6.1.1, we will compare the performance of the SBFL algorithm with the traditional fuzz logic algorithm; in section 6.1.2, we will show the performance of the SBFL algorithm under multiple constraints.

6.1.1 The performance of SBFL algorithm

In this part, we compare the performance of the SBFL with the traditional fuzzy logic algorithm (used in [117] and [204]) on determining the priorities of nodes. Since the traditional fuzzy logic algorithm has limited capability on handling the multiple constraints, so we only consider three parameters for each node in this simulation. These cross-layer parameters are generated by the function *rand()* in MATLAB, which are shown in Table 6.1. In this table, there are five candidate relay nodes, and for each node, three cross-layer parameters are taken into account.

Table 6.1. The cross-layer parameters

	Node 1	Node 2	Node 3	Node 4	Node 5
β_1	0.4505	0.0838	0.229	0.9133	0.1524

β_2	0.602	0.263	0.6541	0.6892	0.7482
β_3	0.8258	0.5383	0.9961	0.0782	0.4427

The results of SBFL algorithm and the traditional fuzzy logic algorithm are shown in Figure 6.1(a) and Figure 6.1(b), respectively. The priorities of the candidate relay nodes calculated by SBFL algorithm are: node 1, node 3, node 5, node 4, and node 2, which is similar to the conclusions that got by traditional fuzzy logic algorithm. This result demonstrates the effectiveness of the SBFL algorithm on determining the priorities of the candidate relay nodes, and the relaying priorities are consistent with the node utilities that shown in Figure 6.1(a). For instance, as the utilities shown in Figure 6.1(a), node 1 is the largest, node 3 and node 5 are alike and they are the medium.

Figure 6.1. (a) The result of the SBFL; (b) The result of the traditional fuzzy logic based routing algorithm (the algorithm used in [117] and [204]).

In Figure 6.1(b), the utility of node 4 is large than node 5; however, as shown in Figure 6.1(a), the utility of node 5 that calculated by SBFL algorithm is larger than that of node 4. Considering the parameters value of these two nodes, the β_2 and β_3 in node 5 are all better than that in node 4, so we can conclude that priority of node 5 should be higher than that of node 4. On this point, the Figure 6.1(a) and Figure 6.1(b) prove that the SBFL algorithm can get a more effective result than that of the traditional fuzzy logic algorithm.

The Figure 6.1 indicates that the SBFL algorithm is more efficient than the traditional fuzzy logic algorithm. Moreover, considering the number of the fuzzy if-then rules, i.e., the computation complexity, the SBFL algorithm has greater advantage than the traditional fuzzy logic algorithm. As shown in Figure 6, in the traditional fuzzy based routing algorithm, the number of if-then rules increases sharply with the increases of the linguistic variables and the number of cross-layer parameters; moreover, this increasing is exponential. On the contrary, in the BCFL, the number of fuzzy rules will keep constant when the cross-layer parameters increase (Figure 6.2(a)), and even when the linguistic variables increase, the growing of the fuzzy if-then rules is linear (Figure 6.2(b)), which is much less compare to the traditional fuzzy logic algorithm.

Figure 6.2. The number of rules: (a) the number of linguistic variables is fixed; (b) the number of fuzzy set is fixed.

The Figure 6.2(a) and Figure 6.2(b) demonstrate that the traditional fuzzy logic algorithm cannot handle multiple constraints. If the number of cross-layer parameters is large, the number of if-then rules will become too large to be accepted. Moreover, the number of linguistic variables has great effect on the fuzzy inference system performance; the more linguistic variables, the accuracy of the result is. For this point of view, the SBFL can increase the number of linguistic variables and reduce the complexity of the algorithm greatly; more importantly, the rules of the new algorithm are clear and fixed which makes it easy to design and accuracy.

6.1.2 A multiple constraints example for SBFL algorithm

The performance of the SBFL algorithm under multiple constraints is shown in this section. From this scenario, we can find the great advantage of the SBFL algorithm more directly. In this simulation, we consider 5 nodes as the candidate relay nodes and 7 cross-layer parameters for each node. So the cross-layer parameter matrix is a 5×7 matrix. This matrix is generated by the function *rand()* in MATLAB. The parameters are shown in Table 6.2 and the result of this scenario is shown in Figure 6.3.

Table 6.2. The cross-layer parameters of multiple constraints

	β_1	β_2	β_3	β_4	β_5	β_6	β_7
Node 1	0.0451	0.2238	0.2751	0.6273	0.571	0.8131	0.9861
Node 2	0.7232	0.3736	0.2486	0.0216	0.1769	0.3833	0.0300
Node 3	0.3474	0.0875	0.4516	0.9106	0.9574	0.6173	0.5357
Node 4	0.6606	0.6401	0.2277	0.8006	0.2653	0.5755	0.0871
Node 5	0.3839	0.1806	0.8044	0.7458	0.9246	0.5301	0.8021

Figure 6.3. The result of the BCFL under multiple constraints

From Figure 6.3, we can find that node 5 has the best performance among all the candidate nodes; because as shown in Table 6.2, the cross-layer parameters of node 5 are more balanced than that of other nodes. From the line graph of utility in Figure 6.3, we can conclude that the performance of node 3 is better than node 1, node 1 has the better performance than node 4, and the performance of node 2 is the worst in these nodes. The simulation result is consistent with the character of the cross-layer parameters in different nodes, which is shown in the histogram of Figure 6.3. The Table 6.2 indicates that the parameters of node 5 are not always the highest one among all the nodes.

In this scenario, as the number of cross-layer parameter is 7, so for the traditional fuzzy logic based routing algorithm, when there are 7 parameters in the system, the number of if-then rules is 2187 (assume that the number of linguistic variables is 3), which is unacceptable. However, for the SBFL algorithm, the number of if-then rules is constant and the same with the number of the linguistic variables (in SBFL algorithm, the number of if-then rules is 7), which is much more simple than the traditional fuzzy logic algorithm. This example also illustrates the huge advantage of the SBFL algorithm.

6.2 The simulation and analysis for the DDA algorithm

In this section, we will evaluate the performance of DDA candidate relay node filter algorithm. We compare the performance of DDA with ExOR [7] and SOAR [17], respectively. The variation parameters are the number of nodes and the number of CBR connections. The number of CBR connections represents the traffic load of the network. The parameters of the simulation environments are shown in Table 6.3.

TALBE 6.3. SIMULATION PARAMETERS

simulation parameter	value
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simulation area	2000m×2000m
number of vehicles	100, 150,..., 300
transmission range	250m
channel data rate	1Mbps
the traffic type	Constant Bit Rate (CBR)
number of CBR connections	20, 40,..., 100
packet size	512bytes
beacon interval	1s
maximum packet queue length	50 packets
MAC layer	IEEE 802.11 DCF
simulation tool	NS2

The algorithms used in this simulation are ExOR, SOAR, and DDA. The introduction of ExOR and SOAR can be found in [7] and [17], respectively. The DDA is the algorithms that proposed in this paper, the detail of DDA can be found in Section IV and Section V.

The performance matrixes are the transmission delay, the packet delivery ratio between sender and the candidate set, and the network throughput: (1) *End-to-End Packet delivery ratio*: the packet delivery ratio is defined as the ratio of the number of packets received successfully by the destination node to the number of packets generated by the source node [149][205]; (2) *End-to-End delay*: the transmission delay of the data packet from the source node to the destination node; (3) *Network throughput*: the network throughput is the ratio of the total number of packets received successfully by the destination node to the number of packets sent by all the nodes during the simulation time [206].

6.2.1. Performance under different network density

In this section, we evaluate the performance of DDA, SOAR, and ExOR under different network density, i.e. the number of nodes in the network varies. In this simulation, the network load is constant, which means that the number of the CBR connections is set to 60. The results can be found in Figure 6.4, Figure 6.5, and Figure 6.6.

In Figure 6.4, the average end to end delays of these three algorithms are presented. In these three algorithms, with the increasing of the number of nodes in the network, the average end to end delay decreases both in these three algorithms. The fewer nodes in the network, the larger decrease is. For instance, in DDA, when the number of nodes in the network increases from 100 to 150, the delay decreases from 780ms to 602ms; however, when the number of nodes increases from 250 to 300, the delay decreases from 520ms to 500ms. The similar conclusion can be found in SOAR and ExOR. This can be explained as: when the number of node increases, the probability of network portion decreases, so the delay will decrease when the network density increases; when the network density is large enough, then the probability of network portion is quite low, so the decreasing of the transmission delay is slow. Moreover, for the same network density, the end to end delay of DDA is much smaller than that of the other two algorithms. This is because in DDA, the relay nodes are fully connected and the relay network which the delay is the small has high priority to be chosen, so the end to end delay in DDA is the smallest in these three algorithms.

In Figure 6.5, the packet delivery ratios of these three algorithms are illustrated. With the

increase of the network density, the packet delivery ratios of these three algorithms increase; the packet delivery ratio of DDA is the largest in these three algorithms. Since with the increase of the network density, for the sender, more relaying nodes can be found in its transmission range, so according to the calculation in (2), the network packet delivery ratio will increase. Since in DDA, the packet delivery ratio is taken into account during the relaying network selection, so the packet delivery ratio of DDA is the largest. In Figure 6.5, when the network density is large enough, this increase becomes slowly; this is due to when the network density is large enough, the number of candidate relaying nodes is large, so there always exists at least one node can receive the data packet and send it to the destination node, which makes the increasing slow. The network throughputs of these three algorithms are presented in Figure 6.6. From Figure 6.6, we can conclude that when the network density increases, the network throughput keeps constant approximately; these values fluctuate in a very small range. For instance, the variation range of DDA is 0.03 approximately and is about 0.02 in SOAR. On one hand, when the network density is small, the packet delivery ratio is small which can be found in Figure 6.5, then the probability of retransmission is high; however, the number of hops to the destination is small when the network density is small, which contributes to the number of control packet reduction. On the other hand, when the network density is large, the packet delivery ratio increases; however, the average number of hops to the destination node increases, which causes the number of control packets increasing. So the network throughput keeps stable in these algorithms; moreover, the network throughput of DDA is the best in these three algorithms.

Figure 6.4. The average end to end delay under different network densities.

Figure 6.5. The packet delivery ratio under different network densities.

Figure 6.6. The network throughput under different network densities.

6.2.2. Performance under different traffic load

In this section, the performance of these three algorithms under different number of CBR connections is presented. In this simulation, the number of nodes in the network is 200 and the number of CBR connections varies. The results can be found in Figure 6.7, Figure 6.8, and Figure 6.9.

In Figure 6.7, the average end to end delays of these three algorithms are shown. The results of the end to end delay under different traffic load are different with that of under different network densities. With the increase of the number of CBR connections, the end to end delay is the smallest when the number of CBR connections is 100; the delay decreases when the number of CBR connections smaller than that and increases when the number of CBR connections larger than that. This is because with the traffic load increase, when the number of CBR connections is not large enough (for instance, smaller than 100), the network resources are far from saturated, so when the traffic load increases, the end to end delay decreases; however, when the number of CBR connection is large enough, the network becomes saturated or over-saturated, so the network contend becomes more and more serious, which will deteriorate the performance of the algorithms.

When the traffic load increases, the packet delivery ratios of these three algorithms decrease, which can be found in Figure 6.8. The reason of the packet delivery ratios decreasing is because when the number of CBR connections increases, the network contend becomes more and more serious. Moreover, similar to the Figure 6.7, when the number of CBR connections is small, this decreasing is slow; however, when the number of CBR connections is large, this decreasing is fast. This is because when the number of CBR connections is small, the network resources, such as the buffer of each node, are not saturated, so even the network contend and the network interference increase, the decreasing of the packet delivery ratio is slow. However, when the network resource is saturated or over-saturated, the network interference and the network contend increase, so the decreasing of the packet delivery ratio becomes more and more serious.

The network throughput of these three algorithms under different number of CBR connections is shown in Figure 6.9. Different with that shown in Figure 6.6, the network throughput shown in Figure 6.9 decreases when the network traffic load increases; however, the decreasing of these three algorithms is slight. The decreasing of the network throughput can be explained by Figure 6.7 and Figure 6.8, when the number of CBR connections increases, on one hand, the end to end delay decreases at first and increases after the inflection point (i.e., 100); on the other hand, when the traffic load increases, the packet delivery ratio decreases; additionally, when the traffic load increases, the network interference, the network contend, and the channel occupation ratio increase seriously, so the network throughput decreases. However, as that shown in Figure 6.9, the decreasing of ExOR and SOAR is much faster than that of DDA; moreover, the network throughput of DDA is the largest in these three algorithms. This is because the duplication transmission in the time-based coordination scheme is reduced as much as possible in DDA, which contributes to the increasing of the network throughput.

Figure 6.7. The average end to end delay under different traffic loads.

Figure 6.8. The packet delivery ratio under different traffic loads.

Figure 6.9. The network throughput under different traffic loads.

6.3 The simulation and analysis of the fuzzy logic based cross layer relay node priority algorithm for opportunistic routing in underwater mobile ad hoc network

In this section, we will evaluate the performance of SBFL based relay node priority algorithm for opportunistic routing algorithm in underwater environment, and compare the result with the ExOR algorithm. The performance matrix are the residual energy, the link lifetime, the node distance to the destination node, the link's ETX [7], the packet queue length, and the transmission delay. The simulation tool is DESERT [207].

Table 6.4. Simulation configuration

parameters	value
Simulation area	3000m×3000m
Number of Nodes	30, 50, 70, 90, 110
Depth	20 m
Water temperature (July)	12° c
Water salinity (July)	18 g/L
Sound speed (July)	1475 m/s
Initial transmission range	1000m
Transducer beam pattern	Horizontally Omni-directional
Data rate	3 kbit/s

Bit error ratio	10^{-10}
Receive power	1.3 W
Transmission power	2.8 W
Channel model	Multi-path + <i>Doppler</i> spreading
Carrier	Sweep spread carrier (S2C)

Figure 6.10. The result of the SBFL relay node selection algorithm.

Different with the conclusions shown in Figure 6.3, the Figure 6.10 shows the result of relay nodes selection (in this simulation, we choose node20 as the source node) in the real opportunistic routing algorithm for the underwater scenario. The node2, node10, node18, node22, node34, node 35, node42, node49, node50 are the relay nodes of node20 and the distances to the destination node are all smaller than that of node20 (the destination node is node37). From Figure 6.10, we can find that the utilities of the SBFL based relay node priority algorithm and the ExOR algorithm are totally different. Based on the SBFL algorithm, the priority of the relay nodes is: *node34*→*node50*→*node49*→*node35*→*node10*→*node42*→*node22*→*node2*→*node18*; however, to the ExOR algorithm, this is: *node2*→*node34*→*node22*→*node49*→*node35*→*node50*→*node42*→*node10*→*node18*, which is the same order as the values of ETX.

As shown in Figure 6.10, in SBFL based relay node priority algorithm, the first priority relay node is node34; however, in ExOR, the first one is node2. Actually, according the parameters shown in Figure 6.10, the residual energy, the link lifetime, the distance to the destination node, and the transmission delay in node34 are all much better than that in node2. In node2, only the ETX and the queue length are slightly better than node34; so the node2 is not the most feasible candidate relay node, since the parameters performance is not balanced. The rest of the nodes in the relay node list of the ExOR algorithm have the same disadvantage compared with the SBFL based relay node priority algorithm. For instance, the node50 in the SBFL based algorithm is the second priority, but in ExOR algorithm, it is only the sixth one, even worse than node22 which the comprehensive utility is obviously worse than node50.

Figure 6.11. The network lifetime under different network scale.

Figure 6.12. The network lifetime under different average node speed.

In Figure 6.10, according to the SBFL based algorithm, not all the cross-layer parameters in node34 are the best compare to the other nodes, such as the distance to the destination node, the link lifetime, the residual energy, the node delay, etc.; however, the aggregate utility of node34 is the most balanced one among the relay nodes. For instance, in Figure 6.10, the parameters which the scatters are large are the ETX, the queue length, and the residual link lifetime (as we know, the network performance is effected greatly by these parameters); moreover, these three parameters in node34 are all better than that in node50, so the aggregate utility will be better in node34 than that in node50. The similar results can be found in the other nodes, such as the node34 and node49, etc. The priorities of the rest relay nodes are got by obeying the same principle.

In Figure 6.11, we show the network lifetime under different network scale. In this simulation, based on [208], we assume that the network lifetime is the time when the first node dead in the network. Figure 6.11 illustrates that when the network scale is small, the network lifetimes of both the SBFL based algorithm and the ExOR algorithm are all small; the network lifetime of the SBFL based algorithm is slightly larger than that of the ExOR algorithm. With the increasing of the node number, both the network lifetimes in these two algorithms increase. However, the network lifetime increases faster in the SBFL based algorithm than that in the ExOR algorithm. When the node number is 110, the lifetime of the SBFL based algorithm is nearly double of that in the ExOR algorithm. Moreover, with the increasing of the network scale, this advantage will more and more obviously, as shown in the line graph of Figure 6.11. The reason why the network lifetime increasing ratio of the SBFL based algorithm is larger than that in the ExOR algorithm can be explained as: in the SBFL based algorithm, since the network performance is balanced, the dilemma that one feasible relay node is used again and again in ExOR algorithm can be avoided; therefore, the network lifetime will longer than that in ExOR algorithm. Moreover, the more nodes in the network, the more choice of the relay nodes, so with the increasing of the node scale, both the lifetime in the SBFL based algorithm and the ExOR algorithm increase; but due to the performance is more balanced in SBFL based algorithm than that in ExOR, the network lifetime increase much faster than ExOR.

In Figure 6.12, with the increasing of the average speed, the network lifetime increases both in SBFL based algorithm and ExOR algorithm; however, this increasing is slightly. In addition, when the speed is fast enough, the increasing ratio is smaller than that when the speed is slow.

The increasing ratio in ExOR algorithm is larger than that in SBFL based algorithm. This is because the ExOR algorithm cannot balance the network load, when the nodes move, the network load is balanced to some extent, so the network lifetime increases; however, the SBFL based algorithm can avoid unbalanced network load, even the node mobile can contribute to equilibrium the network load, this effective is limited. This also demonstrates that the SBFL based algorithm has much more advantages than the ExOR algorithm on balancing the network performance, since the SBFL based algorithm can choose the relay node set based on different cross-layer parameters dynamically.

In Figure 6.13, with the increasing of the operating time, the network throughputs both in the SBFL based algorithm and the ExOR algorithm increase. The increasing trends are similar to the network lifetimes shown in Figure 6.11. With the increasing of the operating time, the network throughput increases faster in SBFL based algorithm than that in ExOR algorithm. This demonstrates that with the increasing of the network operating time, the advantage of the SBFL based algorithm is more and more obviously than the ExOR algorithm. The network throughput increases slowly in ExOR algorithm due to the network lifetime performance in ExOR algorithm; with the increasing of the operating time, more and more nodes dead in ExOR algorithm and this number is much larger than that in SBFL based algorithm; therefore, the network throughput increasing ratio is more and more small with the increasing of the operating time. In contrast, since the network lifetime in the SBFL based algorithm is much longer than that in the ExOR algorithm, so when the operating time increases, there are few node dead; that is why the throughput increases quickly than the traditional opportunistic routing algorithm.

Figure 6.13. The network throughput under different operation time.

6.4 The simulation of the probability prediction based opportunistic routing for VANETs

In this section, for evaluating the performance of the PRO algorithm, we compare it with GPSR, ExOR, and SRPE. Since the performance comparison between GPSR, ExOR, and SRPE has been done by [149] and [205], so for getting fair results, the network configuration in this simulation is similar to that shown in [49] and [205]. The simulation parameters can be found in Table 6.5.

Table 6.5. Simulation Parameter

simulation parameter	value
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simulation area	2000m×2000m
number of vehicles	100, 150,..., 300
network density ¹	0.05, 0.075, 0.1, 0.125, 0.15
transmission range	250m
channel data rate	2Mbps
the traffic type	Constant Bit Rate (CBR)
number of CBR connection pairs	20, 40,..., 100
packet size	512bytes
minimum velocity	30km/h
maximum velocity	60km/h
beacon interval	1s
maximum packet queue length	50 packets
propagation model	Nakagami- <i>m</i> model [170]
MAC layer	IEEE 802.11p
simulation tool	NS2

The varying parameters during the simulation are the number of vehicles per meter in the street and the number of CBR connection pairs [149][163][205]. During the simulation, the performance matrixes used are also packet delivery ratio, end-to-end delay, and network throughput; the definitions of these performance metrics have been introduced in Section 6.2. The routing algorithms evaluated in this section are: GPSR routing algorithm [209], ExOR (street-centric) routing algorithm (street-centric ExOR can be explained as the opportunistic routing in which the basic unit is the sub-network rather than the single vehicle) [163][205], SRPE routing algorithm [149], and PRO algorithm.

6.4.1. Performance under different node density

In this section, the effect of different network densities on the routing performance will be evaluated. The number of CBR connection in this section is set to 20 and the data generation rate is 1 packet per second². The results of the routing performance can be found in Figure 6.14, Figure 6.15, and Figure 6.16.

Figure 6.14 illustrates the performance of the packet delivery ratio of these four routing algorithms under different network densities. With the increase of the network density, the packet delivery ratio increases both in these four algorithms. This is due to the fewer vehicles in the network, the higher probability of network partition is, which means the communication links between different vehicles are easy to break; therefore, the packet delivery ratio is low when the network is sparse. When the network density increases, at the beginning, the packet delivery ratio increases fast. However, when the network density is large enough, the increasing becomes slow. For instance, when the network density is 0.075, the packet delivery ratio increases greatly compared with that when the network density is 0.05; however, when the

¹ In this simulation, we use the number of vehicles per meter in the street to represent the network density.

² Note that this rate relates to the beacon interval. Considering the energy consumption and the accuracy of the algorithm, the difference between the data generate rate and $1/\text{beacon interval}$ should not be too large. The exact relation between these two parameters will be investigated in our further work.

network density is 0.15, this increasing is small compared with that when the network density is 0.125. The reasons can be explained as: 1) when the network is sparse, the probability of network partition is high, this probability reduces with the increasing of the network density; however, when the network density is large enough, the network will fully connect, then even the network density increases, the effect of vehicle number on the packet delivery ratio is slight; 2) with the increasing of the network density, the network interference and competition become more serious than that in the sparse network, which also limits the further routing performance improvement. Moreover, in Figure 6.14, the packet delivery ratio variation of GPSR, ExOR, and SRPE are larger than that of PRO algorithm. This is easy to be understood. Because the SINR and packet queue length are taken into account in PRO algorithm when determining the candidate set, so the packet delivery ratio in PRO algorithm is better than the other three algorithms; for instance, the packet delivery ratio in PRO algorithm is about 20% higher than SRPE when the network density is 0.05.

Not only the packet delivery ratio, but also the performance of end-to-end delay in PRO algorithm is better than the other three algorithms, which can be found in Figure 6.15. In Figure 6.15, when the network density is 100, the end-to-end delay of PRO algorithm is 3s; however, this value is 7s in SRPE algorithm and is 9s in GPSR algorithm, respectively. This can be explained by the performance of packet delivery ratio which is shown in Figure 6.14. The high packet delivery ratio means low probability of retransmission and packet loss, which also contributes to reduce the end-to-end transmission delay. When the number of vehicles in the network increases, more transmission links can be chosen when send data packet to the same vehicle. So with the increasing of the network density, the end-to-end delay in these four algorithms reduces. Moreover, similar to the packet delivery ratio, when the network density is small, this reducing is obviously; with the increase of the network density, this reducing becomes slow. For instance, when the network density increases from 0.05 to 0.075, the decreasing of the end-to-end delay is 3s in SRPE algorithm and is 2s in PRO algorithm, respectively; however, this decreasing is near to 0 in SRPE algorithm and PRO algorithm when the network density increases from 0.125 to 0.15. This is because when the node density is small, the network partition is serious; so once the number of vehicles increases, the end-to-end delay will be reduced greatly. However, when the network density is large enough, the network partition will not be the determinant parameter of the end-to-end delay, the network interference and competition will affect the routing performance seriously; therefore, even the network density increases, the performance of end-to-end delay is not improved prominent.

Figure 6.14. Packet delivery ratio under different network densities

Figure 6.15. End-to-End delay under different number of vehicles

Figure 6.16. Network throughput under different number of vehicles

The excellent performance of packet delivery ratio and end-to-end delay in PRO algorithm also contributes to the performance improvement of network throughput, which can be found in Figure 6.16. In Figure 6.16, the network throughput of the PRO algorithm is much better than that of the other three algorithms. For instance, the network throughput of PRO algorithm is about 18% higher than that of SRPE algorithm. Moreover, the network throughputs of these four algorithms are all stable. The reasons are: 1) when the network density increases, the probability of network partition decreases, so the network throughput increases; 2) when the network density increases, on one hand, the transmission hops to the destination vehicles increase, which reduces the network throughput; on the other hand, when the network density increases, the network interference and competition increase, which also reduces the performance of network throughput. When the number of vehicle is small, the first reason is the leading role; when the network density is large, the second reason has the main effect on the routing performance; so the network throughput is stable.

6.4.2. Performance under different traffic load

In this section, we will evaluate the performance of these four routing algorithms under different number of CBR connection pairs. The number of vehicles in the network is 200 and the data generation rate is 1 packet per second. As shown in [149], [210], and [205], the different number of CBR connection pairs represent different traffic load. The results have been shown in Figure 6.17, Figure 6.18, and Figure 6.19.

In Figure 6.17, the packet delivery ratios of these four routing algorithms under different number of CBR connection pairs have been demonstrated. With the increase of the number of CBR connection pairs, the packet delivery ratios of these four algorithms decrease. When the number of CBR connection pairs is smaller than 60, the decreasing is slow (this number is 40 in GPSR algorithm); however, the decreasing is stable in PRO algorithm. This is due to two reasons: 1) when the traffic load increases, the network interference and competition increase, which causes the increasing of the packet loss and retransmission; so the packet delivery ratio deteriorates; 2) with the increasing of the traffic load, the probability of buffer overflow increases, which causes high probability of packet loss. However, due to the PRO routing algorithm takes the SINR and PQL into account during the routing decision, so on one hand, the performance of packet delivery ratio is much better than the other three routing algorithms; for

instance, the packet delivery ratio in PRO algorithm is about 13% higher than that in SRPE algorithm when the number of CBR connection pairs is 100; on the other hand, the decreasing of the packet delivery ratio is stable in PRO algorithm; this is different with the other three routing algorithms which have sharply inflection points (60 in ExOR and SRPE, 40 in GPSR). The SINR and the packet queue length can not only affect the packet delivery ratio, but also the end-to-end delay. As shown in Figure 6.18, with the increasing of the traffic load, the end-to-end delay decreases when the number of CBR connection pairs is smaller than 60, and increase when this number is larger than 60. The effect of the traffic load on end-to-end delay is different with that of the packet delivery ratio (which is shown in Figure 6.15). This can be explained as follows: when the traffic load is light, on one hand, the network interference and the probability of buffer overflow are small; on the other hand, even these parameters increase with the increasing of the traffic load, the network capability is far away from the saturation state; so the end-to-end delay will decrease. When the traffic load is large enough (number of CBR connection pairs is larger than 60), the network interference and the probability of buffer overflow increase, so the network capability will close to saturation or over-saturated, which increases the end-to-end delay. This also can be found in Figure 6.17. In Figure 6.17, when the number of vehicles is less than 60, the decreasing of the packet delivery ratio is slight, so considering the increasing of the traffic load, the end-to-end delay decreases; similarly, when the number of CBR connection pairs is larger than 60, the decreasing of the packet delivery ratio is sharp, which contributes to the increasing of the end-to-end delay. Actually, the results shown in Figure 6.18 also can be used to explain the conclusion in Figure 6.17. Moreover, since the PRO routing algorithm takes the SINR and the packet queue length into account, so the performance of end-to-end delay is better and more stable than the other three routing algorithms. For instance, the end-to-end delay in PRO algorithm is about 1s less than that in SRPE algorithm; the variation of the end-to-end delay in PRO algorithm is less than 0.2s, which is about 1s in GPSR algorithm.

The network throughputs under different traffic load are shown in Figure 6.19. Due to the excellent performance of packet delivery ratio and end-to-end delay, the network throughput of PRO routing algorithm is much better than that of the other three routing algorithms. With the increasing of the traffic load, the network throughputs of these four routing algorithm decrease. This is because the increasing of the network interference; moreover, the packet queue length is large when the network traffic load is heavy. But since the PRO routing algorithm takes the network interference and the packet queue length into account during the routing decision, so the decreasing of the network throughput in PRO algorithm is slight and the performance of network throughput is stable.

Figure 6.17. Packet delivery ratio under different number of CBR connection pairs

Figure 6.18. End-to-End delay under different number of CBR connection pairs

Figure 6.19. Network throughput under different number of CBR connection pairs

6.5 The simulation about the relationship between energy efficient and interference optimal

In Chapter 5, we investigate the probability based interference analysis model and explore the properties of this model in detail. In this section, we evaluate the performance of this probability based analysis model by simulation.

6.5.1 Homogenous node deployment probability analysis model

The probability density function (shown in (4.18)) can be found in Figure 6.20. The Figure 6.20 indicates that the distribution of the neighbor node distance is Rayleigh Distribution. In Figure 6.20, with the increasing of the node density, the maximal probability increases while the maximal neighbor distance decreases. The reason is that when the node density increases, more and more nodes are deployed in the area, so the distance between nodes decreases. As shown in Figure 6.20, when the node density is 0.1, the maximum neighbor node distance is approximately 5; when the node density is 0.01 and 0.005, the values are approximately 15 and 20, respectively. The similar variation trend can be found in the changing of the neighbor node distances which have the maximal probability.

Figure 6.20. The probability density function of (4.18)

In (4.20), we show the probability function of interference optimal by adjusting the transmission range in homogenous wireless sensor network. From (4.20), we can conclude that the probability relevant to both the original node transmission range and the node density. The result of simulation can be found in Figure 6.21.

Figure 6.21. The probability under different node density

Figure 6.22. The probability under different transmission range in homogeneous network

In Figure 6.21, the node density varies from 0.005 to 0.1, and the original transmission ranges vary from 0 to 25. With the increasing of the original transmission ranges, the probabilities of interference optimal will increase to 1 when the original transmission ranges are larger than maximal neighbor node distances which shown in Figure 6.20. For instance, when the node density is 0.1, with the increase of the original transmission range, the probability increases when the transmission range is smaller than 5. When the transmission range is larger than 5, the probability will level off to 1. The same variation trend can be found when the node densities are 0.01 and 0.005. The trend in Figure 6.21 is consistent with the result in Figure 6.20. In Figure 6.20, when the node density is 0.1, the maximum neighbor node distance is 5 (when the probability is equal to 0 in Figure 6.20). Meanwhile, in Figure 6.21, when the node density is 0.1 and the transmission range is 5, the probability of interference optimal when applying the topology control algorithm is level off to 1. The reason is that under the specific node density, when the original transmission range is larger than the maximum neighbor node distance, then

if the transmission ranges are reduced, we can find interference optimal transmission range with probability 1.

Under different node densities, the probabilities of interference optimal when adjusting the transmission range have great difference. As shown in Figure 6.21, when the node density increases, the probability of interference optimal will increase under the same original transmission range. For instance, when the original transmission range is 10, the probability of interference optimal is 0.85 when the node density is 0.01; however, when the node density is 0.005 and 0.1, the probabilities are 0.51 and 1, respectively. In addition, the best original transmission ranges under different node density are equal to the maximum neighbor node distance shown in Figure 6.20.

Figure 6.22 describes the probability of interference optimal under different transmission range, in which the original transmission range is fixed. In Figure 6.22, the node density is 0.01, and the original transmission range is 10. From Figure 6.22, we can find that the maximum probability is approximately 0.83 when the transmission range is $0.85r$. Therefore, the best transmission range after the transmission range adjustment is $0.85r$. This conclusion means that when the transmission range is $0.85r$, the probability that the network is interference optimal is the highest. This conclusion is consistent with the theoretical analysis in Section 4.1.

6.5.2 Heterogeneous node deployment probability analysis model

Similar with the homogenous wireless sensor network, the probabilities of the interference optimal in heterogeneous network are shown in Figure 6.23 and Figure 6.24.

Figure 6.23. The probability under different node density and original transmission range in heterogeneous network

Figure 6.24. The probability under different transmission range in heterogeneous network

Figure 6.23 and Figure 6.24 indicate that the probabilities in the heterogeneous network are similar with that in the homogeneous network. The differences are the value of the probabilities and the best transmission range. Both in Figure 6.21 and Figure 6.23, the minimum original transmission ranges are consistence with the maximal neighbor node distances shown in Figure 6.20. The differences are due to the different boundary conditions in heterogeneous network and homogeneous network, which can be found in (4.16), (4.34), Figure 4.7, and Figure 4.12. Since the feasible region in heterogeneous network is larger than that in the homogeneous network, the probability of interference optimal also larger than the homogeneous network. For instance, in Figure 6.23, when the node density is 0.01 and the original transmission range is 10,

the probability of interference optimal is 0.897; while in Figure 6.21, under the same conditions, this probability will be 0.862, which is smaller than that in Figure 6.23. The same conclusion can be got when the node density and the original transmission range are changed.

Similar with the homogenous network, in Figure 6.24, with the increasing of the transmission range, the probability increases from 0 to 0.82 and reaches the maximum value when the transmission range is $0.84r$; the probability will decrease when the transmission range is larger than $0.84r$. Therefore, the maximum probability is 0.82 with the best transmission range is $0.84r$. This conclusion is interesting, since the maximal probability of interference optimal and the best transmission range are similar in homogenous wireless sensor network and heterogeneous wireless sensor network.

6.5.3 The relationship between the interference optimal and energy efficient

In this section, we will evaluate the relationship between the interference optimal and the energy efficient. According the conclusion in Section 4.1.5, in heterogeneous network, when the network is interference optimal, the network is also energy efficient with probability 1, approximately. Therefore, in this part, we mainly investigate the probability that the network is energy efficient and interference optimal in homogeneous network, which has been analyzed in Section 4.1.5.

According (4.51) and (4.52), the maximum and minimum probability that the network cannot meet the requirements of interference optimal and energy efficient simultaneous can be found in Figure 6.25. In Figure 6.25, the node density is 0.01.

Figure 6.25. The probability of the network cannot meet the requirements of interference optimal and energy efficient

From Figure 6.25, we can conclude that when the node density is 0.01, if the network is energy efficient, the maximum probability that the network is not interference optimal is approximately 0.028, and the minimum probability is only 0.0016, which are quite small. Therefore, as discussed in Section 4.1.5, when the network is energy efficient, then the network is interference optimal both in the homogeneous and heterogeneous wireless sensor network.

6.6 The Simulation and analysis of the ERTC algorithm

In this section, we will evaluate the performance of ERTC and discuss the properties in detail. The ERTC is introduced in Section 4.2. ERTC is transmission power adjustment based topology control algorithm; we compare the performance of ERTC with LMA and LMN in this

paper. The reasons why the LMA and LMN are chosen as the contrasts are: (1) the ERTC is most similar to LMA and LMN and can be regarded as the extensional of LMN and LMA based on the theory analysis in Section 4.1; (2) LMN and LMA are the two typical and basic power adjustment based topology control algorithms. As a contrast, we use NONE (in which there is no topology control algorithm used) as the control group.

The topology control algorithms that will be simulated in this section are as follows.

- NONE: without using topology control algorithm, i.e., forming the network topology randomly and do not control the network topology artificially.
- LMA: in LMA, there are two node degree thresholds: the minimum threshold and maximum threshold. If the node degree is smaller than the minimum threshold, the node will increase the transmission range by certain factor A_{inc} ; otherwise, reducing the transmission ranges by A_{dec} . The nodes in which the node degrees are between the minimum threshold and the maximum threshold will not change their transmission ranges.
- LMN: in LMN, each node collects the neighbor information from their neighbors, and calculates the average neighbors' node degree. The value will be set as the node degree threshold. If the node degree is large than this threshold, the transmission range will be reduced; otherwise, it will be increased.

6.6.1. The Properties and performance of ERTC Algorithm

In this section, the performance and properties of ERTC will be discussed in detail. The simulation parameters are presented as follows: (1) the node number: 50-200; (2) distribution range: $1\text{km} \times 1\text{km}$; (3) initial transmission range: 0-200m; (4) distance-power gradient: $\alpha = 3$; (4) simulation time: 3000s; (5) initial energy supply: 100J; (6) transmit power: 0-1mW; (7) receive power: 0.5mW; (8) transmission rate: 10kbit/s.

In Figure 6.26, the network is formed randomly (Figure 6.26(a)) and by the ERTC (Figure 6.26(b)), respectively. From Figure 6.26, we can clearly find that the ERTC reduces the number of communication links of the original network and guarantees the network connection at the same time. The communication links in Figure 6.26(b) are less than that in Figure 6.26(a), which means that after using the ERTC, the energy consumption will be reduced. The node degree in Figure 6.26(b) is obviously smaller than that in Figure 6.26(a); the conclusion can be found in Figure 6.27, too.

Figure 6.26. The simulation result: (a) NONE; and (b) ERTC. * The X-axis and Y-axis means the node distribution area.

Figure 6.27. The relationship between node number and node degree.

Figure 6.27 shows the node degree of the original network and the network which uses the ERTC. From Figure 6.27, we can conclude that with the increasing of the node number, the overall trend of node degree is increasing. However, the node degree does not always increase with the rising of the node number, e.g., as shown in Figure 6.27, when the node number is 100, 105, 110, and 120, the node degree does not keep increasing when the node number rises. The reason is that the network is created randomly, so the node degree oscillates near the average node degree; however, the overall trend is increasing. The increasing trend in ERTC is similar with the original one, but node degrees are smaller than that. In addition, when the node number is large than 100, the increasing rate of the original network is faster than that in ERTC. Furthermore, as shown by the blue points in Figure 6.27, with the increasing of the node number, the increasing trends are different between the original network and ERTC. The reason of this issue will be explained in the next section. Moreover, in Figure 6.27, the node degree in ERTC is larger than the minimum node degree threshold, so the network connection can be guaranteed. This is consistent with the conclusion in Figure 6.26(b).

Figure 6.28 shows the numbers of nodes that use different transmission range adjustment strategies (introduced in Section 4.2) to adjust the transmission range. Since the number of nodes which use the rule (i) is pretty huge, so in Figure 6.28, we show the logarithm value of this number. In Figure 6.28, with the increasing of the node number, the nodes which use the rule (i) to adjust their transmission range has the similar increasing trend with the average node degree shown in Figure 6.27. Additionally, in Figure 6.28, the number of nodes use rule (i) is huge, and the number of nodes that use rule (ii) and rule (iii) are quite small. Since most transmission ranges will be set to $(1/2)^{1/\alpha}r$ (which is the optimal transmission range), so the network will have high probability to reduce the energy consumption.

Figure 6.28. The number of different kind of communication links in different scenario.

Due to the randomly formation of the network and the small number of nodes which use rule (ii) and rule (iii), in Figure 10, the statistic characteristics of these values are not regularly, so we cannot get a clear trend from these data.

The inconformity shown in Figure 6.27 (by the blue points) can be explained by the conclusion in Figure 6.28. In Figure 6.28, the number of communication links that use rule (ii) when node numbers are 170, 175, and 180 are 0, 5, and 0, respectively; to the rule (iii), this numbers are 6, 0, and 0, respectively. Note that when the node number is 175, there are more nodes decrease the transmission ranges than that when the node numbers are 170 and 180; and when the node number is 170, there is more nodes increase the transmission ranges than that when the node numbers are 175 and 180, so in Figure 6.27, the node degree increasing trends of the blue points are different with that in the black points.

6.6.2. Compare the Performance of ERTC with Other Topology Control Protocols

In this section, the performance of ERTC will be compared with two typical transmission power adjustment based topology control algorithms: LMA and LMN. The principles of LMA and LMN have been introduced at the beginning of Section 6.6.

Figure 6.29 indicates that the number of communication links in ERTC is the smallest. In Figure 6.29(c) and Figure 6.29(d), different color lines are used to represent different kinds of communication links. In Figure 6.29(c), the black links represent the communication links that have been increased, while the blue lines mean the communication links which have been reduced. Similarly, in Figure 6.29(d), the black lines indicate that the communication range are not changed, the red lines mean the communication links are increased, and the blue lines show the communication links are reduced.

Figure 6.29. The simulation result: (a) NONE; (b) ERTC; (c) LMN; and (d) LMA. * The X-axis and Y-axis means the node distribution area.

Both the LMA and LMN do not take the energy consumption into consideration. Moreover, since the maximum and minimum thresholds of node degrees in LMA are set by users without strict definition, the network topology will change greatly under different thresholds. In ERTC, the node degree thresholds are variation with different network conditions (such as the node numbers, the different topology, etc.), which aims to maintain r -range instead of k -connection for the nodes. Furthermore, as shown in Figure 6.29(b) and Figure 6.31, the protocol can meet the requirements of network connection and energy efficient at the same time in ERTC.

Figure 6.30 shows the node degrees of different algorithms under different scenarios. The node degree of ERTC increases with the increasing of node number, and the trend is similar with that of the original network. For LMA, the node degree will keep oscillating between 8 and 11. The reason is that the minimum and maximum node degree thresholds have been set to 8 and 11 in this simulation. However, the performance of LMA is affected by the value of thresholds greatly. The node degree trend is totally different in LMN, it looks randomly with the increasing of the node number. This is because the LMN decides the node degree only based on their neighbors' average node degree, which is easy to fall into the locally optimal solutions. However, the overall node degree trend in LMN is increasing.

In Figure 6.30, when the node number smaller than 140, the node degree of ERTC is smaller

than that of LMA; otherwise, when the node number is larger than 145, the node degree of ERTC is large than LMA. The reason is that ERTC does not maintain constant node degree which is popular in the topology control algorithm to guarantee network connection. Maintaining constant neighbors cannot reflect the dynamic of WSN, so it cannot guarantee that the node works at the optimal transmission range which is energy efficient with high probability. As a result, in ERTC, the algorithm maintains the r -range for the node rather than the k -connection. The r -range is the optimal transmission range with high probability of energy efficient. In addition, although LMA has stable node degree, the network performance of LMA is seriously affected by the node degree thresholds. Moreover, how to set the node degree threshold has not been discussed strictly in LMA.

Figure 6.30. The relationship between node number and node degree in four protocols.

Figure 6.31 displays the energy consumption in different topology control algorithms. From Figure 6.31, we can conclude that the energy consumption of ERTC is the smallest in these algorithms, and ERTC saves approximately 67.4% energy compare with none topology control network. The energy consumption in LMA and LMN are larger than ERTC; moreover, due to LMN can maintain the node degree in a stable level, so the energy consumption is smaller than LMA. However, the node degree in LMN cannot adapt the topology changing.

Figure 6.31. The energy consumption of different topology control protocols.

In Section 4.1.4, we proved that when the transmission range of node i is $(1/2)^{1/\alpha}r_i$, then the probability that the communication link is energy efficient is highest than others. Correspondingly, in Figure 13, the ERTC whose transmission range is related to $(1/2)^{1/\alpha}r_i$ consumes less energy than other topology control algorithms. This demonstrates that the conclusion that we get in Section 4 is effective in reducing the energy consumption for WSN. Additionally, as shown in [180], when the node degree is larger than $1.5 \log n$, the network is connected with high probability (nearly 1). In Figure 6.26(b) and Figure 6.27, when the node degree in ERTC is larger than $1.5 \log n$, then the network is connected as shown in Figure 6.26(b). Therefore, the simulation results show that the theoretical analyses are correct and effective.

6.7 The simulation and analysis on the probabilistic based underwater topology control algorithm

In this section, we will evaluate the performance of PTC algorithm. For highlighting the outstanding the qualities of the PTC algorithm, we combine the PTC with the FTC algorithm and compare the performance of FTC algorithm with the PTC-FTC algorithm in detail. The simulations shown in [61] have demonstrated that the FTC algorithm is high-efficient on controlling the network topology.

6.7.1 Simulation configuration

Based on the communication architecture of SWARMS project shown in Section 3.1, the simulation configuration of the underwater cooperation AUVs network is shown in Table 6.6.

Table 6.6. Simulation configuration

parameters	value
Simulation tool	DESERT [207]
Simulation area	3000m×3000m
Number of AUVs	3, 5, 7, 9, 11, 13
Depth	20 m
Water temperature (July)	12° c
Water salinity (July)	18 g/L
Sound speed (July)	1475 m/s
Initial transmission range	1000m
Transducer beam pattern	Horizontally Omni-directional
Data rate	3 kbit/s
Bit error ratio	10^{-10}
Receive power	1.3 W
Transmission power	2.8 W
Channel model	Multi-path + <i>Doppler</i> spreading
Carrier	Sweep spread carrier (S2C)

6.7.2 Simulation results

The simulation results can be found from Figure 11 to Figure 15. The simulation tool is DESERT [207], which is an extension toolbox based on the NS-2 simulator. The simulation

parameters can be found in Section 3.1.

In Figure 6.32, the average transmission power adjustment probability of AUV has been shown. From Figure 6.32, we can find that this probability varies between 0.4 and 0.5. When the number of AUV increases, there is no evidence showing that the transmission power adjustment probability increases either. This is because the probability is decided by the residual energy, the transmission power, the node degree, and the queue length jointly, so the increasing of the AUV's number in the network can not affect the probability greatly. For instance, when the number of AUV increases, the transmission power decrease and the residual energy increases, which can be found in Figure 6.34; however, due to the increasing of the AUV's degree, the queue length will increase (shown in Figure 6.36); therefore, the probability may not increase. The transmission power adjustment ratio can be found in Figure 6.33.

We can see that the transmission power adjustment ratio of the PTC-FTC algorithm is much smaller than that of the FTC algorithm in Figure 6.33. The transmission power adjustment ratio in FTC algorithm is about twice larger than that in PTC-FTC algorithm. This demonstrates that the PTC algorithm is efficient on reducing the transmission power adjustment ratio. Similarly to the transmission power adjustment probability shown in Figure 6.32, the transmission power adjustment ratio does not increase with the increasing of the AUV's number in the network. The reason is that when the number of AUV in the network increases, the number of AUVs which need to adjust their transmission power increases, too; moreover, according to the dynamics of the underwater cooperation AUVs network, there is no evidence showing that the increasing of the number of AUVs which need to adjust their transmission power is proportionable when the total number of AUVs in the network increases.

Figure 6.32. The average transmission power adjustment probability of PTC-FTC

Figure 6.33. The average transmission power adjustment ratio of PTC-FTC and FTC

Figure 6.34. The average residual energy of PTC-FTC and FTC

Figure 6.35. The average node degree of PTC-FTC and FTC

Figure 6.36. The average queue length of PTC-FTC and FTC

The notable properties of the PTC-FTC algorithm are shown in Figure 6.34, Figure 6.35, and Figure 6.36. In Figure 6.34, the residual energy of AUV is presented. The residual energy in PTC-FTC algorithm is larger than that in FTC algorithm. With the increasing of the number of AUVs in the network, the residual energy increases when the number of AUVs in the network is smaller than 9 and decreases when this number is larger than 9 both in PTC-FTC algorithm and the FTC algorithm. This conclusion is easily to be understood. When the number of AUVs is smaller in the network, for guaranteeing the network connection, the transmission power of each AUV in the network is larger and the network interference, the retransmission, and the network competition are smaller; moreover, when the number of AUVs in the network is small, the transmission power will play a dominant role, and when this number increases, the transmission power will decrease, so the residual energy increases when the number of AUVs is smaller than 9. However, when the number of AUVs is larger, the dominant parameters will be the network interference, the retransmission, and the network competition, so when the number of AUVs in the network increases, the residual energy decreases.

As talked in Section 3.3, the needed degree of AUV in PTC-FTC algorithm is dynamic and defined based on the conclusion in [180]; moreover, for getting fair simulation result, the AUV's degree in FTC algorithm is set to 3, which is the same as that shown in [61]. The simulation results in Figure 6.35 illustrate this simulation setting. In Figure 6.35, when the

number of AUVs in the network increases, the AUV's degree of the PTC-FTC algorithm increases fast for guaranteeing network connection; moreover, the AUV's degree of FTC algorithm keep stable. When the number of AUVs in the network is smaller than 3, the AUV's degree in PTC-FTC algorithm is smaller than that in FTC algorithm. This can be explained by the different needed degree calculation algorithms in PTC and FTC. In FTC algorithm, this needed degree is fixed; however, in PTC algorithm, according to the conclusion in [180], this number is dynamic according to different network conditions. The interesting conclusions can be found when compare the simulation results in Figure 6.34 with Figure 6.35. In Figure 6.35, the average degree of AUV in PTC-FTC algorithm is larger than that in FTC algorithm; however, the residual energy of PTC-FTC algorithm is larger than that of the FTC algorithm. This can be explained by the conclusion in Figure 6.33. Since the probability adjustment ratio in PTC-FTC algorithm is smaller than the FTC algorithm, the energy consumption on topology control and the retransmission caused by network competition is smaller than the FTC algorithm, so even the transmission range in PTC-FTC algorithm is larger than that in FTC algorithm, the residual energy in PTC-FTC algorithm is large.

In Figure 6.36, the queue length of the PTC-FTC algorithm is much smaller than that of the FTC algorithm, and with the increasing of the number of AUVs in the network, the queue length both in the PTC-FTC algorithm and the FTC algorithm increase. This is because the more AUVs in the network, the more data packets need to be transmitted; therefore, the queue length will increase when the number of AUVs increases. Additionally, due to the transmission power ratio of the PTC-FTC algorithm is much smaller than that of the FTC algorithm (which can be found in Figure 6.32), so the control messages in the PTC-FTC algorithm are much smaller than that in the FTC algorithm, which means the queue length in PTC-FTC algorithm is small, too.

The results presented from Figure 6.32 to Figure 6.36 have demonstrated that the PTC-FTC algorithm is efficient on improving the network performance while reducing the energy consumption of the underwater cooperation AUVs network.

6.8 The simulation and analysis on the packet delivery ratio based opportunistic topology control algorithm

In this section, the CBRT algorithm will be evaluated. The performance of CBRT algorithm will be compared with the ExOR algorithm in this section. The effectiveness of SBFL algorithm has been demonstrated in Section 3.1; so in the first part of this section, the performance of the packet delivery ratio based topology control algorithm is presented; in the second part of this section, the performance of CBRT and ExOR will be compared in detail. The simulation tool is NS-2.

6.8.1. Performance of packet delivery ratio based opportunistic topology control algorithm (OTC)

In this section, the performance of the packet delivery ratio based opportunistic topology control algorithm will be evaluated.

In this simulation, we compare the OTC with the traditional *k-connection* algorithm which is the popular topology control algorithm in wireless sensor and ad hoc networks [30][61][211]. In this simulation, the boundary values of the different regions are the same as that show in

Section 3.3; the value of k in k -connection algorithm is equal to 5. The simulation results can be found in Figure 6.37 and Figure 6.38. The parameters of the simulation are: deployment area: 1000m×1000m; initial node transmission range: 100m; packet length: 1024bits; data rate: 15Kbps; initial energy: 5J; high transmission power: 0.8W; low transmission power: 0.1W; node number: 50-200; average moving speed: 0.2m/s; receiving power: 0.05W.

From Figure 6.37, we can conclude that the transmission range adjustment ratio of OTC is smaller than that of k -connection algorithm. With the increasing of the node number, both the adjustment ratios of OTC and k -connection increase. Additionally, when the number of node increases, the difference of the adjustment ratios between OTC algorithm and k -connection algorithm decreases. In Figure 6.38, the node degrees of k -connection algorithm vary around 5, which is consistent with the value that we set in this simulation. In OTC algorithm, the node degree varies from 7 to 9 which are the boundary values that calculated in Section 3.3. The results in Figure 6.38 illustrates that the OTC algorithm is effective on controlling the network topology.

Fig. 6.37. The transmission range adjustment ration of OTC and k -connection algorithm.

Fig.6.38. The node degree of OTC and k -connection algorithm.

6.8.2. Performance of the cross-layer and reliable opportunistic routing algorithm (CBRT)

As demonstrated in Section 3.1, since the SBFL algorithm can handle more cross-layer parameters than the traditional algorithms without increasing the computation complexity, so in this simulation, the residual energy of the relaying node, the ETX of the communication link, the packet queue length in the relaying node, the delay of the relaying node, the distance to the destination node, the moving speed, and the moving direction will be taken into account to choose and prioritize the relaying nodes for the opportunistic routing. It should be noted that the numbers and kinds of the parameters used in this algorithm are not fixed; they can be changed according to the different applications easily and conveniently. This is also the advantage of CBRT algorithm, which is flexible without increase the algorithm complexity.

In this section, we compare the performance of CBRT with the traditional opportunistic routing ExOR [7]. The results can be found from Figure 6.39 to Figure 6.46. The parameters of the simulation are: deployment area: 1000m×1000m; initial node transmission range: 500m; packet length: 1024bits; data rate: 15Kbps; initial energy: 5J; high transmission power: 0.8W; low transmission power: 0.1W; node number: 25-150; average moving speed: 0.2m/s; receiving power: 0.05W.

Figure 6.39. The ETX of ExOR and CBRT.

Figure 6.40. The transmission delay of ExOR and CBRT.

Figure 6.41. The queue length of ExOR and CBRT.

In Figure 6.39, the ETX of CBRT and ExOR are compared. From Figure 6.39, we can find that with the increasing of the node number, the ETX in ExOR varies between 6 and 7; however, this value is only 1 in CBRT. This conclusion demonstrates that in ExOR, the ETX is about 6 times larger than that in CBRT. In MANETs, small ETX means small transmission delay, which can be found in Figure 6.40. In Figure 6.40, with the increasing of the node number, both the transmission delays in CBRT and ExOR increase. However, the increasing in ExOR is more serious than that in CBRT. This is due to the large ETX of ExOR. Not only the large ETX but also the packet queue length in the node can increase the transmission delay. As shown in Figure 6.41, the packet queue length in ExOR is also larger than that in CBRT. With the increasing of the node number, the queue length increases both in ExOR and CBRT algorithm. However, the queue length increases faster in ExOR than that in CBRT. The Figure 6.40 and Figure 6.41 can be explained by each other: the large packet queue length means large transmission delay; conversely, the large transmission delay makes the increasing of the queue length. Moreover, as shown in Figure 6.39 and Figure 6.41, large ETX and packet queue length deteriorate the performance of transmission delay in ExOR.

The Figure 6.39, Figure 6.40 and Figure 6.41 demonstrate that the network performance has been improved greatly by using CBRT algorithm. As shown in Figure 6.39, Figure 6.40 and Figure 6.41, the parameters in the network are not alone; they relate to and can affect each other. Therefore, the more cross-layer parameters are taken into account, the better network

performance is. Since the CBRT have the ability to handle multi-parameters without increasing the complexity of the algorithm, so the CBRT is more efficient than the traditional opportunistic routing algorithm.

Figure 6.42. The node degree of ExOR and CBRT.

Figure 6.43. The transmission range of ExOR and CBRT.

As shown in Figure 6.42, due to the topology control in CBRT, the RND in CBRT varies between 6 and 10, which is in the healthy region that we define. In Figure 6.42, when the node number increases, due to lack of the topology control in ExOR, the node degree varies greatly in ExOR. For instance, when the node number is 150, the node degree in ExOR is about 5 times larger than that when the node number is 25. The reason is that the transmission range is constant in ExOR, so when the node number increases, the node degree will increase greatly. This also means that the packet delivery ratio varies greatly in ExOR. However, due to the topology control in CBRT, when the node number increases, for maintaining stable RND in the candidate relays set, the transmission range will be adjusted according to the value of RND, which can be found in Figure 6.43. In Figure 6.43, when the node number increases, due to the OTC algorithm, the transmission range of CBRT decreases to maintain stable RND in the candidate relays set, i.e., the more nodes in the network, the smaller transmission range is. So in Figure 6.42, the RND in CBRT algorithm varies slightly, which is in the region that we set in Section 3.3.

Figure 6.44. The residual energy of ExOR and CBRT.

Figure 6.45. The through of ExOR and CBRT.

Another advantage of CBRT is the energy consumption. As shown in Figure 6.44, the residual energy in CBRT is larger than that in ExOR. With the increasing of the node number, the

residual energy decreases both in ExOR and CBRT. However, the energy is consumed faster in ExOR than that in CBRT. The excellent performance of energy consumption in CBRT owes to the balanced performance of the cross-layer parameters, which can be found in Figure 6.39, Figure 6.40, Figure 6.41 and Figure 6.43. The performance of ETX, transmission delay, packet queue length, and transmission range in CBRT deduces the energy consumption greatly. Similar to the residual energy, in Figure 6.45, with the increasing of the node number, the throughput both in ExOR and CBRT decreases; moreover, the decreasing in ExOR is faster than that in CBRT. This is also because the balanced performance of cross-layer parameters in CBRT.

Figure 6.46. The residual link lifetime of ExOR and CBRT.

As shown in Figure 6.46, the only disadvantage of CBRT is that with the increasing of the node number, the link lifetime in CBRT decreases; however, the link lifetime varies slightly in ExOR. This can be explained by Figure 6.43. As shown in Section 3.3, when the moving speed is stable, the larger transmission range, the smaller link lifetime is. Moreover, in CBRT, when the node number increases, the transmission range decreases, which means small link lifetime. However, since the transmission range is not adjusted in ExOR, so the link lifetime keeps steadily.

6.9. The simulation and analysis on the efficient and reliable topology control based opportunistic routing algorithm

In this section, the performance of efficient and reliable topology control based opportunistic routing algorithm is presented. For comparing the performance of ERT, three opportunistic routing algorithms are implemented in this simulation: 1) ExOR [7]; 2) TCOR [188]; 3) EEOR [10]. ExOR is the traditional opportunistic routing algorithm without power control and the performance matrix is ETX; the TCOR and EEOR are power control based opportunistic routing algorithms and the performance matrix of these two algorithms is the expected energy consumption between sender and relay node set. The results are shown in Figure 6.47-Figure 6.53.

In simulation, the nodes are distributed in the event area uniformly. Each node equips GPS device and can exchange their location periodically. Moreover, the antenna of node is the omnidirectional antenna in which the transmission range can be changed based on the transmission power. The constant bit rate (CBR) [190][212][213] is used in this paper to

generate data packet; each CBR data packet is transmitted between two nodes which are chosen randomly. The number of CBR connection pairs represents the traffic load in network. The larger number of CBR connection pairs are, the higher traffic load is. More simulation parameters can be found as follows: deployment area: 1000m×1000m; initial node transmission range: 100m; packet length: 1024bits; data rate: 15Kbps; initial energy: 5J; high transmission power: 0.8W; low transmission power: 0.1W; number of node: 40-120; receiving power: 0.05W; simulation time: 300s; number of CBR connection pairs: 20-100. This simulation is NS-2 based.

The varying parameters during the simulation are the number of nodes in network, the number of CBR connection pairs, and the simulation time. The performance metrics used in this simulation are introduced briefly:

1. *Packet delivery ratio*. As defined in [149] and [205], the packet delivery ratio represents the ratio of all successfully received data packets at receiver to the total number of data packets generated by the application layer at source node.
2. *Transmission delay*. This is the transmission delay of data packet from source node to destination node; the end-to-end delay includes the queuing delay, the delay caused by re-transmission, and the packet-carrying delay [149][205]; the end-to-end delay represents the speed of algorithm, i.e. the performance of real-time; the smaller end-to-end delay, the better routing performance is.
3. *Network throughput*. As the definition in [206], the network throughput is the ratio of the total number of data packets successfully received by destination node to the number of data packets sent by all the nodes during the simulation time; this parameter is important since it represents the comprehensive performance of algorithm including the packet delivery ratio and end-to-end delay.
4. *Residual energy*. Different with the traditional definition of residual energy, the residual energy used in this paper is defined as the ratio of the residual energy of node to the total energy of node, which can be expressed as: $R_p = \frac{\text{residual energy}}{\text{total energy}}$.

6.9.1. Performance under different number of nodes

In this section, the performance of ERTO under different node densities is presented, which can be found from Figure 6.47 to Figure 6.50. In this simulation, the number of CBR connection pairs is fixed and equals to 30.

Figure 6.47 illustrates the packet delivery ratio of these four opportunistic routing algorithms. In Figure 6.47, the packet delivery ratio of ERTO is much higher than that of the other three algorithms, such as 40% higher than ExOR and 20% higher than EEOR when the number of node is 100. With the increasing of node number, the packet delivery ratio increases obviously in ExOR and ERTO while the increasing is slight in TCOR and EEOR. Moreover, when the number of node is large, the increasing in ExOR is smaller than that in ERTO. Two parameters can be used to explain this conclusion: the node degree and the network interference. When the network density is small, the node degree is the domain parameter on determining the packet delivery ratio; when the node degree increases, the packet delivery ratio increases. However, with the increasing of the node density, the network interference becomes more and more serious than that in sparse network. So when the network density is large, the network interference will be the domain parameter. Since the ERTO takes the network interference into

account, so even in density network, the packet delivery ratio of ERTO increases.

The performance of packet delivery ratio can also affect the performance of end-to-end delay, which has been presented in Figure 6.48. On one hand, the higher packet delivery ratio means lower probability of packet retransmission, which reduces the transmission delay; so with the increasing of node density, the transmission delay decreases. On the other hand, the number of transmission hops can also affect the performance of end-to-end delay; the large hop numbers can increase the transmission delay. In ExOR, since the transmission power cannot be changed, so with the increasing of node density, the transmission hops increases slower than that in the other three algorithms. Therefore, considering both the packet delivery ratio and the number of transmission hops, the decreasing of transmission delay in ExOR is larger than that of the other three algorithms. Moreover, since the packet delivery ratio in ERTO is better than that in ExOR, EEOR, and TCOR, so the transmission delay in ERTO is the smallest.

Figure 6.47. Packet delivery ratio under different node densities

Figure 6.48. End-to-end delay under different node densities

Figure 6.49. Throughput under different node densities

The outstanding performance of packet delivery ratio and end-to-end delay in ERTO also contributes to improve the comprehensive performance of the network, such as the network throughput, which has been shown in Figure 6.49. In Figure 6.49, the performance of network throughput has been presented. The throughput of ERTO is the highest among these four algorithms; and with the increasing of network density, the increasing of throughput is slight in these four algorithms. The throughput of ERTO increases larger with the increasing of node density than the other three algorithms. This can be explained as follows. On one hand, when

the network density increases, the packet delivery ratio increases, which can be found in Figure 6.47, so the throughput increases with the increasing of node density; on the other hand, the more nodes in network, the more serious interference which deteriorates the performance of throughput. Considering these two aspects, the throughput in ExOR, TCOR, and EEOR is stable; however, because ERT0 has taken network interference into account, so the throughput increases obviously when the network density increases.

6.9.2. Performance under different traffic load

In this section, the performance of these four algorithms under different traffic load is presented. In this simulation, we use the number of CBR connection pairs to represent the different traffic load [190][212][213]. The results can be found in Figure 6.50, Figure 6.51, and Figure 6.52. In this simulation, the number of nodes in network is 100.

Figure 6.50. Packet delivery ratio under different traffic load

Figure 6.51. End-to-end delay under different traffic load

Figure 6.52. Throughput under different traffic load

Actually, when the traffic load in network increases, the most important parameters which can affect the network performance greatly are the network congestion and contention. The more serious network congestion and contention, the worse network performance is, which can be found in Figure 6.50 and Figure 6.51. In Figure 6.50, with the increasing of traffic load, both the packet delivery ratios of these four algorithms decrease; moreover, the decreasing ratio is the largest in ExOR while it is the smallest in ERT0. Similarly results can also be found in Figure 6.51. In Figure 6.51, when the traffic load increases, on one hand, the network

congestion and contention increase, so the transmission delay increases; on the other hand, due to the packet delivery ratio decreases, the transmission delay increases further. However, since ERTO can adjust the transmission power during the routing process base on network interference, so the performance of packet delivery ratio and transmission delay are all better than that of the other three algorithms.

The throughput of these four algorithms under different traffic load has been shown in Figure 6.52. In Figure 6.52, when the traffic load increases, the throughput decreases. These can be explained as: 1) similar to the performance of packet delivery ratio and transmission delay, when the traffic load increases, the network congestion and contention increases, which deteriorates the performance of network throughput; 2) when the traffic load increases, both the packet delivery ratio and transmission delay become worse than that when the traffic load is small, so the throughput decreases further. However, since the performance of packet delivery ratio and the transmission delay in ERTO are the best, and ERTO takes the network interference into account during the topology control, so the performance of throughput in ERTO is also the best.

6.9.3. Performance of energy consumption under different simulation time

The energy consumption of ERTO is better than that of the other three algorithms, which is present in Figure 6.53. The number of CBR connection pairs is 30 and the number of nodes is 100 in this simulation.

In Figure 6.53, with the increasing of simulation time, both the residual energy of these four algorithms reduces. However, the reduction of ERTO is smaller than that of ExOR, EEOR, and TCOR. Since the ExOR cannot adjust the transmission power and does not take energy consumption into account, so the reduction of ExOR is fastest in these four algorithms. Even EEOR, TCOR, and ERTO all take energy consumption into account during the routing process, considering the performance of packet delivery ratio and transmission delay, the energy consumption in ERTO is better than that in EEOR and TCOR.

Figure 6.53. Residual energy of ExOR, TCOR, EEOR, and ERTO

6.10 Summary

In this chapter, we evaluate performance of the proposed algorithms by simulation. Since the scenarios of algorithms are different, so the simulation parameters in each simulation may different. Through the simulation, we prove the effectiveness of the proposed algorithms.

Chapter 7

Conclusion and Further Works

In this chapter, we will conclude our work in this thesis. In this thesis, we mainly concentrate on the research on the routing algorithm and topology control algorithm of wireless network, including the wireless sensor network, the ad hoc network, the vehicular ad hoc network, the underwater wireless network, etc. The purpose of this thesis is to improving the performance of the wireless network as much as possible under the limitation of the wireless resource based on the optimal theory, probability theory, and decision making theory. Moreover, in this chapter, we also propose the future works in this research area. For improving the network performance of the IoT, which is going to be everlasting and evolving topics, much more effort will deserve in the future. The specific problems this thesis tried to address are only small fraction among the issues many researchers have been working on. The approaches involved in this thesis could be considered as novel trials of the optimization techniques and decision making techniques for the coming area of the IoT, and the results would be hopefully useful for researchers who are interested in similar problems.

7.1 Conclusion

In this thesis, we proposed some algorithms for improving the performance of the opportunistic routing and topology control algorithms. We analyze the properties of these algorithms in detail and evaluate the performance of these algorithms by simulation in different scenarios.

For improving the effective and accuracy of the candidate relay node priority, we propose the fuzzy logic based relay priority determining algorithm. In this algorithm, the inputs of the fuzzy logic system is not the values of the node's parameters, it is the relative variance of each parameter; by this, the computation complexity caused by the increase of the number of input and linguistic variables are reduced. So in this algorithm, many cross layer parameters can be taken into account during the determination of the relaying priority.

The opportunistic routing can improve the packet delivery ratio greatly; however, since more than one neighbors involved in the data packet transmission, so the redundant transmission, the network interference, the transmission delay of opportunistic routing is much higher than that of the deterministic routing. For solving this issue, many candidate relay node filter

algorithms and coordinate schemes are proposed. However, as demonstrated in [11], the candidate relays prioritization and filtering are done separately in the prior works. So the outcome of this phased is not necessarily optimal. For instance, filtering based on the connectivity criterion removes candidates that trigger duplicate transmissions. However, these filtered candidates may be the best in terms of the routing metric and may bring the highest expected performance. Thus, it is necessary to jointly consider the node contribution and its duplicate probability in the CRS selection schemes design. So in this thesis, we propose the delay based redundant transmission avoid candidate relay node filter algorithm. In this algorithm, the node contribution and the transmission delay and the duplicate probability are considered in this algorithm.

Based on the relaying priority algorithm and the candidate relay node filtering algorithms that proposed in this thesis, we apply these two algorithms into the underwater wireless ad hoc network and the VANETs, respectively. Moreover, we evaluated the performance of these two algorithms by simulation.

In this thesis, we also investigate the probability that reducing the network interference and energy consumption by adjusting the transmission power of node; moreover, we also find the most appropriate transmission power which has the highest probability for guaranteeing low network interference and energy consumption. We also proved that for the wireless sensor network, by adjusting the transmission power, the energy consumption optimal also means network interference optimal. Based on the conclusion of this investigation, we propose a topology control algorithm which can reduce the network interference and energy consumption with high probability. For reducing the control cost, we propose the probabilistic topology control algorithm for the underwater ad hoc network. In this algorithm, the transmission power adjustment probability is decided based on the difference between the current value of the parameter and the optimal one; the larger of the difference, the higher adjustment probability is. This algorithm is effective on reducing the transmission power adjustment ratio.

For stabilizing the packet delivery ratio in the opportunistic routing and reducing the energy consumption and network interference, the number of nodes in CRS should not too large or too small; so the number of node in CRS should be controlled. In this thesis, we propose two different control algorithms for the opportunistic routing: (1) the probabilistic topology control based opportunistic routing; in this algorithm, the nodes are divided into different categories (healthy and unhealthy) based on their packet delivery ratios; if the node is healthy, then the transmission power does not need to be adjusted; otherwise, the transmission power is adjusted; after the transmission power adjustment, the node will transmit the data packet from source node to the destination node based on the proposed opportunistic routing in Chapter 3; (2) the Pareto optimal based topology control method; considering the fact that the transmission power and the number of nodes in CRS are related, so they should be optimized jointly rather than separately; therefore, in this algorithm, we optimize the transmission power and the number nodes in the CRS jointly based on the Pareto optimal method; after the transmission power and the number of nodes in the CRS are optimized, then the nodes transmit the data packet from the source node to the destination node based on the proposed opportunistic routing in Chapter 3.

In this thesis, we also evaluate the performance and effectiveness of the proposed algorithms

based on simulation. We analyze the properties of the proposed algorithms. The simulation results demonstrate the effectiveness and accuracy of the proposed algorithms.

7.2 Future works

This section discusses several challenging issues that are expected to be considered in future research. Firstly, the methods and algorithms proposed in this thesis can be improved on some aspects, or can be applied in different scenarios; then, the issues which are not taken into account in this thesis can be investigated in the future; this will give a guideline to the researchers who are interest in this research area.

- For the proposed methods and algorithms:
 1. The network models used in the research of communication and networking of the IoT applications in many research papers are still too ideal, so the algorithms which is perform good in the simulation while bad in practical. This means that the transmission models (such as the disk model), sometimes are inappropriate to model the IoT nodes. However, the practical results imply that the realistic model of the network is much more complex. Therefore, the probabilistic approach can play an important role here, which can be introduced to create more accurate transmission models.
 2. A commonly used model for IoT is always *2-dimension*. However, the IoT can apply also *3-dimension*, such as underwater, atmospheric, high buildings with many floors, mountains, or space communications. Those models, especially referring to transmission models, are necessary to check their performances in *3-dimension*. For instance, in the *2-dimension* model, the transmission range of node is circle; however, this will be sphere in the *3-dimension* model; therefore, the analysis in the *3-dimension* model will be much more complexity than that in *2-dimension* model.
 3. IoT could be a highly dynamical network where the nodes move frequently; for example, it can be applied to vehicle monitoring or wearable sensor devices. It is interesting to study the communication and networking in a dynamical network. It is very likely that those problems, intractable in a static network, could not be easily solved in a dynamic network either. Although the communication and networking in IoT applications are more difficult to model and maintain in a mobile environment, for improving the reliability and effectiveness of the data transmission in the IoT applications in the mobility environment, these issues are worth to be investigated.
 4. Unfortunately, at present, there are still many routing algorithms or topology control algorithms are centralized and have unaffordable complexity. The IoT is a large distributed system, so heuristic algorithms have to be distributed as well. Those non-distributed algorithms harm the scalability and require a higher maintenance cost. The proposed algorithms in this thesis are distributed, but their performances in the distributed networks need to be further studied and improved.
- For the development of the wireless network in IoT environments:
 1. The contradiction between the development of wireless application and the limitation of the wireless resource. The resource in wireless network is limited; with the development of the wireless application, the requirements to the wireless resource increase, such as the

energy, the bandwidth, the calculation speed and capability, etc. So how to improve the network performance as much as possible under the limitation of the wireless resource should exist in the whole research of the wireless network. For instance, the cloud computing and the edge computing are proposed to solve this kind of issue.

2. On one hand, with the development of the wireless application, the requirement of the applications to the network performance increase; for instance, at the beginning, the data packet is text, then the video, at the moment, the data packet can be the virtual reality, or the big data applications; so the network protocols or algorithms should be improved as well. On the other hand, with the development of the communication technology or the hardware, the protocols and the algorithms should be improved too.
3. 3. With the development of the artificial intelligence and intelligence algorithms, introducing the intelligence algorithms into the wireless protocols or algorithms will improve the network performance greatly. However, the calculation of the intelligence algorithm will consume a lot of wireless resource; so in the future, how to introduce the intelligence into the wireless protocol or algorithm without increasing the seriously wireless resource consumption will be investigated. Moreover, the relationship between the network performance improvement caused by the intelligence algorithm and the network resource consumption caused by intelligence algorithm is worth to be investigated.

Appendixes

Appendix A

If $G(V,E)$ is a relaying network, then the network must be fully connected, which means that between any two nodes in this network, there must exist a bi-directional communication link; so according to the principle of permutation and combination, the number of the communications links in $G(V,E)$ can be calculated by:

$$E = C_V^2 = V(V-1)/2 \quad (\text{A.1})$$

Moreover, the number of communication links cannot larger than that calculated in (A.1); so if $E=V(V-1)/2$, the network is fully connected; otherwise, the network is not fully connected.

Appendix B

According to (3.11), let $i=n-1$ and $j=n$, where n is the network degree, then the difference shown in (3.11) can be calculated as:

$$\begin{aligned} \Delta DT_{G(1,2,\dots,n)}^{(n-1,n)} &= \Delta DT_{G(1,2,\dots,n)}^{n-1} - \Delta DT_{G(1,2,\dots,n)}^n \\ &= \left(\prod_{j=1}^{n-2} (1-P_j) \right) \cdot [1 + (P_{n-1} - P_n) \cdot [1 + (1 - P_{n-1})(2 - P_n)]] \end{aligned} \quad (\text{A.2})$$

In (A.2), since $n \rightarrow \infty$, so $(P_{n-1} - P_n) \rightarrow 0$; so when $n \rightarrow \infty$, the (A.2) is level to $\prod_{j=1}^{n-2} (1 - P_j)$;

moreover, since $(1 - P_j) < 1$ and $n \rightarrow \infty$, so $\Delta DT_{G(1,2,\dots,n)}^{(n-1,n)} \rightarrow 0$ holds.

Additionally, according to (3.10), when $n \rightarrow \infty$ and $i=n$, the $\Delta DT_{G(1,2,\dots,n)}^n$ can be calculated as:

$$\Delta DT_{G(1,2,\dots,n)}^n = \left(\prod_{j=1}^{n-1} (1 - P_j) \right) \cdot [n(1 - P_n)(1 + P_n) - (n-1)] \quad (\text{A.3})$$

Since in (A.3), when $n \rightarrow \infty$, $\prod_{j=1}^{n-1} (1 - P_j) \rightarrow 0$, so the Corollary 3.4 holds.

Appendix C

According to (3.13), we can calculate that if $P_i < P_j$, then the condition that $\Delta DT_{G(1,2,\dots,n)}^{(i,j)} < 0$ can

be shown as follows:

$$(P_j - P_i) > \frac{1 + (2 - P_{j-1}) \cdot \prod_{k=i+1}^{j-2} (1 - P_k)}{(2 - P_{j+1}) \cdot \prod_{k=i+1}^{j-1} (1 - P_k)} = \varphi(i, j) \quad (\text{A.4})$$

In (A.4), let:

$$\begin{aligned} \zeta(i, j) &= 1 + (2 - P_{j-1}) \cdot \prod_{k=i+1}^{j-2} (1 - P_k) - (2 - P_{j+1}) \cdot \prod_{k=i+1}^{j-1} (1 - P_k) \\ &= 1 + \prod_{k=i+1}^{j-2} (1 - P_k) \cdot (P_{j+1} + P_{j-1} - P_{j+1}P_{j-1}) \end{aligned} \quad (\text{A.5})$$

In (A.5), since P_k , P_{j-1} , and P_{j+1} are all smaller than 1, so we can conclude that $\zeta(i, j) > 1 > 0$, which means that $\varphi(i, j) > 1$. According to the fact that P_i and P_j are all smaller than 1, so the probability that $(P_j - P_i) = \varphi(i, j) > 1$ is 0.

Appendix D

As shown in (3.15), if the network is o -network and the network degree is 2; in this network, node $_j$ is one of the neighbors of node $_i$, then in the neighbor matrix of node $_i$, the j th and i th values in the neighbor matrix of node $_i$ will be “1”; otherwise, it will be “0”. So according to the sum operator defined in Definition 3.6, if node $_i$ and node $_j$ are the neighbors of each other, then $neib_i(i) \wedge neib_j(i)$ and $neib_i(j) \wedge neib_j(j)$ are all “1”; so the result of (3.16) will be

2. Similar to the analysis above, when the network is $n > 2$, the same conclusion can be got.

If the network is s -network and the network degree is n , which means this network can be derived from an o -network in which the network degree is m and $m > n$. So if the network $G(a, b, c)$ is a s -network and it can be derived from the relaying network $G(a, b, c, d, e)$, then not only $neib_a(a) \wedge neib_b(a) \wedge neib_c(a)$, $neib_a(b) \wedge neib_b(b) \wedge neib_c(b)$, and $neib_a(c) \wedge neib_b(c) \wedge neib_c(c)$ are all “1”, but also $neib_a(d) \wedge neib_b(d) \wedge neib_c(d)$ and $neib_a(e) \wedge neib_b(e) \wedge neib_c(e)$ are all “1”, so $D_G = 5$ which is larger than 3. This is because the node $_d$ and node $_e$ are all the neighbors of node $_a$, node $_b$, and node $_c$. So if the network is s -network then the result of (3.16) will be the node degree of the o -network which it can be derived from. So the Corollary 3.7 holds.

Moreover, for network $G(1, 2, \dots, n)$, if $D_G < n$, it means that there exist at least one $neib_i(j) = 0$, where node $_i$ and node $_j$ are the nodes in $G(1, 2, \dots, n)$. This means that there exist at least two nodes between which there has no bi-directional communication link, so $G(1, 2, \dots, n)$ is not relaying network. So the Corollary 3.6 holds.

Appendix E

Assuming that there are two relaying networks, for the network₁, the order number of Metric₁ is n_i and the order number of Metric₂ is n_j ; for the network₂, the order

numbers of these two Metrics are n_m and n_k , respectively. Let $\Delta_{DT}^n = |n_i - n_j|$, $\Delta_U^n = |n_m - n_k|$,

$\xi = \alpha$, and $v_{rDT} > v_{rU}$, then according to (3.25), the network utilities of these two relaying networks can be calculated as:

$$U_{network_1}^F = v_{rDT} \cdot n_i + v_{rU} \cdot n_m \quad (A.6)$$

$$U_{network_2}^F = v_{rDT} \cdot n_j + v_{rU} \cdot n_k \quad (A.7)$$

Let:

$$|\Delta U_{DT}| = v_{rDT} \cdot |n_i - n_j| = v_{rDT} \cdot \Delta_{DT}^n \quad (A.8)$$

$$|\Delta U_U| = v_{rU} \cdot |n_m - n_k| = v_{rU} \cdot \Delta_U^n \quad (A.9)$$

According to (A.8) and (A.9), if $|\Delta U_{DT}| > |\Delta U_U|$ (which means the network utility will be decided mainly by DT), then: $v_{rDT} \cdot \Delta_{DT}^n > v_{rU} \cdot \Delta_U^n$, which equals to $\Delta_U^n / \Delta_{DT}^n < v_{rDT} / v_{rU} = \alpha$; if

$|\Delta U_{DT}| < |\Delta U_U|$ (which means the network utility will be decided mainly by U), then:

$v_{rDT} \cdot \Delta_{DT}^n < v_{rU} \cdot \Delta_U^n$, which equals to $\Delta_U^n / \Delta_{DT}^n > v_{rDT} / v_{rU} = \alpha$. So Corollary 3.8 holds.

Appendix F

If variable x follows a normal distribution with mean μ and variance σ^2 , then the probability distribution function and the distribution function of x can be expressed as:

$$f_x(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (A.10)$$

$$F_x(x) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^x e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx \quad (A.11)$$

where $f(x) = F'(x)$.

Therefore, if $y = x^{-\alpha}$, then the distribution function of y can be expressed as:

$$F_Y(y) = P\{y \leq Y\} = P\{x^{-\alpha} \leq Y\} = P\left\{x \geq Y^{-\frac{1}{\alpha}}\right\} = 1 - F_x\left(Y^{-\frac{1}{\alpha}}\right) \quad (A.12)$$

Since $f(x) = F'(x)$, so the probability distribution function of y can be gotten by calculating the derivation on (A.12), which can be expressed as:

$$f_Y(y) = \frac{1}{\alpha} y^{-\frac{1+\alpha}{\alpha}} f_x\left(y^{-\frac{1}{\alpha}}\right) \quad (A.13)$$

According to (A.10), the probability distribution function of y expressed in (A.13) can be calculated as:

$$f_Y(y) = y^{-\frac{1+\alpha}{\alpha}} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{\left(y^{-\frac{1}{\alpha}} - \mu\right)^2}{2\sigma^2}} \quad (A.14)$$

Appendix G

When $x \sim N(\mu, \alpha^2)$, for each $x^{-\alpha}$, the probability distribution function can be found in (A.14);

moreover, the $x_i^{-\alpha}$ ($i = 1, 2, \dots, m$) are independent identically distributed. Based on the principle of the distribution of multidimensional random variables, the probability distribution function of $z = \sum_{i=1}^m x_i^{-\alpha}$ can be calculated. For more clearly, the z_i ($i = 1, 2, \dots, m$) can be expressed as:

$$\begin{aligned} z_1 &= y_1 \\ z_2 &= z_1 + y_2 \\ &\vdots \\ z_{m-1} &= z_{m-2} + y_{m-1} \\ z_m &= z_{m-1} + y_m \end{aligned} \quad (\text{A.15})$$

where $y_i = x_i^{-\alpha}$.

Therefore, according to the principle of the distribution of multidimensional random variables, the probability distribution function of $z_m = y_1 + y_2 + \dots + y_m$ can be calculated as:

$$f_{z_m}(z_m) = \int_{-\infty}^{\infty} f_{z_{m-1}}(z_m - y_m) f_{y_m}(y_m) dy_m \quad (\text{A.16})$$

where z_m and z_{m-1} can be found in (A.15). Similar to (A.16), the probability distribution function of $z_{m-1} = z_{m-2} + y_{m-1}$ can be calculated as:

$$f_{z_{m-1}}(z_{m-1}) = \int_{-\infty}^{\infty} f_{z_{m-2}}(z_{m-1} - y_{m-1}) f_{y_{m-1}}(y_{m-1}) dy_{m-1} \quad (\text{A.17})$$

Substituting (A.17) into (A.16), and noticing that $z_{m-1} = z_m - y_m$, the (A.16) can be rewritten as:

$$f_{z_m}(z_m) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_{z_{m-1}}(z_m - y_m - y_{m-1}) f_{y_m}(y_m) f_{y_{m-1}}(y_{m-1}) dy_m dy_{m-1} \quad (\text{A.18})$$

Similarly to (A.18), the $f_{z_{m-i}}(z_{m-i})$ ($i = 1, 2, \dots, m$) can be calculated. Then $f_{z_{m-i}}(z_{m-i})$ ($i = 1, 2, \dots, m$)

are iterative substituted into (A.16), by which the probability distribution function of $z = \sum_{i=1}^m x_i^{-\alpha}$ can be calculated as:

$$f_z(z) = \underbrace{\int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty}}_m f_{z_1}(z_m - \sum_{i=2}^m y_i) \prod_{i=2}^m f_{y_i}(y_i) dy_2 \dots dy_m \quad (\text{A.19})$$

Moreover, substitute (A.14) into (A.19), and considering the probability distribution function of N is $p(N)$, then the (A.19) can be rewritten as:

$$\begin{aligned} f_z(N+z) &= p(N) + \underbrace{\int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty}}_m \left(z - \sum_{i=2}^m y_i \right)^{\frac{1+\alpha}{\alpha}} \frac{1}{\sqrt{2\pi\alpha}} e^{-\frac{\left(\left(z - \sum_{i=2}^m y_i \right)^{\frac{1}{\alpha}} - \mu \right)^2}{2}} \\ &\quad \cdot \prod_{i=2}^m y_i^{-\frac{1+\alpha}{\alpha}} \frac{1}{\sqrt{2\pi\alpha}} e^{-\frac{\left(y_i^{\frac{1}{\alpha}} - \mu \right)^2}{2}} dy_2 \dots dy_m \end{aligned} \quad (\text{A.20})$$

Appendix H

When $x \sim N(\mu, \alpha^2)$, for each $x^{-\alpha}$, the probability distribution function can be found in (A.14);

moreover, since the $x_i^{-\alpha}$ ($i=1,2,\dots,m$) are independent identically distributed, so the

probability distribution function $z = \sum_{i=1}^m x_i^{-\alpha}$ can be calculated by (A.19). Therefore, the probability distribution function of $w = y / z$ can be calculated.

Since the y and z are independent, according to the principle of the distribution of multidimensional random variables, the probability density function of w can be calculated as:

$$\begin{aligned} f_w(w) &= \int_{-\infty}^{\infty} |z| f(wz, z) dz = \int_{-\infty}^{\infty} |z| f_z(z) \cdot f_y(wz) dz \\ &= \int_{-\infty}^{\infty} |z| (wz)^{-\frac{1+\alpha}{\alpha}} \frac{1}{\sqrt{2\pi}\alpha} e^{-\frac{\left((wz)^{\frac{1}{\alpha}-\mu}\right)^2}{2}} \cdot f_z(z) dz \end{aligned} \quad (\text{A.21})$$

where $f_z(z)$ can be calculated by (A.20).

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List of Author's Publications and Projects

Most of the results of this thesis were published in the following journals indexed in Journal Citation Reports (JCR) and international conference as follows; moreover, the projects that the author has taken part in are also listed below.

● Publications en revistas de prestigio rreconocido (journals del indice SCI):

- [1] Ning Li, José-Fernán Martínez-Ortega, Vicente Hernández Díaz, José Antonio Sánche Fernández, "Probability Prediction based reliable and Efficient Opportunistic (PRO) Routing Algorithm for VANETs," IEEE/ACM Transactions on Networking, in press, 2018. DOI: 10.1109/TNET.2018.2852220. (JCR Q1, IF: 3.11)
- [2] Ning Li, José-Fernán Martínez-Ortega, Vicente Hernández Díaz, Juan Manuel Meneses Chaus, "A New High-Efficiency Multilevel Frequency-Modulation Different Chaos Shift Keying Communication System," IEEE Systems Journal, vol.99, no.99, 2017. DOI: 10.1109/JSYST.2017.2715661. (JCR Q1, IF: 4.337)
- [3] Ning Li, José-Fernán Martínez-Ortega, Vicente Hernández Díaz, "Distributed Power Control for Interference-Existed Multi-User Mobile Edge Computing: A Game Theory Approach," IEEE Access, in Press, 2018. DOI: 10.1109/ACCESS.2018.2849207. (JCR Q1, IF: 3.557)
- [4] Ning Li, José-Fernán Martínez-Ortega, Vicente Hernández Díaz, "Cross-layer and Reliable Opportunistic Routing Algorithm for Mobile Ad Hoc Networks," IEEE Sensors Journal, vol. 18, no. 3, 2018. DOI: 10.1109/JSEN.2018.2838023. (JCR Q1, IF: 2.617)
- [5] Ning Li, Baran Cürüklü, Joaquim Bastos, Victor Sucasas, Jose Antonio Sanchez Fernandez, Jonathan Rodriguez, "A Probabilistic and Highly Efficient Topology Control Algorithm for Underwater Cooperating AUV Networks," Sensors, vol.17, no.5, 2017. DOI: 10.3390/s17051022. (JCR Q2, IF: 2.475)
- [6] Ning Li, José-Fernán Martínez, Juan Manuel Meneses Chaus, Martina Eckert, "A survey on underwater acoustic sensor network routing protocols," Sensors, vol.16, no.3, 2016. DOI: 10.3390/s16030414. (JCR Q1, IF: 2.677)
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- [9] Ning Li, José-Fernán Martínez-Ortega, Vicente Hernández Díaz, Juan Manuel Meneses Chaus,

“Probability of Interference-Optimal and Energy-Efficient Analysis for Topology Control in Wireless Sensor Networks,” Applied Sciences, vol.6, no.12, 2016. DOI: 10.3390/app6120396. (JCR Q3, IF: 1.689)

- **Participacion en congresos internacionales:**

- [1] Ning Li, Jose-Fernan Martinez-Ortega, Vicente Hernandez Diaz, and Lourdes Lopez Santidrian, “Cross-layer Balanced Relay node selection algorithm for opportunistic routing in underwater Ad-Hoc Networks,” AINA 2018: The 32nd IEEE International Conference on Advanced Information Networking and Applications, Cracow, Poland.

- **Participacion en proyectos europeos de investigacion:**

- [1] SWARMS-Smart and Networking UnderWater Robots in Cooperation Meshes (ECSEL).