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# **Ground Vehicle and UAV-empowered DTN Protocols for Information Sharing in Post-disaster Scenarios**

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# **Ground Vehicle and UAV-empowered DTN Protocols for Information Sharing in Post-disaster Scenarios**

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## 車両・無人航空機を活用した災害時情報共有のための

### DTN プロトコル

#### 和文概要

地震災害時には、通信インフラが故障し、携帯電話ネットワークが利用できなくなることが予想される。そのため、災害時における通信方式の検討が必要となる。遅延耐性ネットワーク(Delay Tolerant Networking:DTN)技術は継続的なネットワーク接続が不可能な極限的環境における通信をサポートすることができ、災害時における携帯基地局に依存しない情報共有が可能となる。本研究では、車両・無人航空機(Unmanned Aerial Vehicle: UAV)を活用した災害時情報共有のための DTN プロトコルの研究を行っている。車両・UAV の移動性を十分活用し、自律分散通信技術で災害時における情報共有を実現することを目的としている。

本論文では、ア)車両 DTN ネットワークにおけるメッセージ中継プロトコルとバッファ管理方式、イ)UAV を活用したメッセージ転送方式、といった2点に焦点を当て、下記2つの手法を提案している。1 つ目は、車両間の接触履歴に基づき、ネットワークノード間の将来の接続確率を予測し、それに合わせたメッセージの複製方式を提案している。また、各ノードのバッファ(Buffer)をより効率的に利用するために、データの重要度やバッファの空き領域を統合的に考慮したバッファ管理手法を提案している。情報共有プロセスにおいては、メッセージの中継方式とバッファ管理を連携させることで、パケット到達率の向上と遅延の削減を実現している。

2つ目は、車両・UAV 両方を活用した DTN プロトコルを提案している。UAV は各地域間で巡航して、フェリーノード(中継ノード)として地域間でのメッセージ転送を

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サポートするシナリオを想定している。提案方式は, UAV と車両の移動パターンの違いに焦点をあて, まず目的ノードに届く確率の予測を行う。特に, 従来方式では, 確率の予測においては, 接触回数のみを考慮していることに対して, 本研究では, 接触回数に加えて毎回の接触時間を考慮している。その次に, 予測確率及びメッセージの優先順位を統合的に考慮し, UAV を利用するか否か, どの UAV を利用するかといったデータ転送の決断を行う。また, 災害時における道路損傷も考慮し, UAV を利用して孤立地域間の情報共有を可能とするシナリオにおける通信性能の検証を行っている。

The ONE Simulator を利用して, 実際の地図データに基づいた現実的な車両移動シナリオを構築し, 提案プロトコルの性能を評価している。既存の DTN プロトコルである“PRoPHET,” “Spray-and-Wait,” “Bubble Rap”と比較することで提案方式の優位性を十分示している。

上記のように, 本論文は, 災害時における通信を想定し, 車両・無人航空機を活用した DTN プロトコルを提案し, 現実的なネットワークシミュレーションを用いて既存手法と比較しながら, 提案手法の有効性を確認している。

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# Abstract

In recent years, natural disasters frequently occur all around the world. When a disaster happens, the communication infrastructure may break down, and then the mobile phone network becomes unavailable. Therefore, it is imperative to study the communication problem in catastrophe scenarios. Delay Tolerant Networks (DTNs) can support communication in extreme environments where a continuous network connection is impossible, and enable information sharing among users without relying on base stations in a disaster. This thesis studies the DTN protocol for information sharing using vehicles and unmanned aerial vehicles (UAVs) in typical and disaster scenarios. The purpose is to fully utilize vehicles and UAVs' mobility and realize information sharing with autonomous distributed communication technologies.

This thesis includes two main technical contributions: a) a message relay protocol and buffer management scheme in Vehicular Delay Tolerant Network (VDTN), and b) a message forwarding strategy using UAVs in urban scenarios. The first one proposes a routing protocol based on the contact history between vehicles that could be used to predict the future connection probability between network nodes. To use the buffer of each node more efficiently, a buffer management policy is also proposed to consider the importance of data and the buffer size jointly. The thesis aims to improve the packet arrival rate and reduce the latency by linking the message forwarding strategy and buffer management in the information sharing process. Extensive computer simulations are conducted to show that the proposed routing scheme achieves better system performance than the existing baseline routing protocols.

Secondly, a VDTN protocol that utilizes both vehicles and UAVs is proposed. A scenario where UAVs cruise between regions and support message forwarding as ferry nodes is considered. The proposed protocol focuses on the different movement patterns between UAV and vehicles, and predicts the message forwarding delay until it reaches the destination node. Next, the expected delay time and the priority of the message are considered jointly in making the data transfer decision about whether to use UAV or not. In addition, considering road damages in a disaster, the communication performance for information sharing between

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isolated areas using UAVs is verified.

The thesis constructs a realistic vehicle movement scenario based on actual map data and evaluates the proposed protocol's performance using the Opportunistic Networking Environment (ONE) simulator. The superiority of the proposed scheme is demonstrated by comparing it with the existing DTN protocols.

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# Chapter 1

## 1 Introduction

At the beginning of the thesis, this chapter introduces the research about delay tolerant networks (DTNs) and unmanned aerial vehicles (UAVs). The framework of this chapter is shown below. Section 1.1 introduces the background of the research and DTN technologies. Section 1.2 presents the development of vehicular delay tolerant networks (VDTNs) in recent years and problems to be solved. Section 1.3 introduces the use case of UAVs in DTN scenarios. The contributions of this thesis are list in section 1.4. Section 1.5 explains the organization's overview of the thesis.

### 1.1 Research background

The classic TCP/IP protocol can be successfully applied to the Internet depending on the following characteristics of physical links [1][2].

- (1) At the same moment, an end-to-end path exists between the source node and the destination node.
- (2) The round trip time (RTT) between any pair of nodes in the network cannot be too long.
- (3) The network transmission is reliable, and the packet loss rate is low.
- (4) Upper-layer applications do not have to worry about communication performance.

In recent years, a new kind of network called Challenge Networks has sprung up [3-8]. These networks may have intermittent connections due to sparse nodes, high-speed mobility, the alternating activity of nodes, radio silence for security reasons, or malicious attacks. These networks have high latency and low data rates in communication links, may not have stable end-to-end connections, and network nodes' resources are limited. These network features break the TCP/IP model's assumptions introduced above and made the current TCP/IP model

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not well applied to these networks [9][10]. Therefore, researchers proposed a new network architecture called Delay Tolerant Network (DTN) to adapt to these new network characteristics [11].

As shown in Figure 1-1, a message-oriented bundle layer is added between the transport layer and the application layer to overcome the impact of network interruption through persistent storage in the DTN architecture. A hop-by-hop reliable delivery and elective end-to-end acknowledgments to supports network interoperability through a flexible naming mechanism (based on uniform resource identifiers) is added. In addition, it also contains an optional security model to prevent unauthorized use of network devices [12][13]. If a relay node storing the message is offline during the transmission, the message could be stored in relay nodes and transmit to other network nodes whenever the relay node reconnected to the network [14].

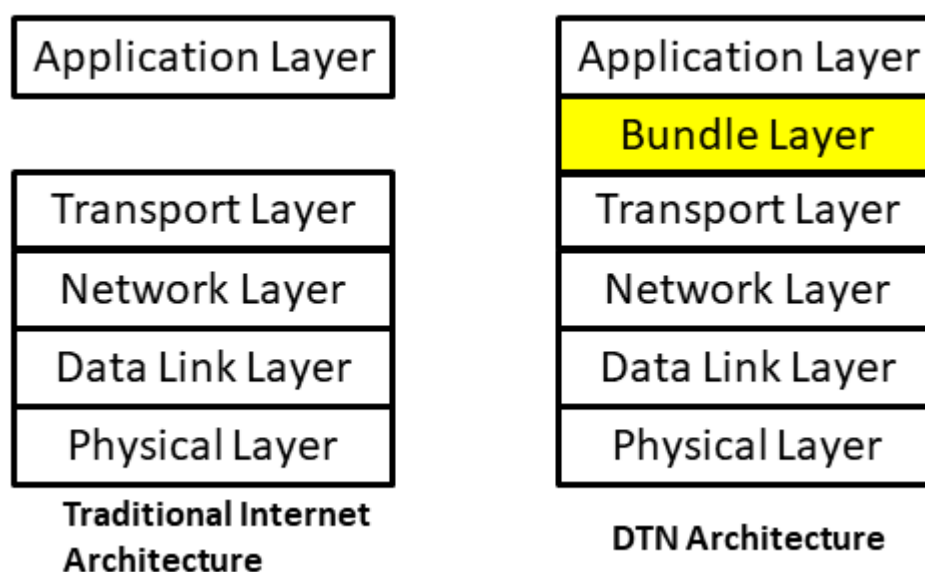


Figure 1-1 The difference in architecture.

The bundle layer could provide essential services such as message delivery in DTN by unicast mode. In order to enhance the reliability of the transport, custody transportation was adapted in the bundle layer. Custody transportation is a coarse-grained retransmission mechanism that transfers the responsibility for reliably transferring messages between nodes. A single transfer of a message between nodes is called single custody transportation. The

node that receives the message and agrees to assume responsibility for its reliable delivery is called a custody node. The custody transportation is initiated by the source node and occurs between layers of neighbor nodes, as shown in Figure 1-2. When message delivery is required, the current custody node transfers the request and initiates a reply time retransmission timer. If the relay node agrees to receive the message and store it in the future, it will send a reply. If no response is returned, the retransmission of the message will start. The custody node usually needs to store the message continuously and cannot be dropped unless another node is found to take over the custodian responsibility or the message TTL (Time to Live) expires. However, custody transportation does not guarantee end-to-end reliability, which is only possible if the source node receives an acknowledgment from the neighbor node after requesting custody transportation [15].

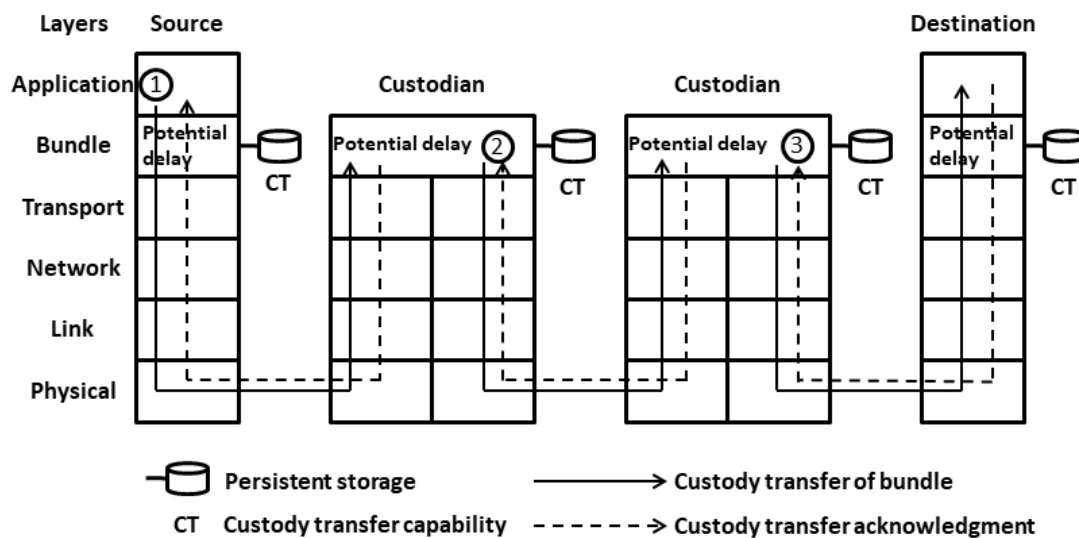


Figure 1-2 Message custody transportation.

The DTN is a network in which the distribution of nodes is sparse. Thus, the delivery of messages is mainly realized by encounters caused by node movement. Since the DTN node is intermittently connected, messages cannot be delivered to the target directly; thus, the relay node is needed to complete the message delivery [16]. As shown in Figure 1-3, the source node *S* has a message that needs to be forwarded to the destination node *D*. At time *t*<sub>1</sub>, the source node and the destination node are located in two different areas. Two nodes cannot forward the message through direct communication, so the source node *S* needs to find a relay node to

deliver it. At time  $t_2$ , node 3 can communicate with node 4 and forward the message. At time  $t_3$ , node 4 moves into the communication range of destination node  $D$  and delivers the message to destination node  $D$ . This is the complete delivery process of the message in DTN.

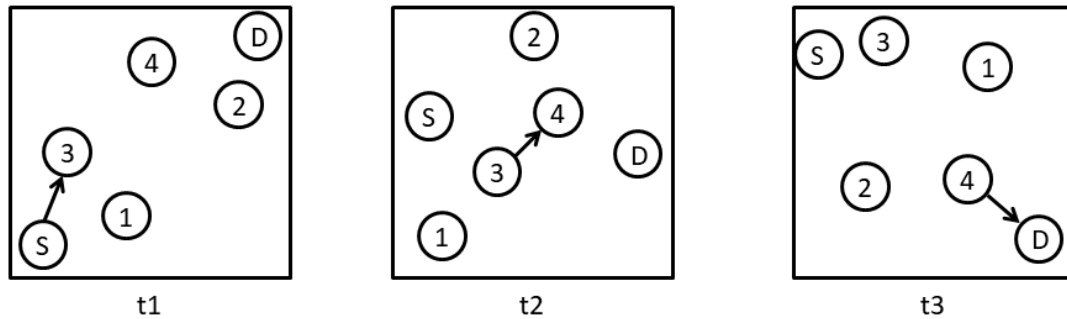


Figure 1-3 Message delivery process in DTN.

As mentioned above, DTN is not based on existing assumptions about transmission links, so DTN has the following characteristics different from traditional TCP/IP networks:

- (1) Intermittent connection: the reasons for the intermittent connection of DTN nodes include the limited bandwidth, the uncertainty movement and the sparseness deployment of nodes. The source node cannot directly transfer messages to the destination node for the above reasons, affecting the delivery probability of messages. Only when nodes are within the communication range can they initiate a communication request and deliver the message. The intermittent connection is a primary DTN feature and an essential prerequisite for DTN routing research [17].
- (2) Node resources are limited: DTN nodes are often distributed in extreme environments. The node resources are limited by weight, the power supply, or other equipment carried that restrict the use time of the node. Usually, DTN nodes have to adopt a specific strategy to save limited resources [18].
- (3) Long latency: the forwarding of messages in DTN needs to use relay nodes, and the messages will be delivered through the random movement of relay nodes. For the intermittent connection characteristics of DTN, the nodes temporarily store the messages in their cache. The source node is able to accomplish the message transferring by using relay nodes, resulting in a long delivery delay [19].



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- (4) Rapid changes in network topology: Compared with the traditional Internet, DTN nodes have random mobility. The spontaneous movement of nodes makes the network topology changed frequently. The random increase and decrease of nodes, the exhaustion of node energy, and the harsh communication environment will continuously change the network topology [20].

Because DTN is always in a harsh and challenging environment, the success rate of message delivery has a great relationship with the choice of a routing protocol. A perfect routing process can significantly improve the success rate of message delivery. Therefore, the research on the DTN routing protocol has always been a hot spot [21-23]. Through the key research on the structure and characteristics of DTN, researchers have proposed several typical routing algorithms, such as flooding-based routing [24], historical-based routing [25], and social-awareness routing [26]. These routing algorithms have a good effect on processing the specific characteristics of the DTN and can ensure the success rate of message delivery.

## **1.2 Vehicular delay tolerant networks**

As shown in Figure 1-4, the VDTN is a special self-organized network. Due to the intermittent and opportunistic connections between nodes in VDTNs, it has the characteristics of DTN, and the routing strategy is more challenging than that in DTNs. Through vehicle to vehicle (V2V), vehicle to infrastructure (V2I) communications in VDTNs, the information exchange between drivers can be effectively promoted. The main application services provided by VDTNs fall into three categories: traffic safety, traffic management, and value-added services [27] [28].

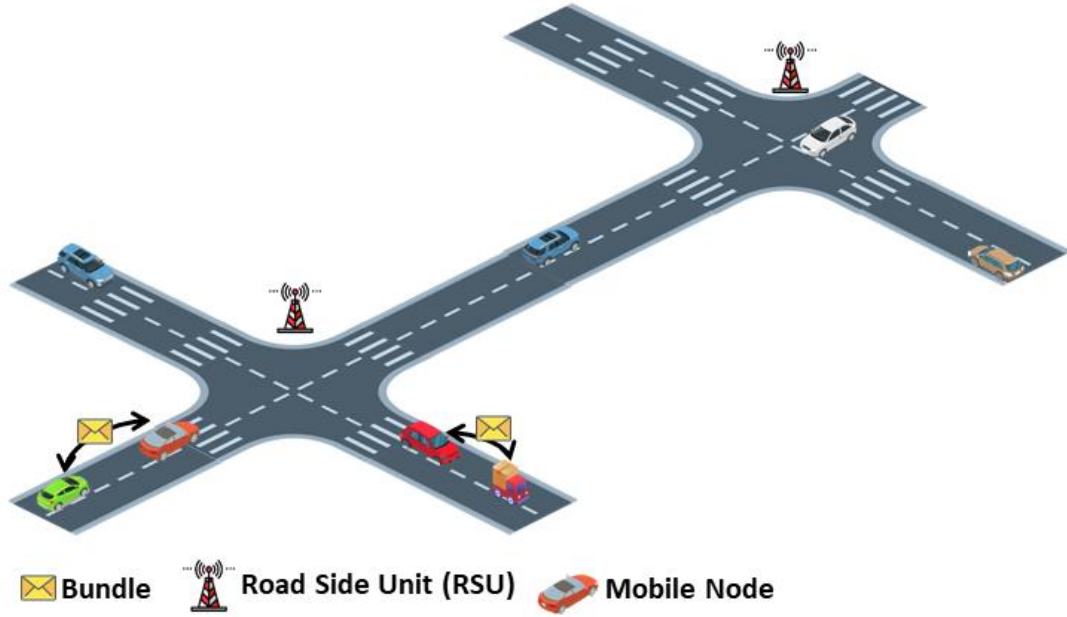


Figure 1-4 A VDTN scenario.

Traffic safety services are the primary and most valuable application services for VDTNs. Through V2V and V2I communications, real-time information can be exchanged periodically. Real-time information mainly includes the movement state of nodes (such as the current speed of nodes, the position of nodes), and surrounding traffic conditions (such as the number of surrounding nodes). By analyzing real-time information, drivers can detect potential hazards around them and take appropriate emergency measures. The application is mainly used to improve the traffic safety of urban roads and avoid traffic accidents such as rear-end collision and side hanging. Typical applications include collaborative collision warning, collaborative lane reservation, and post-accident warning [29].

Traffic management services realize the monitoring of road traffic status through collaborative perception between vehicles or based on the movement of detected cars. For traffic management, the traffic status information can be centrally processed through the traffic control center, and the traffic can be effectively dispatched. The vehicle can re-plan the route based on the real-time traffic status information obtained [30].

Traffic value-added service is a new type of VDTN service application, mainly through the message transmission between vehicles to provide drivers with diverse mobile communication content, mobile sharing, and multimedia entertainment services, thereby increasing the fun in

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the driving process. However, since its service content needs to occupy a large amount of network bandwidth and needs to be compatible with traditional Internet service applications, the service quality needs to be improved [31].

### **1.3 UAVs in DTN**

In the VDTN environment, the communication distance of V2X (vehicle to everything) is limited by the surrounding environment. The vehicle speed is fast, the network topology changes quickly, and the RSU (roadside unit) carries great pressure, causing data congestion, information transmission lag, and reducing network performance. In addition, network performance may be affected by low communication quality and network partitioning in some extreme environments, such as areas where infrastructure is damaged by earthquakes, fires, or floods. Besides, due to obstacles or complex terrain, the quality of the V2X link is likely to be reduced or even obstructed in the worst case.

Unmanned aerial vehicles (UAVs) have great potential in enhancing the performance of the mobile communication system due to their advantages over vehicles or mobile devices [32-34]. It has been widely used in traffic monitoring, disaster rescue, military reconnaissance, and other fields. The combination of UAVs and VDTNs to form an integrated collaborative network can further enhance the information interaction capability of VDTN. First, UAVs can extend the information dimension of ground vehicles. Secondly, the UAV group dispatched to the target area can quickly build a network and provide timely network services for ground vehicles. Finally, when the V2X link is interrupted, the UAV can act as an aerial base station to set up a relay channel for the ground network [35-37]. The deployment of the UAV ferry nodes in the VDTN is shown in Figure 1-5.

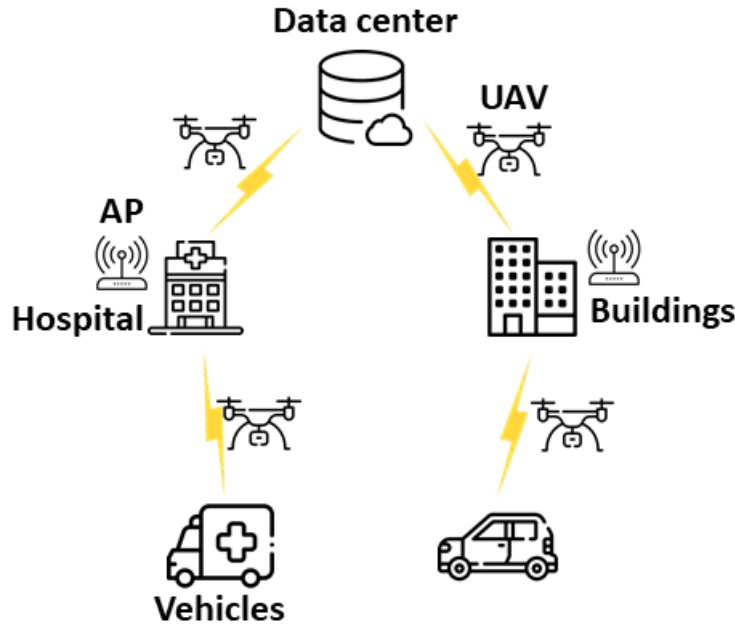


Figure 1-5 UAV ferry nodes in VDTNs.

The UAV-assisted VDTN takes UAV as relay nodes, which can receive and forward data uploaded by ground users, thus improve the reliability of wireless communication links, enhance infrastructure flexibility, and provide communication coverage for areas without networks. The architecture was originally proposed to be mainly used in military fields, such as unmanned tanks and UAVs, for joint operations to improve the judgment of decision-makers due to information asymmetry and thus achieve tactical victory. In recent years, this architecture has been gradually applied to civil industries such as intelligent transportation systems [38], earthquake relief [39], and precision agriculture [40], especially the rapid development of IoT and the 5G industry, which has set off a wave.

The architecture of UAV assisted VDTN usually considers the collaborative control between UAV and UAV (U2U), UAV and cloud (U2C), UAV and vehicle (U2V), and UAV and ground base station (U2G). The introduction of UAV in DTN can provide more reliable services for vehicle nodes and mobile device nodes to meet the needs of message forwarding. Flexible use of UAV nodes is the key to improving network performance.

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## 1.4 Contribution

The aim of this thesis is to design a routing protocol to support large traffic, low latency, and diverse application in the VDTN.

According to the reasons mentioned above, a VDTN-based routing protocol and a specific buffer management algorithm to support handling redundant messages in the cache are proposed in this thesis. Furthermore, a protocol is presented that enables more effective use of UAVs in VDTN environments.

For the VDTN-based routing protocol, the contributions are as follow:

- An improved routing algorithm based on the encounter probability calculated by PRoPHET and combined with a binary Spray-and-Wait copy control strategy is proposed in this paper. Simulation results show that the new algorithm improves the message delivery rates while reducing overhead ratio and delay.
- A specific buffer management algorithm designed for the PRoPHET Based protocol is proposed to improve its congestion mitigation policy. In the algorithm, the impact of the message on the cache, the time factor of the message, and the probability of the message being forwarded to the destination node are comprehensively considered to construct the congestion control metric (CCM). In the node's buffer, each message copy is sorted according to the CCM value. In order to improve the efficiency of buffer utilization, messages with higher CCM will be forwarded first. When congestion happens in the node, the message with the smallest CCM is dropped to reduce the impact of unreasonable message dropping on network performance.

For the UAVs algorithms, the contributions are as follow:

- Improve the forwarding probability factor. The routing algorithm based on the time factor defines the persistent connection time ratio extracted by analyzing the connection mode of two nodes. The encounter probability in the traditional probabilistic routing algorithm is improved by considering the influence of the time factor. In the message forwarding process, the next-hop node is selected according to the improved encounter probability.

- 
- A new routing protocol for UAV assisted VDTN environment is proposed. The proposed protocol considers the persistent connection time between nodes in the message forwarding decision. With the intelligent method of choosing relay nodes, the proposed protocol enables a more effective use of UAVs in DTN environments.

## 1.5 Organization of the thesis

The remainder of the thesis is organized as follows:

- In Chapter 2, the introduction of DTN-related technology is presented, including existing routing protocols, buffer management, and the use of UAVs in the DTN environment.
- In Chapter 3, a new routing protocol for VDTN is proposed. The proposed protocol takes into account the encounter probability between nodes and the number of copies of the message in the forwarding decision. A local optimal buffer management drop strategy based on the proposed protocol is also investigated, which combines the delivery successful estimation, time measurement and buffer overhead ratio to calculate the congestion control metric (CCM) value. The CCM value is the parameter that controls the message drop policy to reduce the impact of blindness message drop to the delivery rate. The effectiveness of the routing protocol is verified by observing network performance evaluation metrics such as message delivery rate and network overhead.
- In Chapter 4, a new routing protocol for UAV assisted vehicular DTN is proposed. The proposed protocol considers the persistent connection time ratio between nodes in the message forwarding decision. With the intelligent method of choosing relay nodes, the proposed protocol enables a more effective use of UAVs in DTN environments. Simulations in typical scenes and post-disaster scenes were carried out. Extensive simulations in various scenarios confirm the advantage of the proposed protocol over existing baselines in terms of message delivery ratio, network overhead, and end-to-end delay.
- Chapter 5 concludes the thesis and discusses future work for the research.

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# CHAPTER 2

## 2 VDTN and related technology

In section 2.1, the classification of routing protocol in VDTNs is introduced. Sections 2.2-2.4 introduce replication-based routing protocols, historical-based routing protocols, and social-awareness routing protocols, respectively. Section 2.5 lists the related research about the buffer management scheme for VDTN. Related studies about UAVs in the VDTN environment is explained in section 2.6. Section 2.7 introduces several DTN technologies in the post-disaster scenario. Finally, section 2.8 concludes this chapter.

### 2.1 Routing protocols in VDTN

Routing refers to the successful delivery of the packet to the destination node by finding a connected path based on the known network information stored in the node. Routing mainly consists of two primary actions: confirm the connecting path and message transmission. There is a complete and stable end-to-end path between the source node and the destination node in the traditional network, but there is no such path in VDTNs. Therefore, VDTN cannot apply traditional routing protocols. Due to the sparse distribution of VDTN nodes and random movement of nodes, network segmentation is easy to occur, and communication between nodes is inconvenient. Therefore, nodes need to transfer messages to relay nodes and repeat this process until the message is delivered to the destination node. Routing algorithm research is the most important and basic content of DTN data transmission and is the most fundamental guarantee of data delivery [41-43].

The traditional Internet routing protocol cannot be applied to VDTNs. According to the sparse distribution of VDTN nodes and the random movement of nodes, a suitable routing protocol is required to meet the communication needs. Researchers have proposed several innovative and effective routing algorithms.

The VDTN routing protocol could be divided into replication-based routing protocols, historical-based routing protocols, and social-awareness routing protocols. The

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replication-based routing protocol includes single-copy routing protocols and multi-copy routing protocols. The single-copy routing protocols refer to the fact that there is only one copy of the same message in the whole network, and the node will only deliver the message to the appropriate relay node. Because there is only one copy of the message in the network, the message delivery rate is low, the delay is large, and the message is easy to lose. Multi-copy routing protocols mean that there are multiple copies of the same message in the whole VDTNs [44]. If one copy is delivered to the destination node, the delivery will be considered successful. At present, multi-copy routing is mostly adopted in the VDTN routing algorithm because it could improve the success rate of message delivery and reduce the communication delay. In the historical-based routing protocol, a node maintaining some network information related to other nodes to establish an Ego Network [45]. Thus, the social connection or characteristics between nodes are measured, and the utility function is calculated. Then, the utility function is used to select the satisfactory forwarding node. Social-awareness routing protocols take the social connections and attributes between nodes as the primary basis for routing design [46]. Compared with the frequent movement of nodes, the social contact between nodes shows relative stability and regularity. As a result, social connections become a more rational way to predict future meeting opportunities.

## **2.2 Replication-based routing protocols in VDTN**

### **2.2.1 Single-copy routing protocols in VDTN**

In single-copy routing protocols, a node does not remain the message copy after delivering it to the relay node, so there is only one copy of the message in the whole network. Single-copy routing protocols take up fewer network resources and use less storage space to reduce the network load. However, only one copy of the message exists in the network, which significantly reduces the delivery success rate of the message, increases network overhead and the delivery delay. Therefore, there are not many studies on the single-copy routing algorithm. Two typical routing algorithms will introduce below: first contact routing protocol and direct delivery routing protocol.

- (1) First Contact routing protocol (FC) [47]: After a message is created by the source node, it stores the message in its cache and carries the message moving randomly. During the process of movement, the message will be delivered to the first node it meets (no matter whether the node is the destination node or not). The source node will



randomly deliver the message to one node when there is more than one node within the transmission range. The relay node will continue to carry the message to move randomly and deliver it in the same way until it is successfully transferred to the target. The message delivery process of the first contact routing protocol is shown in Figure 2-1.

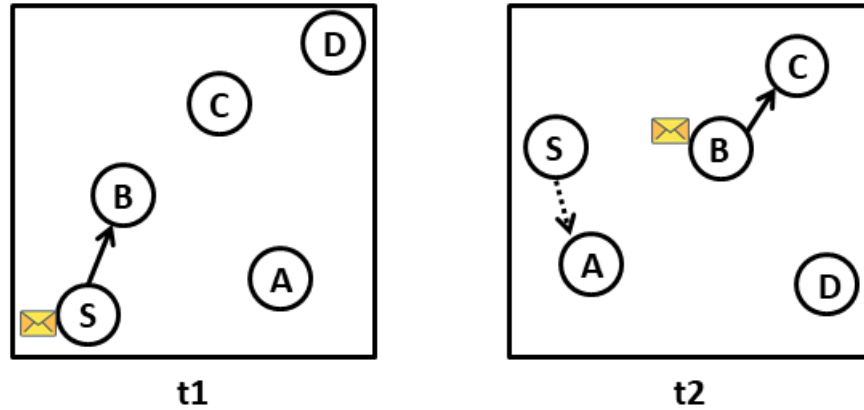


Figure 2-1 Message delivery process of the first contact routing protocol.

A message created in the source node  $S$ , and its destination node is  $D$ . The destination node  $D$  is not in the communication range of  $S$ . At  $t1$ ,  $S$  meets node  $B$ . Whether node  $B$  is the destination node or not,  $S$  will deliver the message to  $B$ , and  $B$  will store it in the cache space and move continuously. At  $t2$ , node  $B$  carrying the message meets node  $C$ , and  $B$  delivers the message to node  $C$ . Source node  $S$  meets node  $A$ , and no message is delivered because there is no stored message in  $S$ . Node  $C$  will transfer the message in the same way, to deliver the message to the destination node  $D$ .

The first contact routing algorithm cannot predict the path between the source node and the destination node. Therefore, the message delivery success rate is low, and the delay is huge.

- (2) Direct Delivery routing protocol (DD) [48]: The main idea is that the source node generates and stores messages in the cache, and the node carries messages to move until it meets the destination node. The message delivery process of direct delivery routing is shown in Figure 2-2.

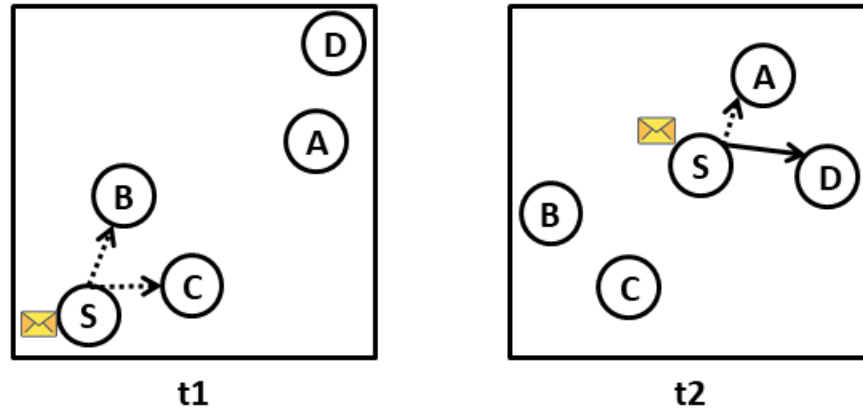


Figure 2-2 Message delivery process of the direct delivery routing protocol.

A message created in the source node  $S$ , and its destination node is  $D$ . Since the destination node  $D$  is not in the communication range of  $S$ ,  $S$  will store and carry the message to move randomly. At  $t_1$ ,  $S$  meets with nodes  $B$  and  $C$ . Since neither node  $B$  nor node  $C$  is the destination node,  $S$  will ignore node  $B$  and node  $C$  and continue moving. At  $t_2$ , node  $A$  and destination node  $D$  appear in the transmission range of node  $S$ . At this time,  $S$  delivers the message directly to node  $D$ .

Since this routing algorithm only relies on the source node and the destination node to meet directly in the network, the success rate of the message delivery is low. In a real network environment, direct delivery routing is likely to result in message delivery failure.

### 2.2.2 Multi-copy routing protocols in VDTN

Due to frequent network segmentation in the DTN, just keep one message copy in the entire network is extremely easy to cause delivery failure. Therefore, send the replica of a message to relay nodes could improve the success rate of message delivery. There will be multiple transmitting copies of the same message in the network at the same time. The proposal of multi-copy routing can significantly improve the success rate of message delivery and reduce network latency. Compared with single-copy routing, multi-copy routing has an advantage under the condition that various network resources are abundant. Therefore, researchers have done many studies on multi-copy routing. Typical multi-copy routing protocols will introduce below.

- (1) Epidemic routing protocol [49]: The Epidemic routing protocol is the earliest

multi-copy routing protocol used in DTN. It is mainly aimed at the intermittent connection of nodes in DTN, which increases the probability of successful message delivery by increasing the number of messages copies in the network. In the Epidemic routing protocol, as long as the source node encounters another node that does not have the message, it will send one copy. The relay node will deliver the message in the same way until it is given to the destination node. The delivery process of the Epidemic routing message is shown in Figure 2-3.

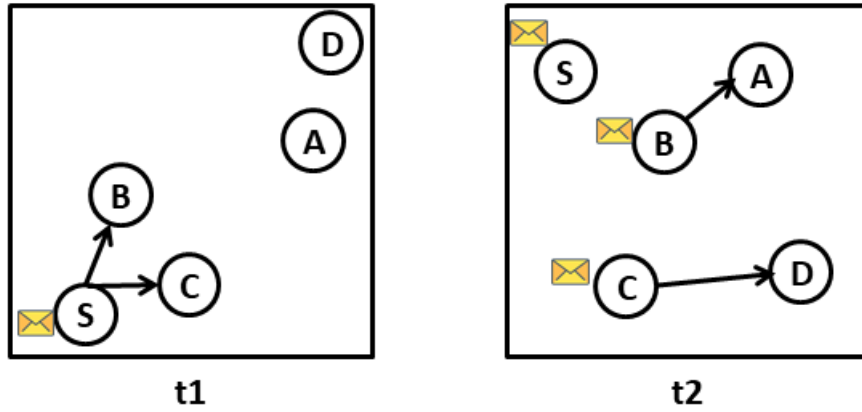


Figure 2-3 Message delivery process of the Epidemic routing protocol.

A message is created in the source node  $S$  that the destination is node  $D$ . At  $t_1$ ,  $S$  encounters nodes  $B$  and  $C$ ,  $S$  duplicates the message and delivers the copy of the message to nodes  $B$  and  $C$ . At  $t_2$ , node  $B$  meets node  $A$  and node  $C$  meets node  $D$ , nodes  $B$  and  $C$  will deliver the message copy to the node they meet. Since the message has been delivered to the target, the message delivery process has ended.

The Epidemic routing is suitable to work in network environments where the network size and data traffic are small. Still, the network communication bandwidth and node cache space are large enough. At this point, the Epidemic routing can significantly enhance the delivery probability and lessen the transmission delay. However, it will consume many network resources, including network bandwidth and the use of nodes cache.

- (2) Spray-and-Wait routing protocol [50]: In order to solve the severe consumption of network resources caused by the redundancy of the message copy in the flood routing algorithm, the Spray-and-Wait routing protocol uses a specific strategy to limit the

message copy while forwarding the message. This algorithm only generates a small number of message copies in the network for forwarding to ensure that the total number of message transmissions can be controlled. Then each message copy will be independently forwarded according to a more effective single-copy routing algorithm. The Spray-and-Wait routing protocol can be regarded as a compromised algorithm between single copy routing algorithm and flood routing algorithm.

The message transfer process of the Spray-and-Wait routing is shown in Figure 2-4. From  $t_1$  to  $t_3$  is the spray phase, during which the node with the message will send half of the message copy to the node that does not contain it. The  $t_4$  is the wait phase. At this time, the message will only be transmitted to the destination node.

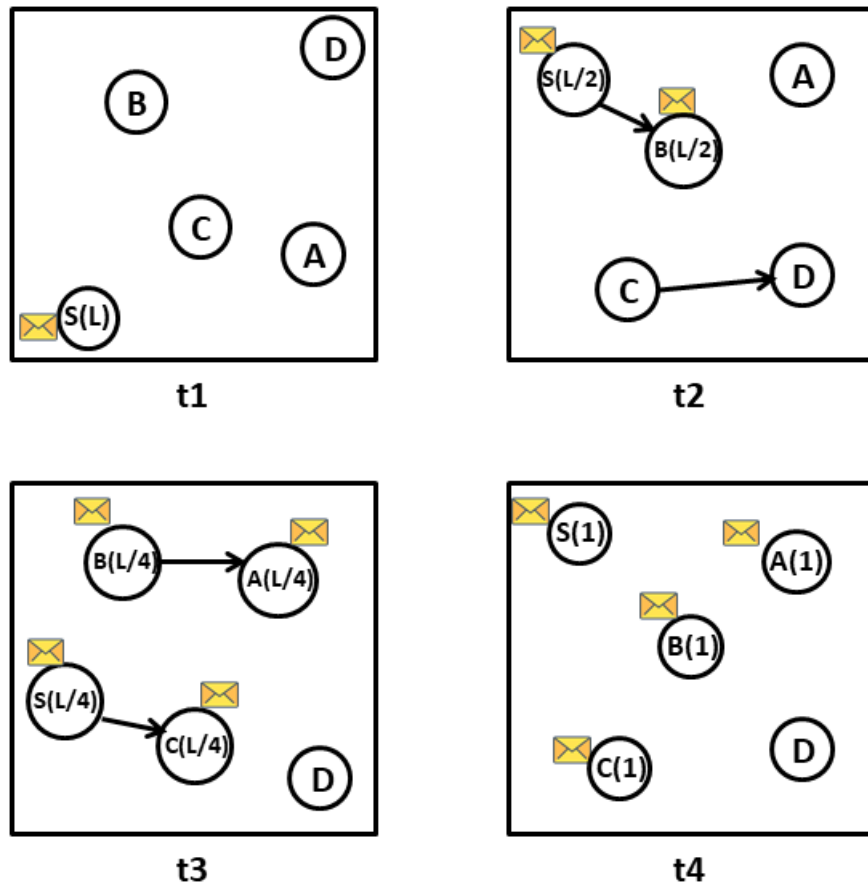


Figure 2-4 Message delivery process of the Spray-and-Wait routing protocol.

In Figure 2-4, at  $t_1$ , a message is created in the source node  $S$  and replicate  $L$  copies. At  $t_2$ ,  $S$  meets node  $B$  delivers  $L/2$  copies. At  $t_3$ , node  $S$  meets node  $C$  and node  $B$  meets

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node  $A$ . Node  $S$  and node  $B$  will give half of their  $L/2$  copies to  $C$  and  $A$ , so each node has  $L/4$  copies of the message. At  $t_4$ , every node only has one message copy, so it enters the wait phase. The message will only be transferred to the destination node.

## 2.3 Historical-based routing protocols in VDTN

In the VDTN, each vehicle may have a particular movement rule. For this reason, the researchers propose the probabilistic routing algorithm. The PRoPHET (Probabilistic routing protocol using the history of encounters and transitivity) routing is a routing algorithm based on the historical encounter information of nodes. Each node in the network maintains an encounter probability table that records the probability of meeting between the node and other network nodes. When two nodes encounter, each node will update its probability table. If the probability of the encountered node to the destination node is higher, the message will be copied and delivered to the encountered node; otherwise, the message will continue to be stored in the cache, waiting for delivery to the node with higher probability [51].

The PRoPHET routing mainly relies on the probability table maintained in the node to select relay nodes.  $P(A, B) \in [0,1]$  represents the encounter probability between node  $A$  and node  $B$ , and the probability calculation process is as follows:

$$P(A, B) = P(A, B)_{\text{old}} + [1 - P(A, B)_{\text{old}}] \times P_{\text{init}} \quad (1)$$

$P(A, B)_{\text{old}}$  is the last encounter probability between node  $A$  and node  $B$ .  $P_{\text{init}}$  is the initial value of encounter probability.

If two nodes do not encounter in a period, the  $P$ -value will gradually decrease. The formula of probability reduction with time is as follows:

$$P(A, B) = P(A, B)_{\text{old}} \times \gamma^k \quad (2)$$

$\gamma$  is the attenuation constant, and  $k$  is the unit number based on historical attenuation from the last encounter between nodes.

If node  $A$  often meets node  $B$ , and node  $B$  usually meets node  $C$ , then the probability of node  $A$  to node  $C$  can be obtained. The equation is as follows:

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$$P(A, C) = P(A, C)_{\text{old}} + [1 - P(A, C)_{\text{old}}] \times P(A, B) \times P(B, C) \times \beta \quad (3)$$

$\beta$  is a transfer factor between 0 and 1.

The PROPHET routing is an improvement on the flooding-based routing. Nodes no longer blindly deliver messages, which reduces the loss of network resources.

Sok et al. proposed a DPRoPHET routing protocol [52] that forwards data through a joint decision of node historical meeting information and transmission distance between nodes. This algorithm takes the distance value between nodes as an essential factor in judging whether the forwarding path is reasonable to improve the forwarding efficiency of messages.

Rashid et al. proposed a weight-based buffer scheduling management method [53] and dynamically adjusted the message weight criteria according to the message properties to selectively drop messages.

Ouadrhiri et al. proposed a probabilistic routing based predictive control forwarding strategy [54], which increased the number of received messages without increasing the relayed message rate and improved the PROPHET protocol performance to optimize the overhead.

Medjiah et al. proposed an improved routing protocol (ORION) [55], which evaluated its neighbor nodes by counting newly added node information. ORION used an autoregressive moving average (ARMA) stochastic process to predict node encounter connections and location coordinates, improving message transmission efficiency.

The message forwarding prediction value used by the above algorithm only represents the frequency of encounters between nodes, and it is assumed that the nodes can establish a connection when they meet and can complete data transmission. However, the successful transmission of a message depends not only on whether the message can reach the destination node through multiple relay nodes but also on whether the connection time is long enough to complete the transmission of the message. Therefore, such an assumption is difficult to hold in the real traffic environment.

MobySpace [56], MVRA [57], MaxProp [58] take advantage of nodes' mobility patterns and frequently-visited areas to design routing protocols. The social connection between nodes

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could be regarded as an essential kind of contextual information.

The SimBet routing protocol [59] based on Ego Network establishes utility function by using the intermedium centrality and similarity information between nodes and destination nodes. The contact lists are exchanged between nodes to update the information of the interface. The information of the destination node is then exchanged. The utility function is calculated and forward the message based on this utility function. Based on SimBet, the SimBetTS routing protocol [60] considers the connection strength information between nodes. The SimBetAge routing protocol [61] adds the concept of Freshness to guide the data forwarding process.

Besides, the regularity of people's movement is another metric to determine the relay node. The Predict and Relay routing protocol [62] uses the homogeneous semi-Markov process model to describe the movement of nodes between several possible locations. The probability distribution of the time a node moves and stays between these positions are determined according to the historical movement record. Nazir et al. hypothesized that people act in a similar mobile pattern every day and built a content distribution system based on this social encounter factor [63].

## **2.4 Social-awareness routing protocols in VDTN**

Many routing protocols are designed with the concept of social communities recently. This feature could effectively help the node predict the chance of encounter and select the appropriate relay node [64]. Communities usually require the support of community detection algorithms. Different communities may coincide with each other in the process of node movement. Social-awareness routing protocols usually divides the data forwarding process into two stages: the inter-community data forwarding stage and the intra-community data forwarding stage, as shown in Figure 2-5.

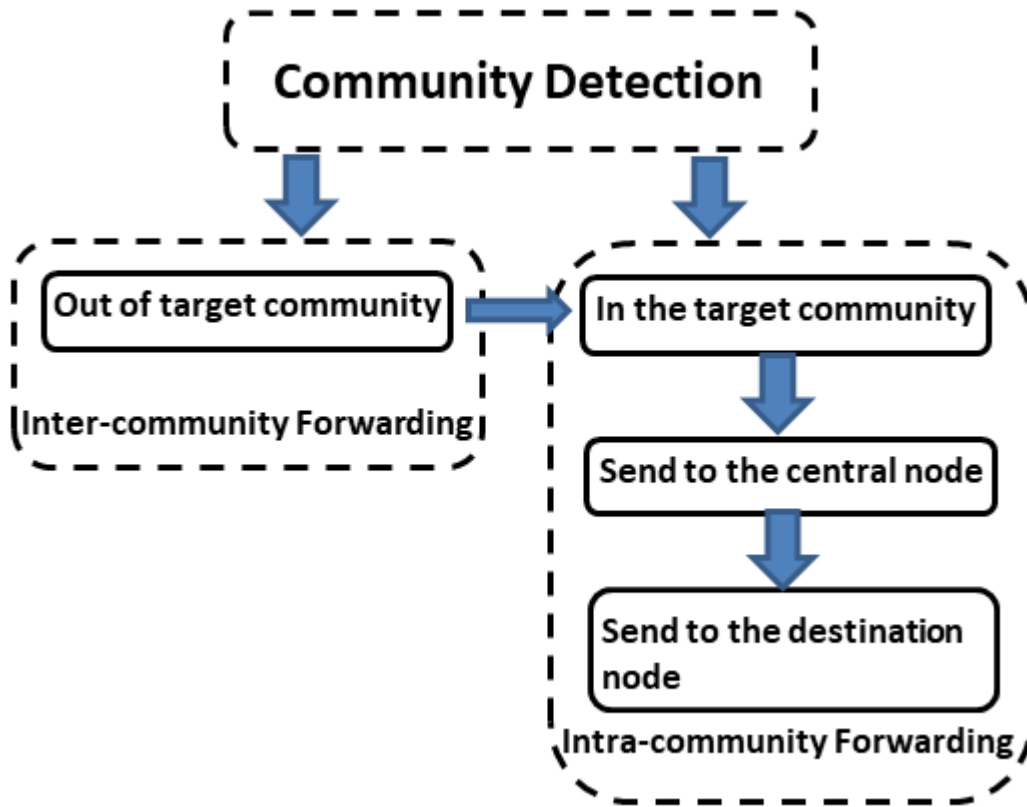


Figure 2-5 Data forwarding process of the social-awareness routing protocol.

When the source node and the target node are not in the same community, a relay node is needed to forward the message to the community where the target node is located. After the message is forwarded to the target community, the relay node will forward the message to the target node according to the specified strategy. The message forwarding strategy within a community is usually different from the message forwarding strategy between communities.

For the social-awareness routing protocol, community detection and construction algorithms are very important. There are three typical algorithms: SIMPLE [65], K-Clique [66], and MODULARITY [67]. Meanwhile, the Bubble Rap routing algorithm based on the K-Clique algorithm is proposed [68]. The protocol generates social contact graphs based on historical encounters to discover communities. Bubble Rap builds and maintains the node ranking table in the network. When data is forwarded, it is first transmitted according to the global ranking until it has arrived at the community that the destination node is located. Finally, the local ranking is used to find the destination node in the community.



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Bulut et al. identify social connections between nodes based on direct and indirect friend connections between nodes and establish friend-based communities [69]. They believe that close friend contact has three characteristics: high contact frequency, long contact time, and regularity. So, they defined social pressure metrics (SPM) and conditional social pressure metrics (conditional SPM) to represent direct and indirect friend contact, respectively. The values of these two indicators are maintained by analyzing the historical contact records. The node where the direct or indirect friend contact exceeds the threshold constitutes the friend-based community. Moreover, in order to show the difference in time, different groups of friends were established for each node at different times of the day. When data forwarding starts, the node with strong connections among friends in the destination community will be selected as the next forwarding node.

Zhou et al. found that the habitual movement of nodes helped to reduce the average communication delay [70]. The behavior deviating from custom will seriously affect the performance of routing. They propose a DR routing protocol that can handle deviant behavior. The protocol divides the network into several adjacent social clusters according to the characteristics of clustering. When the data is forwarded, one copy of the message is delivered for each cluster. In this way, the effect of deviation behavior on routing performance is weakened.

Besides, many studies consider the relationship between communities and specify the data forwarding strategy between communities. The LocalCom protocol [71] uses information such as historical meeting frequencies, meeting lengths, and separation cycles, to define an indicator called “Similarity” and building up Neighboring Graph based on this indicator. Distributed discovery communities based on the Neighboring Graph and Similarity. LocalCom has also developed different strategies for inter-community and intra-community data forwarding. This protocol sets the node that has direct friend contact between the communities as a gate node. Static pre-pruning and Dynamic pruning are used to select forwarding nodes from gateway nodes based on the intermediate number centrality to complete forwarding among communities. In the community, a more suitable relay node is selected by comparing the similarity value.

Xiao et al. proposed a distributed community-based routing protocol [72]. In this paper, the community frequently visited by nodes is named “Home” and the home-aware community

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model is established. The shortest expected delay for each “Home” provides the basis for routing selection in the extended diagram. Besides, the algorithm extends the concept of centrality to all network nodes.

## **2.5 Buffer management in VDTN**

This section will summarize the recent research work on buffer management in the DTN field. Buffer management is generally based on a certain routing algorithm. The effect of adopting the same buffer management policy will be different depending on different routing algorithms. This section summarizes the main buffer management algorithms in DTNs. The purpose of buffer management is to improve the network performance of routing protocols.

The causes and effects of congestion in the traditional Internet can be summarized as follows: congestion caused by regular message transfer; message sharding transmission results in shards that cannot be sent simultaneously; the accumulation of redundant messages, etc. The main effects on network performance are packet loss, increased overhead and energy consumption, an increase in message delivery delay, reduction in the successful delivery rate of messages.

Based on the unique application background of DTN and referring to the traditional network, the thesis proposes that when new messages arrive, the node has remaining cache space that cannot meet the needs of new messages and is forced to take the operation of dropping messages due to insufficient storage as the DTN node is congested define standards.

Most DTN applications are in extreme environments such as deep space, deep sea, remote areas, and the wild, which inevitably have different deployment requirements and restrictions from the traditional Internet. In these special application environments, since communication nodes with large-capacity storage devices are generally unable to be deployed, there are often limited storage resources and tight competition. At the same time, after deploying DTN in these environments, its communication performance requirements are not the same as those of the traditional Internet.

The algorithm design often takes the message delivery rate as an important evaluation index due to the unique network topology and intermittent connectivity of nodes in the DTN. Moreover, network congestion, as an important influencing factor, is also attracting more and

more attention. How to use limited network storage resources reasonably is related to network performance in special application environments. The classification and introduction of DTN buffer management algorithms are shown in Figure 2-6.

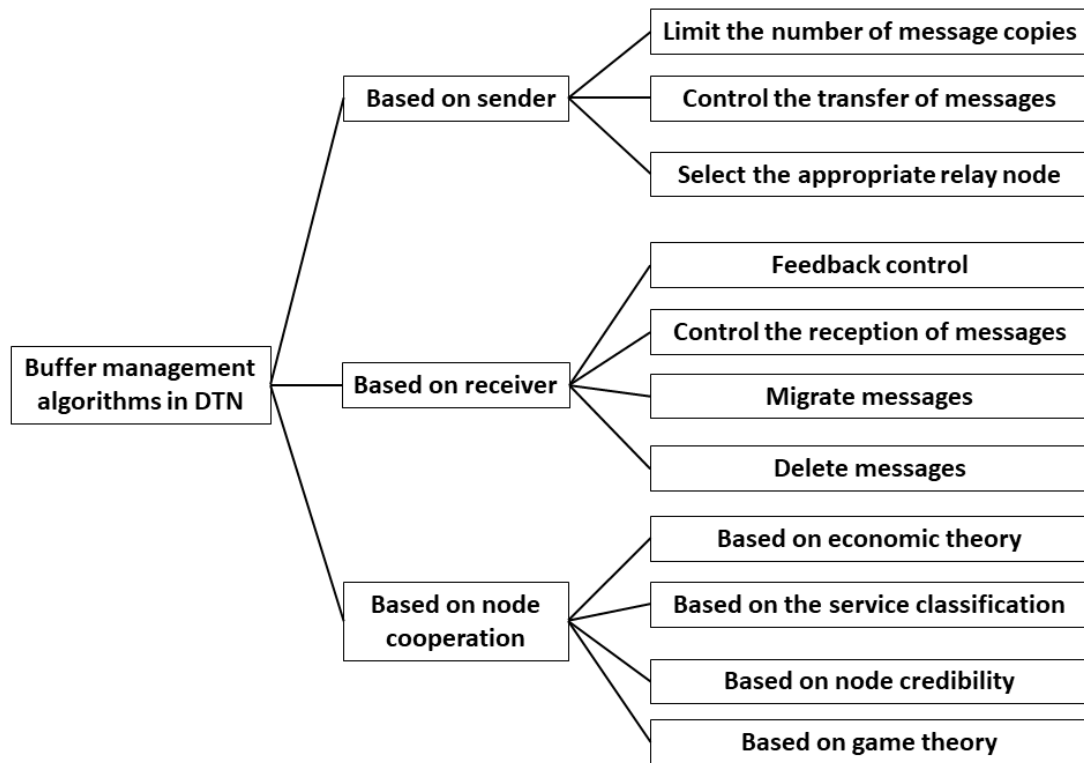


Figure 2-6 DTN buffer management algorithm classification.

## 2.5.1 Buffer management based on the sender

The buffer management algorithm based on the sender is controlled mainly from the perspective of the sender to avoid the unreasonable occupation of the cache space of other nodes. This kind of buffer management algorithm is generally accomplished by restricting the message replicas in the network, controlling sending messages, and selecting appropriate relay nodes.

### 2.5.1.1 Limit the number of message copies

In multi-copy routing algorithms such as Epidemic, the unlimited diffusion of message copies

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will quickly consume the limited network storage resources and inevitably cause congestion. It is necessary to take effective measures to control the unrestricted spread of message copy to suppress network congestion.

In order to overcome the network congestion caused by the routing algorithm spreading messages arbitrarily, the simplest method is to add control of the number of message copies during the flood routing algorithm execution [73]. Nodes control the spread of a message copy by comparing nodes encountered with this message to the total number of nodes encountered over a period of time. The message copy will immediately be cleared to avoid being forwarded further and wasting network storage and communication resources after the transmission. Other nodes perform the cleanup of the delivered copy immediately by publishing the message delivery confirmation table when nodes meet.

SMART [74] groups frequently encountered nodes in a partner group. In the first phase, the source node distributes a fixed number of message copies in the network in a binary spray mode; in the second phase, when a message copy is transferred to the destination node's partner group, the node increases the number of message copies, and only in the group continue to execute the binary spray until the message delivered to the destination node. In this way, SMART reduces the total number of message copies required for successful delivery and relieves congestion. A-SMART [75] is an improved SMART algorithm. In the first phase, the message is not sprayed. After the message is transferred to the destination node partner group according to the minimum number of hops, the same delivery as SMART is performed in the second phase.

RR [76] is based on the idea that more message copies could cause more network congestion. By observing local network congestion, i.e., updating the message copy threshold according to the proportion of the delete operation in the normal relay operation. The worsening of network congestion is avoided.

DCCR [77] uses dynamically adjusting the threshold to avoid congestion. The threshold calculated by collecting the cache usage rate of neighbor nodes, the node divides the congestion of the surrounding network into mild, moderate, and severe (prohibit message copying, and perform a history based on the probability of encountering routing), congestion (moving the longest-lived message to the neighbor node, letting it execute the direct delivery strategy, and no longer transfer the message).

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### 2.5.1.2 Control the transfer of messages

TBCC [78] sets a fixed token in the network for strictly controlling nodes to send and receive messages according to network storage resources. The initial token of each node is the same. When a message needs to be forwarded, the token needs to be used, and the receiver receives the token. In this way, when a node token is used up, no more messages can be sent. Only after helping other nodes to transfer messages to harvest tokens or borrowing tokens from neighbors can they send messages again. When a message is deleted due to congestion, expiration of lifetime, or arrival at the destination, the token of the corresponding node is added. This strategy strictly controls network congestion.

Lakkakorpi et al. [79] broadcast congestion signals to the surrounding nodes when the uplink storage was about to run out. In this way, the current node no longer communicates with surrounding nodes until the congestion signal is removed and resumes the message transmission.

Consider the impact of message retention time on network congestion. If nodes transmit incomplete messages in the limited connecting time, too many message fragments will be scattered in the network and occupy the network storage resources for a long time. This affects the destination node to receive the message once, increases the message delivery delay, and easily triggers network congestion. To avoid the situation mentioned above, Al-Siyabi et al. proposed an access control (AC) [80], which first relays messages that can be transmitted all at once within a limited time of connection. If the remaining connectivity time can only transmit part of the message, the remaining message fragments will be forwarded first the next time there is a connectivity opportunity.

The FRMM [81] uses the Jains equity index and allocates different connection bandwidth for each node according to its weight, which plays a certain role in reasonably allocating resources and controlling congestion.

According to the local flow at each node and the remaining cache space of the relay node, the LFC [82] adjusts the data flow at each node to control the storage overflow of the relay node, the saturation of the transmission link, and the increased burden of useless retransmission to the network. This algorithm is mainly proposed for interplanetary networks.

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Wittie et al. [83] set up fixed base station nodes with low communication bandwidth and long communication distance in mobile nodes with a relatively fixed movement range of high communication bandwidth and short communication distance to complete information collection of each node and message status in the network, so as to centrally control network resources and shunt, and control congestion of each node.

### **2.5.1.3 Select the appropriate relay node**

Sometimes, congestion control needs to consider message generation and transmission and select the appropriate relay node to complete the message delivery. Many factors need to be considered in choosing a suitable message relay node to get an optimal relay operation, which can ensure the successful delivery of messages and effectively control network congestion.

In the algorithm that only uses a single factor to select appropriate relay nodes, MobySpace [56] selects nodes with a similar movement model of destination nodes as the relay nodes.

There are various combinations of specific parameters to determine the appropriate node in careful consideration of many factors. In terms of only considering the node itself and local static attributes of the network, CAFE [84] exchanges state information and historical encounter records of each node when it meets, and maintains two management modes. Congestion management is concerned with the availability of neighbor nodes, such as remaining storage and average latency. Contact management focuses on previous contacts (duration, frequency, last encounter time) and message forwarding between neighbor nodes and other nodes. Combine these two kinds of information to select the appropriate relay node

Radenkovic et al. [85] integrate node sociality, node resources (remaining storage, delivery delay, and historical congestion rate), and local network characteristics (the overall storage remaining status in the network, the possible increased delivery delay and congestion rate) guide message transfer to avoid hotspot areas with high delivery probability but prone to congestion. While increasing the number of hops required for successful delivery, it guarantees the message delivery rate and avoids congestion.

Khuu et al. [86] take into account the number of hops, the connection rate, and the interference from other nodes in the message delivery process (density of neighbor nodes) to jointly determine the effectiveness of the available link as an assessment of congestion

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standard to select the appropriate relay node for message delivery.

GRCCM [87] prevents nodes from over-selecting nodes with high delivery capabilities (such as base stations) to relay messages, resulting in node congestion and network performance degradation. The node's remaining buffer space, the number of neighbors, the transmission bandwidth, and the game theory is used to determine the proportion of messages distributed to high delivery capability nodes and low capability nodes (regular vehicles) to achieve maximum delivery performance. While using high-capacity nodes to assist delivery to maximize network performance, rational use of low-capability nodes to assist delivery can avoid the congestion of high-capability nodes.

DFR [88] considers dynamic factors such as node movement in selecting relay nodes. When the nodes meet, compare the list of node position coordinates they carry and decide whether to update the node position information according to the node coordinate age index. The relay node selection is based on whether the azimuth angle between nodes is less than the threshold, and the relative movement trend of the two nodes. At the same time, it is also based on the density of messages that have been disseminated, the delivery possibility, and TTL to determine which types of messages to transfer or delete can improve the network performance. Furthermore, use ACK to delete the delivered message copy in time.

## **2.5.2 Buffer management based on the receiver**

In the buffer management algorithm based on the receiver, the node buffer is allocated from the perspective of the receiver to effectively reduce its storage burden and alleviate and suppress network congestion. This kind of buffer management is generally accomplished through feedback control, control the reception of messages, migrate messages, and delete messages.

### **2.5.2.1 Feedback control**

Due to the stable end-to-end connection of the traditional Internet, the method of controlling congestion from the global network is generally adopted. The purpose of eliminating congestion is achieved by establishing a global feedback control system [89] and using the Nyquist criterion [90]. Due to the unique communication characteristics of DTN, coupled

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with the intermittency of DTN connection and the unpredictability of node encounter time, feedback generally has a severe lag, which cannot sufficiently reflect the real-time condition of network congestion. The lagging congestion control will also cause a large jitter in the message sending rate and instability of the DTN data transmission rate.

Godfrey et al. [91] directly used feedback to adjust the message sending rate. When the node gets the feedback that the message is lost, it directly rolls back the message sending rate to the rate of the last successful message delivery. Cen et al. [92] used the TFRC method [93] in the traditional Internet to pass an acknowledgment between the destination node to the source node to adjust the message sending rate of the source node. Johari et al. [94] proposed a buffer management method to stabilize the network transmission performance by analyzing the relationship between message queuing delay, propagation delay, and congestion obtained from feedback. ATP [95] is based on this principle that the message delivery delay can reflect the characteristics of network congestion, and the message delivery delay is fed back to the source to adjust the message sending rate of the source and control congestion.

### **2.5.2.2 Control the reception of messages**

From the perspective of using the limited storage resources of nodes efficiently, C2AM [96] considers the encounter interval between nodes, the number of messages waiting to be transmitted in the node, and the transmission bandwidth, to estimate the time that the message stays in the node cache. Try to avoid receiving large messages that may remain in storage for a long time or messages with a short lifetime. This method can ensure that the node helps transfer multiple messages as much as possible in a short time. At the same time, it also avoids that the message is deleted due to the end of its lifetime before successfully delivered and the waste of storage resources used along the process.

Zhang et al. used the revenue principle in ref [97], tended to receive more high-weight and easy-to-deliver messages, and increased the delivery rate as revenue. At the same time, the storage cost paid for receiving low-weight and difficult-to-deliver messages, resulting in no remaining storage for nodes to receive higher priority messages in the later time, is taken as the expected overhead.

Drawing on the principles of economics, CC [98] estimates the price of a message based on



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the attributes of the node and message (weight, TTL). Set the node's remaining cache space as the funds of the node. The probability of the node transferring the message is set as the node trust degree. In this way, if the message is larger than the remaining cache of the node, the node will directly give up receiving it. If the node has enough funds, that is, the remaining storage is greater than the threshold, the message is directly received. If the funds are less than the threshold, start to consider the message price as a congestion warning. If the price is too high, refuse to receive it, and if it is too low, accept it directly. If the price is too low, it will decide whether to receive the message by checking whether the node trust degree is higher than the threshold and the drop rate is lower than the threshold.

Al-Siyabi et al. [99] set the communication access mechanism in DTN, reasonably allocates communication resources according to different communication needs, restricts communication between nodes, and makes communication proceed in order. It reduces the occurrence of disorderly preemption of storage resources, controls congestion, and improves network performance and service quality. The conditions for deciding whether to admit are: the number of available resources, the number of requests, the amount of communication requested by the user, the number of user requests, the agreement between users, and the user priority.

### **2.5.2.3 Migrate messages**

When a new message arrives, and the remaining storage of the node can no longer accept the new message, congestion occurs immediately. At this time, the node can choose to migrate the new message to other neighboring nodes or migrate the old message in the storage to effectively relieve the congestion and ensure the successful delivery rate of the message.

Seligman et al. [100] proposed a migration algorithm. When congestion occurs, messages are migrated to neighboring nodes to relieve the congestion. This method needs to solve the problem of which message to migrate, which node receives the migrated message, and how the message continues to be forwarded. However, migration will always bring about an increase in message delivery overhead, a decrease in the rate of successful message delivery, and an increase in message delivery delay.

Choose which message to migrate can be based on time or hop count. Migrate new

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messages that have just arrived or messages that have been transferred by a small number of nodes will increase the cost of successful delivery and is not conducive to short-distance transmission. Migrate messages stored for the longest time or transferred by multiple nodes may be closer to the destination node. Migrating the message will reduce the successful delivery rate of the message, which is not conducive to long-distance transmission.

If the node migrates message according to message size. Migrating large messages may cause congestion of neighbor nodes. However, migrating small messages may not meet the need to make enough cache space for new arrivals at one time, and it requires multiple migrations to complete the process. This greatly increases the cost of message delivery.

In terms of node selection, Seligman et al. [101] based on the consideration of message size, calculated storage overhead based on the remaining storage of neighbor nodes and the transmission overhead determined by point-to-point latency and bandwidth, jointly determine the migration target node. A node close to the migration source point is usually selected as the migration target point. However, some remote target points generate less migration overhead than nearby target points due to the intermittent connectivity of the DTN.

After the congestion is relieved, the retransmission of the migrated message can be directly responsible for the migration target node. This method does not select the optimal next hop and route, which reduces the rate of successful message delivery. If the source node is migrated by backhaul, and the transfer is continued, it will inevitably increase the delivery cost due to the backhaul operation. At the same time, when the congestion of the migration source node is relieved, and the message can be transmitted back, whether it and the migration destination node are still within the communication range of each other depends mainly on the network environment and the movement of the node.

Yin et al. [102] used the fairness principle and cost calculation rules in economics to reduce the possibility of other nodes relaying messages to selfish nodes that are unwilling to assist other nodes. When congestion occurs, for selecting the message migration node, the congestion status of the node is calculated according to the storage space occupied. Combined the estimated carrying distance, time, and message size to calculate the transmission cost and select the node with the lowest economic cost for migration.

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#### 2.5.2.4 Delete messages

When congestion occurs, deleting redundant messages is a more direct and simple way to remove congestion. The deletion strategy can effectively alleviate the tight situation of storage space occupation. It is easy to cause permanent loss of the message. However, it is still a more commonly used method for removing congestion.

Message deletion operations usually need to specifically determine which types of messages to delete based on factors such as message weight, remaining lifetime, number of times that have been forwarded, number of copies, and estimated probability of successful delivery to remove congestion more effectively.

- (1) Based on message weight or size: Cao et al. [103] simply predict congestion based on node storage changes, divide messages into two groups according to high and low weights, and take the strategy of deleting low-level messages in advance to remove the threat of congestion. ORWAR [104] stipulates that high-priority messages enjoy priority occupation of storage resources. When the storage is insufficient, the low priority messages are removed first. DLA [105] drops the largest message when congestion occurs. E-Drop [106] discards the message that can free up the new arrival message's required storage space when congestion occurs.
- (2) Based on the remaining message lifetime: SHLI [107] drops messages with the least remaining lifetime when congestion happens. Ref [106] [108] introduced Drop Front (DF) or Drop-Least-Recently-Received (DLR): drop the message that arrived first in the node cache; DropLast (DL): drop the newly arrived message in the node cache; Drop Oldest (DOA): drop the message with the least remaining lifetime in the node storage; Drop Youngest (DY): drop the message with the largest remaining lifetime in the node storage.

Simulations have proved that DF and DOA have good congestion relief. Because for multiple copies, a long-lived message is dropped, a message copy has likely been sent to the destination node. Moreover, it does not affect the successful delivery rate of the message, and it also relieves network congestion.

Ref [109] uses a utility function to represent the probability of successful delivery.

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The fewer lifetimes and more copies a message has left, the less quality it will have. When congestion occurs, first drop messages with low quality, that is, messages with a low probability of being successfully delivered.

Ref [110] compares whether the saving weight of the new message is less than the average saving weight when the node is congested, and dropping it if it is less, otherwise dropping the message with the smallest saving weight in the cache. The larger the remaining lifetime and the smaller the message, the greater the saving weight.

- (3) Based on the hop count: When a message has been forwarded more than a certain threshold, a copy may have reached the destination node or barely delivered to the destination node, and there is no need to waste limited storage space for it. When the congestion needs to be removed by deleting the message, delete this kind of message first. This method is suitable for the scenario with a small number of nodes, short spread range, and close distance between the source node and destination node. However, in an environment with a large number of nodes, widespread range, and long-distance between the source node and the destination node, the more times the message has been forwarded, the more likely it is to be close to the destination node. Deleting the message at this time will reduce the successful delivery rate and increase the delivery delay. MOFO drops the most forwarded messages during congestion.

Li et al. [111] proposed an N-drop algorithm to set the threshold value of the number of times a message has been forwarded as N. When node congestion requires message drop, select a message that has been forwarded more than N times to drop. If the need for storage is not met, the message is deleted in the order in which it entered the store.

Li et al. [112] improved the algorithm and proposed the AFNER algorithm later. When the storage space to be freed for this message receipt is greater than the sum of the storage space occupied by the message whose forwarding times are greater than the average in the node, all messages that forwarding times are greater than the average are deleted. If the storage space required by the incoming message is not met, the remaining incoming messages are rejected. Otherwise, the messages in the node store are dropped in the order of forwarding times.

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- (4) Based on the number of copies: Kim et al. [113] believed that messages with the most copies could be dropped to minimize the impact of packet loss on the successful delivery rate of messages. In the case of multiple copies, the number of copies of each message at the beginning is fixed. Since the fewer message copies left in a node means that the message has been forwarded many times, comparing the number of copies left in a node to determine which message to drop can have the same effect as the message dropped according to the number of forwarding times.

After some copies of messages are deleted, the flood propagation of messages will enter the node cache in a short time, which results in a reciprocating cycle, which wastes storage and aggravates congestion. Leela-amornsinsin et al. [114] avoided this phenomenon by recording the deleted messages in nodes and keeping them for a period of time.

- (5) Based on the estimated probability of successful delivery: Krifa et al. [115] sorted the messages in the node cache by delivery probability and used this as the criterion for selecting the message dropping. While reducing the delay, the algorithm improves the successful delivery rate. However, predicting the probability of whether a message can reach the destination node requires a large amount of information about current and future network topology changes, which is difficult to achieve.

Regarding the method of predicting the successful delivery rate, Yu et al. [116] set a threshold of node counts. In flooding based routing, if the nodes have the same message copy when they meet, they will increment the counter each other. If the counter of one node reaches the threshold, it means that the message has been fully distributed, and the probability that the message has been successfully delivered is extremely high. The node continues to carry the message no longer helps increase the successful delivery rate, but will increase congestion, thus deleting the copy of the message. However, the node still saves the record of storing the message copy to meet the needs of no longer receiving the message copy and incrementing the counter corresponding to the message of the encountering node.

HWDP [117] combines the probability that the message copy stored in this node is directly delivered to the destination node and the probability that the message copy stored in other nodes is successfully delivered to the destination node and considers

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the weight of the two in different node density networks (the former has the most weight in the sparse network, and the latter has the most weight in the dense network), comprehensively evaluate the sum of the two probabilities of each message in the node storage. When congestion occurs, the message with the smallest sum of probabilities is dropped. The former is calculated by the interval between two nodes meeting and the remaining lifetime of the message. The greater the interval, the less the remaining lifetime, and the smaller the probability. The latter is calculated by the number of message copies in the network. The larger the number of message copies, the lower the probability.

### **2.5.3 Buffer management based on node cooperation**

The nodes in DTN often represent different devices, and the devices are controlled and held by people. Different personalities and preferences of people determine different attributes of nodes. Selfishness, as a human attribute, will also be reflected in DTN. Selfish nodes only consider maximizing their message delivery rate and reducing the probability of congestion. It hopes that other nodes will forward as many messages as possible, and it will forward as little as possible for other nodes. This kind of behavior that unwillingly encroaches on other nodes' storage resources and is unwilling to serve other nodes can easily cause storage congestion of other nodes and decrease the delivery probability under the condition of limited network storage resources. The chain effect caused by the congestion of a few nodes will cause congestion to spread to most of the network nodes, resulting in a sharp drop in network performance. How to balance the interests of both sender and receiver is a concern for controlling network congestion.

The buffer management policy requires strengthening the cooperation between nodes to ensure normal communication between nodes and restrain the nodes' uncontrolled transfer behavior.

#### **2.5.3.1 Based on economic theory**

Both DTN buffer management and market economy theory in economics needs to meet the relationship between supply and demand balance in terms of resource allocation to achieve a reasonable allocation of resources and maximization of overall interests. The principle of

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equivalent exchange in economics can be used to coordinate all nodes in DTN to strengthen cooperation. The meaning of equivalent exchange is mainly reflected through the balance of income and expenditure [118].

The earlier method [119] is that the source node provides virtual currency for the messages generated by itself to supply the relay node to transfer the message before reaching the destination node. However, in DTN, it is often impossible to predict the number of transfer links, which will result in a waste of virtual currency or failure message transmission.

The method of increasing the charging price per hop, and finally, the destination node uniformly pays the bill came up later [119]. This method is vulnerable to attacks by malicious nodes sending a large number of messages to the same target, causing its funds to be quickly exhausted. The method [120] of setting up a settlement center in the network to pay the remuneration of relay nodes is challenging to achieve in a network with sparsely distributed nodes like DTN. Therefore, in the latter studies, the nodes often have their own virtual currency and require other nodes to provide virtual currency when transferring and collecting virtual currency when helping other nodes transmit messages [121] [122].

### **2.5.3.2 Based on the service classification**

After identifying the node type, Mekouar et al. [123] provided services are corresponding to the node type according to the pre-determined type classification. Furthermore, within the acceptable range of the node, it puts forward its service responsibility requirements for other nodes in the network and correlates the node type with its revenue and contribution.

Zhao et al. [124] proposed that nodes also perform selfish behavior when encountering selfish nodes, and when encountering unselfish nodes, they will increase their service level accordingly.

### **2.5.3.3 Based on node credibility**

Different message transfer services are provided for nodes with different credibility according to node long-term behavior records [125]. Once a node is found to be a selfish node, it will no longer receive messages from this node and isolate it from the network. The evaluation of credibility can come from direct or indirect methods.

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The direct method [126] can use watchdog technology and get directly through cooperative behavior after nodes meet. Watchdog technology has problems such as high energy consumption, slow direct detection speed, and inconsistent credibility.

The indirect method [127] can be combined with the evaluation of other nodes. In the case of considering energy and storage overhead, indirect credibility can be received from neighbor nodes. The main problems of using indirect methods are: since establishing a third-party credibility testing agency is often difficult to achieve in DTN, the credibility evaluated by other nodes must be considered. The credibility of the assessment can be inferred by providing the credibility of the node itself [128].

#### **2.5.3.4 Based on game theory**

Game theory has a typical application in promoting cooperation between nodes through negotiation. The premise of game theory is that individuals are pursuing the maximization of their interests. The acquisition of individual interests depends not only on their own strategic choices but also on the strategies of other game participants. Individuals need to consider other individuals in the competition and deal with them according to the same thinking logic. Individuals need to adjust their strategies to seek stable and high profits constantly. Game theory is based on this assumption by regulating the behavior of each node, using reward and punishment to force each node to adopt a cooperative attitude, helping each node achieve a win-win situation in terms of interests, and maximize overall interests.

Jaramillo et al. [129] borrowed the repentance-type tit-for-tat theory in game theory. When a misjudgment is made on the opponent's cooperativeness, immediate corrections can be made to restore the correct cooperative relationship to avoid further expansion of the hostile relationship and ensure the maximization of overall interests.

There are usually multiple encounters between nodes; thus, there is a phenomenon of repeated games. Ref [130] regards each node encounter as a game, and through multiple encounters, it summarizes the coherent cooperative tendency of each node. Based on the established game rewards and punishments, any selfish behavior of non-cooperative nodes will be damaged in the long-term game. Thus, each node is forced to follow the cooperative strategy as much as possible during the encounter process to ensure the maximum benefit of



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each node and the optimal network performance. However, how to ensure this cooperative tendency's authenticity still needs to be studied. Ref [131] considers that in the case of non-repetitive games, each node is solely based on the prisoner's dilemma theory, and each time node encounters, the node makes a decision whether to cooperate according to the current real-time situation.

The preceding briefly analyzed the existing methods for balancing the interests of the sender and receiver, restraining the selfish behavior of nodes, and motivating cooperation between nodes. Nevertheless, before implementing the incentive strategy, confirm the nodes' behavior to adopt effective strategies for the selfish nodes. There are two detection methods: the unified centralized method and the flexible distributed method.

The unified centralized method collects and analyzes the communication behavior characteristics between nodes by deploying special professional equipment in the network to locate selfish nodes and determine specific incentive strategies. This method requires additional professional equipment to be added to the network to collect information, which is expensive, and the statistical results have lagging characteristics and sometimes one-sidedness.

The flexible distributed method allows each node to comply with a flexible incentive strategy and decide whether to cooperate and the degree of cooperation in the short moment when the nodes meet. The execution of this method entirely depends on the instantaneous state and judgment of each node, and the result is often random. Since selfish nodes sometimes have a certain degree of disguise, and some normal nodes sometimes have a sudden increase in communication due to emergencies, this will affect the instantaneous judgment of the node and increase the amount of calculation used by the node to ensure the correct decision.

As an improvement of the flexible distributed method, each node can retain the historical information observed on the behavior of meeting nodes and distribute this information in the network. When nodes meet, they make a judgment according to each other's long-term behavior, namely the integrity record. However, such methods cannot avoid the collision of selfish nodes. Due to the lag of historical records, the current behavior of nodes is often misjudged. Moreover, due to the limitation of DTN storage resources, nodes also need to spend a certain amount of storage space to store such information, which further intensifies

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the competition of network storage resources and easily causes network congestion.

## **2.6 Studies of UAVs in VDTN**

### **2.6.1 The introduction and characteristics of the ferry node**

In DTNs, whether using the single-copy routing with a lower overhead or the multi-copy routing with a higher delivery success rate, message delivery depends on network connectivity and cannot be completed if the split network cannot be reconnected.

In order to improve the connectivity of the network and the success rate of message delivery, ref [73] introduces a kind of node with controllable movement, which can move in a specific area of the network and deliver messages for other nodes in the region. The movement of this node is similar to that of ferry ships, so it is called the ferry node [132] [133].

The main idea of the ferry node is to introduce a non-randomness and repeatability movement of the node so that the node will visit a specific area according to certain regularity. The non-randomness and repeatability of the ferry node can be used to assist other nodes in message delivery and to reconnect the divided network. As shown in Figure 2-7, the whole network has four separate areas, and the nodes in different areas cannot communicate normally. Suppose a ferry node is deployed in the network to make it move periodically between different areas. In that case, messages can be delivered to nodes in other areas so that the whole network can be reconnected.

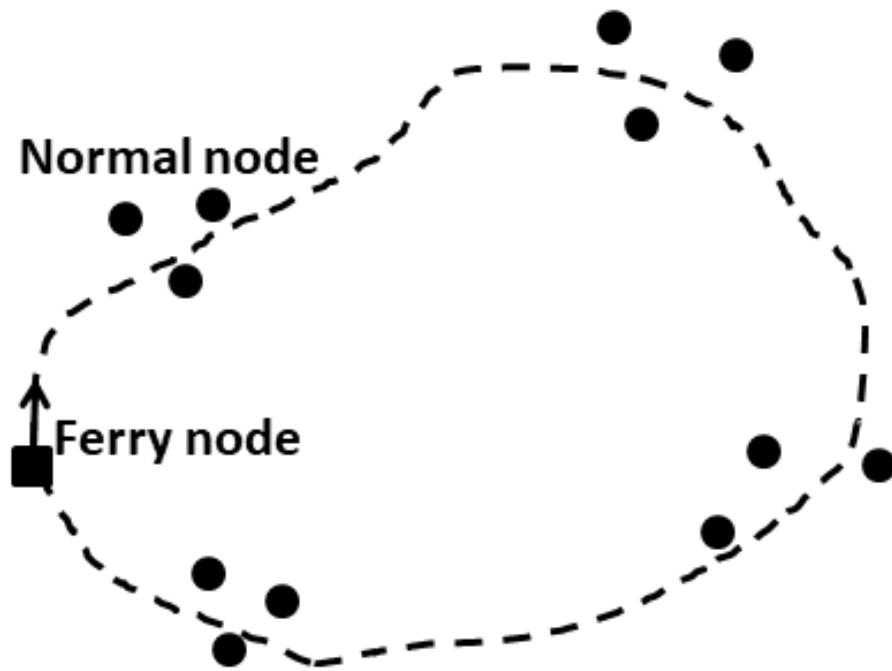


Figure 2-7 Example of a ferry node.

The ferry node is introduced to assist other nodes in message delivery and improve network connectivity. In order to achieve its goal, the ferry node needs to have the following characteristics:

- 1) **Controllable movement model:** The ferry node is a kind of node that the movement model is controllable. Through a reasonable configuration of parameters such as the movement path of the node, it can play its role to the maximum extent, deliver messages for other nodes, and make the divided network reconnect [134].

There are two kinds of nodes with a controllable movement model: one is deployed for non-communication reasons. For example, the primary function of a bus is to provide public transport services. It is not specifically set for communication, but as it moves on a certain route, it can carry messages and act as a ferry node [135]. Another category is designed specifically for communication, for example, when a disaster happens, some UAVs or other equipment can be deployed to shuttle between high-risk areas and other areas where communication is difficult to provide transferring messages in those areas [136].

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- 2) Repeatable movement: If the movement of nodes is not repeatable, it can only visit other nodes once, although it can forward messages to other nodes, it cannot play an obvious role in network connectivity. When a ferry node is deployed, it is often necessary to repeatedly visit the same area to improve its ferry performance. It should be noted that the repeatability requirements of ferry nodes are not strict, and the order and time of visiting other nodes can be changed [137].
  - 3) Large buffer size: The purpose of deploying a ferry node is to deliver messages to other nodes. Therefore, compared to a normal node, a ferry node must have a large buffer size to save the received messages during the running cycle and forward them when they encounter the destination node. If the buffer size is insufficient, data will be lost, and the role of the ferry node will be affected [138].

Although ferry nodes have a large buffer space, if the running cycle of ferry nodes is long, and the cache will still overflow. Therefore, when designing the movement model or routing protocol of the ferry node, it is necessary to consider the abundant energy resources [139].

- 4) Abundant energy resources: The movement of the ferry node needs to consume more energy, so in order to ensure its continuous operation, it needs to be equipped with a larger capacity of batteries. In practical use, the ferry node is usually large equipment such as UAVs and vehicles, so the energy consumption of the ferry node is generally not considered [140].

## 2.6.2 UAV technologies in VDTN

UAVs can receive and forward data as a ferry node in the air, improving the reliability of wireless communication links, enhancing infrastructure flexibility, and providing communication coverage in sparse areas [141] [142]. UAVs are mainly used in military fields for joint operations [143]. In recent years, UAVs have been gradually applied to civil industries such as intelligent transportation systems [144], earthquake relief [145], and precision agriculture [146], especially the rapid development of IoT and the 5G industry [147] [148], which have set off a wave.

Based on the traditional message ferry algorithm, researchers study the routing for

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multipath ferry under the condition that the number of ferry nodes is limited, and four algorithms were proposed: single routing algorithm (SIRA), multi-routing algorithm (MURA), node relay forwarding algorithm (NRA) and ferry relay forwarding algorithm (FRA) [149].

The SIRA algorithm optimizes the UAV flying path when all UAVs follow the same path. The MURA algorithm optimizes multiple flying paths for UAVs. In addition to multiple flying paths, the NRA algorithm uses some preinstalled fixed network nodes to provide information exchange between different UAVs belonging to different flying paths. The FRA algorithm optimizes multiple UAV flying paths by considering the encounter probability between different UAVs from different flying paths but without the pre-installed fixed network nodes.

In the Optimization Way Point ferry routing (OPWP) [150], the movement path of a single ferry node is determined by calculating the probability between the ferry node and other nodes according to a specific movement model.

Burns and Brock studied the control of autonomous agents to improve the performance of DTN, which is feasible for arbitrary movement of nodes. This study does not disrupt the mobility of nodes [151].

Other related work includes the study of integrated caching and path management schemes in DTN with ferry nodes. In this work, a cache allocation scheme is designed for message ferries using the max-min fairness model [152].

These works reflect the achievements of researchers in the field of DTN routing and the progress of message ferry technology in the application of DTNs. However, due to the harshness of the DTN environment, the current routing design focuses on either saving storage and energy consumption, reducing transmission delay, or successful data transmission rate, so it is difficult to take both into account [153].

Through a period of study and accumulation, UAV assisted VDTN technology has made great progress. However, there are still some key problems that have not been well solved. The UAV assisted VDTN is faced with the challenge of network interruptions or intermittent connectivity. There are still no unified standards and methods for network modeling, connectivity definition, and measurement. Connectivity in UAV assisted VDTN is based on two dimensions of time and space. The current research is still limited to networks that are

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fully measurable in advance for node movement and contact opportunities in the future, which also limits the application scope of UAV assisted VDTN.

When developing and designing the UAV assisted VDTN routing protocol, defining system performance in the UAV assisted VDTN is still an open question. When circumstances permit, routing protocols should be designed with node locations, topologies, and future trajectories in the network.

## **2.7 DTN technologies in the post-disaster scenario**

Natural disasters, such as floods and earthquakes, often result in large-scale damage to infrastructure such as bridges, roads, and power equipment, as well as a surge in demand for communications services. May cause the following damage to the communication system:

- (1) Power equipment damage, resulting in power supply interruption so that communication equipment cannot work;
- (2) Stationary communication facilities and communication base station collapse, resulting in the damage of broadband fiber;
- (3) Due to damage to the infrastructure, some areas have been cut off to form isolated islands, and communication cannot be carried out between them;
- (4) The communication demand in the disaster area has increased, the channel and spectrum resources are insufficient, the communication link is incredibly congested, and the message cannot be transmitted normally.

Due to the characteristics of network segmentation, long delay, sparse node distribution, and limited resources in the post-disaster environment, some traditional communication methods can no longer meet the needs of communication in the post-disaster environment. DTN uses the store-carry-forward method for data transmission, which can be applied to the network environment with sparse nodes and intermittent links and is an effective means to construct an emergency communication network quickly.

Ref [154] conducted an in-depth study of earthquake emergency communication requirements and proposed that there are generally three kinds of communication

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requirements after an earthquake: communication between command centers, between rescue teams, and between the command center and the general command center. On this basis, taking Sichuan terrain as an example, the DTN network formation mode is proposed. Rescue teams carry wireless detection communication equipment to carry out the rescue in three different disaster areas. The UAV carries relay cruise over the three disaster areas to realize the communication between rescue teams and command centers. Ref [155] proposed a heterogeneous DTN routing protocol under disaster scenarios, in which nodes adopt different routing protocols according to their mobility characteristics and those of their neighbors. According to the mobile characteristics of nodes, different routing protocols are adopted to improve the network performance of the DTN.

Shibata et al. proposed using the portable mobile equipment carried by the post-disaster rescue team to set up the post-disaster DTN for data transmission and use the wireless communication vehicle as the ferry node moving between the disaster-stricken area and the shelter to realize the message transmission [156]. On this basis, Trono E proposed DTN MapEx [157], a distributed computing system based on DTN, aiming at the generation and sharing of post-disaster real-time maps. This system evenly distributed the post-disaster map data and map generation tasks to multiple nodes to minimize the load on a single computing node. In the system, rescue teams act as mobile sensor nodes, recording map data of the movement tracks experienced during the rescue operation. Then, the mobile node forwards its data to the relevant computing node through the DTN route, and the computing node will aggregate the data to generate a map in the post-disaster scenario and return the map to the mobile sensor node randomly, thus completing the generation and sharing of the post-disaster real-time map.

## **2.8 Conclusion**

This chapter first classifies and introduces the routing protocols and buffer management policies in DTN. Finally, the technology of DTN with UAVs as ferry nodes is introduced and summarized.

Although there are numbers of studies that have been proposed in DTNs to support the dynamic network topology changes, the buffer management policies to overcome the problem of limited network resources, the related research still needs to be improved to keep up with the

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increasing requirement for the network quality. A new routing protocol with an optimal local buffer management drop strategy of DTNs and a specific routing protocol for UAV assisted VDTN are proposed, aiming to increase the delivery probability and reduce transmission delay.



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## CHAPTER 3

### 3 A VDTN scheme with enhanced buffer management

In this chapter, the historical-based DTN routing protocol with a buffer management policy is presented to support message transmission. It is very important to study practical and effective routing algorithms in a network environment with limited node resources. The algorithm presented in this chapter controls the number of copies in the message transfer process and selects the relay node combined with the historical-based protocol.

In section 3.1, two traditional routing protocols are discussed, and their shortcomings in supporting the VDTN environment are presented. Besides, the disadvantages of existing buffer management policies are discussed.

In section 3.2, the proposed routing protocol architecture is shown to support the message transmission in VDTN. Relay node selection algorithm and message copy control strategy are used to improve routing performance and control network overhead. Section 3.3 discusses the time complexity of the proposed routing protocol.

In section 3.4, the proposed buffer management policy is introduced to solve the node congestion problem. The proposed approach considers the node communication quality and the attributes of the message, the congestion control metric of each message in the node is calculated. When congestion occurs, the message with the smallest congestion control metric is dropped to avoid the impact of random packet loss on network performance. Section 3.5 discusses the time complexity of the proposed buffer management policy. The fairness of the DTN routing protocol is discussed in section 3.6.

In section 3.7 and section 3.8, the simulation works are designed to evaluate how the proposed scheme affects network performance. Finally, section 3.9 summarizes this chapter.

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### 3.1 Problem discussion

The P<sub>Ro</sub>PHET routing relies on the encounter probability to select the next-hop relay node of a message. Compared with the Epidemic routing, P<sub>Ro</sub>PHET routing reduces the network congestion caused by a large number of message copies and improves the network performance. However, one problem with P<sub>Ro</sub>PHET routing is that it does not limit the number of message copies in a network. Besides, it is unreasonable to select the next-hop node of a message solely based on the encounter probability, ignoring other message attributes or the node resources.

Assuming that two nodes  $A$  and  $B$  encountered and attempt to deliver message  $m$ . If the encounter probability between node  $A$  and the destination node is significantly greater than that of node  $B$ , then it is correct that node  $A$  chooses to relay a message copy to Node  $B$ . If the encounter probability of  $A$  and the destination node is almost the same with  $B$ , then the node resources such as the remaining cache space and the message TTL become vital points:

- (1) If the message TTL runs out of time soon, unless the next-hop node is the destination node, transferring the message could only consume the next node cache.
- (2) If the message takes up a large amount of cache space, passing a copy to the next node will only cause congestion on the other nodes, which should not be transmitted first.

Compared with flooding routing protocols, the Spray-and-Wait routing controls the number of message copies, alleviating network congestion, and reducing the message drop rate and network overhead. However, this routing protocol has randomness in the selection of relay nodes. Also, only the number of transmitted copies is controlled when transferring message copies, but the copies in the cache are not well managed.

The buffer management strategy mainly uses different message dropping strategies to selectively drop messages in the cache when the node is congested, thereby reducing node congestion. Besides, it is necessary to minimize the impact of dropped copies on network performance.

This chapter first combines P<sub>Ro</sub>PHET routing and Spray-and-Wait routing in DTN to overcome the shortcomings mentioned above and gives an improved routing algorithm. Based

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on the characteristics of nodes, the proposed protocol controls the number of copies in the process of message dissemination and use the binary transfer algorithm for copy distribution. The main contribution is in the spray phase, the node with higher delivery probability in the communication range of the source node is selected to be the relay node; in the wait phase, the proposed algorithm takes into account the historical information of the node to continue the transmission of the message. The proposed routing protocol not only improves the delivery rate of messages but also controls network overhead and improves routing performance.

Second, from the existing buffer management policies mentioned in the previous chapter, most current research on buffer management only considers unilateral attributes such as message TTL or message size, instead of comprehensively considering the relationship between various attributes. Therefore, there is an unfairness when dropping messages to ease congestion. This chapter proposes a buffer management policy based on the congestion control metric. Considering multiple attributes of the node and the message, such as the remaining lifetime of the message, the delivery probability, and the node's buffer overhead rate, construct the congestion control metric. Sort messages within a node according to the congestion control metric. When messages need to be dropped to relieve node congestion, drop the message with the smallest congestion control metric, which can reduce the network performance degradation caused by unreasonably dropping.

## 3.2 PRoPHET-based VDTN routing protocol

The message replication process is shown in Figure 3-1. In section a, node *S* is the source node and has a message *m*. At the beginning of the message transfer stage, node *S* replicates message *m* into four copies. In section b, there are two nodes *A* and *E* within the communication range of node *S*. Then, the encounter probability with the destination node is compared between node *A* and *E*. If node *A*'s encounter probability is larger than node *E*, Node *S* will only consider communication with node *A*. Before sending a message, a node updates the encounter probability using the same method as the PRoPHET protocol. When node *S* decides to send a message, two copies will send to node *A* according to the binary transfer algorithm, node *S* maintains the left. In section c, node *S* encounters node *B*, node *B*'s encounter probability is higher than node *S*, node *S* sends one copy to node *B*. In section d, node *C* appears in the communication range of node *A*.

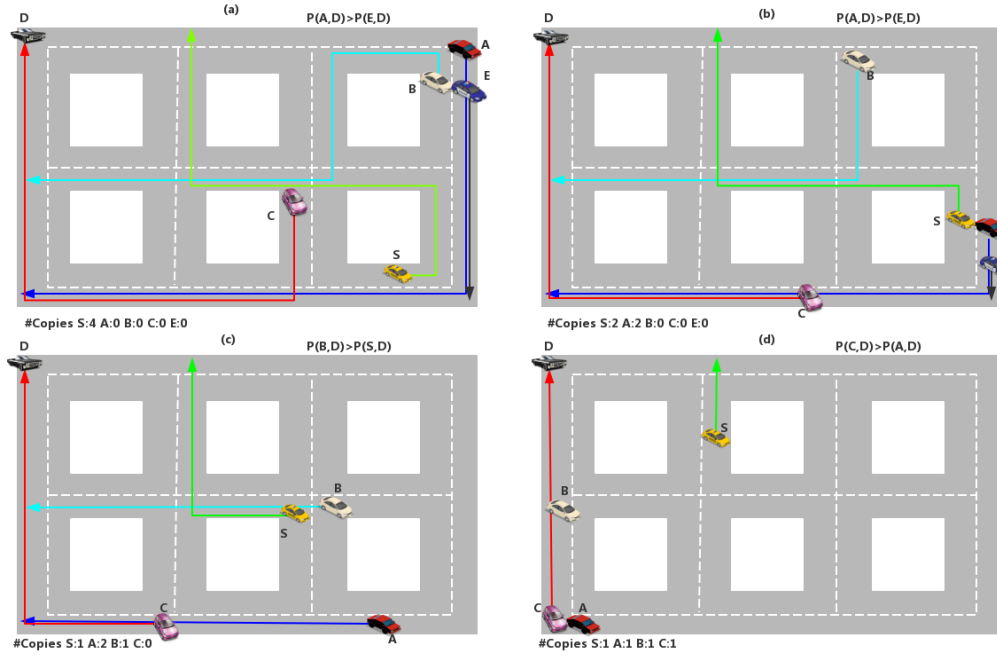


Figure 3-1 Message delivery process of the proposed routing protocol.

Node A sends one copy to node C because node C has a higher encounter probability with the destination node. Finally, node C sends the copy to the destination node to finish the message transfer process.

The proposed scheme is shown in Figure 3-2. In the first step, source node A generates message  $M$  to  $L$  copies. The second step executed on A checks whether node B is the final destination for any of the bundles stored in node A's buffer or not. If it happens, these bundles are scheduled for being transmitted first to B, followed by the remaining bundles sent in an order determined by the execution of the next steps. As expected, bundles whose final destination is B after being delivered are removed from A's buffer and are added to A's list of delivered bundles.

The third step is to determine whether to send the message. Node A and node B are compared with the probability of encountering the destination node. If node B's encounter probability is higher, node B is more likely to encounter the destination node and should be selected as the relay node and then enter the next step.

In the last step, first, confirm the number of message copies in node A. If the number of message copies is greater than 1, node A will send half of the message copies to node B. If there is only one message copy in node A, then send the message copy. As expected, the

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process is repeated until the message is sent to the destination node.

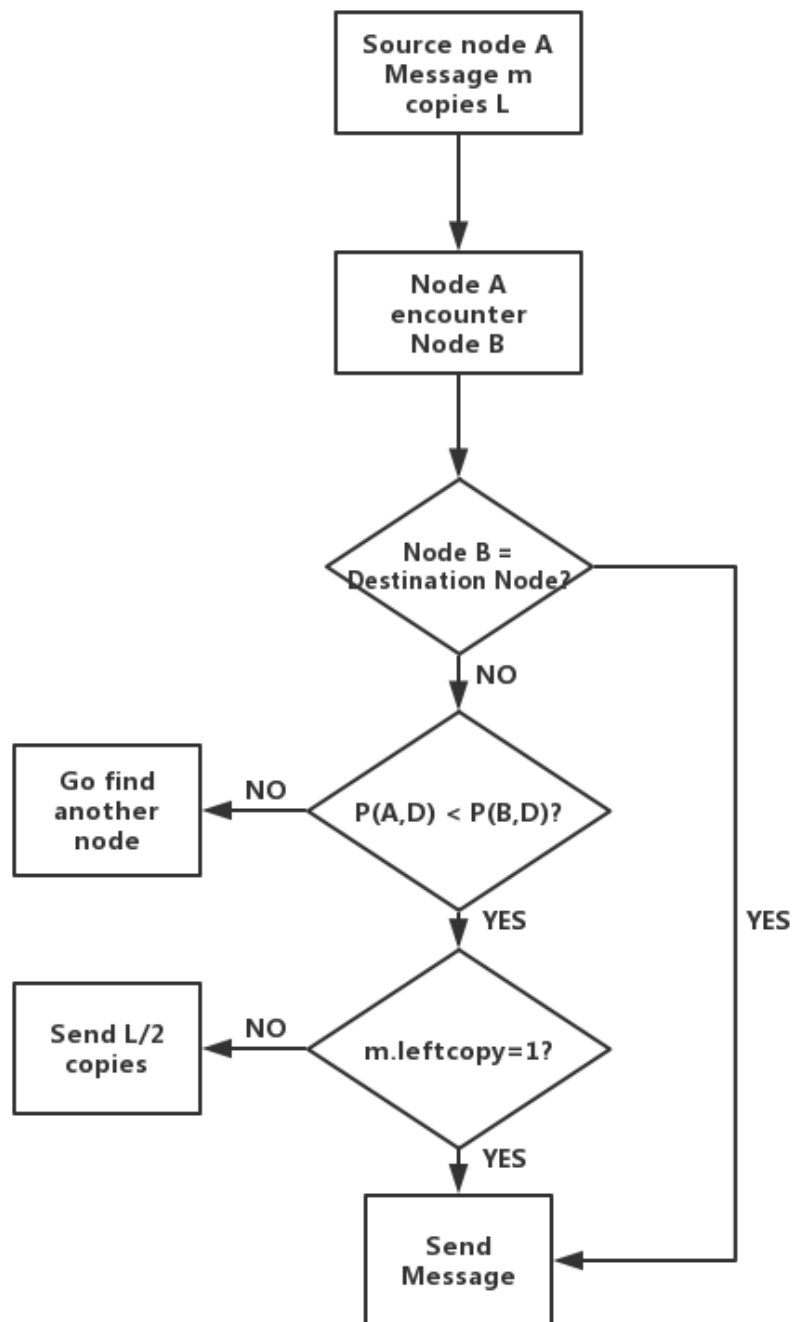


Figure 3-2 Flowchart of the proposed routing scheme.

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Figure 3-3 shows the operation of the proposed protocol in the actual scene. The purple vehicle represents the source node, the orange vehicle represents the destination node, and other vehicles are candidate relay nodes within the communication range of the source node. There is often no direct link between the source node and the destination node to transfer messages in actual DTN scenarios, so relay nodes need to be used to forward messages.

When there are multiple selectable relay nodes within the communication range of the source node, selecting the most appropriate node can increase the message delivery rate and reduce the network overhead caused by blind forwarding.

According to the proposed routing protocol, the source node selects the node that meets the destination node most frequently as the relay node. The proposed routing protocol limits the number of copies of the message in the entire network when the source node generates the message. After the source node decides the relay node, it sends half of the message copy to avoid the problem of too many same message copies in the network. The source node and the relay node continue to forward the message according to the proposed routing protocol in the subsequent movement process until it reaches the destination node.

Existing protocols usually only consider how to choose a better relay node or how to control the number of message replications. The proposed routing protocol combines the selection of relay nodes and controls the number of message replications, which improves the message delivery rate and reduces the network load. Besides, the following chapters will introduce a buffer management policy designed according to the proposed routing protocol, which further improves the network performance.

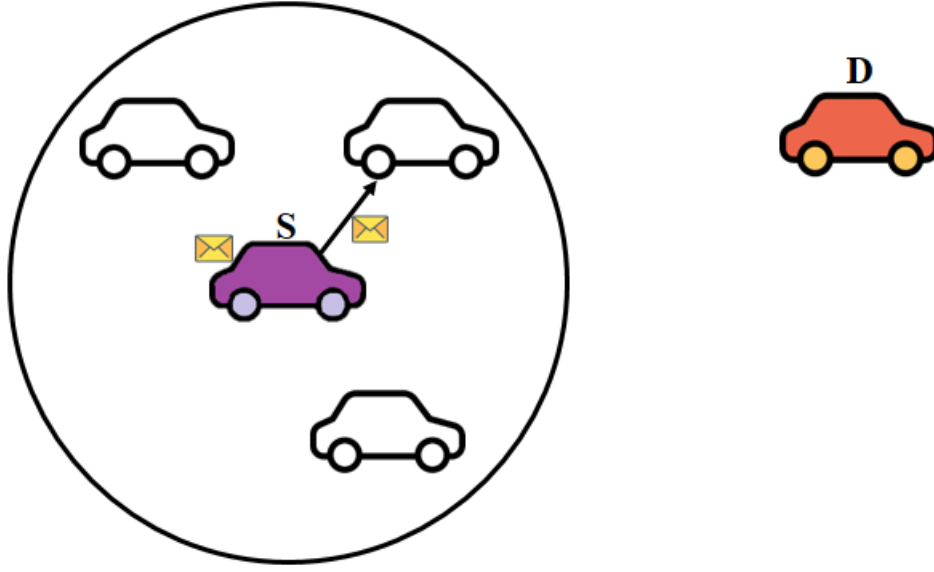


Figure 3-3 Message forwarding in the actual scene.

### 3.3 The time complexity of the proposed routing protocol

Each time a node contact another node, it updates its encounter probability to the destination node of each message. Thus, the time complexity of the PRoPHET and the proposed routing protocol is  $O(n)$ , where  $n$  denotes the number of destination nodes of messages in the node. For the proposed routing protocol, half of the message copies will be sent during the message transferring stage, the overhead is higher than the PRoPHET but does not affect network performance too much.

### 3.4 Proposed buffer management policy

This section presents a buffer management method policy on the proposed protocol. The buffer management policy combined the encounter probability of each node with the message cache occupancy rate, message TTL (Time to Live) to calculate the congestion control metric. This metric could indicate the preservation value of messages. When congestion happens in a node, the message with the lowest congestion control metric is selected for priority deletion. The calculation method of the congestion control metric is described below.

### 3.4.1 The network model

The network model is shown in Figure 3-4. The source node  $S$  and other nodes  $D1 \sim D4$  in the network. Among them, nodes  $D1$  and  $D2$  are directly connected to source node  $S$  and can be used as next-hop relay nodes. Other nodes are reachable for multiple hops, but they are not directly connected to the source node at the moment. The cache occupation of source node  $S$  is analyzed below.

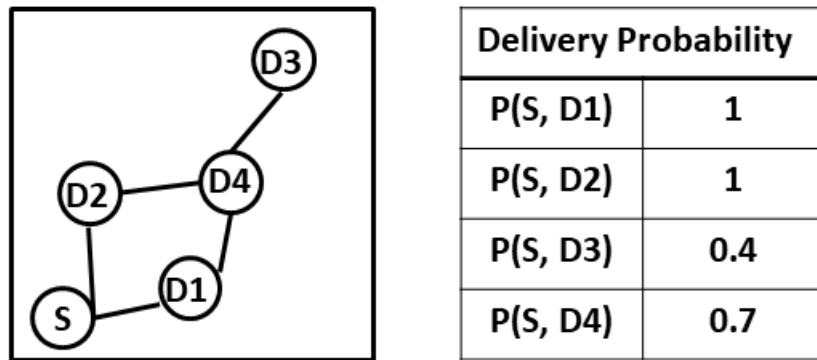


Figure 3-4 Network model.

Assume that the cache space of the source node is shown in Figure 3-5. There are five messages from  $M1$  to  $M5$  in the cache. The attribute values of information are shown in the figure. When  $D1$  requests data transfer to node  $S$ , since  $P(S, D2) > P(D1, D2)$ ,  $S$  will not send  $M2$  to node  $D1$ . Consider the order of other messages, if using the first in first out send queue model, the node  $S$  will send  $M4$  first, but the destination node of  $M4$  is  $D3$ , and there is no communication link between  $S$  and  $D3$ . On the other hand, the destination node of  $M1$  is  $D1$ ,  $M1$  should transfer as long as the remaining cache space of  $D1$  is greater than the size of the  $M1$ . Therefore this section optimizes the sending queue sorting method.

Since  $P(S, D4) > P(S, D3)$ ,  $M5$  should be sent before  $M3$ ; however, the information for the message copy should also be considered. In contrast, messages that take up too much cache should not be sent first when there is no congestion on the current node; otherwise, congestion could occur on other nodes, which is not conducive to network performance. Furthermore, the message TTL is small, which means a message that spends too much time in the cache is not good for message delivery. Therefore, comparing  $M3$ ,  $M4$ , and  $M5$ , it is found



that messages copies of  $M3$  and  $M5$  take up less space, exist in the cache for a shorter time, which means  $M5$  and  $M3$  should have a higher sending priority than  $M4$ . Through the optimized sending queue algorithm, it can be concluded that the more efficient sending order is  $M1 \rightarrow M5 \rightarrow M3 \rightarrow M4$ , and  $M2$  is not be sent.

M1	M2	M3	M4	M5	Remaining buffer area
----	----	----	----	----	-----------------------

M1	
Size	2M
Destination	D1
TTL	2H
Receive Time	20min

M2	
Size	3M
Destination	D2
TTL	2H
Receive Time	15min

M3	
Size	1M
Destination	D3
TTL	2H
Receive Time	20min

M4	
Size	3M
Destination	D3
TTL	1H
Receive Time	50min

M5	
Size	1.5M
Destination	D4
TTL	1H
Receive Time	25min

Figure 3-5 Cache status of source node S.

### 3.4.2 Buffer overhead ratio

In the DTN, node resources are often limited. In order to use the buffer space of nodes more efficiently, the buffer overhead ratio is used to describe the buffer usage of a message replica in a node. Obviously, the larger the message size is, the greater its impact on the node buffer. Therefore, in Equation (4), the message replica's size is  $S_i(m)$ , the remaining buffer size of node  $i$  is  $BS_i$ . Using the ratio of message size and the remaining buffer space represents the buffer overhead ratio  $BO_i(m)$ .

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$$BO_i(m) = \frac{S_i(m)}{BS_i} \quad (4)$$

From Equation (4), since the buffer size is constant, if the message size is larger, the influence on other messages in the buffer is greater, so the buffer overhead ratio is a negative factor in the buffer management. The range of  $BO_i(m)$  is 0 to 1.

### 3.4.3 Time measurement

Since there is usually no direct path from the source node to the destination node in DTN, the message needs to be stored in the relay node and then forwarded, so the message TTL is an essential element in buffer management. Suppose the message is stored in the buffer for a long time. In that case, other copies of the message may have been delivered to the destination node, and continuing to store the message will seriously affect the utilization of the node buffer. Therefore, deleting the message copy that arrives at the node earliest is beneficial to the entire network. Therefore, this section combines the message TTL with the receive time to the buffer and uses their ratio to describe the effect of the time factor on the message.

In Equation (5),  $TREC_i(m)$  is the live time of message  $m$  in node  $i$ ,  $TTL_i(m)$  is the remaining TTL of message  $m$  in node  $i$ , and  $TM_i(m)$  is the time measurement of message  $m$  in node  $i$ .

$$TM_i(m) = 1 - e^{\frac{-TTL_i(m)}{TREC_i(m)}} \quad (5)$$

The  $TM_i(m)$  is a monotonically increasing function from 0 to 1 and has a positive factor in the evaluation of message preservation value.

### 3.4.4 Estimation delivery successful value

Due to the discontinuous characteristics of DTN and the topology of the network changes quickly, nodes are required to use the known information to estimate the whole network situation. In this part, the message hop count and the encounter probability is used to estimate the delivery probability. The greater the estimated delivery success value of the message, the more likely the message will be sent to the destination node, and the higher the stored value of the message in the node buffer.

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Since the proposed protocol is based on the encounter probability concept and uses a binary distribution algorithm to send message replicas, the number of relay nodes  $RN(m)$  can be estimated by Equation (6).

$$RN(m) = \min\{2^{hop_i(m)}, CN(m)\} \quad (6)$$

In Equation (6),  $hop_i(m)$  is the hop count when node  $i$  receives message  $m$ , and  $CN(m)$  is the total number of message copies.

The ratio of the number of relay nodes to the total number of nodes in the network is used to indicate the probability that a node in the network contains a message  $m$ , and the product of this ratio and the encounter probability is used to estimate the probability that the message can be transferred to the destination node.

$$DS_i(m) = \frac{RN(m)}{N} \times P(i, d) \quad (7)$$

In Equation (7),  $DS_i(m)$  is the estimation delivery successful value for message  $m$  in node  $i$ , and  $N$  is the number of nodes in the network.  $P(i, d)$  is provided in the proposed protocol and shows the probability of one replica of message  $m$  transferred from node  $i$  to destination node. Since the ratio of  $RN(m)$  and  $N$  is from 0 to 1, the range of  $DS_i(m)$  is from 0 to 1.

### 3.4.5 Congestion control metric

In the node cache, if the message size is bigger, the fewer messages can be stored in the cache; If the message TTL is longer, the fewer times the nodes can receive the new message and the lower active level the nodes are; If the encounter probability that messages reaching the destination node is lower, the number of relay nodes of the message is less, and the successful delivery ratio is lower. In summary, there are many factors that can affect whether the message can be successfully delivered to the destination node.

Therefore, in this part, these influencing factors are comprehensively considered and evaluate the preservation value of the messages in many aspects. In the message dropping policy, the estimation delivery successful value and the time measurement are positive factors, and the buffer overhead ratio is a negative factor. The weight of these three parameters is the congestion control metric, which used as the criterion for the node's buffer management.

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$$CCM_i(m) = \alpha \times DS_i(m) + (1 - \alpha) \times \frac{TM_i(m)}{BO_i(m)} \quad (8)$$

In Equation (8),  $CCM_i(m)$  is the congestion control metric for a message in node  $i$ .  $\alpha$  is the impact factor between 0 and 1. When the value of  $\alpha$  is greater than 0.5, the estimation delivery successful value plays a major role in CCM. When the value of  $\alpha$  is less than 0.5, the ratio of time measurement and buffer overhead plays a major role in CCM. The value of  $\alpha$  will have an impact on the performance of the proposed buffer management policy. The results of multiple simulation experiments given in the following section show that when the value of  $\alpha$  is 0.85, the proposed buffer management policy has the best control effect on the node congestion problem. Therefore, the value of the impact factor  $\alpha$  is set as 0.85 in the following section.

The CCM value indicates whether a message should be stored in the cache. The smaller the DS value of a message is, the less likely it is for the message to reach the destination node, and should be dropped when congestion occurs. The larger the TM value of a message is, the shorter lifetime of the message in the buffer, and it should continue to be stored in the cache. A smaller TM value indicates that the message has been stored in the cache for a long time, and other copies of the message are likely to have been transferred to the destination node by other nodes, and the message should be dropped. The larger the BO value, the larger the message size, and continuing to store the message will affect other messages that need to be forwarded, and the message should be dropped.

The larger the CCM value, the message should be stored in the cache and be transferred first. The smaller the CCM value, the message should be dropped when congestion occurs.

### 3.4.6 Proposed buffer management algorithm

The algorithm is shown in Algorithm 1. When a node receives a message, it must first perform congestion detection. Each node in the network establishes a message set D and stores it in its cache. The communication process between node A and node B is as follows:

- (1) Node A and node B discover each other by exchanging the HELLO message. The HELLO message contains an ACK control character (ACK is 1 indicates that the confirmation number is valid, and 0 indicates that the message does not contain

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confirmation information), and the message set D.

- (2) Node A sends A's message set AD to node B, and node B updates its ACK according to the ACK sent by node A, dropping the packets that have been delivered to the destination node to release the buffer. Node B compares BD and AD to determine which message node A has, but node B does not. If there is a message in node A that is not in node B, go to step (3).
- (3) Node B sends a request to node A to obtain the message that (2) knows it does not have.
- (4) After receiving the request, node A sends messages to node B one by one and updates the CCM value by equation (8).
- (5) Node B accepts node A's message and performs congestion detection before storage.
- (6) Perform the congestion avoidance step (7) if congestion happens. Go to step (8) if there is no congestion.
- (7) Node B drops the message with the lowest CCM value in its cache. If there is not enough storage space after dropping, node B continues to drop the message with the lowest CCM value until it is sufficient to receive the new message.
- (8) Node B stores the message and updates the CCM value of all messages.

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**Algorithm 1** Buffer management

**Message queue**  $M_1, M_2, \dots, M_i, \dots, M_n$

Node  $N$

Receive messages from other nodes.

**while** FreeBufferSize of  $N$  bellows zero

$MIN = CCM(M_1)$  **do**

**for** each message  $M_i$  **do**

            figure out the value of  $CCM(M_i)$

**if**  $CCM(M_i) < MIN$  **then**

$MIN = CCM(M_i)$

$M_{min} = M_i$

**end if**

**end for**

$N$  delete  $M_{min}$

**end while**

Sort messages in buffer order by CCM DESC.

Send messages to other nodes.

### 3.5 The time complexity of proposed buffer management

Before the message forwarding phase, the CCM value of each message in the node should be calculated first. The time complexity of this process is  $O(N)$ , where  $N$  is the number of messages in the node. The CCM value can be calculated based on the node and message copy's property value, so for each message copy, the time complexity of calculating the CCM

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value is  $O(1)$ . Thus the time complexity of updating all message copies is  $O(N)$ . After updating, all message copies in the cache should be sorted in descending order according to the CCM value. The quicksort algorithm is used, and the time complexity is approximated to  $O(N\log N)$ . When congestion occurs, the last bit in the message queue is dropped until the congestion is removed. Since the cache is already managed, the time complexity of sending and receiving process is  $O(1)$ . Generally speaking, the time complexity of proposed buffer management is slightly higher than that of the existing buffer management. However, the time complexities are both at the same level, the impact can be ignored.

### 3.6 Fairness issue in DTN routing protocols

Because DTN has the characteristics of rapid network topology changes, the intermittent connection of nodes, and long message delay, the bundle layer is added in DTN to complete message delivery, carrying, and deletion. As discussed in section 1.1, the bundle layer can cope with the dynamic changes of the network topology and network compatibility issues between different architectures, ensuring good interconnection and intercommunication between heterogeneous networks.

Unlike the traditional request/response mode that requires the repeated exchange of message-related information, DTN's uniqueness requires the bundle layer to pack the content related to a message delivery and application data as much as possible and deliver it as a complete application data unit. In this way, the relay node and the destination node can simultaneously process the bundle, reducing unnecessary communication and interaction between nodes.

Meanwhile, the cache space and bandwidth of nodes in the network are always limited. Due to the limitations of these factors, the message size in DTN is often not very large. For large bundles, communications are carried out by segmentation and reorganization, which improves the successful delivery rate and avoids the retransmission of messages caused by connection interruption.

Therefore, the fairness problem between different communication flows can be ignored in the research of DTN routing protocol. The important Quality of Service (QoS) metrics in DTN will be introduced in the next section.

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## 3.7 Simulation and result

### 3.7.1 Simulation tool

The ONE (Opportunistic Networking Environment) simulator [158] is a simulation platform based on JAVA and is used to implement and simulate the proposed routing algorithm. This paper uses the message delivery rate, average delay, and network overhead to evaluate the performance of the routing protocol. The proposed routing protocol given in this chapter is compared with the Epidemic routing, the Spray-and-Wait routing, the P<sub>Ro</sub>PHET routing, and the Bubble Rap routing to verify the superiority.

In addition to paying attention to the realization of the routing protocol, it must also combine factors such as the node's mobility model and event generation approach in DTN simulation. Also, a graphical user interface is essential for researchers to understand algorithms and models. The ONE simulator meets all the above requirements. The main functions of ONE include node movement model establishment, message processing between nodes, visual interface display, and generating data reports. The software structure of ONE is shown in Figure 3-6.



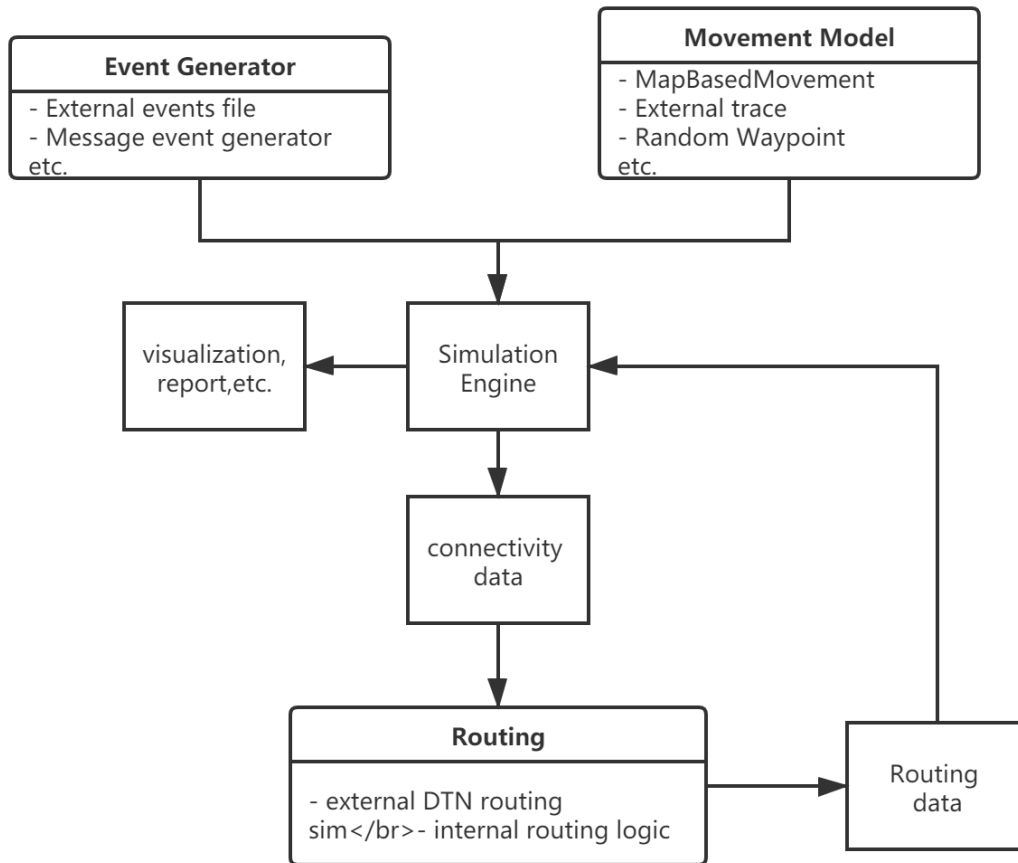


Figure 3-6 The software architecture of ONE.

Each module in the ONE simulator is encapsulated in different packages, as shown in Figure 3-7. The simulator's startup class and the main network element class definitions are placed in the core package. The graphics-related classes are placed in the GUI package. The DTN basic graphics classes and text output graphics classes are placed in the UI package. The movement package encapsulates various mainstream movement models, which provide nodes to move during the simulation process. The routing package has many existing routing protocol classes and is easy to extend. Many report classes are defined in the report package. In the report class, information such as the node contact, message forwarding, and node movement is registered, and the relevant listeners are used to monitor the whole simulation.

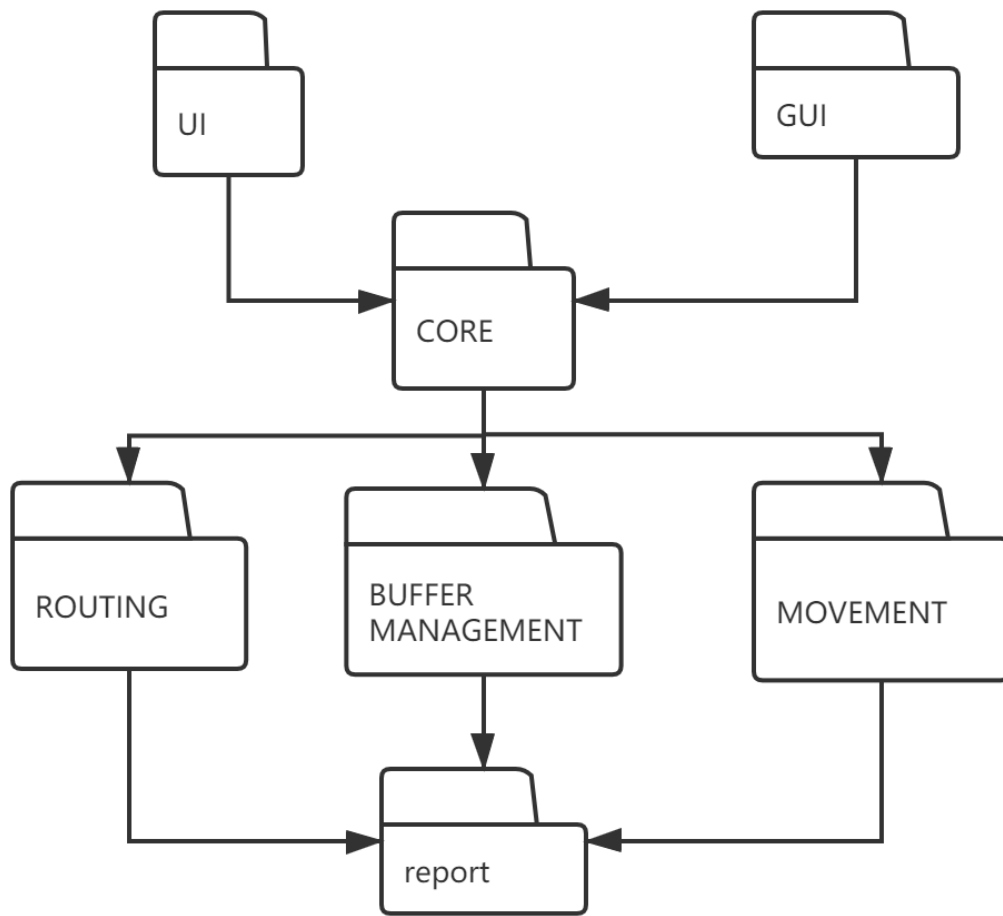


Figure 3-7 Packages of ONE.

The ONE simulator also has some shortcomings. In order to meet the feasibility requirements of simulation, it is necessary to approximate or discard some factors in the real environment. Besides, the ONE simulator lacks support for the physical layer and the link layer. In the simulation, when two nodes communicate, the communication rate is constant. However, in the real environment, the transmission rate is usually could not up to the expected theoretical value due to the influence of the distance between nodes or external interference. The default communication interface of the node in the simulation is always on. However, in actual applications, in order to save power, the device is sometimes switched to the idle state. Therefore, the contact time in the simulation is often too optimistic compared to the actual situation. In summary, the ONE simulator is carried out under ideal conditions, and in some aspects, it cannot be entirely consistent with the real situation.

The visualization of the ONE is shown in Figure 3-8, which can display the loaded map, node movement, message interaction, etc.

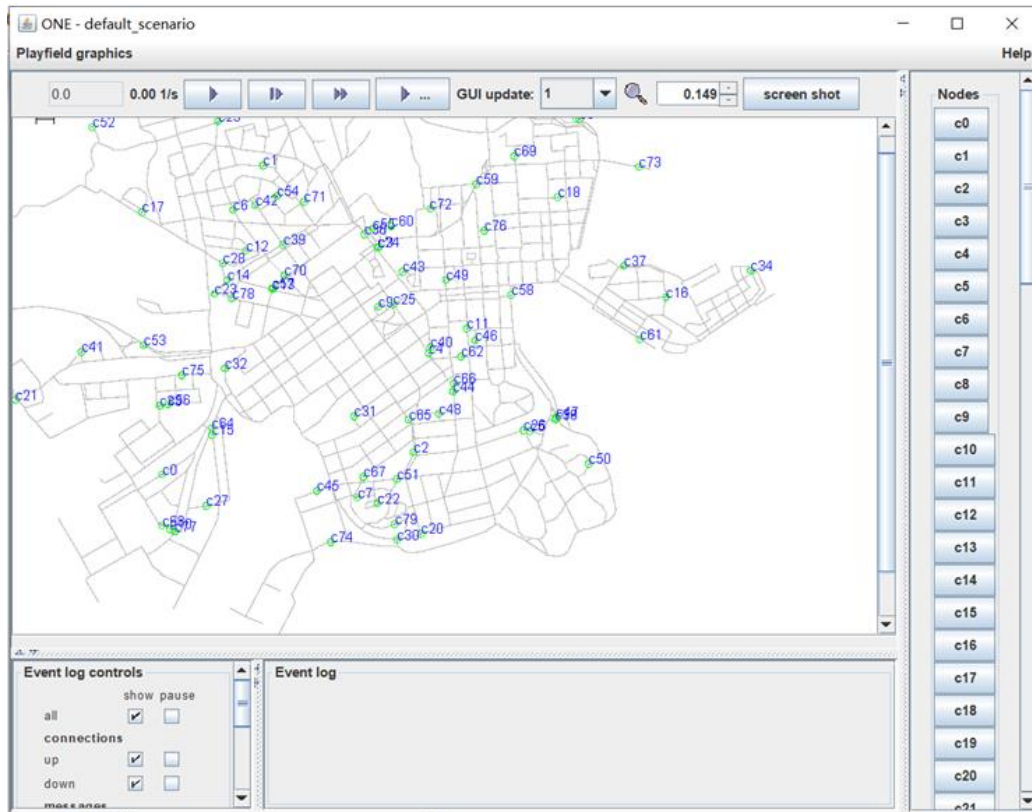


Figure 3-8 The map of Helsinki in The ONE.

### 3.7.2 Simulation Set up

Parameters for simulation setup and routing algorithms are specified in Table 1 and 2, respectively. In the simulation, the city map of Helsinki as the moving area. The simulation time is 43,200 seconds, the number of nodes varies from 35 to 95, all the nodes are cars, and the moving speed is 10-50 km/h. Node's buffer size varies from 1MB to 10MB. Message generation time varies from 10s to 100s. Message living time varies from 60 minutes to 300 minutes. Because it uses the Wi-Fi interface, the communication speed between nodes is 7.5 Mbps, and the communication distance is 50 meters. The size of the message is an arbitrary value of [500k, 1m]. By changing the buffer size of the node and the number of nodes to compare the performance of the proposed protocol with the existing routing protocols.

Table 1 Simulation setting and parameters

Parameters	Values
Simulation Time	43200s
Number of Nodes	35,50,65,80,95
Interface	Wi-Fi Interface
Transmit Speed	7.5Mbps
Transmit Range	50m
Buffer Size (MB)	1, 3, 5, 7, 10
Message Interval (s)	10, 30,50,70,100
Message TTL (min)	60, 120,180,240, 300
Movement Model	Shortest Path Map Based
Message Size	500KB-1MB
Simulation Area Size	4500m×3400m

Table 2 Parameters for routing algorithms

Routing Algorithm	Parameters	Values
PRoPHET	Seconds in Time Unit	30
Spray-and-Wait	Number of Copies	10
Proposed	Seconds in Time Unit	30
Proposed	Number of Copies	10
Bubble Rap	K-clique	3

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### 3.7.3 Simulation result

#### 3.7.3.1 The decision of $\alpha$ in the proposed buffer management

Before the simulation, the most suitable value of  $\alpha$  in Equation (8) must be obtained to achieve the optimal management of node cache. The simulation setting is shown in Table 3. In this group of simulations, only the value of  $\alpha$  is changed to observe the change of the message drop probability. The message drop probability is the ratio of the number of dropped message copies to the total number of message copies.

Table 3 Simulation parameters

Parameters	Values
Simulation Time	43200s
Number of Nodes	80
Interface	Wi-Fi Interface
Transmit Speed	7.5Mbps
Routing Protocol	Proposed routing protocol
Transmit Range	50m
Buffer Size (MB)	5
Message Interval (s)	30
Message TTL (min)	300
Movement Model	Shortest Path Map Based
Message Size	500KB-1MB
Simulation Area Size	4500m×3400m

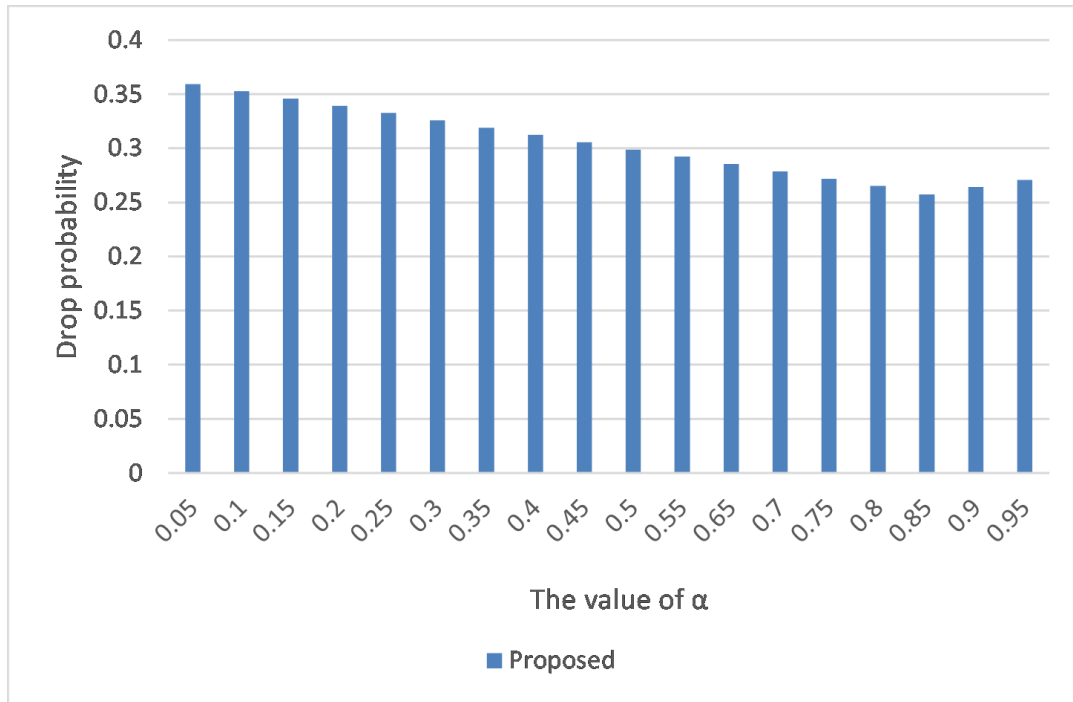


Figure 3-9 Drop probability for the various value of  $\alpha$ .

Figure 3-9 shows the change of the drop probability when the value of  $\alpha$  is different. When  $\alpha$  is 0.85, the drop probability is the lowest. When congestion occurs, the node needs to drop messages in the buffer to alleviate the congestion. The low drop probability indicates that the proposed buffer management policy efficiently handles the congestion and improves the probability of messages being forwarded to the destination node. Therefore, in the subsequent simulation, the value of  $\alpha$  is 0.85.

### 3.7.3.2 Quality of Service metrics in DTN

In order to solve the unique challenges of QoS provisioning in DTN with intermittent and non-deterministic network connections, a smart message forwarding algorithm and a buffer management policy to adapt message queue priority are proposed. The former is used to guide transferring messages through the best routing path that meets the expected QoS requirements with high probability. The latter supports effective resource utilization through appropriate congestion control. The following metrics are used to judge the QoS of the routing protocol in all applications.

**Delivery probability:** Delivery probability is the ratio of the delivered message to the total

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sent message. It represents the success rate of the message reaching the destination node. The larger value of delivery probability means better performance. It is considered to be the most important measure of QoS in DTN. The following formula is the definition of delivery probability.

$$\text{Delivery Probability} = \frac{\text{Number of Delivered Messages}}{\text{Number of Created Messages}} \quad (9)$$

**Overhead ratio:** Overhead ratio is the ratio of the difference between the relayed message and the delivered message to the delivered message. The following formula is the definition of the overhead ratio. It represents resource usage across the entire network. The low value of the overhead ratio means fewer required network resources to deliver the messages. It is also an important measure of QoS in DTN because it will indicate whether the resource utilization is reasonable.

$$\text{Overhead ratio} = \frac{\text{Number of Forwarded Messages} - \text{Number of Delivered Messages}}{\text{Number of Delivered Messages}} \quad (10)$$

**Latency average:** Latency average is the average time it takes for the message to be forwarded to the destination node. The following formula is the definition of latency average. First, the sum of time that the message was successfully delivered minus the time that the message created was counted. Then, the latency is the ratio of the value to the number of delivered messages. The lower latency time means the better performance of the entire network.

$$\text{Latency Average} = \frac{\sum(\text{Time of Delivered} - \text{Time of Created})}{\text{Number of Delivered Messages}} \quad (11)$$

### 3.7.3.3 Results and analysis

In this section, simulation results obtained from the simulations of the investigated routing protocols as per the parameters defined in table 1 and 2 using ONE simulator are analyzed in terms of three performance metrics: message delivery ratio (i.e., the successfully delivered messages over the total generated messages), the average message end-to-end delay, and the overhead ratio which gives the ratio of “number of extra relays made” to “number of direct relays made to destinations.” The thesis has carried out simulations under different scenarios

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to study the impact of different network parameters on network performance. The proposed routing scheme with enhanced buffer management policy is compared with the proposed routing scheme without buffer management policy, P<sub>Ro</sub>PHET protocol, Spray-and-Wait protocol, and Bubble Rap protocol. In all figures, S&W bar represents the Spray-and-Wait protocol, the proposed bar denotes the proposed routing scheme with enhanced buffer management policy, and the proposed w/o bmp bar denotes the proposed routing scheme without buffer management policy.

### **3.7.3.3.1 Effect of buffer size**

Figure 3-10 clarifies that the message delivery probability of the five routing protocols increases as the buffer size increases. Among them, the message delivery ratio of the proposed scheme with buffer management policy is the highest. These results indicate that the proposed scheme can deliver the vast majority of the packets to the final destination. This is because the proposed scheme avoids the blindness of the Spray-and-Wait Protocol, which selects the relay node that is more likely to reach the destination node. Since the P<sub>Ro</sub>PHET protocol does not limit the number of message copies in the network, the message delivery ratio is unsatisfactory. The proposed scheme shows a significant advantage over other protocols by combining the smart relay node selection method and the limitation on the number of copies.

Figure 3-11 shows a change in the overhead rate of the five routing protocols, which is measured by the number of packet transfers needed for each packet delivery to the destination. As the buffer size increases, the number of messages that can store before meeting the destination increases, and the redundancy of data is considered to be the cause of the overhead. Since the proposed scheme and the Spray-and-Wait protocol initially control the copy of the messages, the overhead rate is suppressed. On the other hand, The P<sub>Ro</sub>PHET routing protocol and Bubble Rap routing protocol do not limit the number of message replications in the network and have a higher network overhead.

Figure 3-12 depicts the change in the average delay time of the five routing protocols. The average delay becomes higher as the buffer size increases. With the efficient control of message replication, it is possible to observe that the proposed buffer management has the lowest average latency time in all cases.



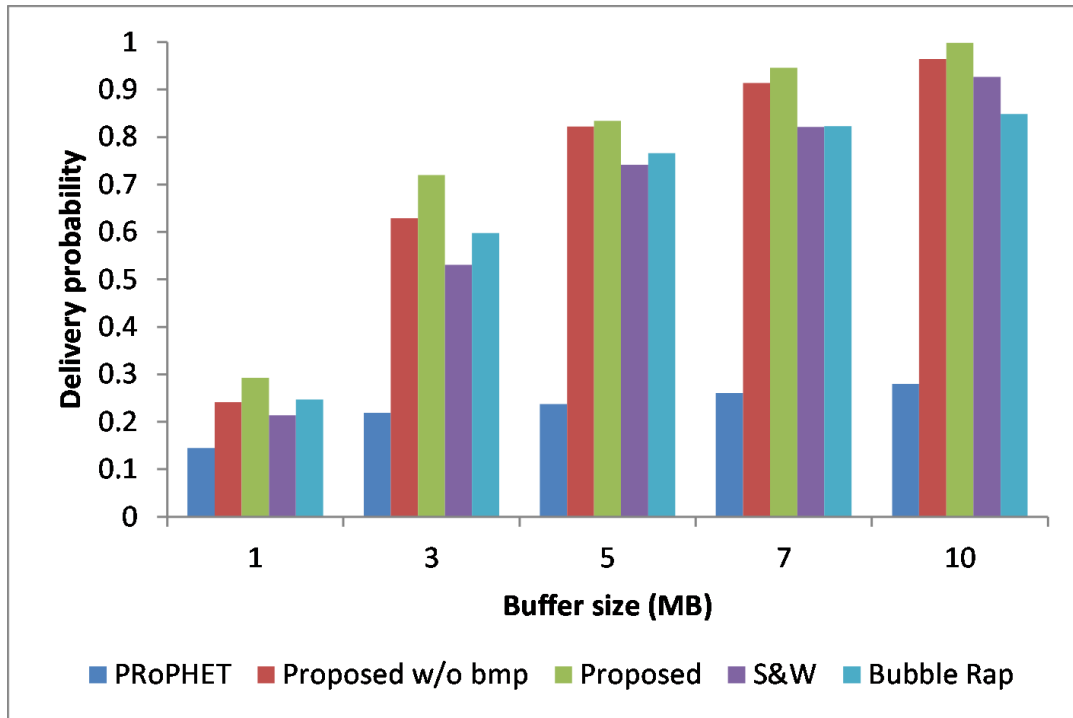


Figure 3-10 Delivery probability for various buffer sizes.

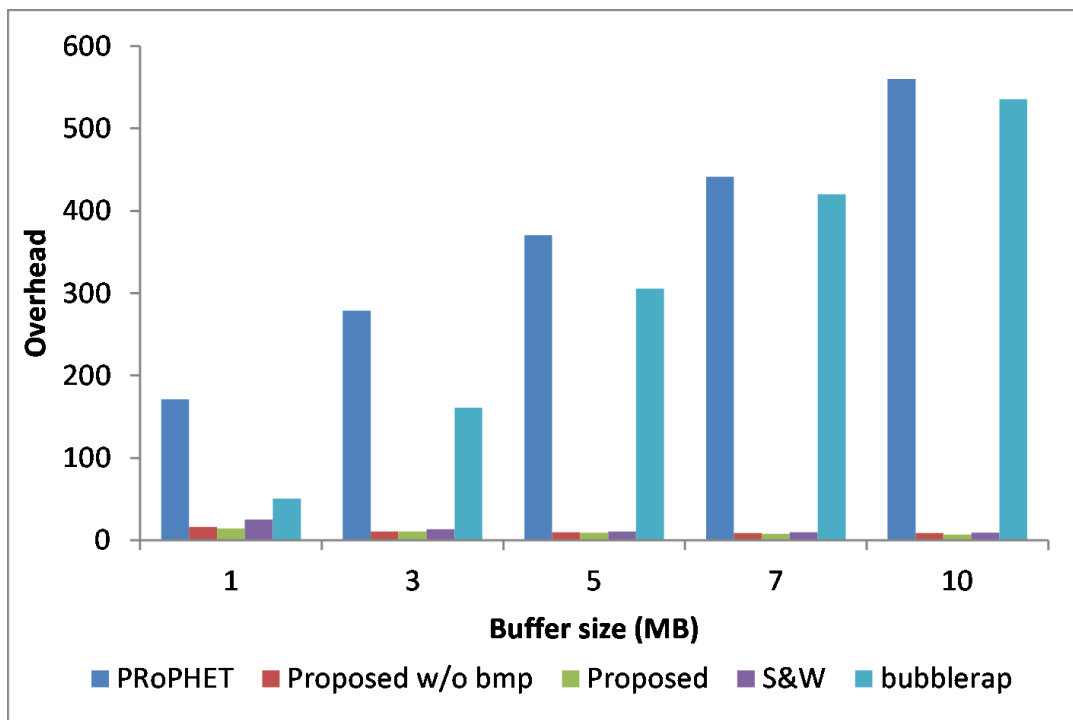


Figure 3-11 Overhead ratio for various buffer sizes.

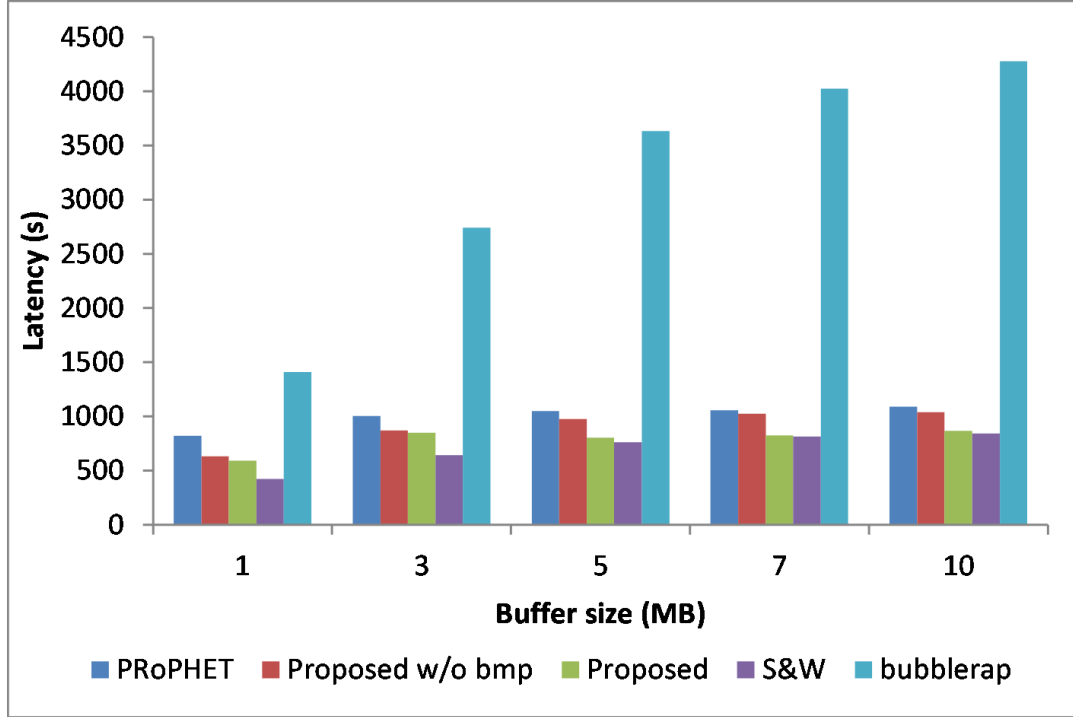


Figure 3-12 Average latency for various buffer sizes.

### 3.7.3.3.2 Effect of message interval

Figure 3-13 clarifies that the message delivery probability of the five routing protocols increases as the message interval increases. Among them, the message delivery probability of the proposed scheme with buffer management policy is the highest. This is because the proposed scheme avoids the blindness of the Spray-and-Wait protocol and controls the use of buffers. The PРоPHET protocol chooses the route to the target node, but since there is no limitation on the copy of messages, message delivery is also affected.

Figure 3-14 shows a change in the overhead rate of the five routing protocols. It is found that the overhead rate of PРоPHET protocol and Bubble Rap protocol increases as the message interval increases but the overhead rate decreases in the case of the proposed scheme and Spray-and-Wait protocol. As the message interval increases, the number of messages created in a certain simulation time is less, so the possibility of trouble occurring when message communication is low. The redundancy of data is considered to be the cause of the overhead rate becoming larger. On the other hand, the proposed scheme and the Spray-and-Wait protocol controlled the copy of the message from the beginning, so the

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overhead rate is suppressed.

Figure 3-15 shows the change in the average latency of the five routing protocols. The average latency becomes higher as the message interval increases together. Since the average latency of the proposed scheme is lower than the existing routing protocol, the network performance has been increased.

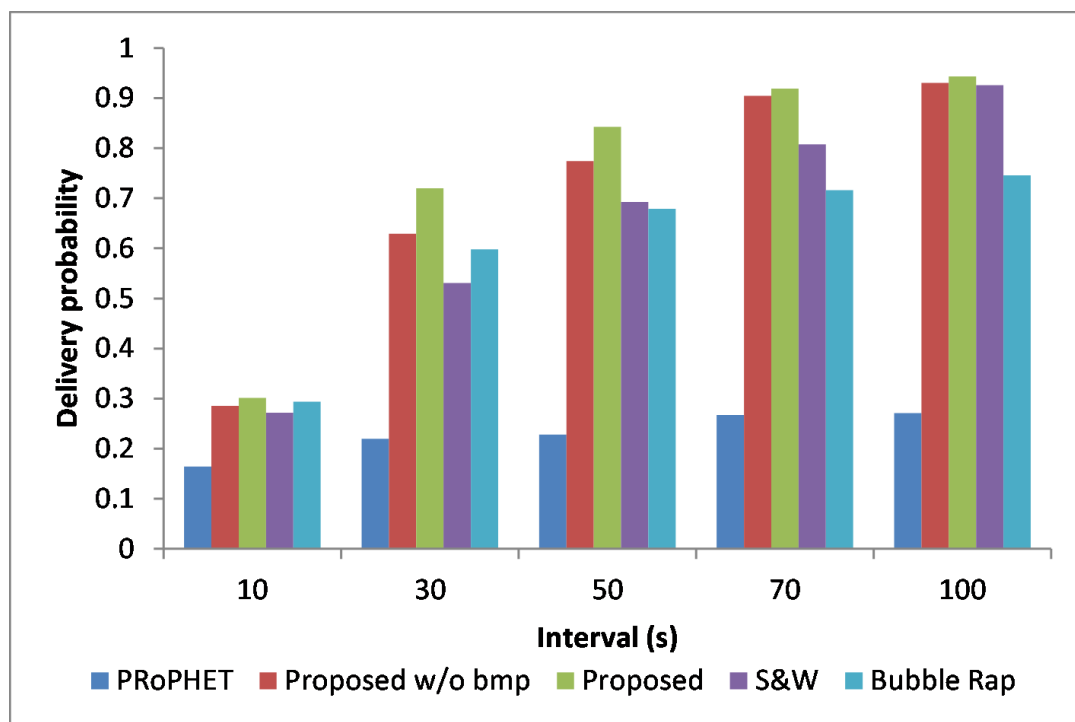


Figure 3-13 Delivery probability for various message intervals.

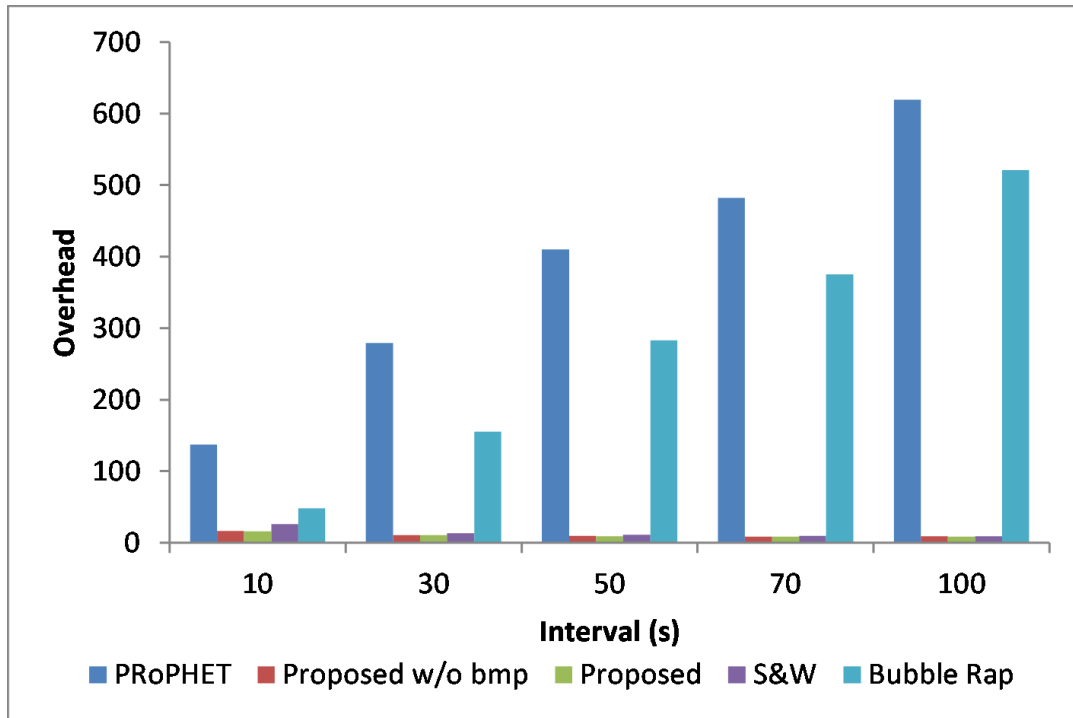


Figure 3-14 Overhead ratio for various message intervals.

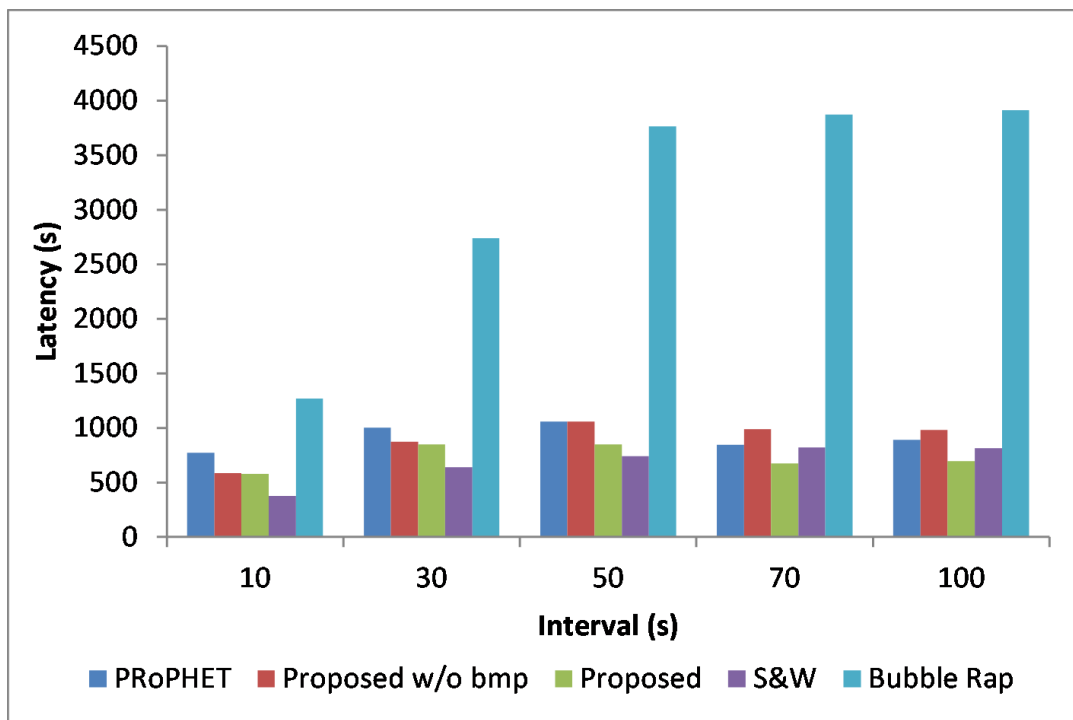


Figure 3-15 Average latency for various message intervals.

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### 3.7.3.3 Effect of message TTL

The simulation results are shown in Figure 3-16, Figure 3-17, and Figure 3-18. In this set of simulations, the message TTL is changed to evaluate the five protocols. Because of limited resources and the short lifetime of a message in VDTN, investigating the impact of TTL changes on network performance is very important when verifying the superiority of routing protocols.

PRoPHET relies on historical information of encounters between nodes to select relay nodes. The forwarding strategy can choose a node with a greater probability of encountering the destination node to increase the message delivery rate, but a dynamic environment may cause many nodes to have similar encounter probabilities. Therefore, more redundant nodes are selected as relays, which increases network overhead. Since the proposed scheme and the Spray-and-Wait protocol can control the number of message copies, when the message TTL increases, the opportunity to forward to other nodes will increase. Meanwhile, the overhead rate and average delay are not affected.

On the other hand, the PRoPHET protocol cannot limit the number of copies of the message, and it will not significantly affect network performance. The Bubble Rap routing protocol groups nodes based on social perception to improve the efficiency of message forwarding. Because the number of message copies in the network is not limited, the number of message copies increases during the forwarding process, resulting in a large network overhead.

The figure shows that the message TTL has very little impact on social-oblivious Spray-and-Wait and the proposed scheme while having an impact over the social-aware Bubble Rap protocol at different levels. This performance study led us to select the message TTL value that allows the protocols to deliver the most messages in less time and with the least associated cost.

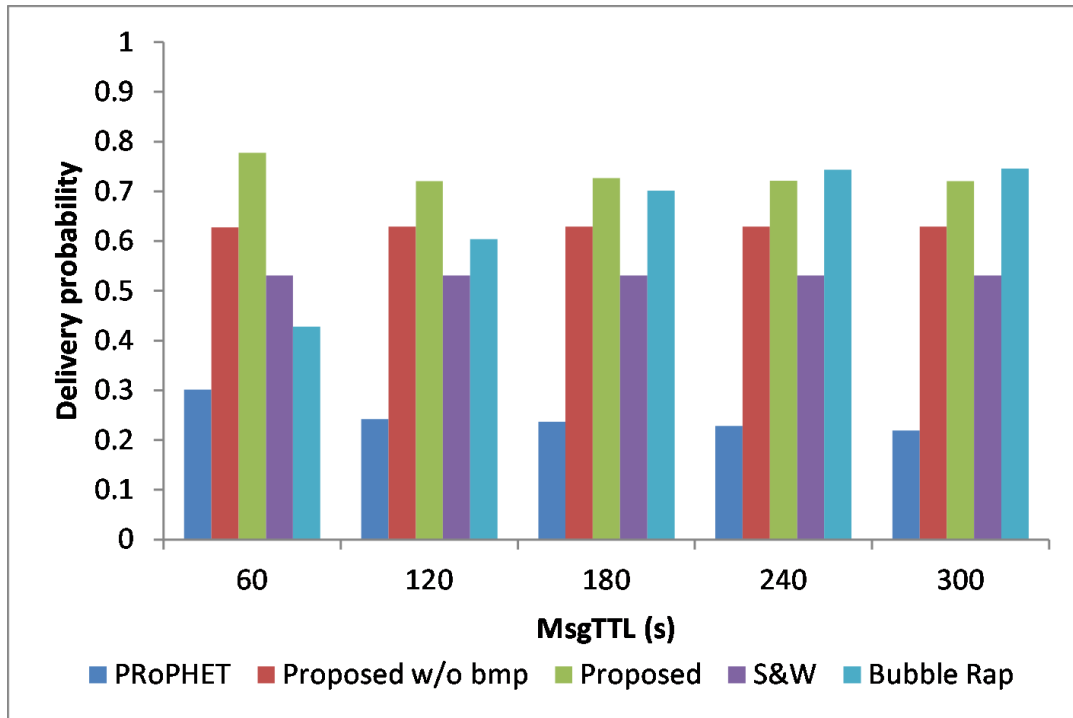


Figure 3-16 Delivery probability for various message TTL values.

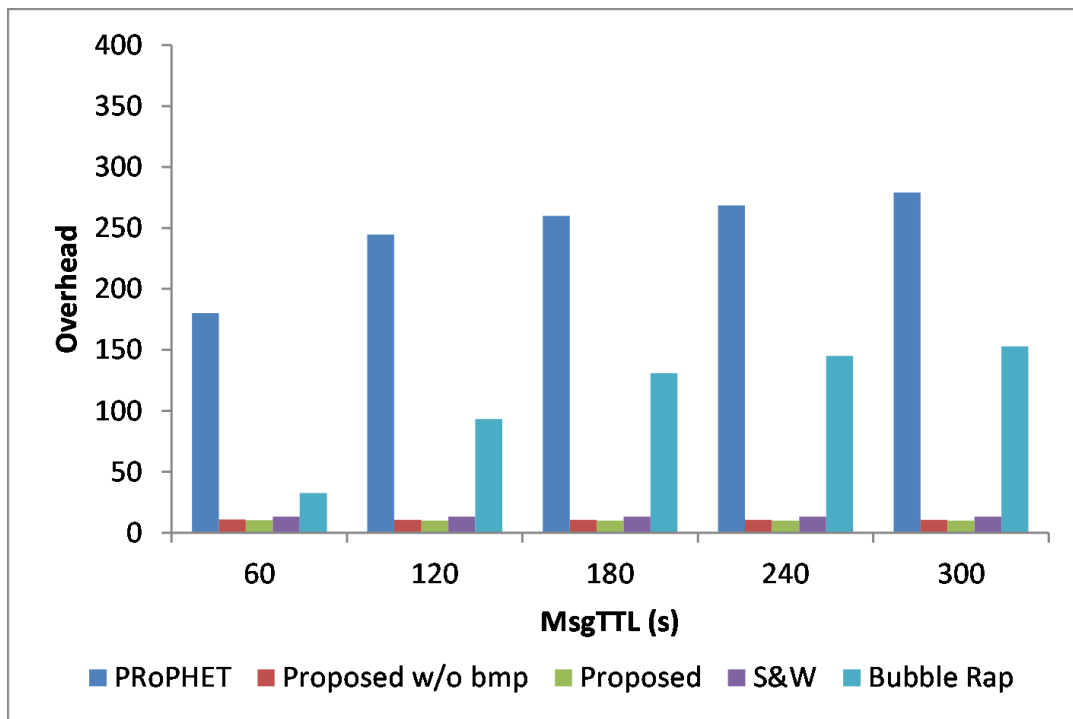


Figure 3-17 Overhead ratio for various message TTL values.

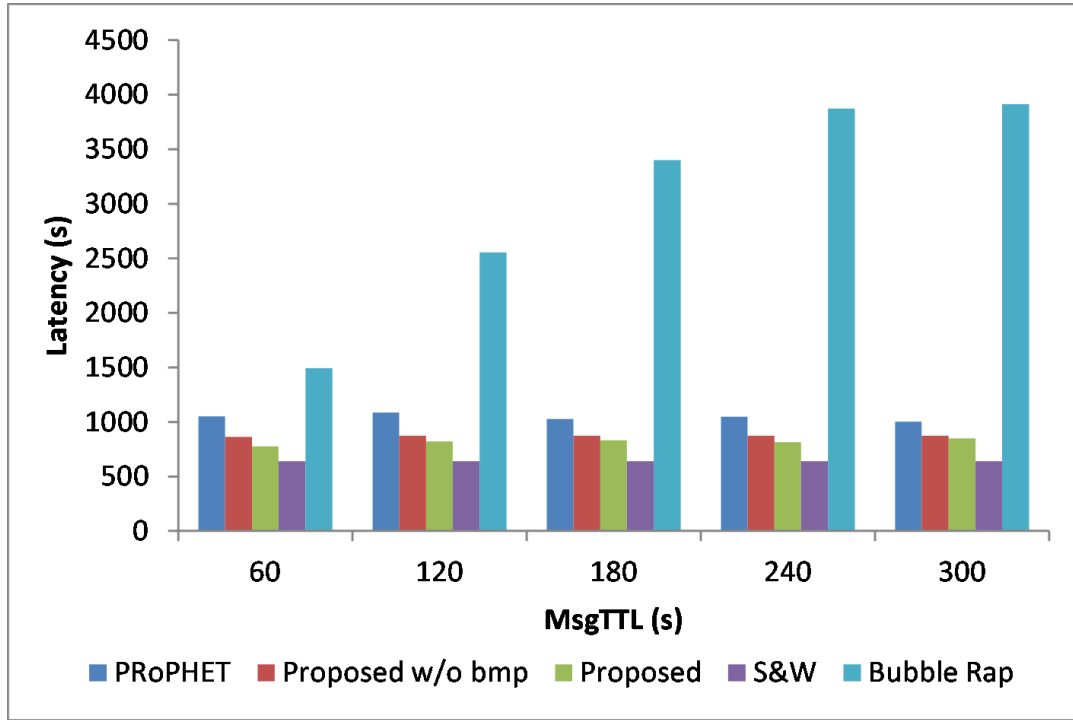


Figure 3-18 Average latency for various message TTL values.

### 3.7.3.3.4 Effect of vehicle densities

Figure 3-19 clarifies that the message delivery probability of the five routing protocols increases as the number of nodes increases. Since the proposed scheme and the Spray-and-Wait protocol can control the number of copies of messages, when the number of nodes is increased, the opportunity to communicate with other nodes is increased. The proposed routing protocol selects a better relay node while manages the node's buffer reasonably, so it has the highest message delivery rate in all cases.

Figure 3-20 shows the network overhead of the delivered messages for various numbers of nodes. After the number of nodes in the network increases, the number of nodes that can be selected as relay nodes also increases. The number of hops for a message to reach the destination node increases, resulting in an increase in the network overhead of each routing protocol. The network overhead of PRoPHET routing protocol and Bubble Rap routing protocol is higher than other routing protocols because they do not limit the number of message copies in the network.

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As shown in Figure 3-21, the delay of the proposed algorithm is lower than that of the other algorithms, which is another indication that the proposed protocol is effective. The proposed routing protocol selects a relay node with a higher probability of contact with the destination node to forward the message, reducing the average delay when the message is delivered. Besides, limiting the number of message copies and effective management of node buffers also reduces the average delay.

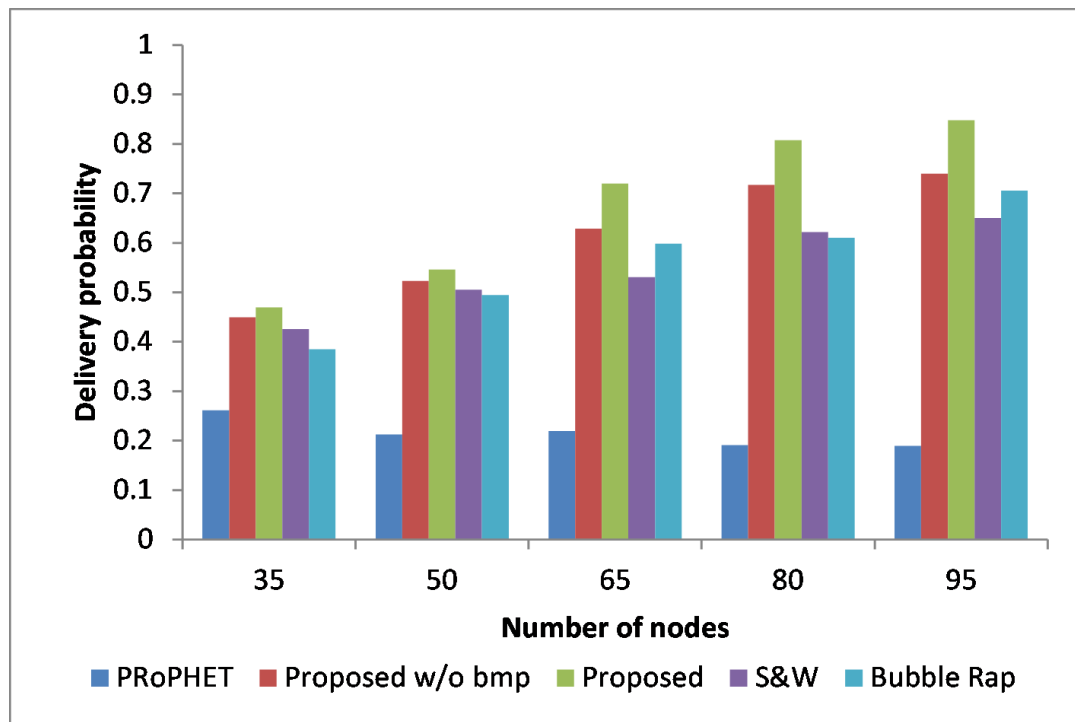


Figure 3-19 Delivery probability for various numbers of nodes.



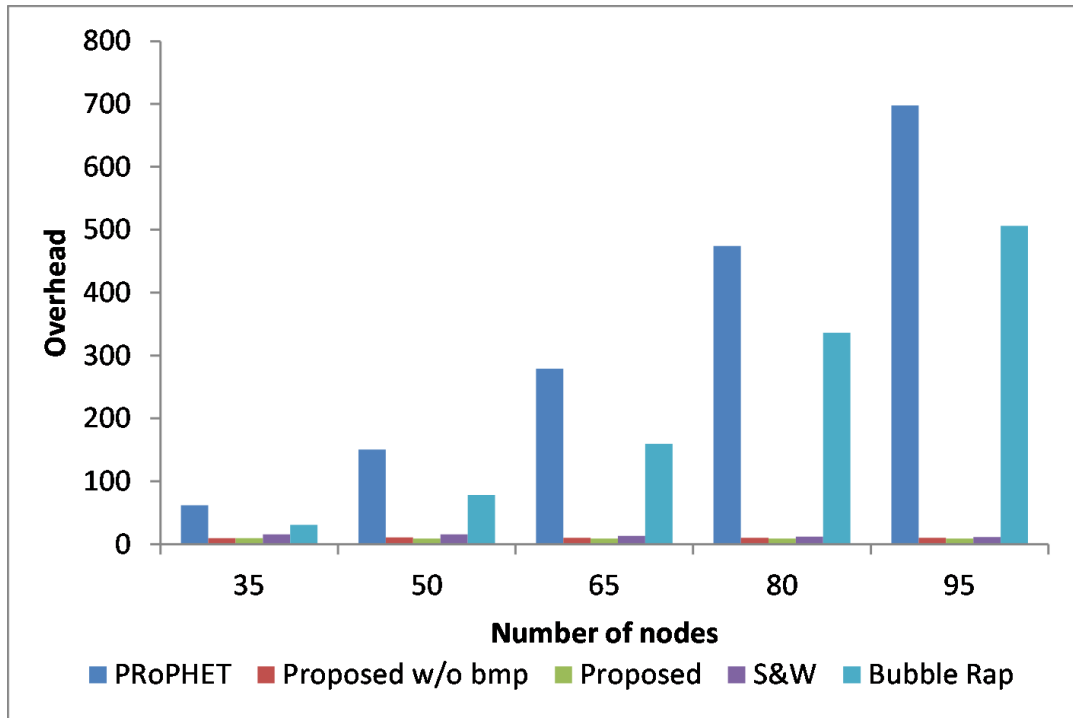


Figure 3-20 Overhead ratio for various numbers of nodes.

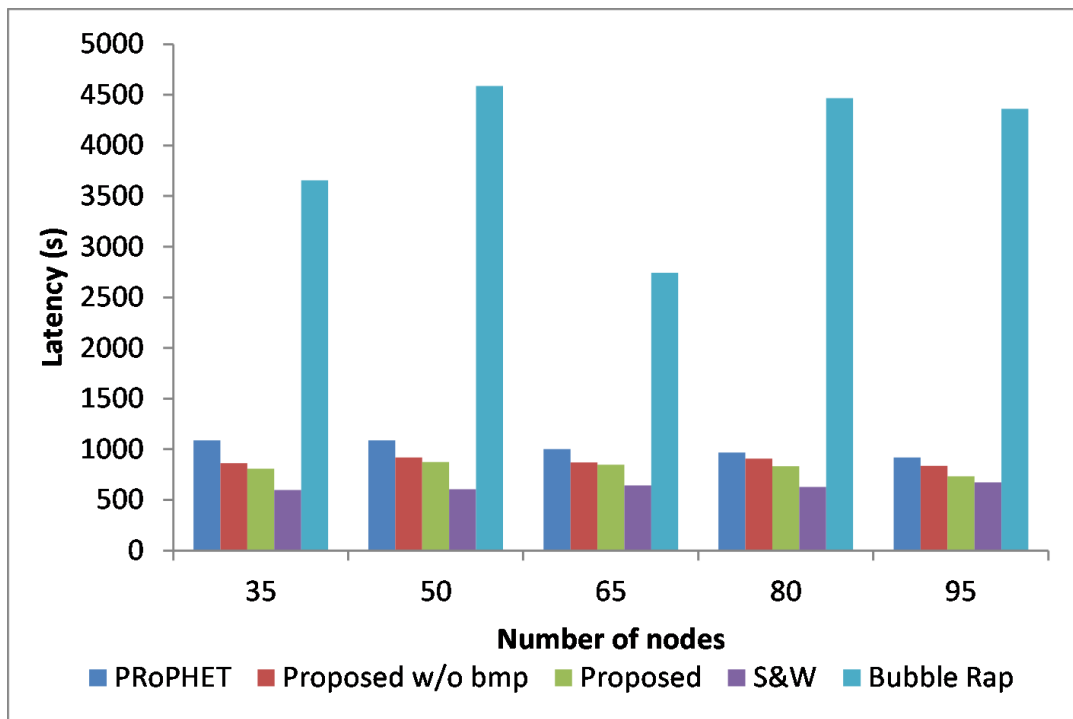


Figure 3-21 Average latency for various numbers of nodes.

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### **3.7.3.3.5 Effect of buffer size for the vehicle joining and leaving the scenario**

This section adds the entry and exit of vehicles in the scene for a more realistic simulation based on the settings in section 3.7.3.3.1. Two new vehicle sets have been added to the simulation in this section. The activity time of one group of vehicles is set from 0 to 18000 seconds (0 to 5 hours). The activity time of the other group of vehicles is set from 36000 to 43200 seconds (10 to 12 hours). Each group contains 20 vehicle nodes.

As shown in Figure 3-22, the message delivery probability in this scenario increases as the buffer size increases. Besides, the message delivery probability in this scenario is higher than that in section 3.7.3.3.1. When the newly added two groups of vehicle nodes are active, the number of nodes in the scene increases, and the number of candidate relay nodes increases. On the other hand, although the number of nodes has increased, the message delivery probability increase is not very obvious. When the new node enters the scene, the probability of encountering other nodes is low, and it is difficult to be selected as a relay node. However, with the movement of nodes and the update of the delivery probability, the possibility of a new node being selected as a relay node increases, which improves the overall network performance. The proposed routing protocol can select a relay node with a higher delivery probability to the destination node when forwarding a message, and efficiently utilize the node's buffer, so it performs better than other existing protocols in various buffer situations.

Figure 3-23 shows the changes in network overhead. The network overhead is slightly lower than that in section 3.7.3.3.1. This shows that the joined two groups of nodes can be selected as relay nodes during the movement, reducing network consumption. Besides, Figure 3-24 shows that the average delay of messages reaching the destination node is also slightly lower than in the previous section.

This set of simulations shows that the proposed routing protocol can be applied to DTN scenarios with nodes joining and leaving. Through the analysis of simulation data, it can be seen that the proposed routing protocol has the best network performance under different conditions. Since the number of messages distributed in the historical-based routing protocol is limited and the proposed buffer management method is used to manage the node's cache space effectively, the proposed scheme has advantages over existing routing protocols.

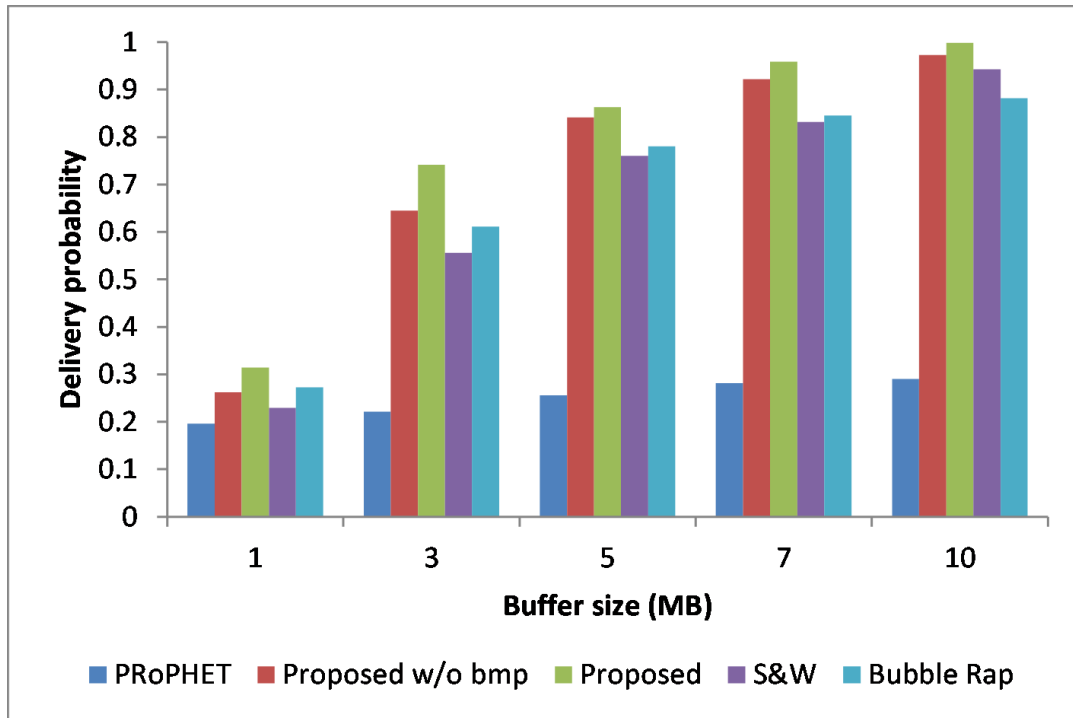


Figure 3-22 Delivery probability for various buffer sizes.

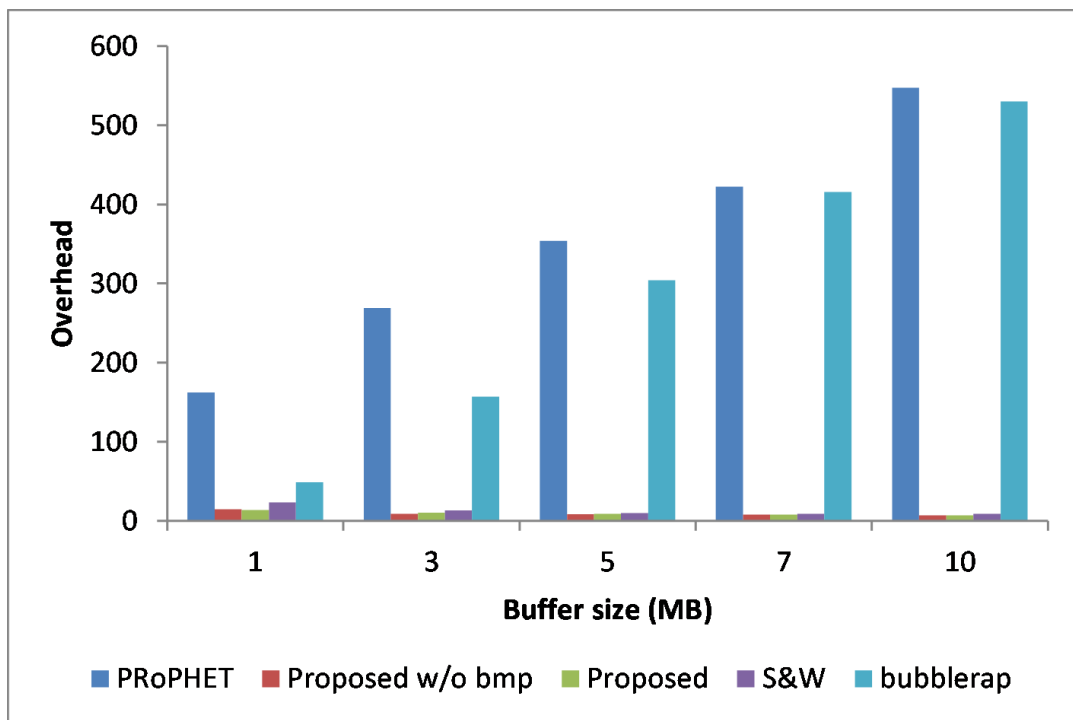


Figure 3-23 Overhead ratio for various buffer sizes.

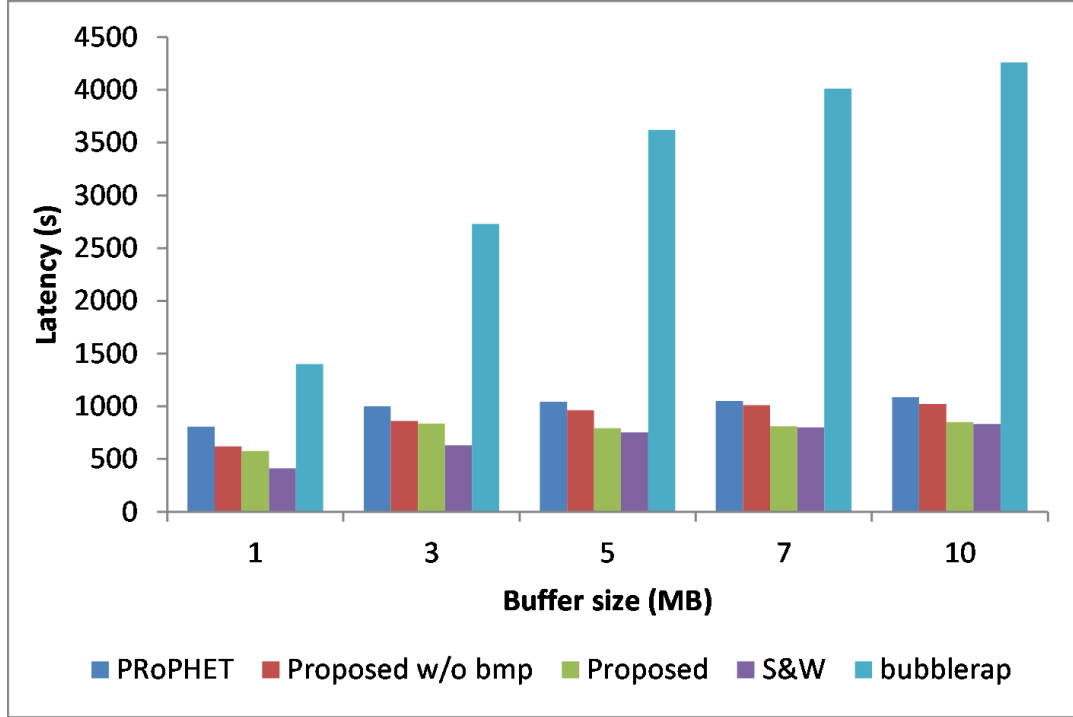


Figure 3-24 Average latency for various buffer sizes.

### 3.8 Analysis of post-disaster DTN environment

In recent years, many solutions have been proposed for post-disaster communication. Ref [142] introduces mobile devices to form a post-disaster DTN environment for data transmission, use wireless cars as ferry nodes moving between the disaster area and shelters, and realize message transferring between the command center and other areas. The DTN consists of many different types of nodes, such as emergency communications vehicles, stations, and rescue teams carrying mobile communication equipment. Although the importation of these nodes contributes to the forwarding of messages, these devices cannot be arranged in a short time due to the characteristics of the post-disaster scene, and it is difficult for ordinary victims to use these devices with good performance. With the popularity of smartphones, these devices have communication and storage capabilities. If the disaster victims carry smartphones as regular DTN nodes, the emergency communication network can be quickly established.

After the disaster, the emergency departments will quickly set up shelters and hospitals,

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making the distribution and movement of the victims show specific rules. Although the victims are moving randomly, they generally show the characteristics of group movement based in a particular gathering area such as shelters and temporary medical centers. For example, people in shelters always go to the regional supply centers for daily necessities, go back to the shelters for rest at night, and line up for treatment at temporary medical centers. The moving model based on “cluster” can reflect the movement pattern of people based on the clustering center in the post-disaster scene.

Besides, natural disasters are accompanied by the destruction of roads, bridges, and other infrastructures. The road traffic between some affected areas is blocked, the safety areas may be geographically isolated, and the DTN is composed of the disaster victims will appear network segmentation problem.

### **3.8.1 Introduction of the regional center node**

As shown in Figure 3-25, according to the crowd's agglomeration after the disaster and the crowd's movement characteristics in the area, a stationary regional center node is added to each gathering area to store and forward messages. The regional center node can communicate with the mobile node in the region, and the ferry node responsible for the message transfer task between regions. Adding stationary regional central nodes in the aggregation area can improve the contact opportunities between normal network nodes in the area and play a role in collecting and forwarding inter-regional message transmission, improving the message delivery rate and average delay of message transmission.

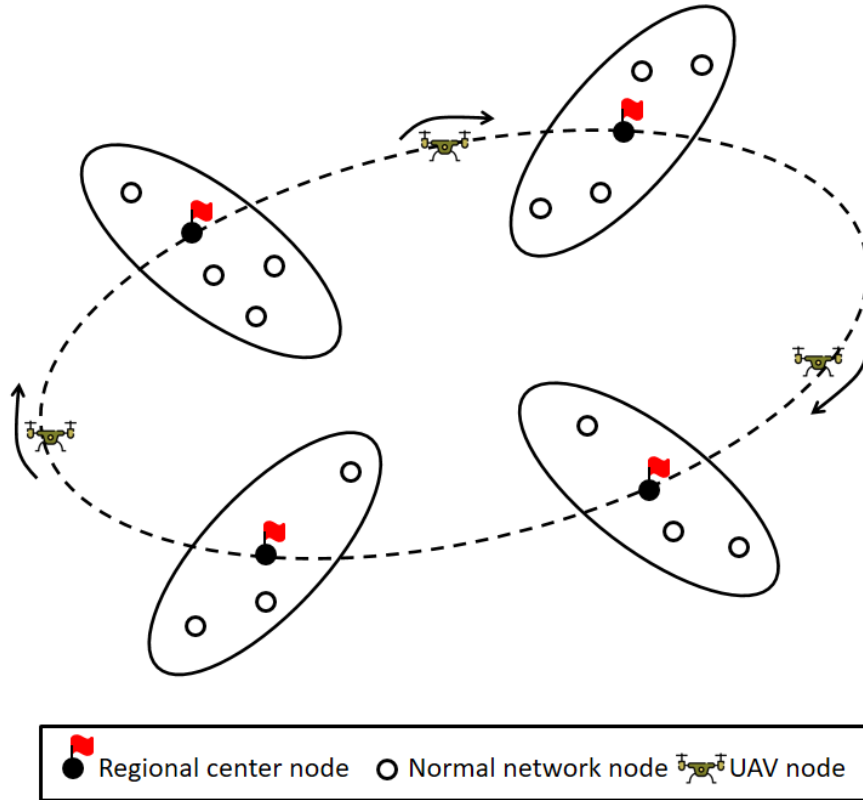


Figure 3-25 Post-disaster DTN environment with regional center node.

Besides, the introduction of regional center nodes also meets the emergency needs of post-disaster scenarios. The regional center nodes serve as the gathering centers for the people after the disaster. These places are usually used as special service areas after the disaster, such as medical aid stations, living supply stations, and accommodation areas for the affected people.

Suppose the regional center node is placed in these places. In that case, the regional center node can collect or forward more messages in the region and record the status information of the mobile nodes in the region. Through this status information, we can understand the living conditions of the affected people after the disaster. Therefore, the introduction of regional center nodes is of great significance for post-disaster rescue work.

Although the introduction of regional center nodes can improve DTN's performance after disasters, the situation after disasters is often difficult to predict. Damage to infrastructure or secondary disasters sometimes causes the unavailability of regional center nodes. Therefore, the proposed routing protocol regards the regional center node as an ordinary node for

message forwarding. When the regional center node is unavailable, it will not affect the operation of the proposed routing protocol, so the proposed routing protocol has strong usability in the DTN environment.

## 3.8.2 Simulation and result

### 3.8.2.1 Simulation set up

In this section, the ONE simulation is used to simulate the communication scene after a disaster. The network performance is verified by comparing the Epidemic routing protocol, the Spray-and-Wait routing protocol, the PROPHET routing protocol, and the proposed routing protocol.

Five regions are selected in the simulation scene, and each region is set with a regional center node. The regional center node has the characteristics of a larger buffer space and a wider communication range. Each area contains 16 nodes to simulate the daily activities of people after the disaster. A group of rescue vehicle nodes patrols each area along the delineated route to complete the message forwarding between each region. The patrol route is shown in Figure 3-26. Verify the effectiveness of the routing protocol by observing the impact of the change in the number of the rescue vehicle node on the network performance. The specific settings of the simulation are shown in Table 4-6.

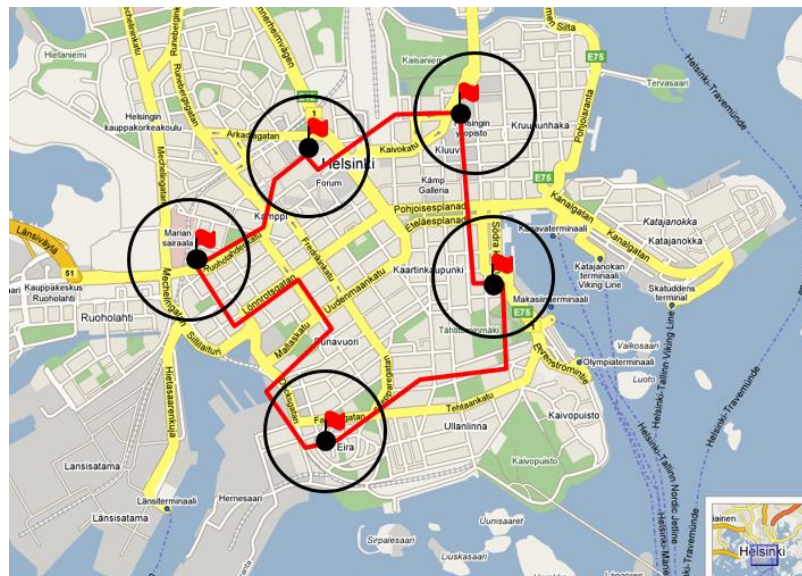


Figure 3-26 Patrol route for rescue vehicle nodes.

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Table 4 Simulation settings and parameters for regular nodes

<b>Parameters</b>	<b>Values</b>
Simulation Time	43200s
Number of nodes	80
Interface	Bluetooth Interface
Movement Speed (m/s)	0.5-1.5
Transmit Speed	2Mbps
Transmit Range	10m
Buffer Size (MB)	5
Message Interval (s)	50
Message TTL (s)	300
Movement Model	ClusterMovement
Message Size	500KB-1MB
Simulation Area Size	4500m×3400m

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Table 5 Simulation parameters for rescue vehicle nodes

Parameters	Values
Number of vehicles	0,5,10,15,20
Interface	Wi-Fi Interface
Movement Speed (m/s)	3-7
Transmit Speed	7.5Mbps
Transmit Range	30m
Buffer Size (MB)	50
Movement Model	MapRouteMovement

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Table 6 Simulation parameters for regional center nodes

Parameters	Values
Number of nodes	5
Interface	Wi-Fi Interface
Transmit Speed	7.5Mbps
Transmit Range	50m
Buffer Size (MB)	100m

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### 3.8.2.2 Simulation result and analysis

This section gives the performance of each routing protocol in the post-disaster DTN environment. A group of rescue vehicles patrols the divided areas along the established route to achieve message forwarding. A regional center node is set in each separated area to help message forwarding.

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Figure 3-27 shows the change of message delivery probability as rescue vehicles increase. When there is no rescue vehicle, the message can only be forwarded within the area, and the overall message delivery probability of the network is not high. After the rescue vehicle joins, the message can be forwarded to other areas. With the increase in the number of rescue vehicles, the number of successfully forwarded messages has also increased, and the message delivery probability has been improved.

As shown in Figure 3-28, network overhead increases with the increase of rescue vehicles. When there is no rescue vehicle in the scenario, the message can only be forwarded within the area, so the network overhead is low, but the demand for forwarding the message to other areas cannot be met. The introduction of rescue vehicles can enable messages to be forwarded to other regions. Although network overhead has increased, the need for message forwarding between regions in the post-disaster DTN environment has been realized. The proposed routing protocol maintains the lowest network overhead in all cases, which proves its superiority.

Figure 3-29 clarifies that the average delay of messages arriving at the destination node decreases as the number of rescue vehicles increases. In the scenario where rescue vehicles are not added, the reason for the lower average delay is that messages can only be forwarded within each separated region, and messages that are not successfully forwarded to other areas are not counted. After joining the rescue vehicle, the message can be forwarded to other areas, so the average delay of all messages being delivered increases. When the number of rescue vehicles increases, the number of messages that can be forwarded also increases, and the average delay decreases accordingly. The proposed routing protocol can select better relay nodes and manage the node cache reasonably, so it has the lowest average delay in all cases.

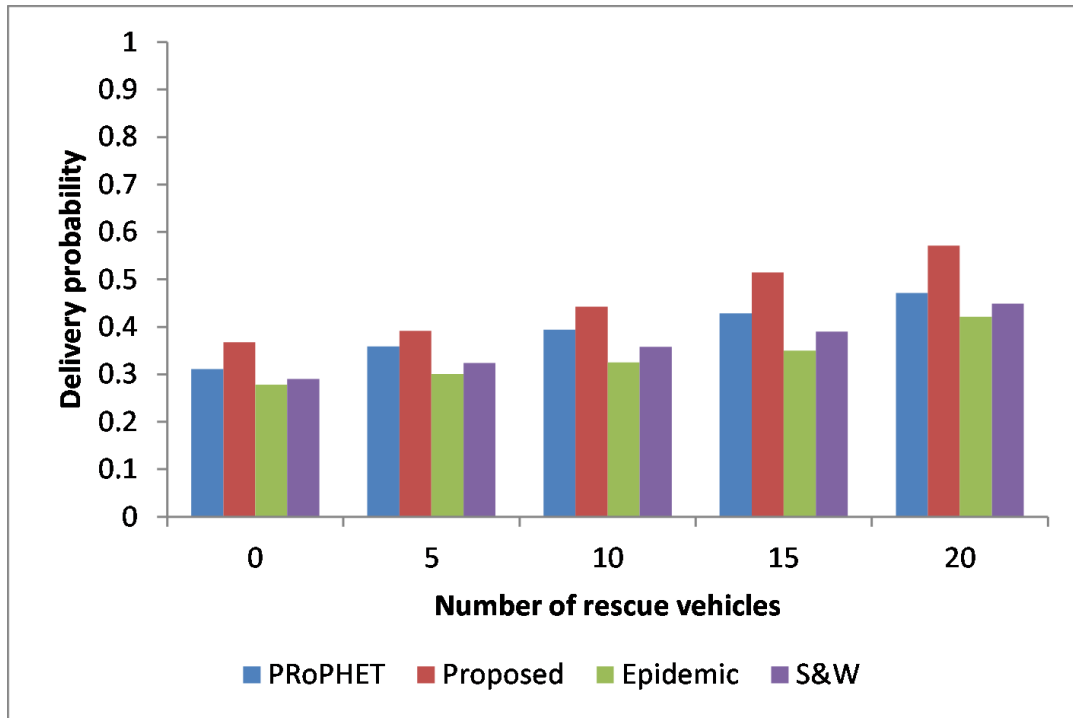


Figure 3-27 Delivery probability for various numbers of rescue vehicles.

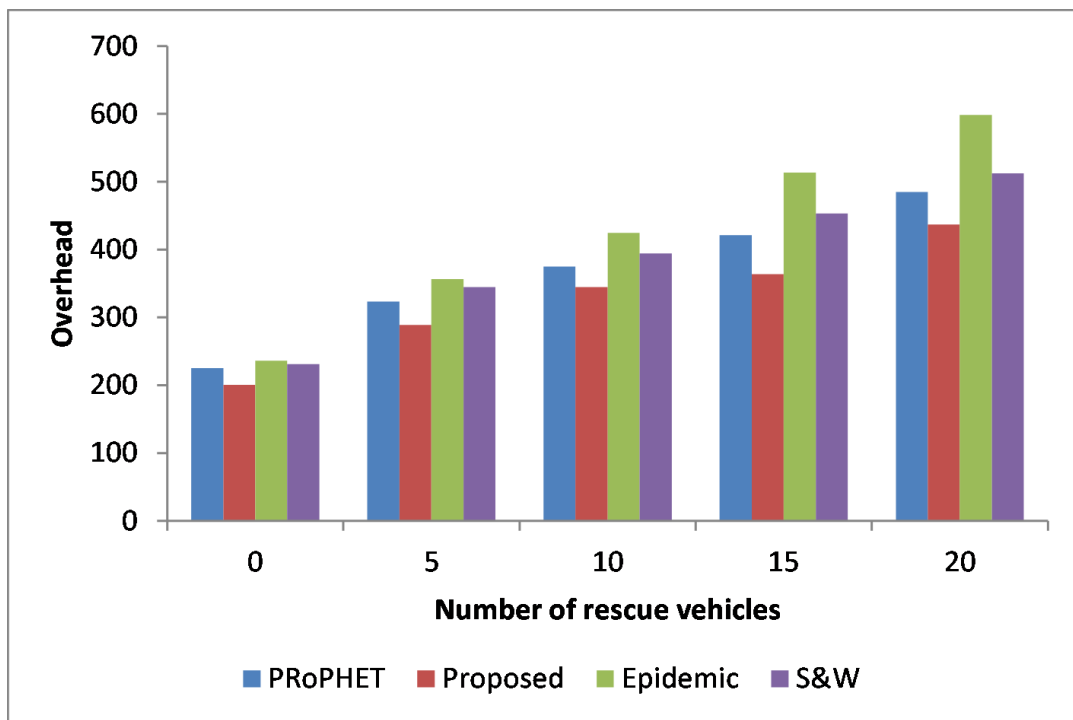


Figure 3-28 Overhead ratio for various numbers of rescue vehicles.

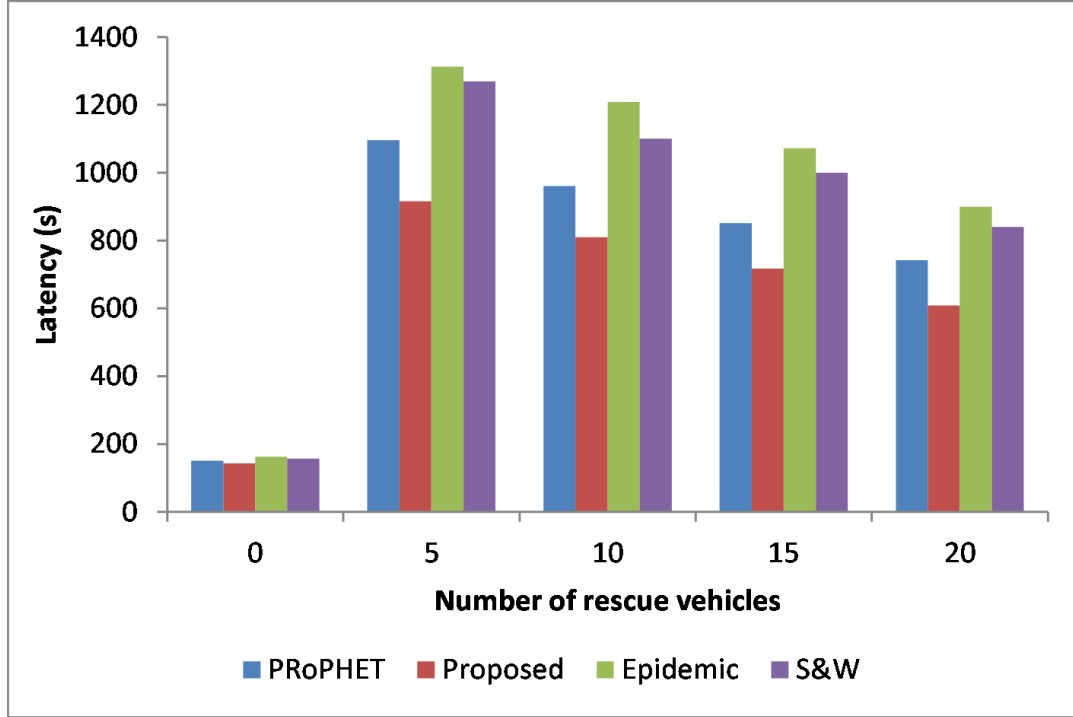


Figure 3-29 Average latency for various numbers of rescue vehicles.

### 3.9 Conclusion

In this chapter, a historical-based routing protocol with a buffer management policy is proposed in order to support message transmission in a highly dynamic VDTN scenario. Section 3.1 analyzed the existing routing protocols and buffer management policies, then discussed the necessity of a high-performance routing protocol in VDTN.

The design of the message forwarding process is introduced in section 3.2. The proposed protocol takes into account the encounter probability between nodes and the number of copies of the message in the forwarding decision. The routing protocol in this chapter is similar to the PProPHET routing in that it calculates the encounter probability between nodes before message forwarding, updates the encounter probability value to each node, and then determines the message forwarding. The historical-based routing algorithm is used because it can reduce the blindness of message forwarding, improve the delivery rate of messages in the DTN, and keep the buffer capacity and communication overhead at a low level. The difference is that the proposed protocol strictly controls the number of copies of each message in the network and the number of message copies in the message forwarding process, and

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uses the binary algorithm to distribute the message copies. Compared with the PRoPHET routing algorithm, the proposed protocol further reduces network overhead and delay. The time complexity of the proposed routing protocol is discussed in section 3.3. The time complexity of the proposed routing protocol is at the same level as that of the existing protocol. Although the load when the message is sent increases, the impact on network performance is negligible.

In section 3.4, the buffer management policy is explained in detail according to the effect of the properties of the message on the node cache. The proposed buffer management policy comprehensively considers the impact of the various attributes of the message in the node cache, calculates the congestion control metric, and sorts message copies according to this value. Messages with high congestion control metrics are sent first. These messages have the characteristics of high delivery rate, small copies, and high TTL time. When a node is congested, the message with the smallest CCM is deleted until the congestion is removed. Compared with the existing buffer management policy, the proposed buffer management policy enhances fairness when selecting messages to be dropped. Section 3.5 discusses the time complexity of the proposed buffer management policy. The time complexity of the proposed buffer management policy is at the same level as the existing buffer management policy, and the impact on network performance is negligible.

Finally, Sections 3.7 and 3.8 give a comparative analysis of the network performance of the proposed routing protocol and the existing protocol in daily and post-disaster scenarios. The evaluation of the proposed routing scheme is conducted using simulation tools in different network environments by changing the node buffer size, message interval, message TTL, and the number of nodes. The results showed that the proposed routing protocol apparent advantages compared with the traditional algorithms in the VDTN. The message delivery probability is increased, and the overhead rate is decreased as well.

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# CHAPTER 4

## 4 UAV-empowered protocol in VDTN

The VDTN is a special opportunity network, which is of great practical significance in the dissemination of all kinds of service applications. Due to the mobility of vehicle nodes and fast change of network topology, VDTNs use opportunistic forwarding to transmit messages to improve link quality. The low reliability of VDTNs can be improved by selecting a more suitable relay node to establish a communication link for message transmission.

This chapter proposes the use of UAVs as ferry nodes to supplement the lack of backbone network coverage. These nodes collect messages and deliver the message to the target in other areas since UAVs could have strong mobility and carry sufficient energy.

Through the discussion of the shortcomings of PROPHET routing protocol, the thesis designs an improved routing algorithm based on persistent connection time ratio between network nodes, the algorithm combining the characteristics of UAVs and PROPHET routing algorithm of probability prediction not only increase the message forwarding efficiency but also enhanced the stability of the communication link.

Section 4.1 analyzes the challenges that the PROPHET routing protocol faces and explains the necessity of developing efficient routing protocols in VDTN environments where UAVs are introduced as ferry nodes.

In section 4.2, the improved forwarding strategy based on the PROPHET routing protocol is introduced in detail. The proposed protocol considers the persistent connection time ratio between nodes in the forwarding decision. Section 4.3 discusses the time complexity of the proposed routing protocol.

In section 4.4, the simulation works are designed to evaluate how the proposed scheme affects network performance.

Section 4.5 analyzes the post-disaster scene and discusses the characteristics of the movement and distribution of the disaster victims. The UAVs deliver messages from one area to another after the disaster. Finally, ONE simulator is used to verify the effectiveness of the

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routing strategy. Finally, section 4.6 summarizes this chapter.

## 4.1 Problem discussion

In general, communication links in the VDTN environment are unstable, and messages are delivered through the store-carry-forward mechanism. Considering poor network connectivity and intermittent communications between forwarding nodes, the store-carry-forward mechanism forwards a copy of a message to the destination node by replicating the message to some nodes that possibly encounter the destination node in the future via a path leading to the destination node. The research problem explained here using P<sub>Ro</sub>PHET since it is a well-known probabilistic DTN protocol.

The message replication process of P<sub>Ro</sub>PHET routing messages is shown in Figure 4-1. The two neighbor nodes (nodes *A* and *B*) are located in the communication range of a source node *S*. Without considering the persistent connection time, node *S* chooses the node with a higher encounter probability as the relay node to forward a message to the destination node *D*.

Suppose nodes *A* and *B* have the same encounter probability. Following the traditional P<sub>Ro</sub>PHET routing mechanism, node *S* transmits the message to both nodes *A* and *B* without considering the persistent connection time. Since multiple copies of the same message are forwarded in the network, it causes an excessive consumption of network resources.

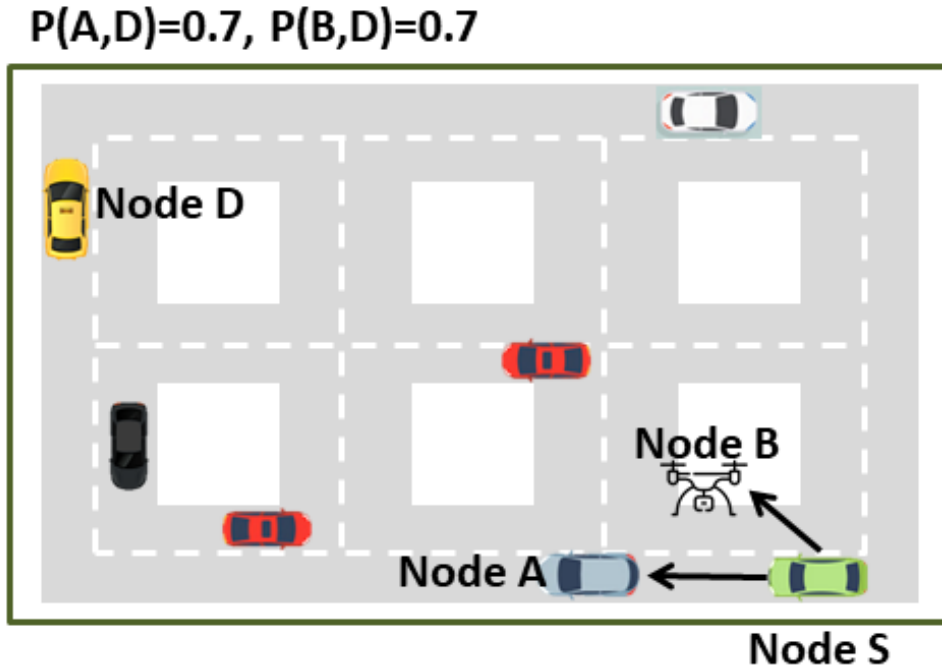


Figure 4-1 Forwarding decision scenario A.

Another VDTN scenario is shown in Figure 4-2, where the encounter probability of node *A* and *B* are very close. As mentioned in the introduction of the PRoPHET protocol, the source node *S* forwards the message to node *A*. However, node *A* is moving out of the transmission range of node *S*. If we choose node *A* as the relay node, it could lead to a data transmission delay and performance degradation since the unpredictable behavior of node *A*. Node *B*, which is a UAV patrolling in the region, has a larger transmission range to form a more reliable connection. However, the encounter probability is lower than that of node *A*. The disadvantages are summarized as follows.

- (1) When neighbor nodes have the same encounter probability, the source node may choose an inappropriate relay node, causing network resource wastage.
- (2) When a neighbor node has a slightly lower encounter probability, but with a larger transmission range and more predictable movement path as compared with other neighboring nodes, the source node may not choose this node as the forwarder node.



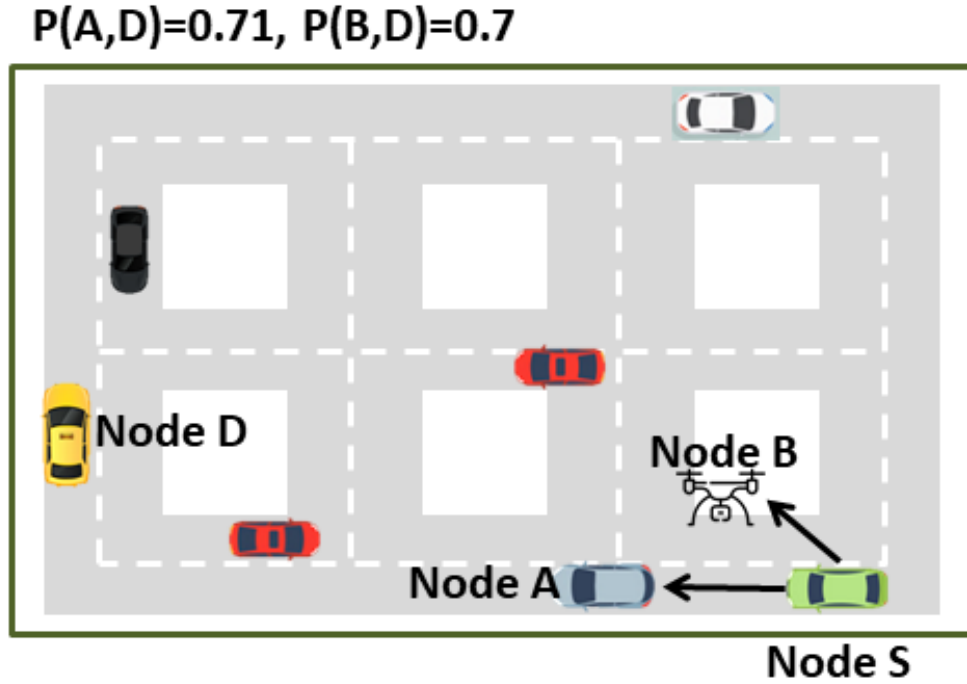


Figure 4-2 Forwarding decision scenario B.

In order to solve the disadvantages of the PROPHET routing described above, this chapter designs a historical-based routing algorithm with the persistent connection time as the main influencing factor. The algorithm considers whether the nodes are reliable and effective in the communication process, and flexibly uses UAV nodes in the VDTN environment to improve the transmission performance of the network.

## 4.2 Proposed routing protocol

### 4.2.1 Definition of the persistent connection time ratio

In the message transmission process, due to the fast movement of nodes and limited communication link rate, the connection time between nodes is very short, and the intermittent connectivity nature of the underlying network topology causes the communication link unstable. The introduction of UAVs can solve this problem. However, after joining UAVs in the VDTN environment, it is unreasonable to choose the relay node using the same method as before. Therefore, the persistent connection time, which is the

connection time for each encounter is introduced to select nodes that can establish stable communication links and ensure the transmission quality. This chapter characterizes the reliability of packet communication link through the persistent communication time ratio between nodes.

As shown in Figure 4-3, at time  $t1$ , two moving nodes form a direct communication link that can be used for data transmission. At time  $t2$ , when the two nodes leave the transmission range of each other, communication becomes disconnected and message forwarding cannot be completed successfully. The time period of  $(t2-t1)$  is the effective connection time when two neighbor nodes are located in the transmission range of each other.

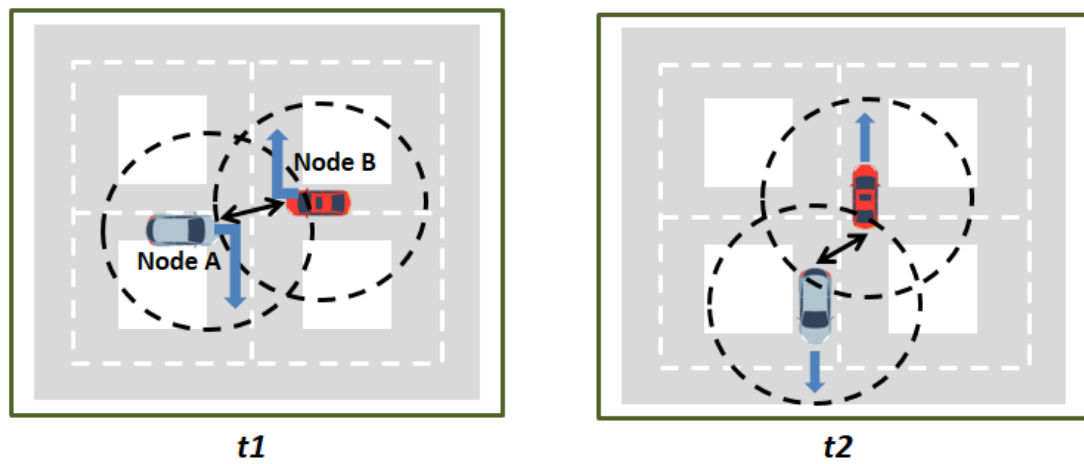


Figure 4-3 Communication link between nodes.

The persistent connection time refers to the statistics of the time for two nodes to maintain the continuous connection state of the communication link based on the historical encounter connection information of the node. The average value of the connection time of two nodes in the historical process is calculated. Taking the average value as an important reference, it shows the connection ability of nodes in the past time and selects nodes with longer connection time to ensure the stability of packet transmission. Statistics of the meeting process between nodes are shown in Figure 4-4.

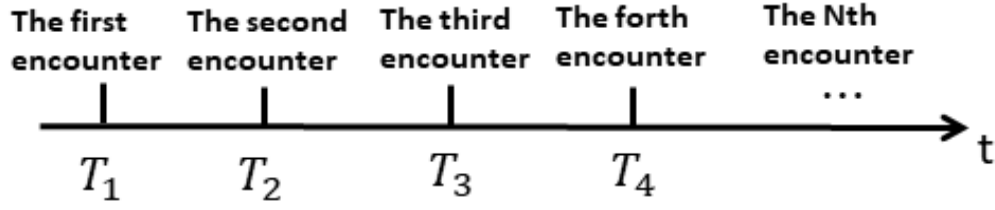


Figure 4-4 The encounter times of two nodes.

In this figure, the two nodes meet and connect with each other for  $n$  times in a predefined time interval, where  $T_1$ ,  $T_2$ ,  $T_3$ ,  $T_4$ , and  $T_i$  represent the connection time between them for the corresponding encounters. The longer the connection time of an encounter between the two nodes in the history, the longer the link interaction time that the nodes can maintain in subsequent connections, contributing to a more reliable message forwarding.

## 4.2.2 Proposed message delivery process

As shown in Figure 4-5, UAV nodes possibly have a larger transmission coverage than vehicle nodes. This is because a communication link involving a UAV is not easily blocked by obstacles. So, the achievable communication rate is basically higher than that in the communication between ground vehicles. Taking this aspect into consideration in the routing protocol has become a key move to improve network performance.

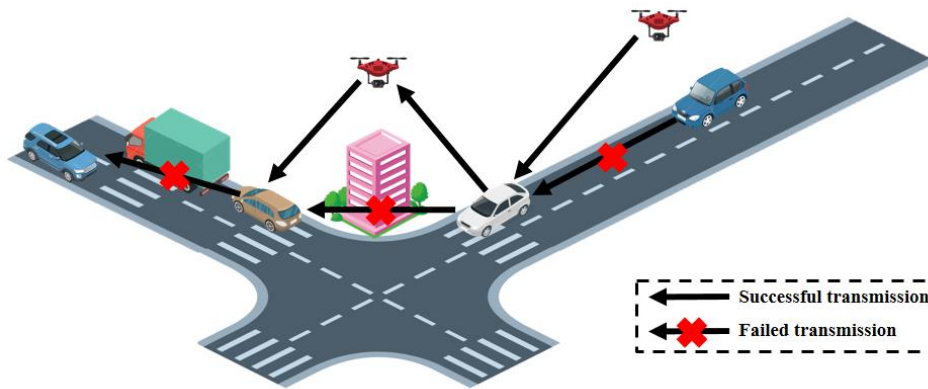


Figure 4-5 Comparison of an UAV-vehicle communication link and an inter-vehicle link.

The node communication link in the VDTN environment is unstable, and the node transmits

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the message in the “store-carry-forward” mechanism. In poor network connectivity and unstable or even interrupted communication links between nodes, this communication mechanism can select the relay node to forward the copy of the message to the destination node. In the PRoPHET forwarding strategy, most nodes need to determine whether the message should be forwarded to the meeting node. If the delivery predictability of the meeting node relative to the destination node is greater than the packet carrier, forwarding will be carried out. In section 4.1, the shortcomings of this method are analyzed, which mainly lie in the link instability caused by the difference in the encounter probability of the encountering nodes. Therefore, based on the PRoPHET routing algorithm, this chapter introduces the persistent connection time between nodes in order to select better relay nodes. The persistent connection time ratio is calculated as follows:

$$K_{(r,d)} = \frac{\sum_{n=1}^w T_{rd}(n)}{T_{con}} \quad (13)$$

where  $\sum_{n=1}^w T_{rd}(n)$  represents the total length of connection times between a relay node  $R$  and the destination node  $D$ , and  $w$  represents the number of encounters between nodes  $R$  and  $D$ .  $T_{con}$  represents the total time since the wireless interface of node  $R$  starts to work.  $K_{(r,d)} \in (0,1)$  shows the ratio between the connection time of relay node  $R$  and destination node  $D$ , and the connection time of relay node  $R$  and all other nodes in the network.

The proposed protocol considers both the encounter probability and persistent connection time by defining a  $Q$  value, which is calculated using the following formula to evaluate whether a candidate node is suitable for relaying messages.

$$Q_{(r,d)} = \alpha \times P_{(r,d)} + (1 - \alpha) \times K_{(r,d)} \quad (14)$$

where  $P_{(r,d)}$  is calculated in equation (1), and  $\alpha \in (0,1)$ . When the value of  $\alpha$  is greater than 0.5, the encounter probability plays a dominant role in the decision of the relay node. When the value of  $\alpha$  is less than 0.5, the persistent connection time ratio becomes the dominant factor in the decision of the relay node. The value of  $\alpha$  will have an impact on the performance of the proposed routing protocol. Hence, the  $\alpha$  value has a notable impact on the performance of the proposed routing protocol. The results of multiple simulation experiments presented in the following section show that when the value of  $\alpha$  is 0.35, the combination of the encounter probability and persistent connection time ratio is the best, which leads to the best network performance. Therefore, the value of the smooth factor  $\alpha$  is

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set as 0.35 in the following experiments.

Figure 4-6 shows the selection of relay nodes in the proposed routing protocol. Assuming there are two nodes  $A$  and  $B$  in the transmission range of a source node  $S$ . The  $Q$  value of node  $A$  is greater than that of node  $B$ , so the source node  $S$  chooses node  $A$  as the relay node and sends a message to it. The calculation of the  $Q$  value combines the encounter probability and the persistent connection time ratio between the two nodes. By comparing the  $Q$  value, the source node can select a relay node with a high probability of encountering the destination node with a more reliable link, thereby improving network performance.

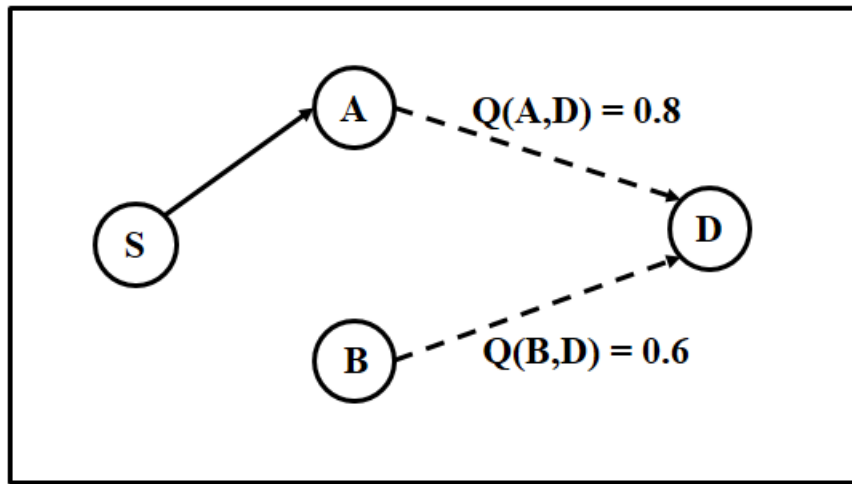


Figure 4-6 The selection of a relay node in the proposed protocol.

The routing procedure of the proposed protocol is shown in Algorithm 2. Each node maintains its own  $K$  based on the encounter history maintained by each node. Then the sender node updates  $Q$  as the basis for selecting the relay node. Finally, a more reliable relay node is selected by comparing  $Q$  values of all candidate nodes.

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**Algorithm 2** The proposed routing protocol for UAV-assisted VDTNs

D is the destination node;

Each source/forwarder node  $A$  does the following step;

**for** each node  $X$  that the current node  $A$  meets **do**

Drop the message with an expired lifetime.

Receive  $K_{(R,D)}$  from  $X$ .

Calculate  $Q$  value for  $X$  according to Eq. (14).

**if**  $Q_{(A,D)} > Q_{(X,D)}$  **then**

Continue to carry the message.

**else**

Replicate the message and forward it to node  $X$ .

**end if**

**end for**

Each candidate node (for forwarder) does the following steps:

Calculate  $K_{(R,D)}$ .

Send  $K_{(R,D)}$  to node  $A$ .

**end**

In the actual scenario, due to the introduction of UAV, the message can be transmitted to a remote area. In Figure 4-7, the purple vehicle represents the source node, and the orange vehicle represents the destination node. The red line represents the path of the UAV. Since

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there is almost no end-to-end connection in DTN, when the source node needs to send a message to the destination node, a relay node needs to be used to forward it. The source node will select a relay node according to the proposed routing protocol. The proposed routing protocol ensures that the source node can select a relay node that has a greater chance of contact with the destination node and can establish a reliable link, thereby ensuring network performance.

In daily scenarios, the relay node can be a vehicle node or a UAV node. In the post-disaster scenario, UAV nodes patrol between the divided areas according to the established route. When the message needs to transfer to other areas, the UAV node will be selected as a relay node for message forwarding. When the destination node and the source node are in the same area, other vehicle nodes in the area are usually selected for message forwarding.

Compared with vehicle nodes, UAV nodes have a broader transmission range and controllable moving paths. In response to this feature, the proposed routing protocol puts forward the concept of the persistent connection time between nodes to evaluate whether the nodes can establish a more reliable link. Through the combination of the encounter probability and the persistent connection time between nodes, the proposed routing protocol can avoid transmission failures caused by the disconnection of node links. Based on this strategy, the proposed routing protocol also flexibly uses UAV nodes to improve network performance.

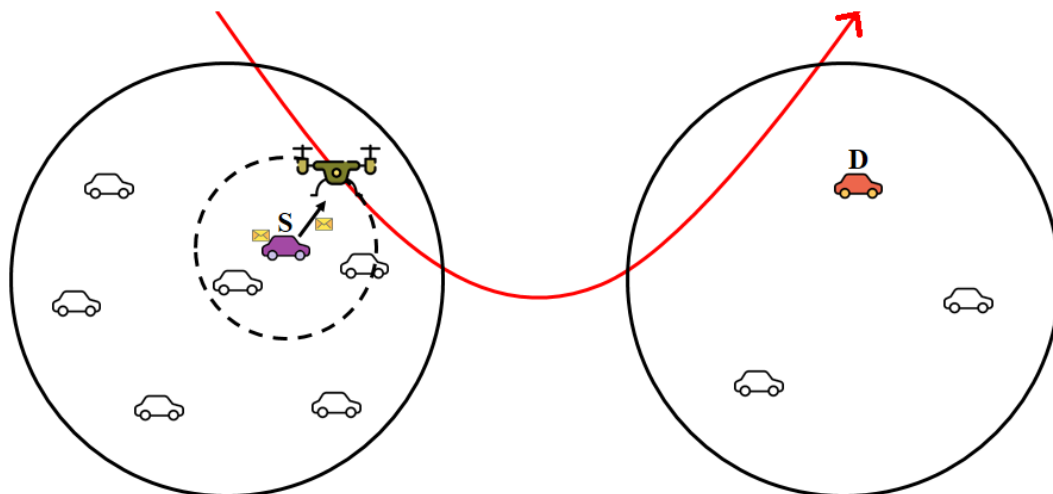


Figure 4-7 Message forwarding in a post-disaster scenario.

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### 4.3 The time complexity of the proposed routing protocol

The time complexity consists of updating the improved encounter probability value introduced in the proposed routing protocol. In the implementation of the proposed routing protocol, the calculation of equations (1), (3), and (14) only occurs at the moment of node encounter, while the calculation of equations (2) and (13) is performed at both node encounter and message forwarding. Therefore, the time complexity of the proposed routing protocol is  $O(n)$ , where  $n$  denotes the number of messages in the node.

### 4.4 Simulation and result

#### 4.4.1 Simulation set up

In this section, the ONE simulator is used to evaluate the network performance of the proposed protocol. The proposed protocol is compared with Epidemic routing, Spray-and-Wait routing, and PRoPHET.

Parameters for regular nodes and simulation settings are specified in Table 7. The parameters of UAVs are introduced in Table 8. In the simulation, the city map of Helsinki as the moving area of regular nodes. As shown in Figure 4-8, the red line is the patrol route of UAVs. Two sets of the simulation were completed to evaluate the proposed routing protocol by changing the number of UAVs and regular nodes.

A new QoS metric is added in this chapter, called the average hop count. The average hop count describes the path length required for a node to successfully forward a data packet. The smaller the average number of hops, the more efficient the routing algorithm, the smaller the transmission delay, and the fewer resources it will occupy in the network.



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Table 7 Simulation settings and parameters for regular nodes

<b>Parameters</b>	<b>Values</b>
Simulation Time	43200s
Number of nodes	40, 80, 120, 160, 200
Interface	Wi-Fi Interface
Movement Speed (m/s)	2.4-13.9
Transmit Speed	7.5Mbps
Transmit Range	50m
Buffer Size (MB)	5
Message Interval (s)	50
Message TTL (s)	300
Movement Model	Shortest Path Map Based
Message Size	500KB-1MB
Simulation Area Size	4500m×3400m

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Table 8 Simulation parameters for UAVs

Parameters	Values
Number of UAVs	0, 5, 10, 15, 20
Interface	Wi-Fi Interface
Movement Speed (m/s)	5-15
Transmit Speed	7.5Mbps
Transmit Range	50m
Buffer Size (MB)	100
Movement Model	MapRouteMovement



Figure 4-8 Patrol route of UAVs.

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## 4.4.2 Simulation result

### 4.4.2.1 The decision of $\alpha$ in the proposed routing protocol

Before comparing the proposed routing protocol with the existing baselines, it is necessary to determine the best possible value for the smooth factor  $\alpha$  of the proposed routing protocol. The  $\alpha$  value is used to balance the impact of the encounter probability and the persistent connection time ratio for the selection of relay nodes so that the optimal relay node can be selected for message forwarding.

The simulation settings are shown in Table 7 and Table 8. The number of vehicle nodes is 80, and the number of UAV nodes is 10. Simulations are conducted to find the best possible value of  $\alpha$  by observing the change in the message delivery ratio.

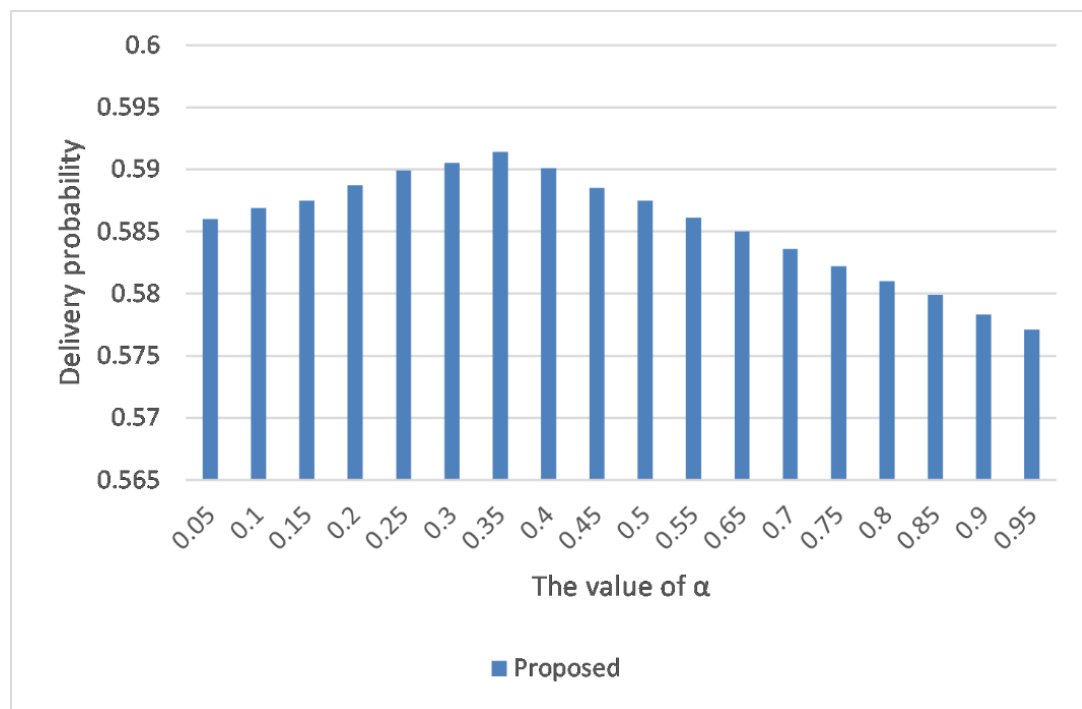


Figure 4-9 Delivery probability for the various value of  $\alpha$ .

As shown in Figure 4-9, the closer the value of  $\alpha$  to 0, the more reliable is the link between the selected relay node and the destination node. The closer the value of  $\alpha$  is to 1, the greater the likelihood that the selected relay node will encounter the destination node. When the value of  $\alpha$  is 0.35, the proposed protocol shows the best possible performance, contributing to the

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highest possible delivery ratio. Therefore, in the subsequent simulation, the value of  $\alpha$  is 0.35.

#### 4.4.2.2 Effect of UAV count

In this section, each routing protocol is evaluated with different numbers of UAVs.

Figure 4-10 shows the message delivery ratio of the routes established using the routing protocols for different numbers of UAVs. When more UAVs participate in the routing process, the message delivery ratio increases for all the protocols. However, since other protocols do not adequately address the characteristics of UAVs in the route selection, the increase is less significant than the proposed protocol. In the process of selecting relay nodes, the proposed protocol considers the encounter probability and persistent connection time ratio, therefore UAVs can be utilized more efficiently.

Figure 4-11 illustrates the overhead of the routing protocols for different numbers of UAVs. When the number of UAV nodes increases, there is a trend of increase in the overhead because more message copies are generated with the increased number of forwarding nodes. The proposed protocol shows a low overhead. When the number of UAVs is large, the advantage of the proposed protocol over other protocols is notable. This is because the use of persistent connection time ratio makes it possible to find a better relay node and reduce the average number of hops to the destination node, thus reducing the number of message replications.

Figure 4-12 shows the average delay of the routes established using the routing protocols for different numbers of UAVs. We can observe that the average delay of the proposed protocol is lower than that of other protocols. It is also clear that the proposed protocol can efficiently utilize the UAVs to reduce the message delivery delay. While PRoPHET also shows a notable reduction of delay, particularly when more UAVs are participating in message forwarding, the improvement provided by the proposed protocol shows the importance of considering the persistent connection time ratio in message forwarding.

Figure 4-13 shows the average number of hops of the routes established using the routing protocols for different numbers of UAVs. Since the other protocols do not adequately address the characteristics of UAVs in message replication, increasing the number of UAVs increases the average hop count. The proposed protocol considers the persistent connection time ratio,

therefore its message forwarding decisions reduce the average number of hops successfully. The consideration of the persistent connection time ratio ensures that a message can be transmitted from a sender node to a next-hop forwarding node successfully as expected.

This simulation set shows that the proposed protocol improves the message transmission rate, reduces the average hop count, and reduces network resource consumption.

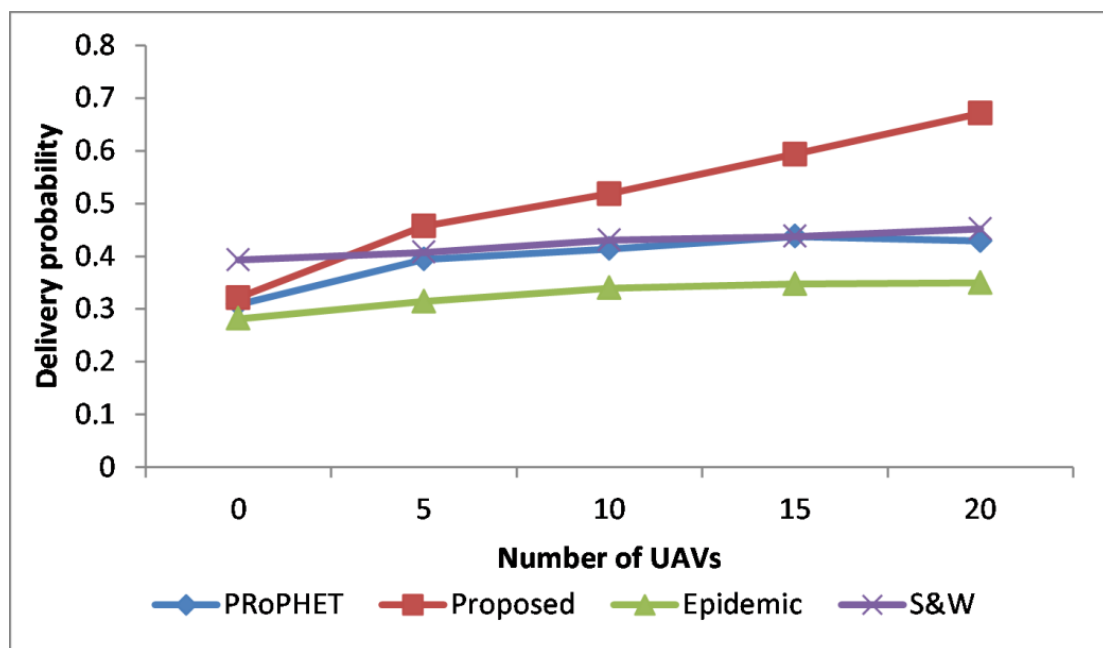


Figure 4-10 Delivery probability for various numbers of UAVs.

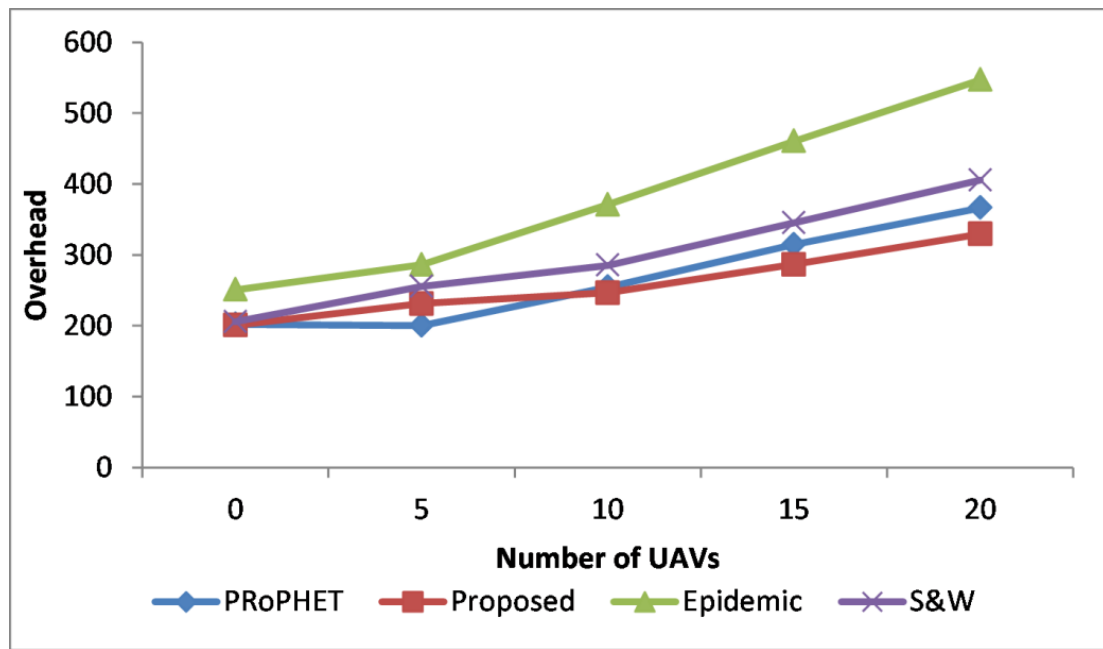


Figure 4-11 Overhead ratio for various numbers of UAVs.

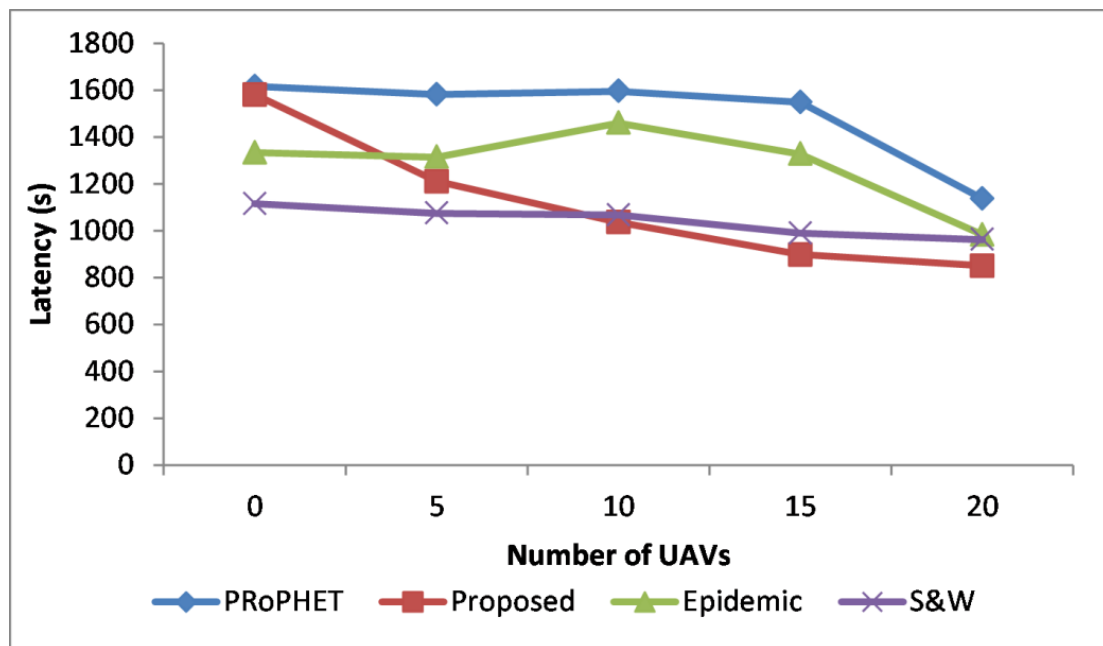


Figure 4-12 Average latency for various numbers of UAVs.

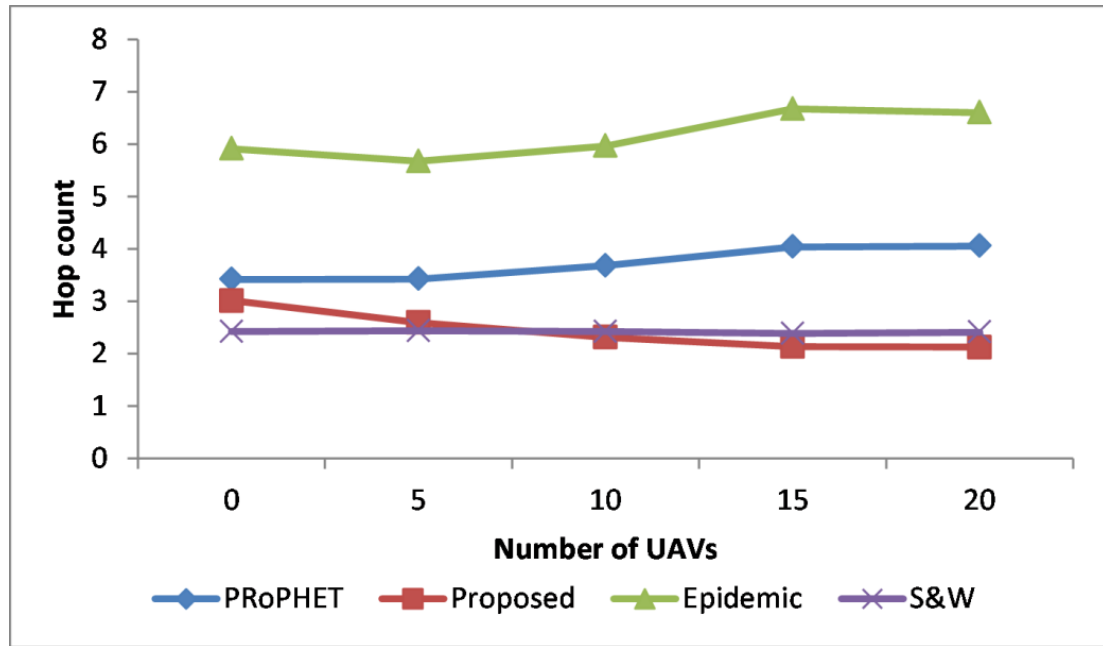


Figure 4-13 Average hop count for various numbers of UAVs.

#### 4.4.2.3 Effect of vehicle density to the typical scenario

In this section, comparative simulations are carried out to show the effects of vehicle density on the message delivery ratio, network overhead, average latency, and average number of hops. Ten UAVs and different numbers of vehicles (or nodes) are used in the simulations to facilitate the message transmission process.

Figure 4-14 shows the message delivery ratio of the routes established using the routing protocols for different numbers of vehicles. When the number of vehicles in the network is small, the sparse node density leads to fewer available relay nodes in the network, and so the established message forwarding link is unstable. Therefore, it is difficult to complete a message forwarding task to the destination, and the rate of successful message forwarding is low. As the number of vehicles increases, the rate of successful message forwarding of each routing protocol increases. However, other routing protocols do not effectively utilize the UAV nodes, and therefore the message delivery ratio is lower than that of the proposed protocol. Simulation results show that the proposed protocol can achieve a significantly higher message delivery ratio as compared with other protocols, and therefore it is suitable for scenarios with different vehicle densities.

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Figure 4-15 shows the overhead of the routing protocols for different numbers of vehicles. We can observe that as the number of vehicles increases, the overhead also increases due to the increased number of message replications. The proposed protocol achieves the lowest overhead due to the use of the persistent connection time ratio, making it possible to find a better relay node and reduce inefficient message replications.

Figure 4-16 shows a comparison of the average latency of the routes established using the routing protocols for different vehicle densities. When the number of vehicles increases, all the routing protocols show a decrease in latency. This is because the chance of encountering the destination node increases with more vehicles involved in message forwarding. In particular, in a dense network, the proposed routing protocol uses both the encounter probability and the persistent connection time ratio to select the best possible relay node, thus reducing the transmission delay caused by inefficient relay nodes carrying copies of the message for a long time.

Figure 4-17 shows the average number of hops of the routes established using the routing protocols for different numbers of vehicles. When the number of vehicles increases, more messages can be successfully transmitted to the destination before the messages expire otherwise, resulting in a higher number of hops as compared with the case where those messages are dropped and not counted in the average end-to-end delay. By taking into account both the encounter probability and the persistent connection time ratio in the relay selection, the proposed protocol can deliver a message to the destination with a smaller number of hops.



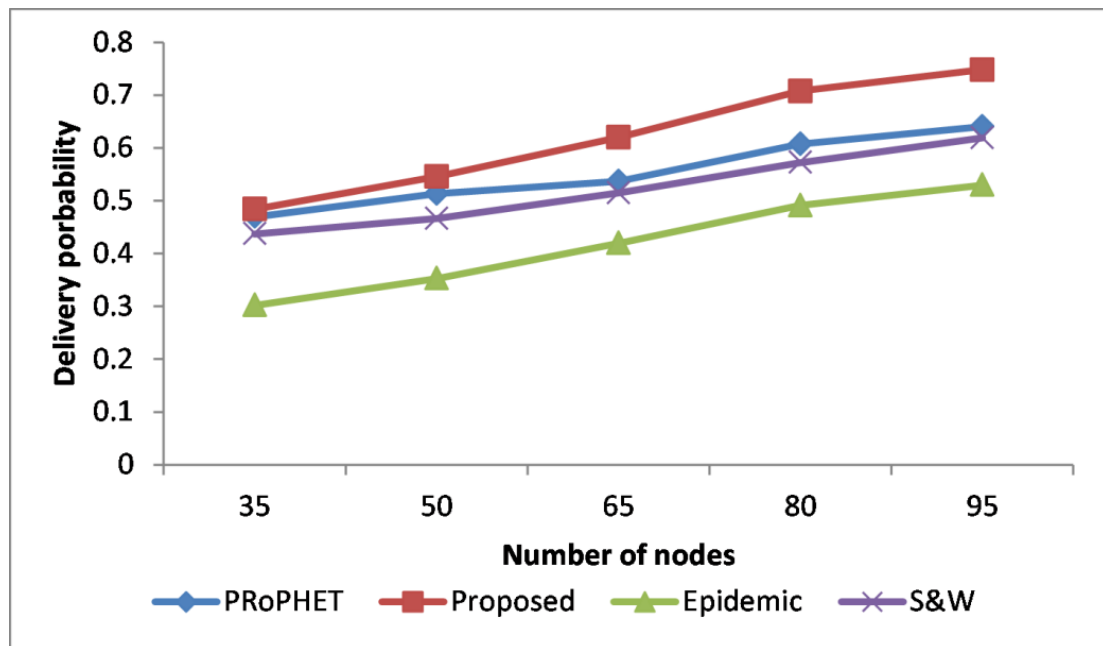


Figure 4-14 Delivery probability for various numbers of nodes.

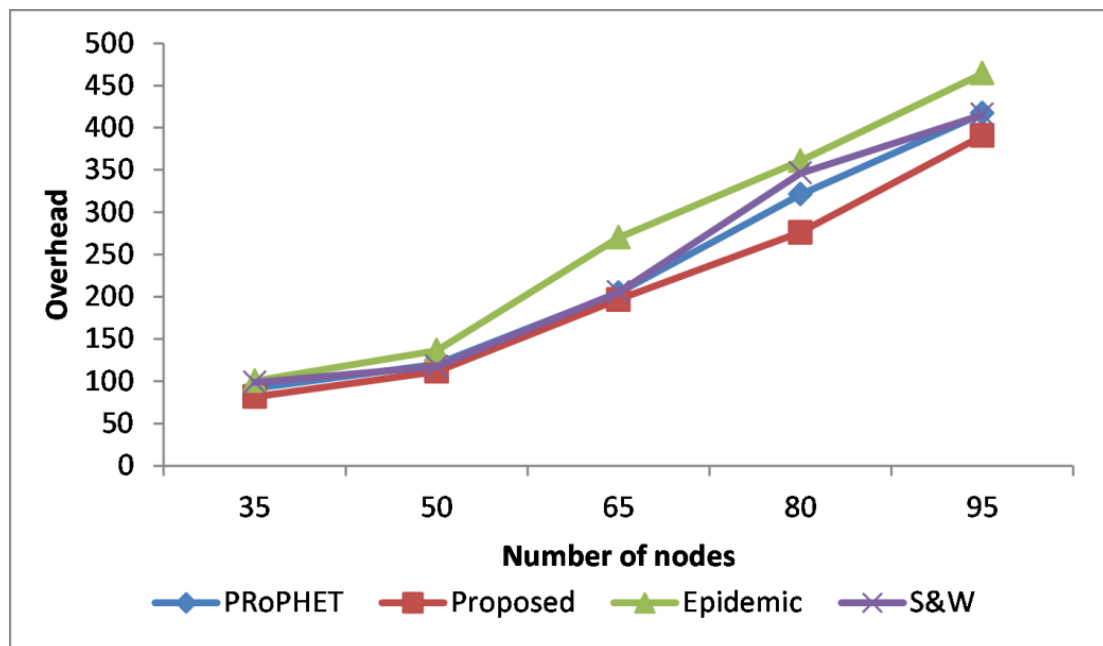


Figure 4-15 Overhead ratio for various numbers of nodes.

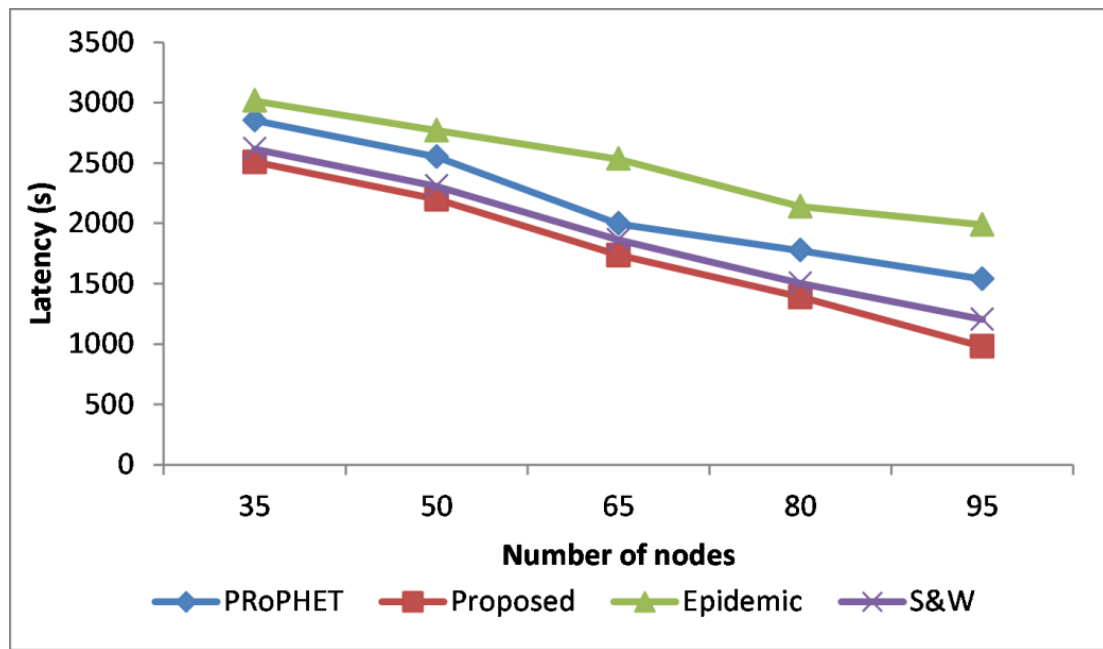


Figure 4-16 Average latency for various numbers of nodes.

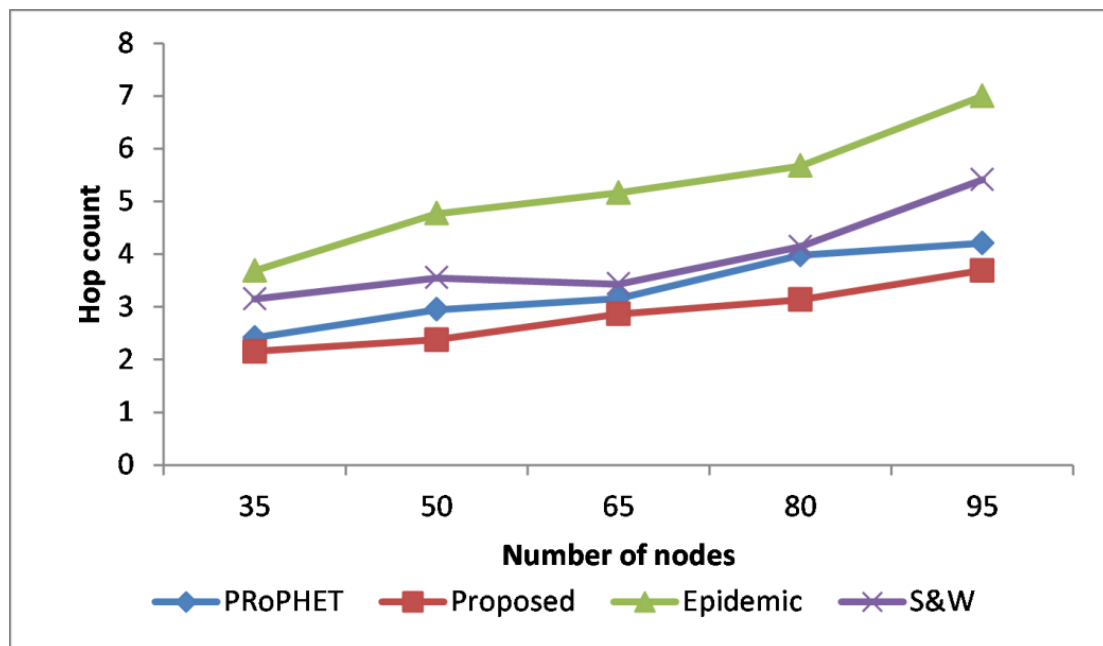


Figure 4-17 Average hop count for various numbers of nodes.

In summary, according to the simulation results, the proposed routing protocol could take into account the reliability connection problem during node communication. Combined with the persistent connection time between nodes, the algorithm could select a more effective relay node to achieve message forwarding. Comparative simulation analysis shows that the

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improved protocol has a higher delivery rate in urban traffic scenarios while reducing the average number of hops and reducing network resource consumption.

#### **4.4.2.4 Effect of vehicles joining and leaving the typical scenario**

Vehicles that newly join a network do not have sufficient information about it, which can affect the forwarding decision of each node. A scenario where nodes joining and leaving the map is designed in this section. The simulation parameters are set based on section 4.4.2.2, and two groups of vehicle nodes are added. The activity time of one group of vehicles is set from 0 to 18000 seconds (0 to 5 hours). The activity time of the other group of vehicles is set from 36000 to 43200 seconds (10 to 12 hours). Each group contains 20 vehicle nodes.

Figure 4-18 shows the message delivery ratio of the routes established using the routing protocols for different numbers of UAVs. Compared with the existing routing protocol, the proposed protocol makes a better use of the UAV nodes in the map. Therefore, when the number of UAV nodes increases, the message delivery rate increases significantly. As for newly joined nodes, the existing nodes have limited historical encounter information about them, so the possibility of the newly joined nodes being selected as relay nodes is low. In this case, the use of persistent connection time ratio becomes more important.

As shown in Figure 4-19, the network overhead increases as the number of UAV nodes increases. When the number of nodes in the network is small, the number of messages to be forwarded is small, and the network overhead is not high. After the UAV node joined, the message delivery rate increased while also increasing the network load. The increase in the number of vehicle nodes in this section also causes the network load to be higher than in section 4.4.2.2. The proposed routing protocol maintains the lowest network load under all circumstances, proving its superiority.

Figure 4-20 shows the average delay of the routes established using the routing protocols for different numbers of UAVs. In general, the proposed protocol can effectively use UAV nodes to reduce the average delay. Compared with vehicles, UAVs have larger transmission ranges due to their elevated look angle. More importantly, the proposed protocol considers the persistent connection time ratio between nodes, allowing the sender node to select a relay node to establish a more reliable connection towards the destination node.

Figure 4-21 shows the average number of hops of the routes established using the routing protocols for different numbers of UAVs. For existing routing protocols, as the number of nodes increases, more nodes can be selected as relay nodes, so the average number of hops increases slightly. The proposed protocol can select the best possible relay nodes as compared with other protocols, which prevents from excessive message replications and saves network resources.

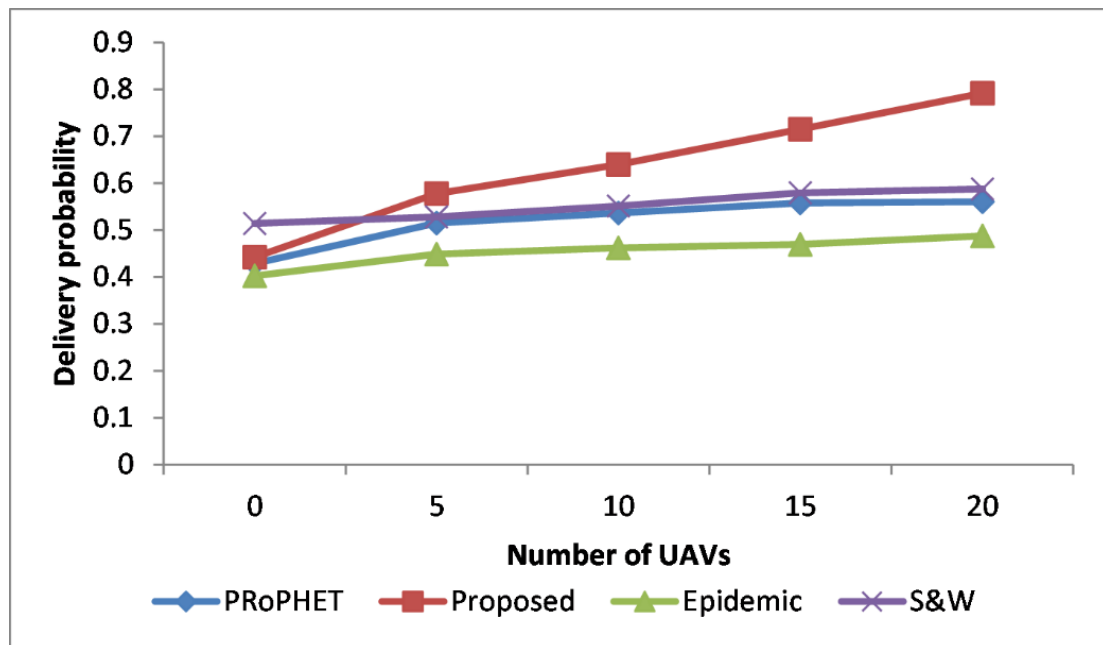


Figure 4-18 Delivery probability for various numbers of UAVs.

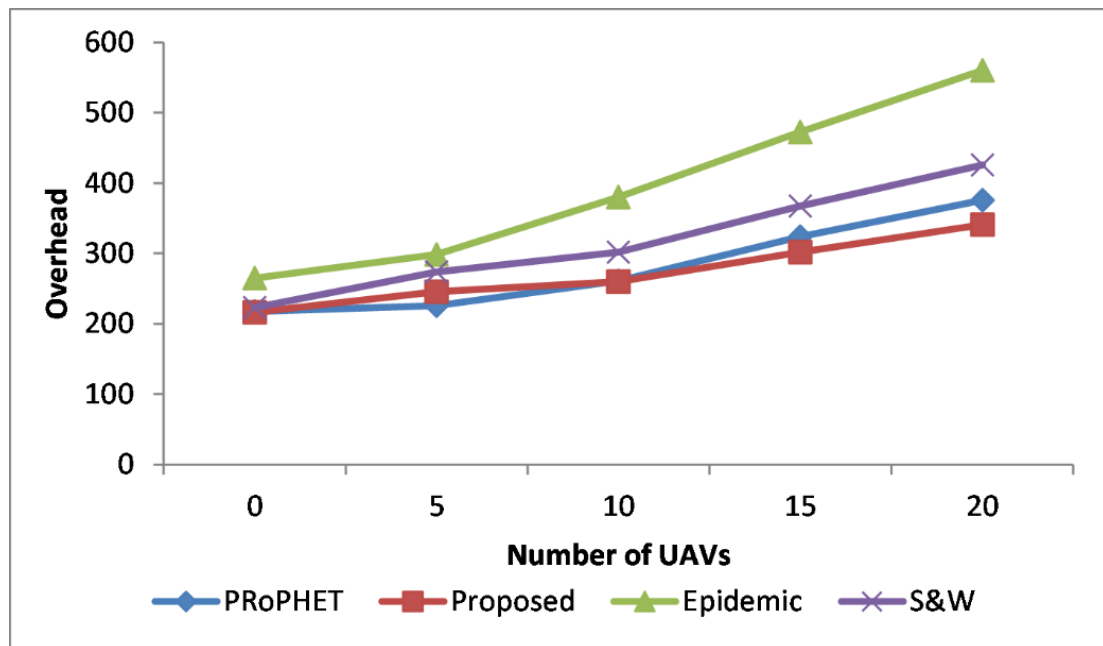


Figure 4-19 Overhead ratio for various numbers of UAVs.

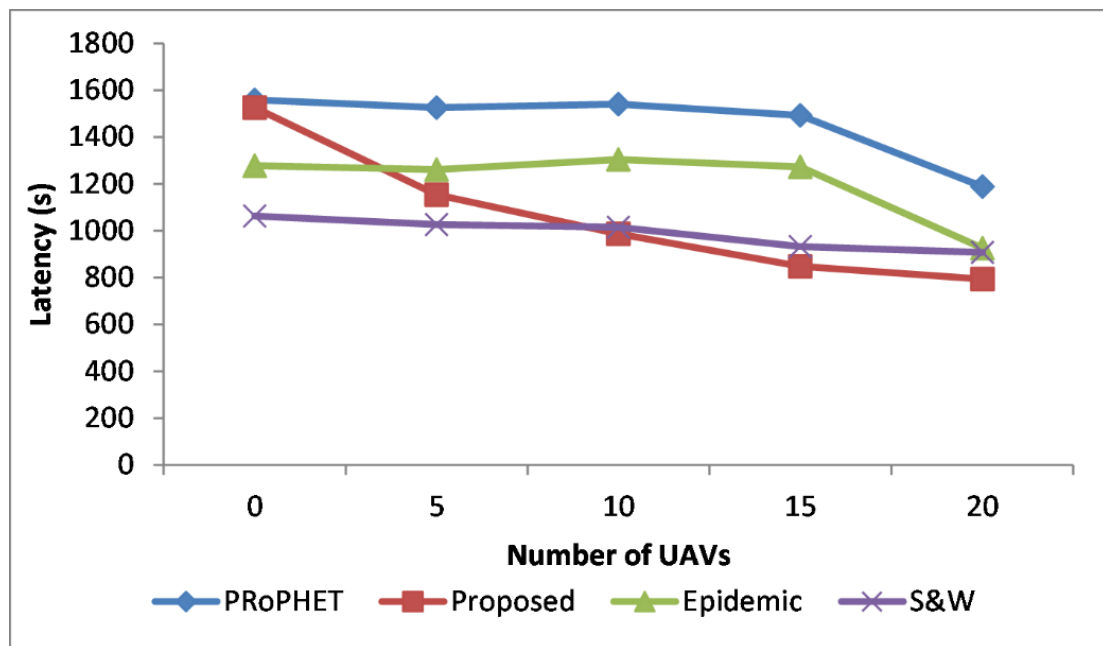


Figure 4-20 Average latency for various numbers of UAVs.

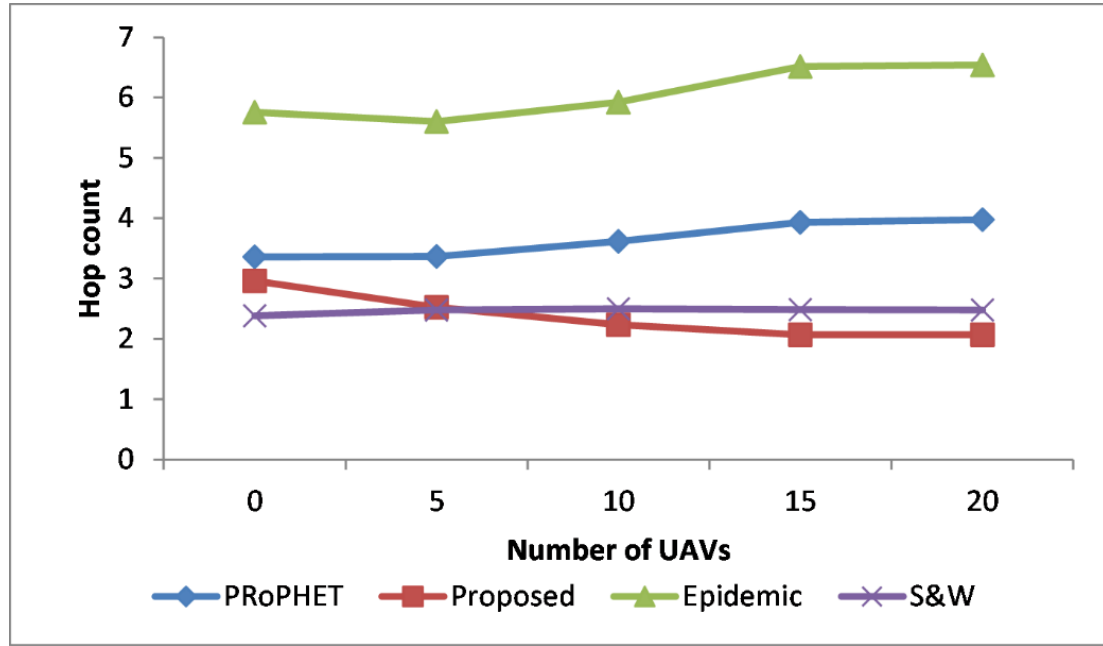


Figure 4-21 Average hop count for various numbers of UAVs.

## 4.5 Analysis of post-disaster DTN environment

Natural disasters such as earthquakes will lead to the destruction of traditional communication infrastructure. The demolition of buildings and traffic in the disaster will also affect the behavior of communication users, so the communication application scene after the disaster has its unique characteristics. This section first analyzes the DTN emergency communication scenarios and discusses the available nodes in the network. The UAV is then introduced into the post-disaster DTN environment as a ferry node to achieve communication between the safe areas. Finally, the network performance of each strategy is evaluated by several simulations.

### 4.5.1 Analysis of post-disaster application scenarios

UAVs are introduced in this section to solve this problem as ferry nodes into the post-disaster DTN environment to achieve communication between the safe areas.

Figure 4-22 shows a UAV-assisted VDTN for emergency communication in post-disaster scenario. Safe areas shall be set up in hospitals, schools, and other places where people gather. Within the areas, messages are stored, carried, and forwarded by mobile devices carried by

the victims and rescue workers. UAVs embedded with communication equipment serve as forwarder nodes to enable inter-regional message transmissions between the isolated regions.

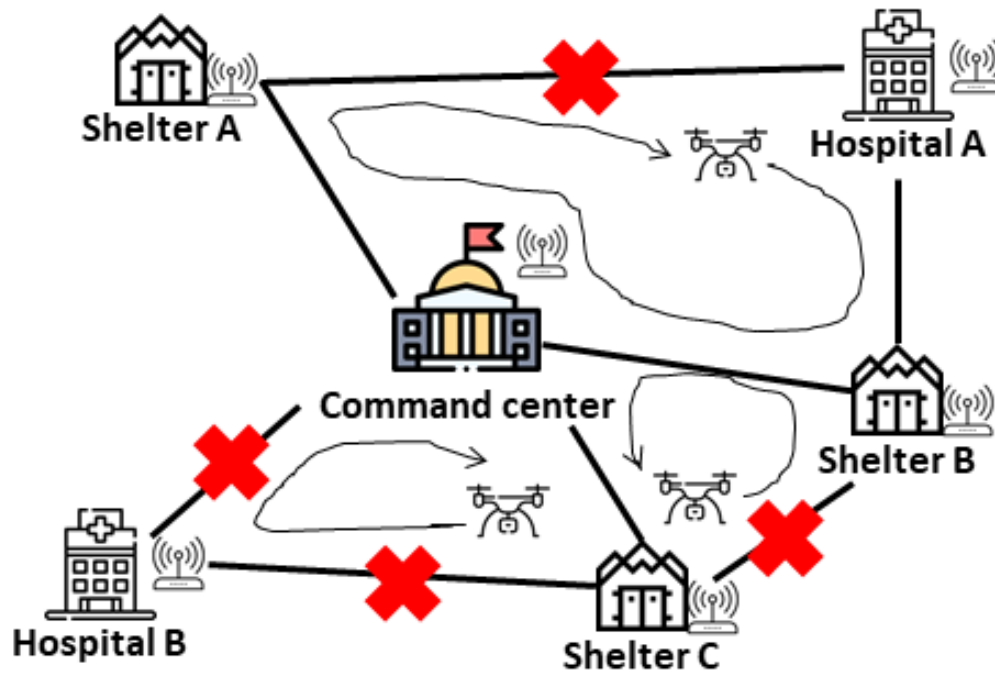


Figure 4-22 Post-disaster emergency communication network based on DTN.

## 4.5.2 Simulation set up

### 4.5.2.1 Scenario without regional center nodes.

In section 3.8, the scene of using rescue vehicles as ferry nodes to forward messages between divided regions after a disaster is discussed. However, in actual scenarios, roads are often damaged after disasters such as earthquakes or tsunamis. The damaged road sometimes causes the rescue vehicle to fail to reach the designated location, making the message forwarding task impossible to complete as required. The UAV has the characteristics of convenient and fast deployment and is more suitable as a ferry node for message forwarding between divided areas.

In this section, the ONE simulation is used to simulate the communication scene after a disaster. The network performance is verified by comparing the network performance metrics.

As shown in Figure 4-23, some safe areas, such as shelters and command centers, are selected after the disaster in the simulation. Regular nodes in each area use the ClusterMovement model. UAV patrols along the red line, use the MapRouteMovement model to realize communication between partition areas. Considering the limited power of the UAV, the UAV will have a random stay after a certain time (such as replacement of the UAV's spare battery) to complete the data transfer between areas and the necessary endurance power supply. After the disaster, the regular nodes in the scene use Bluetooth as the communication mode. In contrast, to speed up data transmission, UAVs use Wi-Fi as the communication mode. Specific simulation parameters are shown in Table 9 and Table 10 below:

Table 9 Simulation settings and parameters for regular nodes

Parameters	Values
Simulation Time	43200s
Number of nodes	80
Interface	Bluetooth Interface
Movement Speed (m/s)	0.5-1.5
Transmit Speed	2Mbps
Transmit Range	10m
Buffer Size (MB)	5
Message Interval (s)	50
Message TTL (s)	300
Movement Model	ClusterMovement
Message Size	500KB-1MB
Simulation Area Size	4500m×3400m



Table 10 Simulation parameters for UAVs

Parameters	Values
Number of UAVs	0, 5, 10, 15, 20
Interface	Wi-Fi Interface
Movement Speed (m/s)	5-15
Transmit Speed	7.5Mbps
Transmit Range	40m
Buffer Size (MB)	100
Movement Model	MapRouteMovement

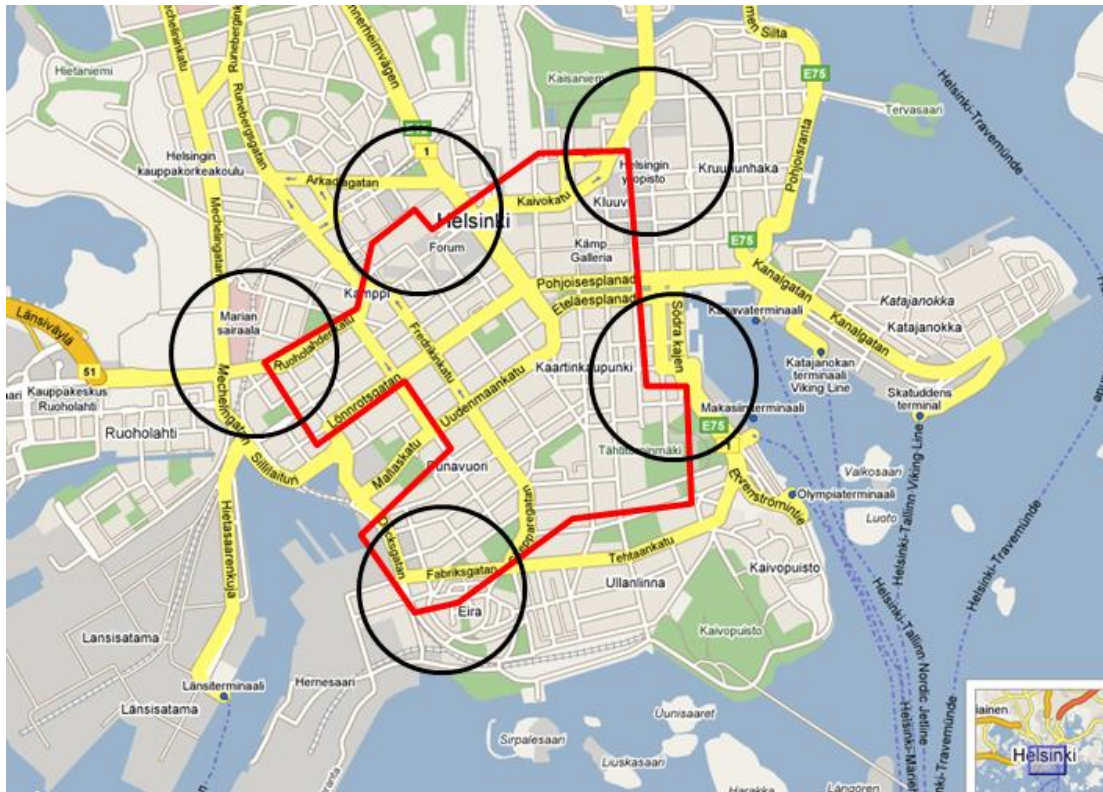


Figure 4-23 The simulation scenario.

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### 4.5.2.2 Simulation result and analysis

In this section, the network performance of each routing protocol in post-disaster scenarios is evaluated by changing the number of UAVs.

Figure 4-24 shows the message delivery ratio. Since communication between two isolated regions must require the help from a UAV, the number of UAVs has a significant impact on the message delivery ratio for all routing protocols. It is clear that the message delivery ratio of the proposed protocol is better than that of other protocols for different numbers of UAVs. The efficient message forwarding decision considering the persistent connection time ratio contributes to this improvement.

Figure 4-25 shows the overhead. The simulation results show that the proposed protocol achieves the lowest overhead for different numbers of UAVs. This proves that the relay node selection strategy of the proposed protocol is efficient so that the message can be delivered through the best possible relay nodes in the forwarding process, resulting in a more efficient network resource utilization.

As shown in Figure 4-26, shows the end-to-end delay. When the number of vehicles changes from 0 to 5, we observe an increase in the end-to-end delay. This is because the communication between two isolated regions becomes possible. By further increasing the number of UAVs, a smaller delay can be observed due to the increased number of forwarder nodes for inter-region communications. The proposed protocol shows a significantly lower delay as compared with other protocols.

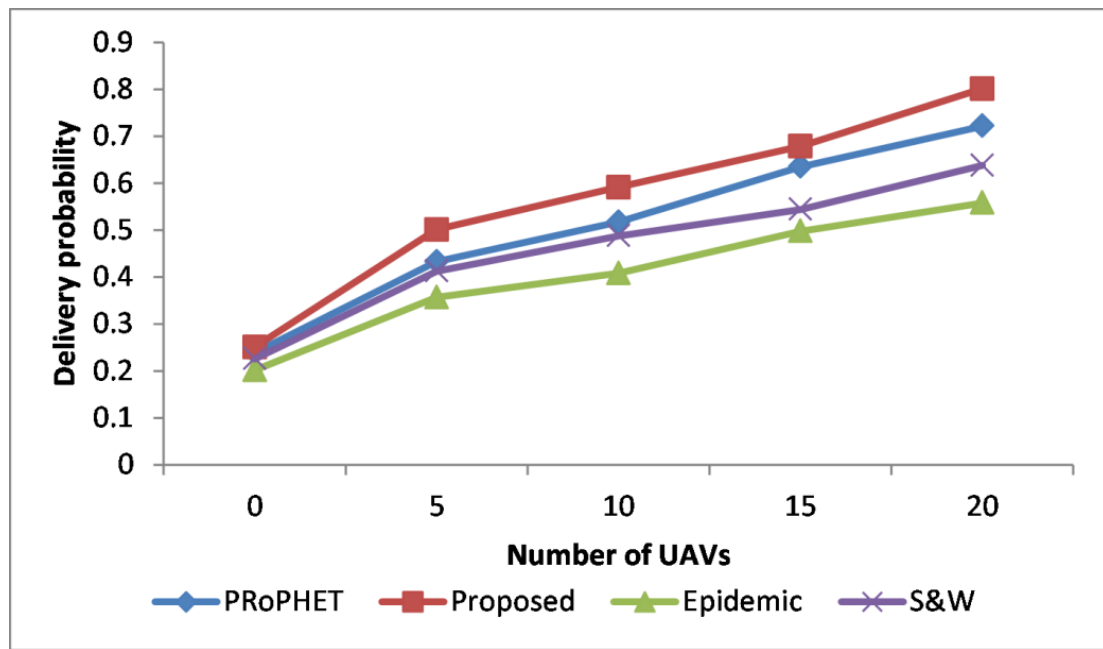


Figure 4-24 Delivery probability for various numbers of UAVs.

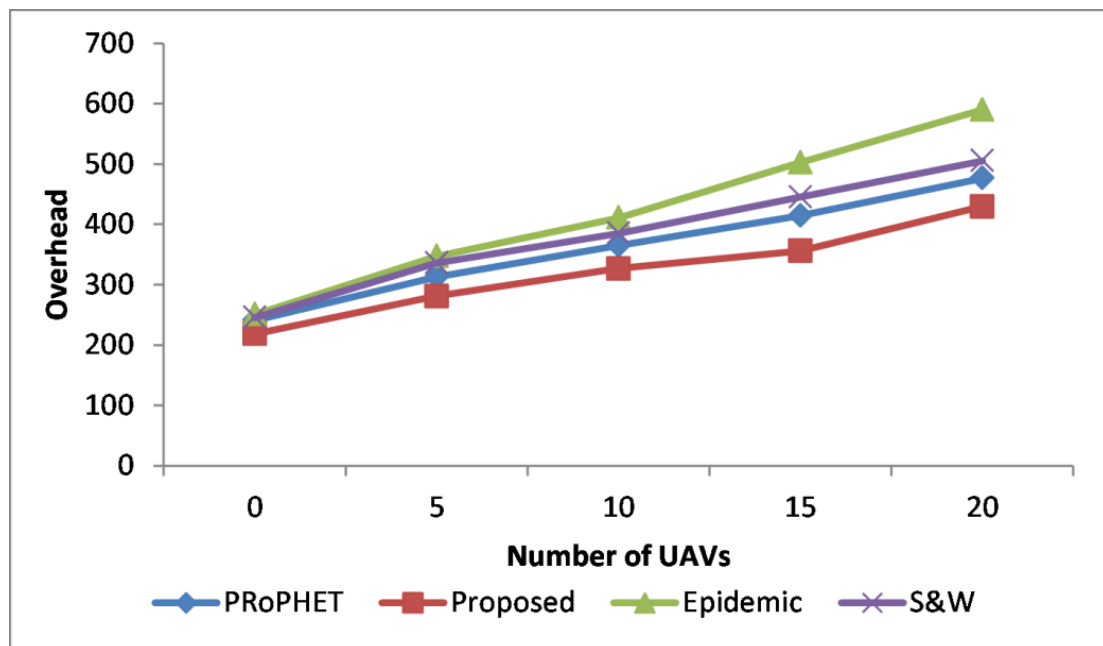


Figure 4-25 Overhead ratio for various numbers of UAVs.

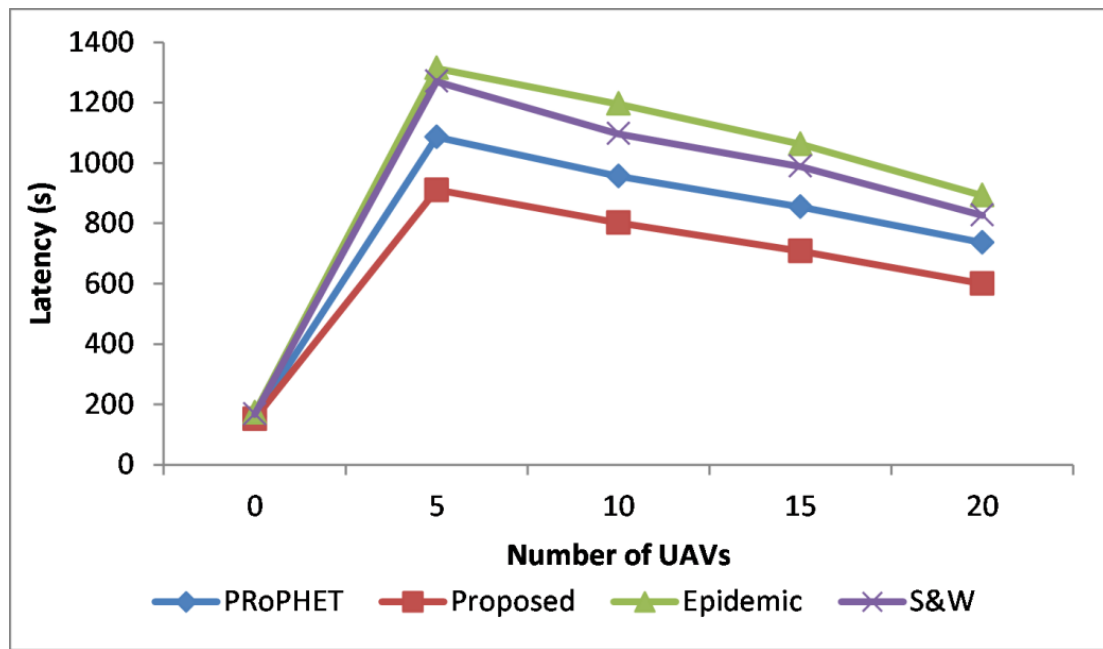


Figure 4-26 Average latency for various numbers of UAVs.

#### 4.5.2.3 Scenario with regional center node.

This section adds a regional center node to each region. Observes the changes in network performance of the routing protocol after joining the regional center node by changing the number of UAVs. The setting of the regional center node is shown in Table 11.

Table 11 Simulation parameters for regional center nodes

Parameters	Values
Number of vehicles	5
Interface	Wi-Fi Interface
Transmit Speed	7.5Mbps
Transmit Range	50m
Buffer Size (MB)	100

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#### 4.5.2.3.1 Simulation result and analysis

In this section, each divided area is joined with a regional center node, which is usually a refuge, a hospital, or a disaster relief command center. Compared with other nodes, this kind of node has a larger buffer space and a wider transmission range. The introduction of regional center nodes improves network performance.

The changes in the delivery probability are shown in Figure 4-27. The introduction of regional center nodes has improved the delivery probability. The regional center node can store more messages, which helps a lot in the intra-region message forwarding process. Meanwhile, the regional center node also has a wider communication range. When the ferry node passes through the area, it can establish a stable link with the ferry node, and the message forwarding between regions is also improved.

Figure 4-28 shows the changes in network overhead. When there is no ferry node in the scene, messages will only be forwarded in each segmented area. The overall network overhead is small, but the demand for forwarding messages to other areas cannot be met. After using UAVs as ferry nodes, although the network overhead increases, separated areas are reconnected together, the message can be successfully forwarded to different areas. Regional center nodes can store more messages, thereby reducing the number of times that messages are forwarded, and network overhead is also suppressed.

As shown in Figure 4-29, after adding UAVs as ferry nodes, the average delay has a decreasing trend. In the scenario without regional center nodes, the ferry node must contact the mobile node to transmit messages, which increases the difficulty of message exchange between network nodes. After joining the regional center node, the number of forwarded messages increased, thereby reducing the average delay.

In the post-disaster DTN scenario with regional center nodes, the network performance metric of the proposed method in each case is better than that of the existing routing protocol, which proves the superiority of the proposed routing protocol in this scenario.

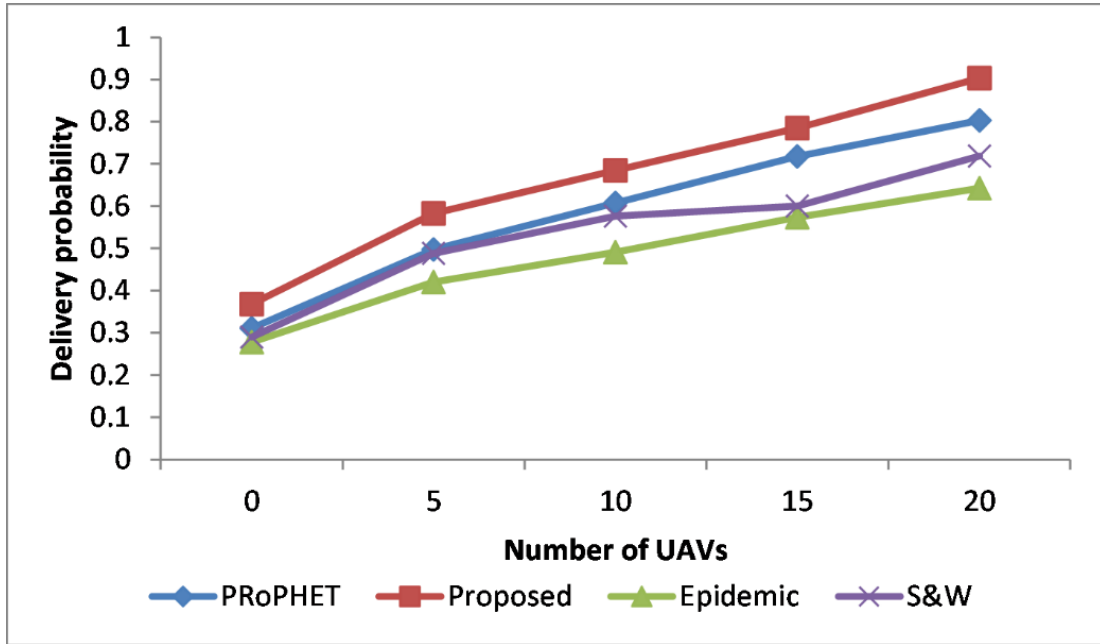


Figure 4-27 Delivery probability for various numbers of UAVs.

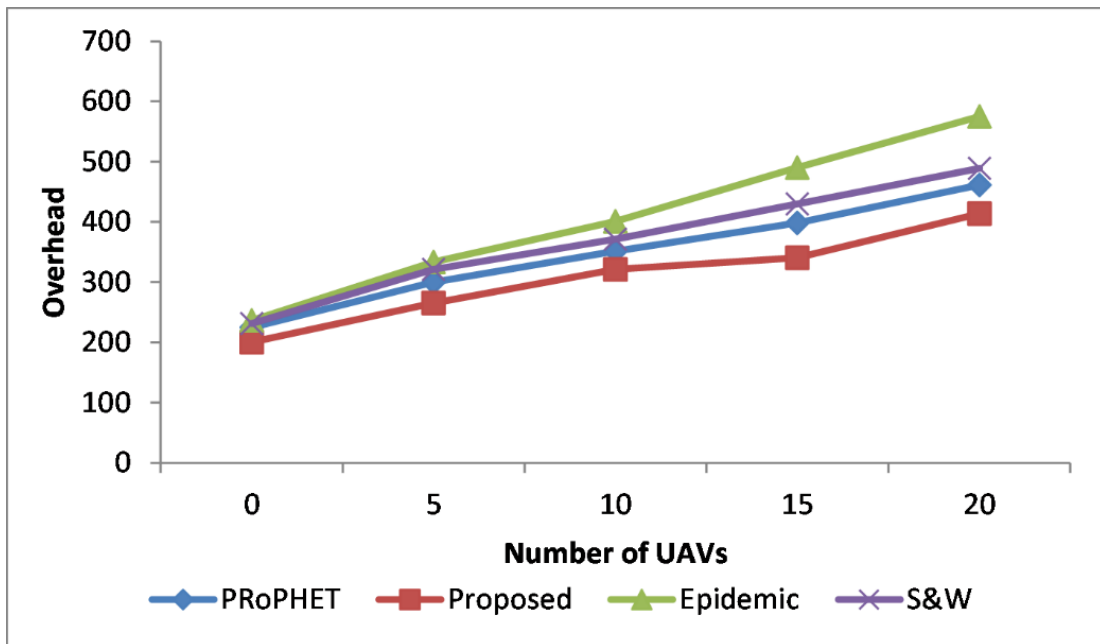


Figure 4-28 Overhead ratio for various numbers of UAVs.

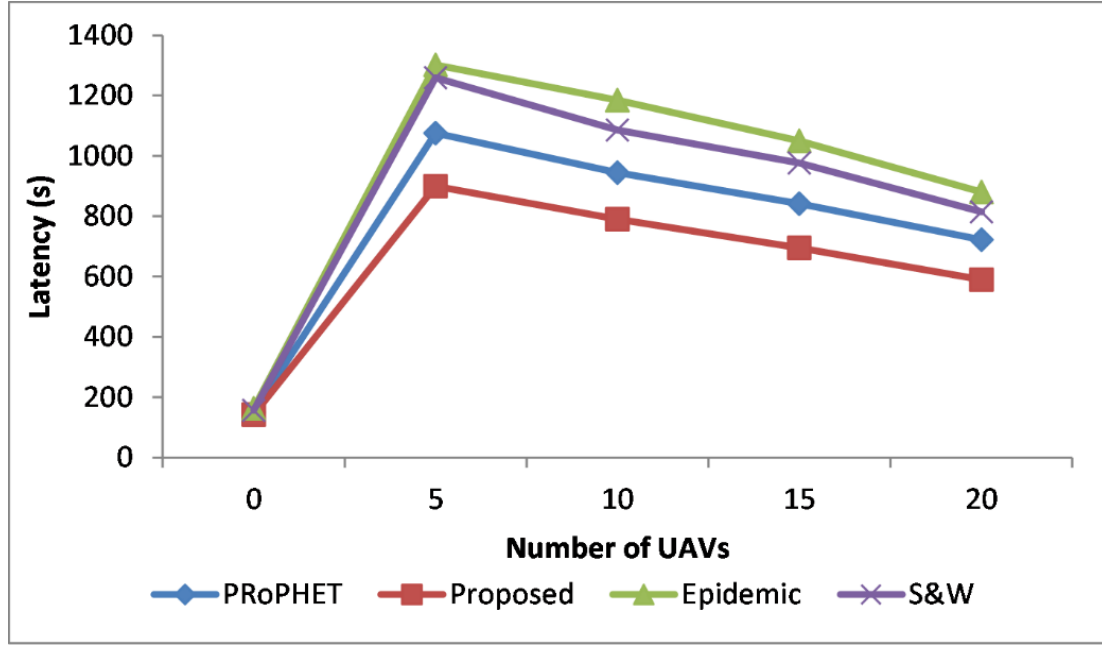


Figure 4-29 Average latency for various numbers of UAVs.

## 4.6 Conclusion

In this chapter, a new routing protocol for UAV assisted vehicular DTN is proposed. Section 4.1 analyzes the drawbacks of the PRoPHET routing protocol and the characteristics of message transmissions that need to be considered in UAV assisted VDTN scenarios.

Section 4.2 defines the persistent connection time and explains its importance. The design of the message forwarding process is introduced next. The persistent connection time between nodes can be obtained from changes in the network topology, and it is one of the factors that affect the metric of traditional historical-based routing. The signal strength of the UAV node in the DTN is robust, which can speed up the message transmission speed and increase the transmission ratio, thereby reducing hop counts and overhead. Therefore, to make more effective use of UAV nodes, the proposed protocol selects better relay nodes by calculating the duty ratio of the connection time between nodes in the historical process, so that the message can be forwarded to adjacent nodes that have relatively stable communication links.

In section 4.4, the evaluation of the proposed routing scheme is conducted using simulation tools in different network environments. The simulation in this section considers the UAV assisted VDTN scenario in the general case. The results showed that the proposed routing

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protocol apparent advantages compared with the traditional algorithms in the VDTN.

Section 4.5 designs a post-disaster VDTN scenario. This section first analyzes the characteristics of the cluster movement model and distribution in the areas separated by infrastructure damage after a disaster. The UAV is then introduced as the ferry node to complete the message forwarding between the divided regions. Simulation results show that the proposed routing protocol can better use the UAV in the environment, increasing the message forwarding rate, and reducing network resource consumption.



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# CHAPTER 5

## 5 Conclusion and future work

This chapter summarizes the research on the routing protocol and buffer management policy in the UAV-assisted VDTN. Section 5.1 concludes the study from two aspects: the proposed routing protocol with a buffer management policy and the proposed routing protocol for UAVs in typical and post-disaster DTN scenarios. Then, section 5.2 discusses possible future works.

### 5.1 Conclusion

The VDTN is an opportunity network mainly used to reach communications between nodes in poor environments with limited resources. The VDTN is a new type of network, which is different from the traditional TCP/IP communication protocol network. It is suitable for the extreme environment where end-to-end communication connection cannot be established stably. Several realistic applications could use VDTNs to achieve QoS needs, such as the transport system, military system, interplanetary communication, and ocean monitoring.

Among the routing algorithms of the VDTN, the historical-based routing algorithm has a higher delivery probability and a better network performance. Thus, it is necessary to provide an efficient routing algorithm based on historical information. However, VDTN node resources are always limited. The routing mechanism brings many redundant messages, which is easy to cause the buffer congestion of nodes and excessive consumption of network resources. Therefore, while proposing an effective and reliable routing algorithm, it is also important to introduce an appropriate buffer management policy to manage the redundant message efficiently if congestion happens.

In chapter 3, the PROPHET routing protocol and buffer management policy in VDTN are studied, and the shortcoming of these algorithms are investigated. Long delays, intermittent networks, and redundancy in message replicas result in reduced routing efficiency and low network performance. In this thesis, an improved routing algorithm is presented, which calculates the encounter probability according to the PROPHET algorithm, and controls the

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message replicas in the network to reduce the network overhead while improving the message delivery rate. Aiming at the congestion problem caused by limited node buffer, a buffer management policy is proposed. The congestion control metric is constructed to manage messages in node buffer reasonably to avoid congestion. Moreover, when network congestion occurs, messages with the smallest congestion control metric are dropped to gain cache space for other messages and improve the message delivery rate.

Major natural disasters are often accompanied by the destruction of bridges, roads, mobile communications, and other infrastructure. As a result, some areas are cut off to form isolated communication islands. The VDTN with UAVs and other ferry nodes is an effective means to build an emergency communication network after a disaster quickly. Establishing a stable and flexible emergency communication network can provide accurate information, assist emergency management departments in making timely and effective decisions, and improve emergency rescue and disaster relief.

Chapter 4 focuses on studying and analyzing the PRoPHET routing algorithm and the disadvantages of its poor reliability in the UAV-assisted VDTN environment. Combined with the actual traffic environment, this thesis raises the concept of persistent connection time. The message forwarding strategy combines the PRoPHET routing and persistent connection time ratio between nodes, considering the efficiency of data forwarding and taking into account the stability in establishing a communication link in the UAV-assisted VDTN environment. Then the distribution characteristics and movement characteristics of the disaster victims are analyzed. After the disaster, the disaster victims are carrying mobile terminals as DTN nodes in the network environment. The UAV is used as a ferry node for inter-region message transmission, and the ferry node cruises each region regularly according to the planned path to complete the message transmission among the separated areas. The proposed routing algorithm is simulated by the ONE simulator, and different protocols were compared. The simulation result verifies that the proposed routing protocol improves the efficiency of successful message forwarding, reduces the network load, and optimizes the network performance. By changing the number of vehicles and other influencing factors, the performance change of the routing is analyzed, and multiple sets of simulations are carried out in both post-disaster scenes and daily scenes.

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## 5.2 Future work

This thesis first proposes a routing protocol in the VDTN environment. Second, to manage the node buffer reasonably, a buffer management policy is proposed. Then, the UAV-assisted VDTN is introduced, and a routing protocol to support UAV communications in both typical and post-disaster scenes is proposed. To further improve the communication quality of VDTNs, there are still many unsolved problems that should be considered.

Feedback mechanism in DTN: In this thesis, there are few studies on DTN's message feedback mechanism. Most of the existing routing protocols did not adopt an effective feedback mechanism either. However, in the actual DTN environment, many redundant message copies exist in the limited cache space of nodes, greatly reducing the network resource utilization, seriously affecting the routing performance. Therefore, it is an important direction of future research to design the message feedback strategy that can adapt to the DTN environment and improve the network service quality.

Multicast and Anycast communications: Most of the existing studies on DTN routing algorithms only consider unicast routing, and many valuable results have been produced, while there are relatively little researches on multicast and anycast technologies. However, in the actual DTN communication environment, nodes usually show the information interaction between certain groups. Therefore, the study of multicast and anycast technologies is conducive to improving the communication quality, enhancing the communication service level, and saving network resources.

Different message types after the disaster: This thesis does not consider the types of post-disaster messages. Different message types have different priorities, which have an important impact on the decision of post-disaster scheduling. In future works, the type of message in the post-disaster network should be studied, and a routing strategy based on message priority needs to be proposed.

Movement model: The research on the UAV movement model in this thesis is ideal, only discussing the case where the UAV moves on a given path and transmits messages as a ferry node. If conditions permit, the node movement trajectory data is needed to propose a more realistic movement model in the actual disaster rescue scenario.

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## List of Abbreviation

DTN	Delay Tolerant Networks
VDTN	Vehicular Delay Tolerant Networks
V2V	Vehicle to Vehicle
V2I	Vehicle to Infrastructure
V2X	Vehicle to Everything
UAV	Unmanned Aerial Vehicle
U2U	UAV to UAV
U2C	UAV to Cloud
U2V	UAV to Vehicle
U2G	UAV to Ground base station
RTT	Round-Trip Time
PRoPHET	Probabilistic routing protocol using history of encounters and transitivity
TTL	Time To Live
S&W	Spray-and-Wait
FC	First Contact
DD	Direct Delivery
DPRoPHET	Distance-based PRoPHET
SPM	Social Pressure Metric
ARMA	Autoregressive Moving Average
RR	Retiring Replicants
DL	Drop-Last
DF	Drop-Front
DLR	Drop-Least-Recently-Received
DO	Drop-Oldest
DY	Drop-Youngest
DLA	Drop-Largest
DCCR	Dynamic Congestion Control Based Routing
TBCC	Token Based Congestion Control
AC	Access Control
FRMM	Fair Resources Management Model
LFC	Local Flow Control
CAFE	Context Aware Forwarding Algorithm
GRCCM	Game based Routing algorithm for Congestion Control

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	of Multimedia transmission
AOBMP	Adaptive Optimal Buffer Management Policies
DFR	Directional Forward Routing
TFRC	TCP Friendly Rate Control
ATP	Ad-hoc Transport Protocol
C2AM	Contact-Based Congestion Avoidance Mechanism
CC	Novel Congestion Control
AFNER	Average Forwarding Number based on Epidemic Routing
HWDP	Historical based Weighted Dropping Protocol
SR	Storage Routing
SIRA	Single Routing Algorithm
MURA	Multi-Routing algorithm
NRA	Node Relay forwarding Algorithm
FRA	Ferry Relay forwarding Algorithm
OPWP	Optimization Way Point ferry routing
ONE	Opportunity Network Simulation
CCM	Congestion Control Metric
5G	Fifth-Generation cellular network
Wi-Fi	Wireless Fidelity
QoS	Quality of Service

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## Author Biography

Zhaoyang Du received the BE degree from Beijing Information Science and Technology University, China, in 2013, and the ME degree from The University of Electro-Communications, Japan, in 2018.

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# List of Publication

## Journal Paper

[1] Zhaoyang Du, Celimuge Wu, Xianfu Chen, Xiaoyan Wang, Tsutomu Yoshinaga, and Yusheng Ji, "A VDTN scheme with enhanced buffer management," *Wireless Networks*, vol.26, pp.1537–1548, Jan. 2020.

(Related to the content of Chapter 3)

[2] Zhaoyang Du, Celimuge Wu, Tsutomu Yoshinaga, Xianfu Chen, Xiaoyan Wang, Kok-lim Alvin Yau, and Yusheng Ji, "A Routing Protocol for UAV-assisted Vehicular Delay Tolerant Networks," *IEEE Open Journal of the Computer Society*, 14 pages, 2021, doi: 10.1109/OJCS.2021.3054759, Early Access.

(Related to the content of Chapter 4)

[3] Zhaoyang Du, Celimuge Wu, Tsutomu Yoshinaga, Kok-lim Alvin Yau, Yusheng Ji, and Jie Li, "Federated Learning for Vehicular Internet of Things: Recent Advances and Open Issues," *IEEE Open Journal of the Computer Society*, vol.1, pp.45-61, May 2020.

(Related to the content of Chapter 2)

## International Conference

[1] Zhaoyang Du, Celimuge Wu, Tsutomu Yoshinaga, Yusheng Ji, "A Prophet-Based DTN Protocol for VANETs," in *Proceedings of 4th IEEE International Conference on Cloud and Big Data Computing (CBDCoM 2018)*, Guangzhou, pp.1876-1879, Oct. 2018.

(Related to the content of Chapter 3)

[2] Zhaoyang Du, Celimuge Wu, Tsutomu Yoshinaga, "UAV-empowered Protocol for Information Sharing in VDTN," in *The 16th International Conference on Mobility, Sensing and Networking (MSN 2020)*, Tokyo, pp. 640-641, Dec. 2020.

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## Other Conference

- [1] Zhaoyang Du, Celimuge Wu, Tsutomu Yoshinaga, "Empowering ICN in Intermittent Connectivity Scenarios," *IEICE Society Conference 2019*, BS-4-20, Sep. 2019.
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