IEEE Open Journal of the
Computer Society

Received 2 January 2021; accepted 23 January 2021. Date of publication 26 January 2021; date of current version 4 March 2021. The review of this article was arranged by Associate Editor Deze Zeng.

Digital Object Identifier 10.1109/OJCS.2021.3054759

A Routing Protocol for UAV-Assisted Vehicular Delay Tolerant Networks

ZHAOYANG DU [1], CELIMUGE WU [1] (Senior Member, IEEE), TSUTOMU YOSHINAGA [1] (Member, IEEE), XIANFU CHEN [2] (Member, IEEE), XIAOYAN WANG [3] (Senior Member, IEEE), KOK-LIM ALVIN YAU [4] (Senior Member, IEEE), AND YUSHENG JI [5] (Senior Member, IEEE)

[1] Graduate School of Informatics and Engineering, The University of Electro-Communications, Tokyo 182-8585, Japan
[2] VTT Technical Research Centre of Finland, Oulu 90570, Finland
[3] Graduate School of Science and Engineering, Ibaraki University, Ibaraki 310-8512, Japan
[4] School of Engineering and Technology, Sunway University, Sunway 47500, Malaysia
[5] Information Systems Architecture Research Division, National Institute of Informatics, Tokyo 101-8430, Japan

CORRESPONDING AUTHOR: CELIMUGE WU (e-mail: yoshinaga@uec.ac.jp)

This work was supported in part by ROIS NII Open Collaborative Research 2020-20S0502, and in part by JSPS KAKENHI under Grants 18KK0279, 19H04093, and 20H00592.

ABSTRACT Vehicular delay tolerant networks (VDTNs) enable information sharing among mobile nodes in scenarios where cellular base stations are unavailable and the connections between the mobile nodes are intermittent. While unmanned aerial vehicles (UAVs) have shown to improve the performance of VDTNs, existing routing protocols, such as PRoPHET, consider the encounter probability between mobile nodes only, which does not fully address the characteristics of UAVs in route selection. In this paper, we propose a routing protocol, which considers both the encounter probability and the persistent connection time between mobile nodes for each encounter, in UAV-assisted VDTNs. By introducing the persistent connection time in route selection, the proposed protocol is able to evaluate the stability of a communication link more accurately in the UAV-assisted VDTN environment. The proposed protocol is evaluated using realistic simulations by comparing it with existing baselines. The simulation results verify that the proposed protocol can improve the reliability of message forwarding while reducing network overhead and end-to-end delay.

INDEX TERMS Delay tolerant network, unmanned aerial vehicle, routing protocol.

I. INTRODUCTION

Delay Tolerant Networks (DTNs) can support communications in extreme environments where a continuous network connection is impossible [1]–[5]. In DTNs, the communications between mobile nodes experience a high latency and low data rate due to intermittent and unstable connections. Since mobile nodes in DTNs are intermittently connected with each other, relay node selection has become more important for improving message delivery ratio. Recent studies have advocated the need for a new routing protocol to address specific characteristics of DTNs including intermittent connections of mobile nodes and low end-to-end packet delivery ratio [6]–[8]. However, the selection of a next-hop relay node has been mainly based on the encounter probability between mobile nodes.

In DTNs, mobile nodes face different kinds of harsh and challenging environments in which the success rate of message delivery is affected significantly by the design of the routing protocols. Therefore, various DTN routing protocols have been proposed to improve the multi-hop routing performance, including flooding-based routing to cater for intermittent connectivity [9], historical-based routing to cater for limited chance of encountering destination [10], and social-awareness routing to cater for social behavior of mobile nodes [11].

As compared with the conventional DTNs, it is more challenging to design routing protocols for vehicular delay tolerant networks (VDTNs) which are characterized by the distinguishing features of high mobility and varying densities of vehicles [12], [13]. In the VDTN environment, the effective transmission range of vehicle-to-everything

(V2X) is limited by the surrounding environment. In a sparse and highly mobile vehicular network, the encounter period between vehicles could be small, and therefore it is difficult to achieve a satisfactory end-to-end message delivery ratio. In addition, network performance can be further degraded by network partitioning in some extreme environments, such as areas where infrastructure has been damaged by earthquakes, fires, or floods. Besides, the quality of V2X links is likely to deteriorate due to obstacles or complex terrain, and the links can even be broken in the worst case. Unmanned aerial vehicles (UAVs) have great potential in enhancing the performance of mobile communication due to its advantages over ground vehicles, particularly higher freedom of movement and better wireless channel condition [14]–[16]. UAV has been widely used in traffic monitoring, disaster rescue, military reconnaissance, and other fields.

The introduction of UAVs in VDTNs forms an integrated collaborative network that can further enhance the information exchange capability of VDTN. UAVs can extend the dimension of information exchange among ground vehicles by using air-ground integrated communications. When the V2X links are interrupted, the UAV can act as an aerial base station to set up a relay channel for the ground network [17]. A UAV group dispatched to the area of interest can quickly build a network and provide timely network services to ground vehicles, which is very useful for post-disaster scenarios.

The UAV-assisted VDTN uses UAVs as relay nodes, which can receive and forward messages sent by ground users, improve the robustness of wireless communication, enhance infrastructure flexibility, and provide extended communication coverage for isolated areas. The UAV-assisted VDTN architecture is originally introduced in the military field, such as unmanned tanks and UAVs, for joint operations of ground and air vehicles to improve the communication efficiency. In recent years, this architecture has gradually been applied to civil industries, such as intelligent transportation systems [18], earthquake relief [19], and precision agriculture [20].

However, existing VDTN protocols face some challenges in supporting UAV-assisted VDTNs. Existing routing protocols basically make a message replication decision based on the encounter probability to the destination node (considering multi-hop forwarding of the message). However, since the persistent connection time of a communication link for each encounter is not considered, a forwarder node may fail to deliver the expected number of messages in each encounter (meeting a neighbor node). In this work, we propose a routing protocol that considers both the encounter probability and persistent connection time for each encounter, resulting in a more effective use of UAVs for message forwarding in DTN environments. The main contributions of this paper are summarized as follows.

- We introduce a new metric, namely the persistent connection time, for the DTN routing decision. This metric takes account of the characteristics of UAVs, i.e., higher communication capability and freedom of movement, more effectively in the routing decision, making the design of an efficient UAV-assisted message forwarding mechanism possible.
- Based on the joint consideration of both the persistent connection time and message encounter probability, we propose a new routing protocol that can achieve a much better network performance as compared with existing baselines.
- We generate realistic scenarios integrated with UAVs and ground vehicles based on a real city map to evaluate the proposed protocol in terms of message delivery ratio, network overhead, and end-to-end delay under various network settings. The results are compared with those of existing baselines.

This paper is an extension of our conference paper [21]. While [21] only discusses about the basic idea of the persistent connection time, this paper includes the details of the routing algorithm and new results that have not been presented before. The remainder of this paper is organized as follows. Section II provides a brief overview of UAV-assisted VDTNs, focusing on VDTN-related and UAV-related studies on routing protocols. Section III introduces the proposed routing protocol in detail and highlights our contributions. The comparative analysis of the proposed VDTN routing protocol with some existing protocols is provided in Section IV. Section V concludes this paper.

II. RELATED WORK

A. ROUTING PROTOCOLS IN VDTNS

Routing refers to a decision made to find a data forwarding path based on the understanding of the network topology in order to improve the successful delivery of messages to the destination node. While there exists a connected end-to-end path between a source node and a destination node in the conventional networks, there is no such path in VDTNs. Therefore, routing protocols for conventional networks are not applicable for VDTNs. Due to the sparse distribution and fast movement of vehicle nodes, link disconnections and network partitions are inevitable in vehicular environments. This makes routing in VTDNs more challenging [22]–[24].

The Epidemic routing protocol [25] is the simplest routing protocol for DTN environments. In this multi-copy routing protocol, when the source node encounters another node without its message, it replicates and sends the message. All intermediate nodes forward the message in the same way until the destination node is reached. Since all messages (packets) are forwarded to all nodes encountered, the message replication overhead of Epidemic is extremely large due to the redundancy of the message copies, causing a low message delivery ratio as a result of the limited wireless resources and buffer size at intermediate nodes. Spray-and-Wait routing protocol [26] limits the number of message copies. Focusing only on the reduction of message replication overhead, Spray-and-Wait does not consider the encounter probability in the routing decision.

PRoPHET (or Probabilistic Routing Protocol using the History of Encounters and Transitivity) [27] is a routing algorithm based on the historical encounter information of nodes. Each node in the network maintains an encounter probability table that records its probability of encounter with other network nodes. When two nodes encounter, each node updates its probability table. If the probability of the encountered node to the destination node is higher, the message is copied and forwarded to the encountered node; otherwise, the message continues to be stored in its cache, waiting for delivery to an encountered node with a higher probability. PRoPHET mainly relies on the encounter probability to select relay nodes. The encounter probability between node i and node j is $P(i, j)_{new} = P(i, j)_{old} + [(1 - P(i, j)_{old})] \times P_{\text{init}}$, where $P(i, j) \in [0, 1]$, $P_{\text{init}} \in [0, 1]$ is a predefined initial constant, and $P(i, j)_{old}$ is the previous encounter probability. The PRoPHET routing protocol controls the number of replications for each message by calculating the encounter probability based on historical data. However, since the valid connection time for each encounter is not considered in the message replication process, PRoPHET fails to achieve a satisfactory result.

Bubble Rap [28] is a typical social-awareness routing protocol. It generates social contact graphs based on historical encounters, and then builds and maintains a table to record a ranking of network nodes according to social relationship, which helps to discover social communities used to facilitate the forwarding process. A network node with a higher ranking is used with a higher probability in forwarding until the message is delivered to the community where the destination node is located. However, a common problem of this protocol is that it does not consider the connection time for each encounter in the message replication process.

Wu *et al.* [29] propose a Bayesian network based approach to predict the movement pattern of vehicles in DTN scenarios. Dong *et al.* [30] discuss the incentive problem in VDTN routing, and use the Q-learning algorithm to calculate the credit value of each candidate node. Both [29] and [30] do not consider the link quality between two nodes in the forwarding decision. Xia *et al.* [31] study the use of fog computing in delay-tolerant communications for Internet of vehicles. Focusing on vehicle-to-infrastructure communications, [31] does not adequately address the routing problem for vehicle-to-vehicle communications.

B. UAV-ASSISTED VDTNS

In order to improve the connectivity of the network and the success rate of message delivery, Wang *et al.* [32] introduce the concept of using a UAV as a ferry node, which is a kind of node with controllable movement, that can move in a specific area of the network and deliver messages received from other nodes in the region. Similar concepts have been used in [33], [34]. The main idea of the ferry node is to take account of the non-randomness and repeatable movement of UAVs that visit a specific area according to a certain regularity. The ferry node can be used to assist other nodes in message delivery and to connect with nodes in isolated areas. UAVs can serve as ferry nodes in the air to receive and forward data messages, improving the reliability of wireless communication links, enhancing infrastructure flexibility, and providing communication coverage in sparse areas [35], [36].

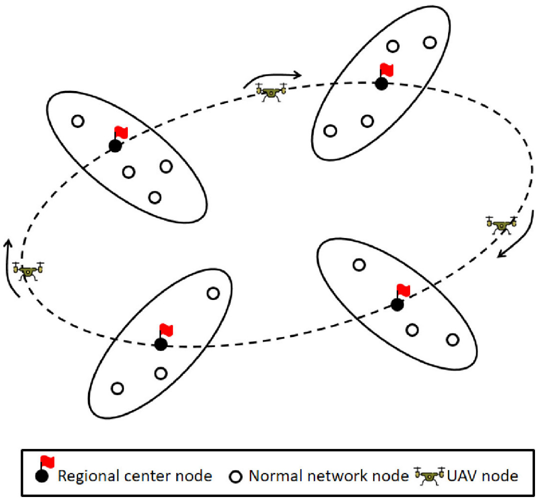

FIGURE 1. **Regional center nodes in post-disaster DTN environments.**

Some studies discuss about the trajectory design of UAVs in DTN environments. Zhao *et al.* [37] propose four algorithms, namely single routing algorithm (SIRA), multi-routing algorithm (MURA), node relay forwarding algorithm (NRA) and ferry relay forwarding algorithm (FRA), for flying path optimization of UAVs in order to improve network performance. 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 pre-installed 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 [38], the use of UAVs in a post-disaster scenario is discussed. Some regions 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. As shown in Fig. 1, according to the crowd's agglomeration after the disaster and the crowd's movement characteristics in the area, a fixed regional center node can be deployed at each gathering area to store and forward messages. The regional center node can communicate with mobile nodes in its region, and the UAVs are responsible for transferring messages between regions. Adding fixed regional center nodes in the aggregation region can improve the contact opportunities between normal nodes in the entire network and play a role in collecting and forwarding inter-regional messages, hence improving the message delivery ratio and average delay of message transmission between the source and destination nodes. UAV-assisted VDTN is of great importance for providing communications in post-disaster scenarios.

UAV-assisted VDTN technologies have attracted increasing interests in recent years. However, existing studies focus on planning the flying paths of UAVs to improve network connectivity. There is a lack of studies about designing communication routes for UAV-assisted VDTNs. Since different cities have different conditions that require different designs, it is difficult to find the optimal solution in a short time. Therefore, in this paper, we discuss about the design of an efficient routing protocol for UAV-assisted VDTNs.

III. PROPOSED PROTOCOL

We first explain the use-case of the proposed protocol and provide the overview of the proposed protocol. After that, we discuss the main technical problem and introduce our solution.

A. APPLICATION SCENARIOS

The application scenarios of UAV-assisted VDTNs can be classified into two main categories, namely the typical scenario (or the non-isolated scenario) and the post-disaster scenario (or the isolated scenario). Here, the typical scenario means a daily scenario where vehicles could exchange information without the help of UAVs. In this case, UAVs can be used to further enhance the communication performance. In the post-disaster scenario, the entire region consists of multiple isolated regions, where UAV nodes patrol between the isolated regions and provide a gateway functionality between the regions. When a message is required to be delivered to other regions, a UAV node must be selected as the relay node for message forwarding. When the source and destination nodes are in the same region, other vehicle nodes in the region are selected for message forwarding, which is the same as the typical scenario.

Compared with a vehicle node, a UAV node basically has a larger transmission range and predictable moving paths. In response to this feature, the proposed protocol puts forward the concept of the encounter connection time between nodes to evaluate whether a node can establish a reliable link in a path leading to the destination node. Through the combination of the encounter probability and the encounter connection time between nodes, the proposed routing protocol can reduce transmission failures caused by link disconnections and network partitions.

Fig. 2 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.

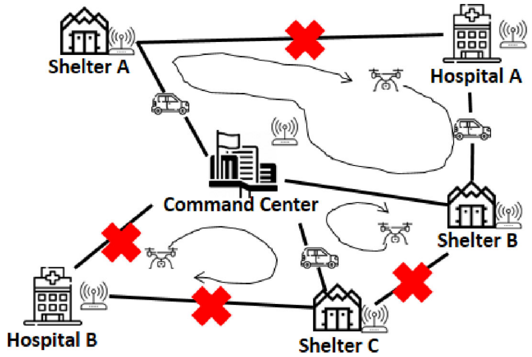

FIGURE 2. Post-disaster emergency communication network based on UAV-assisted VDTN.

B. PROTOCOL OVERVIEW

Due to the mobility of vehicle nodes and fast change of network topology, VDTNs use opportunistic forwarding to transmit messages in order to improve link quality. The reliability of VDTNs can be enhanced by considering both the encounter probability to the destination and the communication capability of each encounter in the decisions made on message replication (or message forwarding) in order to increase the message delivery ratio and reduce network overhead. Specifically, we extend PRoPHET, which considers the encounter probability only, by introducing a new metric, namely the persistent connection time, to characterize the suitability of UAVs in message forwarding.

C. 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 future via a path leading to the destination node. We explain the research problem here using PRoPHET since it is a well-known probabilistic DTN protocol. The message replication process of PRoPHET" is shown in Fig. 3. Two neighbor nodes (i.e., nodes A and B) are located in the transmission 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 its destination node D.

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

Another VDTN scenario is shown in Fig. 4, where the encounter probability of nodes A and B are very close. As explained in the introduction of the PRoPHET protocol (see

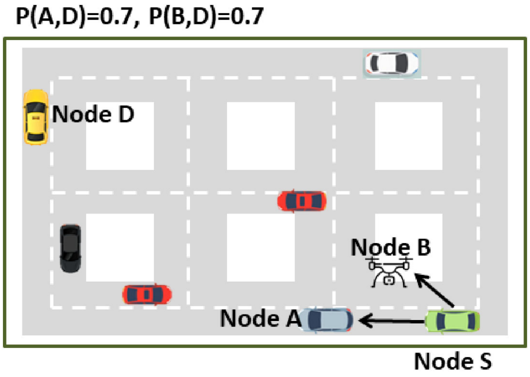

FIGURE 3. **Forwarding decision made when two neighboring nodes have the same encounter probability (the white boxes are buildings, and dotted lines are roads).**

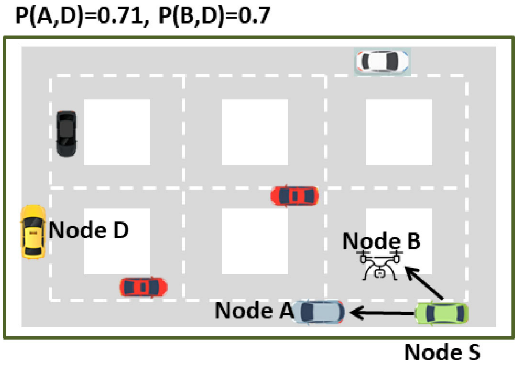

FIGURE 4. **Forwarding decision made when neighboring nodes have slightly different encounter probabilities (the white boxes are buildings, and dotted lines are roads).**

Section II-A), 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 due to 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 of the UAV is lower than that of node A. The disadvantages of PRoPHET 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.

In order to solve the above disadvantages of PRoPHET, we design a routing algorithm with the consideration of the connection time for each encounter. The algorithm considers whether the nodes are reliable and effective throughout the communication process, and flexibly uses UAV nodes in the VDTN environment to improve the transmission performance of the network.

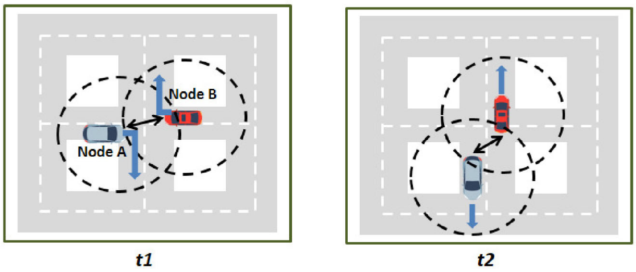

FIGURE 5. **The importance of considering the persistent connection time of a link (the four white boxes are buildings, and dotted lines are roads).**

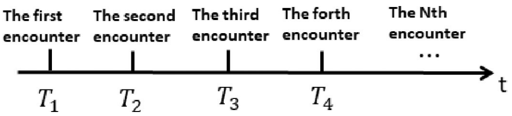

FIGURE 6. **The encounter history of two nodes.**

D. 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. Here, we introduce persistent connection time, which is the connection time for each encounter, to select nodes that can establish stable communication links. As shown in Fig. 5, at time $t1$, two moving nodes form a direct communication link. 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.

We introduce the persistent connection time ratio, which shows the average connection time between two nodes in the encounter history. Taking the persistent connection time as an important reference can ensure the stability of message transmissions.

Consider the occurrences of the encounters between two nodes as shown in Fig. 6. 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.

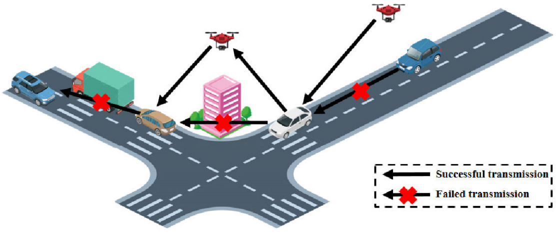

FIGURE 7. **Comparison of the UAV-vehicle communication link and the inter-vehicle link.**

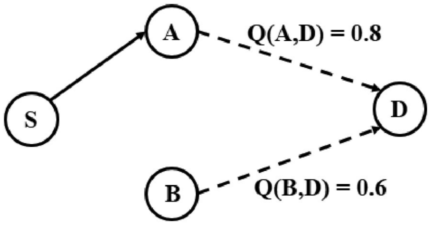

FIGURE 8. **The selection of a relay node A in the proposed protocol.**

The persistent connection time ratio is calculated as follows:

$$T_{(R,D)} = \frac{\sum_{q=1}^{w} T_{RD}(q)}{T_{con}} \tag{1}$$

where $\sum_{q=1}^{w} T_{RD}(q)$ represents the total length of the connection time 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. Hence, $T_{(R,D)} \in (0, 1)$ shows the ratio between the connection time of relay node R and destination node D, and the connection time between relay node R and all other nodes in the network.

E. ROUTING ALGORITHM

As shown in Fig. 7, 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.

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.

$$Q_{(R,D)} = \alpha \times P_{(R,D)} + (1 - \alpha) \times T_{(R,D)} \tag{2}$$

where $\alpha \in (0, 1)$ is the smooth factor. When the value of α is greater than 0.5, the encounter probability plays the dominant role in the selection of the relay node. When the value of α is less than 0.5, the persistent connection time ratio becomes the dominant factor in the selection of the relay node. Hence, the α 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 α is 0.35, the combination of the encounter probability and encounter connection time ratio is the best, which leads to the best network performance. Therefore, the value of the smooth factor α is set as 0.35 in our experiments.

Fig. 8 shows the selection of relay nodes in the proposed 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 send 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 higher probability of encountering the destination node with a more reliable link, thereby improving network performance.

Algorithm 1: The Proposed Routing Algorithm.

```
D is the destination node;
Each source/forwarder node (A) does the following steps:
for each node X that the current node A meets
    Drop the message with an expired lifetime.
    Receive $T_{(X,D)}$ from X.
    Calculate Q value for X according to Eq. (2).
    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 $T_{(X,D)}$.
Send $T_{(X,D)}$ to node A.
```

The routing procedure of the proposed protocol is shown in Algorithm 1. Each node maintains own T 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.

IV. SIMULATION RESULTS

In this section, the ONE simulator [39] 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. The simulation parameters are shown in Table 1 and Table 2. We use four performance metrics, specifically, message delivery ratio (the ratio of successfully delivered messages over the total sent messages), the average end-to-end delay of messages, the number of hops, and the overhead (or the ratio of the number of message replications divided by the number of messages for deliveries). The traffic

TABLE 1. Simulation Parameters for Vehicles in Typical Scenarios

Parameters	Values
Simulation Time (s)	43200
Number of Nodes	40, 80, 120, 160, 200
Interface	Wi-Fi Interface
Movement Speed (m/s)	2.4-13.9
Transmission Rate (Mbps)	7.5
Transmission Range (m)	50
Buffer Size (MB)	5
Message TTL (s)	300
Message Interval (s)	50
Nodes Movement Model	ShortestPathMapBasedMovement [39]
Message Size (B)	500K-1M
Simulation Area Size	4500m×3400m

TABLE 2. Simulation Parameters for UAVs in Typical Scenarios

Parameters	Values
Number of UAVs	0, 5, 10, 15, 20
Interface	Wi-Fi Interface
Movement Speed (m/s)	5-15
Transmit Speed (Mbps)	7.5
Transmit Range (m)	50
Buffer Size (MB)	100
Nodes Movement Model	MapRouteMovement [39]

flows are randomly generated from all the ordinary vehicles (UAVs do not generate traffics).

A. EFFECTS OF THE SMOOTH FACTOR α IN THE PROPOSED PROTOCOL

Before comparing the proposed routing protocol with existing baselines, it is necessary to determine the best possible value for the smooth factor α of the proposed routing protocol. The α 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 number of vehicle nodes is 80, and the number of UAVs is 10. We conduct simulations to find the best possible value of α by observing the change in the message delivery ratio.

Based on Eq. (2), the closer the value of α to 0, the more reliable is the link between the selected relay node and the destination node. The closer the value of α to 1, the greater the likelihood that the selected relay node encounters the destination node. In our experiment, Fig. 9 shows that, when the value of α is 0.35, the proposed protocol shows the best possible performance, contributing to the highest possible delivery ratio. Therefore, in our simulations, we set $\alpha = 0.35$.

B. SIMULATIONS IN TYPICAL SCENARIOS

In general, the typical scenario does not have isolated regions. In the simulation, the city map of Helsinki as shown in Fig. 10 is used, and the vehicle movement is generated based on the simulation parameters presented in Tables 1 and 2. The red path is the patrol route of UAVs. Two sets of simulations are conducted to evaluate the proposed routing protocol with respect to the different numbers of UAVs and regular nodes (vehicles).

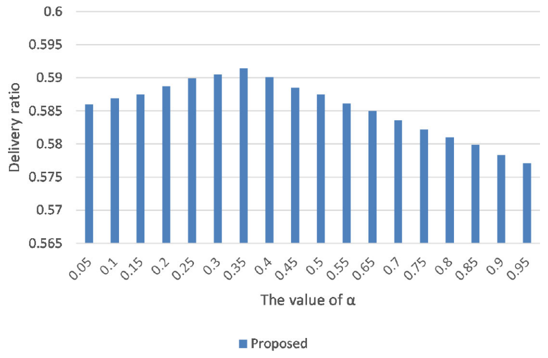

FIGURE 9. Delivery ratio for various values of α.

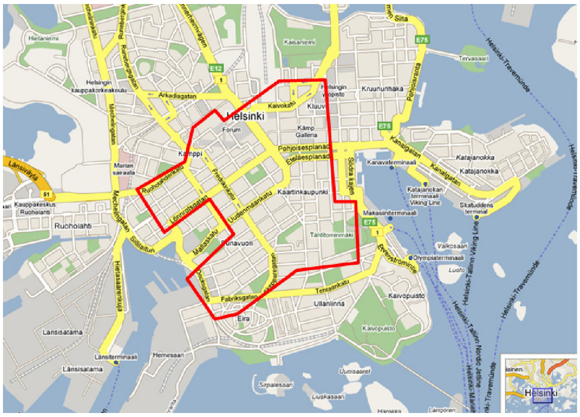

FIGURE 10. Patrol route of UAVs.

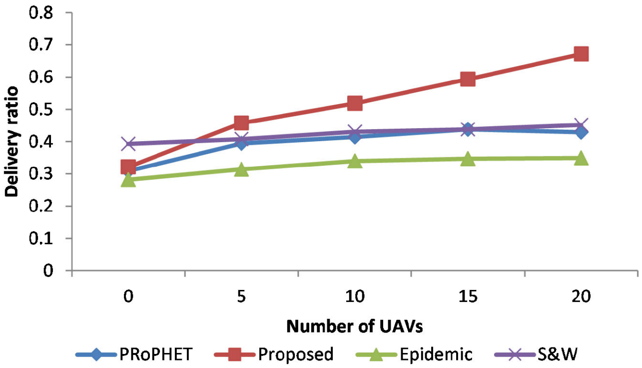

FIGURE 11. The message delivery ratio of the routes established by the proposed routing protocol is generally higher than that of the other routing protocols for different numbers of UAVs.

1) EFFECT OF THE NUMBER OF UAVS

Here, each routing protocol is evaluated with different numbers of UAVs. Fig. 11 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,

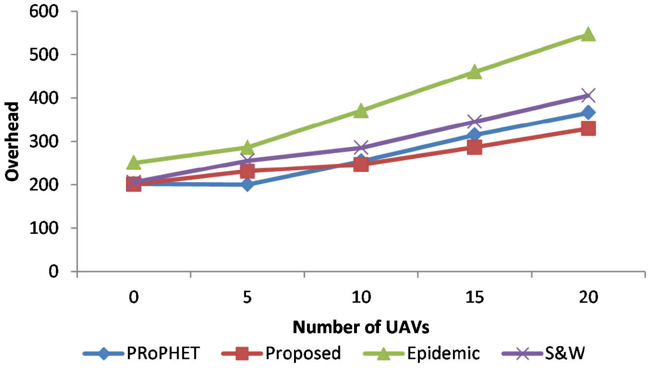

FIGURE 12. **The overhead of the proposed routing protocol is generally lower than that of the other routing protocols for different numbers of UAVs.**

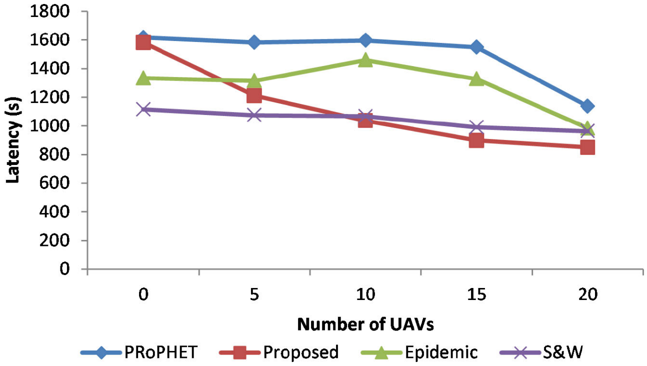

FIGURE 13. **The average latency of the routes established by the proposed routing protocol is generally lower than that of the other routing protocols for different numbers of UAVs.**

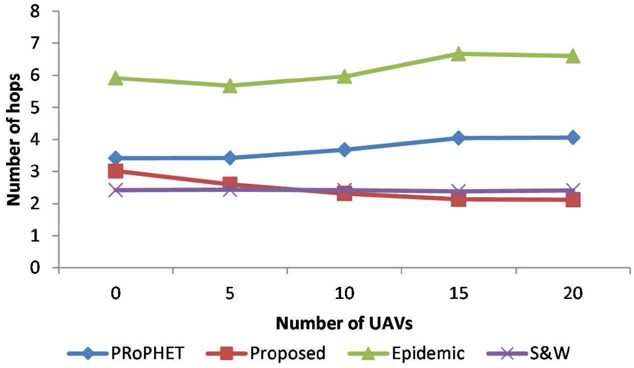

FIGURE 14. **The average number of hops of the routes established by the proposed routing protocol is generally lower than that of the other routing protocols for different numbers of UAVs.**

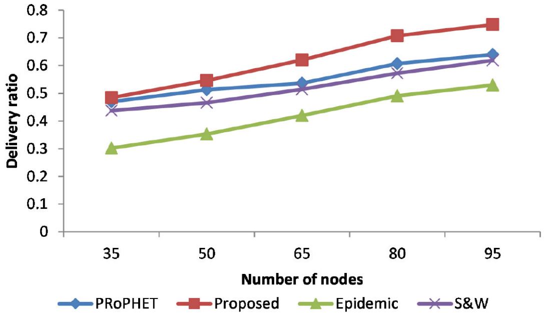

FIGURE 15. **The message delivery ratio of the routes established by the proposed routing protocol is generally higher than that of the other routing protocols for different numbers of vehicles.**

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.

Fig. 12 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.

Fig. 13 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.

Fig. 14 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.

2) EFFECTS 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.

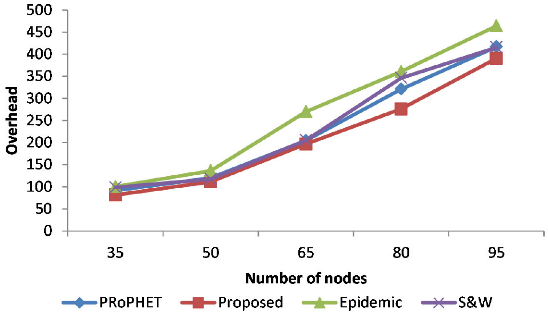

FIGURE 16. The overhead of the proposed routing protocol is generally lower than that of the other routing protocols for different numbers of vehicles.

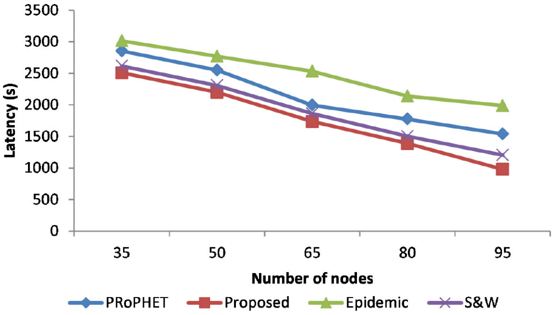

FIGURE 17. The average latency of the routes established by the proposed routing protocol is generally lower than that of the other routing protocols for different numbers of vehicles.

Fig. 15 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.

Fig. 16 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.

Fig. 17 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.

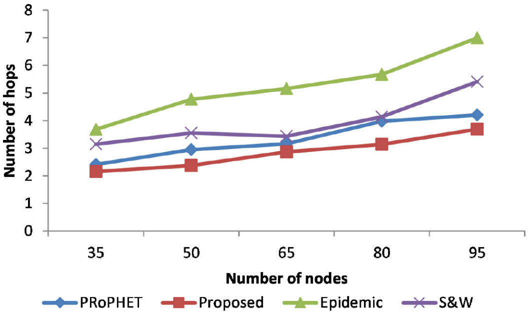

FIGURE 18. The average number of hops of the routes established by the proposed routing protocol is generally lower than that of the other routing protocols for different numbers of vehicles.

Fig. 18 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.

3) EFFECTS 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. Here, we use simulations to evaluate the routing protocols in a typical scenario with vehicles joining and leaving. Two groups of vehicle nodes are included in the simulation. The activity time of one group of vehicles is set from 0 to 18 000 seconds (1st to 5th hour). The activity time of the other group of vehicles is set from 36 000 to 43 200 seconds (11th and 12th hours). Each group contains 20 vehicle nodes.

Fig. 19 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

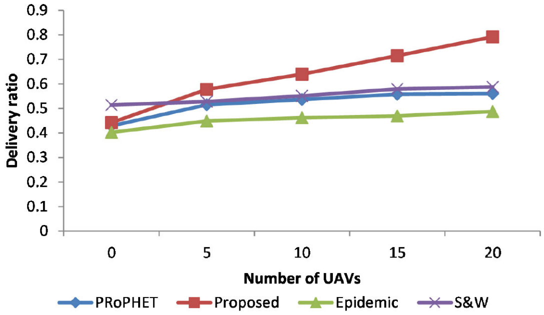

FIGURE 19. **The message delivery ratio of the routes established by the proposed routing protocol is generally higher than that of the other routing protocols under typical scenarios with joining and leaving vehicles for different numbers of UAVs.**

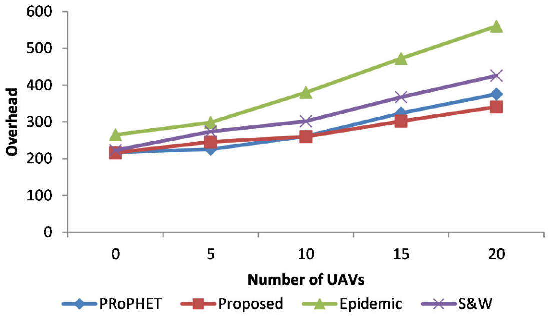

FIGURE 20. **The overhead of the proposed routing protocol is generally lower than that of the other routing protocols under typical scenarios with joining and leaving vehicles for different numbers of UAVs.**

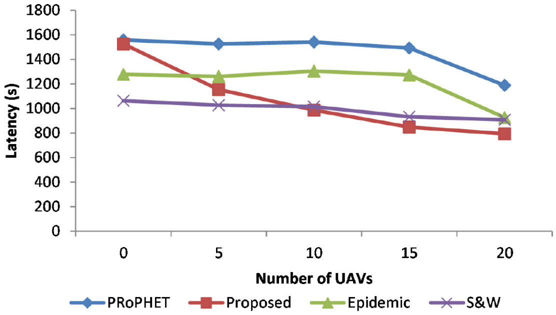

FIGURE 21. **The average latency of the routes established by the proposed routing protocol is generally lower than that of the other routing protocols under typical scenarios with joining and leaving vehicles for different numbers of UAVs.**

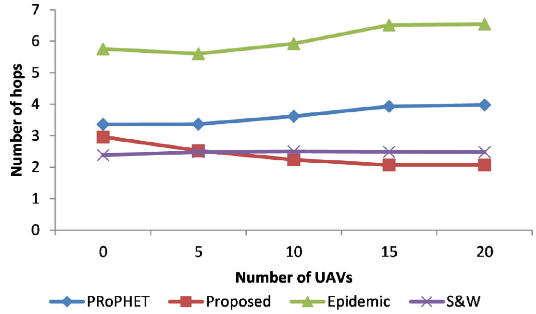

FIGURE 22. **The average number of hops of the routes established by the proposed routing protocol is generally lower than that of the other routing protocols under typical scenarios with joining and leaving vehicles for different numbers of UAVs.**

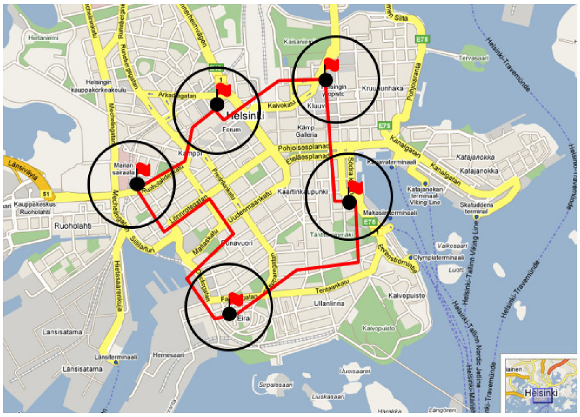

FIGURE 23. **The simulation scenario with regional center nodes.**

newly joined nodes being selected as relay nodes is low. In this case, the use of persistent connection time ratio becomes more important. We can also observe from Fig. 20 that the proposed routing protocol achieves the lowest overhead under most circumstances, proving its superiority.

Fig. 21 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.

Fig. 22 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.

C. EFFECT OF ISOLATED REGIONS

When a disaster strikes, such as an earthquake or a tsunami, roads are often damaged. So, rescue vehicles are unable to reach designated locations, making the message forwarding task difficult to complete as required. We discuss VDTNs for post-disaster scenarios into two categories, namely, the scenario with and without regional center nodes. In the scenario with regional center nodes, there is a single regional center node for each region as shown in Fig. 23, which is usually a

FIGURE 24. The simulation scenario without regional center nodes.

TABLE 3. Simulation Parameters for Regular Nodes in Isolated Scenarios Without Regional Center Nodes

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

refuge, a hospital, or a disaster relief command center. Compared with other network nodes, a regional center node has a larger buffer space and a larger transmission range.

1) SCENARIO WITHOUT REGIONAL CENTER NODES

Here, we first use simulations to evaluate the performance of the proposed protocol in a scenario without regional center nodes. As shown in Fig. 24, several areas, such as shelters and command centers, become isolated after a disaster. Vehicles in each area use the ClusterMovement model [39]. UAVs patrol along the red path following the MapRouteMovement model while establishing communication between isolated areas. Considering the limited power supply, the UAVs have a random stay after a certain time period (such as for the replacement of a UAV's spare battery). Here, the regular network nodes are pedestrians, and they use Bluetooth for communication. UAVs have both Bluetooth and Wi-Fi interfaces. Specific simulation parameters are shown in Table 3 and Table 4 below.

TABLE 4. Simulation Parameters for UAVs in Isolated Scenarios Without Regional Center Nodes

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

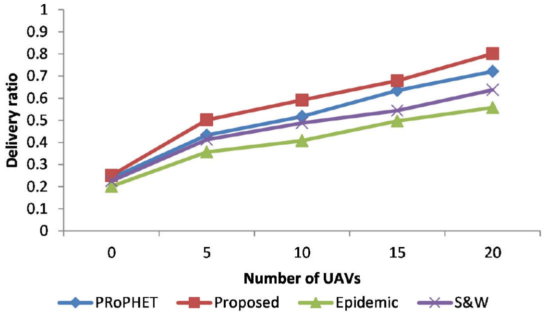

FIGURE 25. The message delivery ratio of the routes established by the proposed routing protocol is generally higher than that of the other routing protocols for different numbers of UAVs in isolated scenarios without regional center nodes.

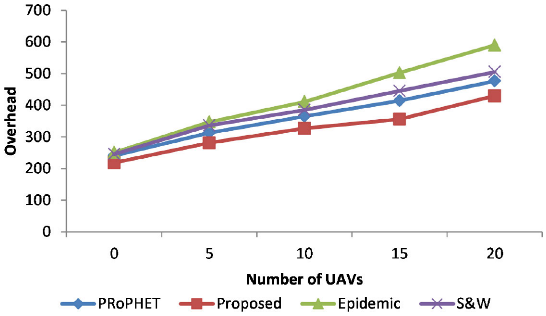

FIGURE 26. The overhead of the proposed routing protocol is generally lower than that of the other routing protocols for different numbers of UAVs in isolated scenarios without regional center nodes.

We evaluate the performance of the routing protocols with respect to the different number of UAVs. Fig. 25 shows the message delivery ratio. Since a 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.

Fig. 26 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.

Fig. 27 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, we observe a smaller delay due to the

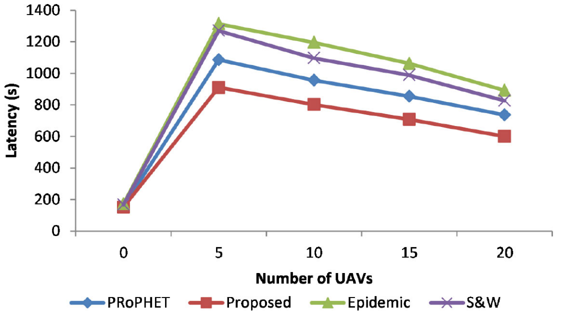

FIGURE 27. **The average latency of the routes established by the proposed routing protocol is generally lower than that of the other routing protocols for different numbers of UAVs in isolated scenarios without regional center nodes.**

TABLE 5. **Simulation Parameters for Regular Nodes in Isolated Scenarios With Regional Center Nodes**

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

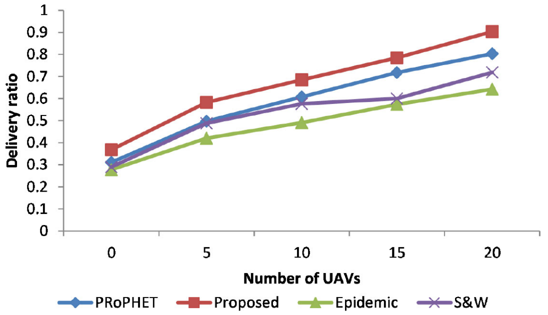

FIGURE 28. **The message delivery ratio of the routes established by the proposed routing protocol is generally higher than that of the other routing protocols for different numbers of UAVs in isolated scenarios with regional center nodes.**

increased number of forwarder nodes for inter-region communications. The proposed protocol shows a significantly lower delay as compared with other protocols.

2) SCENARIOS WITH REGIONAL CENTER NODES

We also evaluate the routing protocols in a scenario with regional center nodes. The simulation parameters of regional center nodes are shown in Table 5.

The comparison of the message delivery ratio is shown in Fig. 28. By comparing this result with Fig. 25, we can observe that the introduction of regional center nodes can improve the message delivery ratio. The regional center node can store more messages, which helps to keep waiting messages in the intra-region message forwarding process. Meanwhile, the regional center node also has a large transmission range, therefore it can establish stable links with UAVs, resulting in more efficient message forwarding between regions.

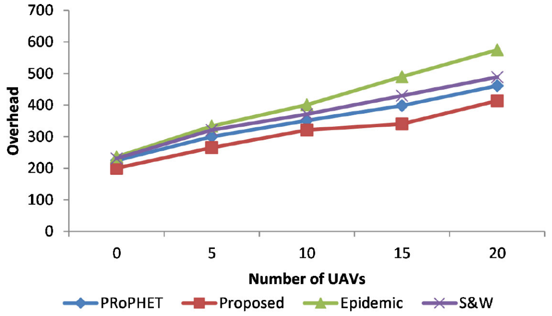

FIGURE 29. **The overhead of the proposed routing protocol is generally lower than that of the other routing protocols for different numbers of UAVs in isolated scenarios with regional center nodes.**

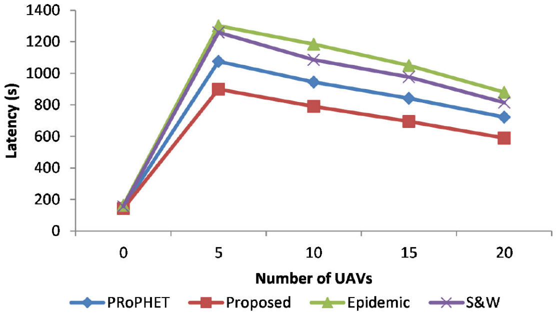

FIGURE 30. **The average latency of the routes established by the proposed routing protocol is generally lower than that of the other routing protocols for different numbers of UAVs in isolated scenarios with regional center nodes.**

Fig. 29 shows the overhead. When none of the UAVs arrives in a region, messages are only forwarded in each isolated area. By using UAVs, the isolated areas are connecte. While the messages are successfully forwarded to different regions, there is an increased network overhead. However, by selecting stable relay nodes, the proposed protocol is able to control the overhead better as compared with other protocols. The proposed protocol also achieves the shortest delay for different numbers of UAVs, which can be seen from Fig. 30.

The network performance of the proposed protocol is generally better than other protocols, which proves its superiority. Although the introduction of regional center nodes can improve DTN's performance after disasters, the aftermaths are often difficult to predict. Damage to infrastructure or secondary disasters sometimes causes the unavailability of regional center nodes. Therefore, the proposed protocol does not specifically differentiate the regional center nodes from ordinary network nodes for the sake of generality.

V. CONCLUSION

This paper proposes a new routing protocol for UAV-assisted vehicular delay tolerant networks (VDTNs). The proposed protocol takes into account the encounter probability and the persistent connection time for each encounter in the forwarding decision. By considering the persistent connection time, the proposed protocol is able to evaluate the stability of a communication link more accurately in the UAV-assisted VDTN environment. 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.

REFERENCES

[1] Z. Du, C. Wu, X. Chen, X. Wang, T. Yoshinaga, and Y. Ji, "A VDTN scheme with enhanced buffer management," *Wireless Netw.*, vol. 26, pp. 1537–1548, Jan. 2020.

[2] C. Wu, T. Yoshinaga, D. Bayar, and Y. Ji, "Learning for adaptive anycast in vehicular delay tolerant networks," *J. Ambient Intell. Humanized Comput.*, vol. 10, no. 4, pp. 1379–1388, Oct. 2016.

[3] J. G. Filho, A. Patel, L. Bruno, and C. Joaquim, "A systematic technical survey of DTN and VDTN routing protocols," *Comput. Standards Interfaces*, vol. 48, pp. 139–159, 2016.

[4] P. Matzakos, T. Spyropoulos, and C. Bonnet, "Joint scheduling and buffer management policies for DTN applications of different traffic classes," *IEEE Trans. Mobile Comput.*, vol. 17, no. 12, pp. 2818–2834, Dec. 2018.

[5] Z. Du, C. Wu, T. Yoshinaga, K.-L. A. Yau, Y. Ji, and J. Li, "Federated learning for vehicular internet of things: Recent advances and open issues," *IEEE Open J. Comput. Soc.*, vol. 1, pp. 45–61, May 2020.

[6] S. M. Tornell, C. T. Calafate, J. Cano, and P. Manzoni, "DTN protocols for vehicular networks: An application oriented overview," *IEEE Commun. Surveys Tut.*, vol. 17, no. 2, pp. 868–887, Apr.–Jun. 2015.

[7] Y. Wu, S. Deng, and H. Huang, "Control of message transmission in delay/disruption tolerant network," *IEEE Trans. Computat. Social Syst.*, vol. 5, no. 1, pp. 132–143, Mar. 2018.

[8] C. Sobin, V. Raychoudhury, G. Marfia, and A. Singla, "A survey of routing and data dissemination in delay tolerant networks," *J. Netw. Comput. Appl.*, vol. 67, pp. 128–146, 2016.

[9] Z. Jin, J. Wang, S. Zhang, and Y. Shu, "Epidemic-based controlled flooding and adaptive multicast for delay tolerant networks," in *Proc. 7th Int. Conf. Ubiquitous Intell. Comput. 7th Int. Conf. Autonomic Trusted Comput.*, 2010, pp. 191–194.

[10] H. Huang, Y. Mao, and X. Zhang, "Probability routing algorithm based on historical throughput in DTN network," in *Proc. 3rd Int. Conf. Consum. Electron., Commun. Netw.*, 2013, pp. 450–453.

[11] F. Xia, L. Liu, J. Li, J. Ma, and A. V. Vasilakos, "Socially aware networking: A survey," *IEEE Syst. J.*, vol. 9, no. 3, pp. 904–921, Sep. 2015.

[12] W. Gao *et al.*, "Emulation-based performance evaluation of the delay tolerant networking (DTN) in dynamic network topologies," in *Proc. Int. Conf. Softw. Eng. Res., Manage. Appl.*, 2019, pp. 23–41.

[13] R. Wang, X. Wu, T. Wang, X. Liu, and L. Zhou, "TCP convergence layer-based operation of DTN for long-delay cislunar communications," *IEEE Syst. J.*, vol. 4, no. 3, pp. 385–395, Sep. 2010.

[14] Y. Niitsu, T. Sakuma, and H. Date, "Power utilization efficiency improvement method for DTN using a message ferry," in *Proc. 8th Int. Conf. Ubiquitous Future Netw.*, 2016, pp. 954–956, 2016.

[15] P. Li, X. Wu, W. Shen, W. Tong, and S. Guo, "Collaboration of heterogeneous unmanned vehicles for smart cities," *IEEE Netw.*, vol. 33, no. 4, pp. 133–137, Jul./Aug. 2019.

[16] B. Liu, W. Zhang, W. Chen, H. Huang, and S. Guo, "Online computation offloading and traffic routing for UAV swarms in edge-cloud computing," *IEEE Trans. Veh. Technol.*, vol. 69, no. 8, pp. 8777–8791, Aug. 2020.

[17] C. Barroca, A. Grilo, and P. R. Pereira, "Improving message delivery in UAV-based delay tolerant networks," in *Proc. 16th Int. Conf. Intell. Transp. Syst. Telecommun.*, 2018, pp. 1–7.

[18] T. Jonson, J. Pezeshki, V. Chao, K. Smith, and J. Fazio, "Application of delay tolerant networking (DTN) in airborne networks," in *Proc. IEEE Mil. Commun. Conf.*, 2008, pp. 1–7.

[19] S. Krug and J. Seitz, "Challenges of applying DTN routing protocols in realistic disaster scenarios," in *Proc. 8th Int. Conf. Ubiquitous Future Netw.*, 2016, pp. 784–789, 2016.

[20] B. Yang and X. Bai, "A review of UAV ferry algorithms in delay tolerant network," in *Proc. 12th Int. Symp. Computat. Intell. Des.*, 2019, pp. 94–98.

[21] Z. Du, C. Wu, and Y. Tsutomu, "UAV-empowered protocol for information sharing in VDTN," in *Proc. 16th Int. Conf. Mobility, Sens. Netw.*, 2020, pp. 640–641.

[22] S. H. Ahmed, H. Kang, and D. Kim, "Vehicular delay tolerant network (VDTN): Routing perspectives," in *Proc. 12th Annu. IEEE Consum. Commun. Netw. Conf.*, 2015, pp. 898–903.

[23] M. Benamar, S. Ahnana, F. Z. Saiyari, N. Benamar, and M. Ouadghiri, "Study of VDTN routing protocols performances in sparse and dense traffic in the presence of relay nodes," *J. Mobile Multimedia*, vol. 10, no. 1, pp. 78–93, 2014.

[24] J. J. P. C. Rodrigues *et al.*, "The vehicular delay-tolerant networks (VDTN) Euro-NF joint research project," in *Proc. 7th EURO-NGI Conf. Next Gener. Internet Netw.*, 2011, pp. 1–2.

[25] X. Lu and P. Hui, "An energy-efficient n-epidemic routing protocol for delay tolerant networks," in *Proc. IEEE 5th Int. Conf. Netw., Architecture, Storage*, 2010, pp. 341–347.

[26] T. Spyropoulos, K. Psounis, and C. S. Raghavendra, "Spray and wait: An efficient routing scheme for intermittently connected mobile networks," in *Proc. ACM SIGCOMM Workshop Delay-tolerant Netw.*, 2005, pp. 252–259.

[27] S. Grasic, E. Davies, A. Lindgren, A. Doria, "The evolution of a DTN routing protocol-PRoPHETv2," in *Proc. 6th ACM Workshop Challenged Netw.*, 2011, pp. 27–30.

[28] P. Hui, J. Crowcroft, and E. Yoneki, "BUBBLE rap: Social-based forwarding in delay-tolerant networks," *IEEE Trans. Mobile Comput.*, vol. 10, no. 11, pp. 1576–1589, Nov. 2011.

[29] J. Wu, Y. Guo, H. Zhou, L. Shen, and L. Liu, "Vehicular delay tolerant network routing algorithm based on bayesian network," *IEEE Access*, vol. 8, pp. 18727–18740, 2020.

[30] Y. Dong, F. Zhang, I. Joe, H. Lin, W. Jiao, and Y. Zhang, "Learning for multiple-relay selection in a vehicular delay tolerant network," *IEEE Access*, vol. 8, pp. 175602–175611, 2020.

[31] B. Xia, F. Kong, J. Zhou, X. Tang, and H. Gong, "A delay-tolerant data transmission scheme for internet of vehicles based on software defined cloud-fog networks," *IEEE Access*, vol. 8, pp. 65911–65922, 2020.

[32] X. Wang, Y. Shu, Z. Jin, Q. Pan, and B. Lee, "Adaptive randomized epidemic routing for disruption tolerant networks," in *Proc. 5th Int. Conf. Mobile Ad-hoc Sensor Netw.*, 2009, pp. 424–429.

[33] Z. Song, C. Wu and Z. Tang, "An efficient group signature scheme in ferry-based delay-tolerant networks," in *Proc. 10th IEEE Int. Conf. Comput. Inf. Technol.*, 2010, pp. 2816–2821.

[34] Y. Nakamura, T. Kaneta and O. Takahashi, "A temporary communication system using DTN for improving power consumption of mobile terminals," in *Proc. Int. Conf. Comput., Netw. Commun.*, 2019, pp. 235–239.

[35] H. Sedjelmaci, S. M. Senouci, and N. Ansari, "A hierarchical detection and response system to enhance security against lethal cyber-attacks in UAV networks," *IEEE Trans. Syst., Man, Cybern. Syst.*, vol. 48, no. 9, pp. 1594–1606, Sep. 2018.

[36] M. Y. Arafat and S. Moh, "Location-aided delay tolerant routing protocol in UAV networks for post-disaster operation," *IEEE Access*, vol. 6, pp. 59891–59906, 2018.

[37] W. Zhao, M. Ammar, and E. Zegura, "Controlling the mobility of multiple data transport ferries in a delay-tolerant network," in *Proc. IEEE 24th Annu. Joint Conf. IEEE Comput. Commun. Soc.*, 2005, pp. 1407–1418.

[38] M. M. Qirtas, Y. Faheem, and M. H. Rehmani, "Throwboxes in delay tolerant networks: A survey of placement strategies, buffering capacity, and mobility models," *J. Netw. Comput. Appl.*, vol. 91, pp. 89–103, 2017.

[39] A. Keränen, J. Ott, and T. Kärkkäinen, "The one simulator for dtn protocol evaluation," in *Proc. 2nd Int. Conf. Simulation Tools Tech.*, 2009, pp. 1–10.

ZHAOYANG DU received the B.E. degree from Beijing Information Science & Technology University, Beijing, China, and the M.E. degree from The University of Electro-Communications, Chofu, Japan, where he is currently working toward the Ph.D. degree. His current research interests include delay tolerant networks, vehicular ad hoc networks, and IoT.

CELIMUGE WU (Senior Member, IEEE) received the M.E. degree from the Beijing Institute of Technology, Beijing, China, in 2006 and the Ph.D. degree from The University of Electro-Communications, Chofu, Japan, in 2010. He is currently an Associate Professor with the Graduate School of Informatics and Engineering, The University of Electro-Communications. His current research interests include vehicular ad hoc networks, sensor networks, intelligent transport systems, IoT, and mobile cloud computing. He is the TPC Co-Chair of the Wireless Days 2019, the ICT-DM 2018 and the track Co-Chair of many international conferences, including the ICCCN 2019 and the IEEE PIMRC 2016. He is an Associate Editor for IEEE ACCESS, *IEICE Transactions on Communications*, *International Journal of Distributed Sensor Networks*, MDPI *Sensors*, and the Guest Editor of IEEE TRANSACTIONS ON EMERGING TOPICS IN COMPUTATIONAL INTELLIGENCE, IEEE Computational Intelligence Magazine, and ACM or Springer MONET.

TSUTOMU YOSHINAGA (Member, IEEE) received the B.E., M.E., and D.E. degrees from Utsunomiya University, Utsunomiya, Japan, in 1986, 1988, and 1997, respectively. From 1988 to July 2000, he was a Research Associate with the Faculty of Engineering, Utsunomiya University. From 1997 to 1998, he was also a Visiting Researcher with Electro-Technical Laboratory. Since August 2000, he has been with the Graduate School of Information Systems, The University of Electro-Communications, where he is currently a Professor. His research interests include computer architecture, interconnection networks, and network computing. He is a Fellow of IEICE, and a Member of ACM and IPSJ.

XIANFU CHEN (Member, IEEE) received the Ph.D. degree (with honors) in signal and information processing from Zhejiang University, Hangzhou, China, in 2012. He is currently a Senior Scientist with the VTT Technical Research Centre of Finland, Espoo, Finland. His research interests include various aspects of wireless communications and networking, with emphasis on human-level and artificial intelligence for resource awareness in next-generation communication networks.

XIAOYAN WANG (Senior Member, IEEE) received the B.E. degree from the Department of Electrical Engineering and Automation, Beihang University, Beijing, China, and the M.E. and Ph.D. degrees from the Department of Computer Science, Graduate School of Systems and Information Engineering, University of Tsukuba, Ibaraki, Japan. From 2013 to 2016, he was an Assitant Professor, by special appointment, with the National Institute of Informatics, Tokyo, Japan. He is currently an Associate Professor with the Graduate School of Science and Engineering, Ibaraki University, Ibaraki, Japan.

KOK-LIM ALVIN YAU (Senior Member, IEEE)) received the B.Eng. degree (Hons.) in electrical and electronics engineering from Universiti Teknologi PETRONAS, Seri Iskandar, Malaysia, in 2005, the M.Sc. degree in electrical engineering from the National University of Singapore, Singapore, in 2007, and the Ph.D. degree in network engineering from the Victoria University of Wellington, Wellington, New Zealand, in 2010. He is currently a Professor with the Department of Computing and Information Systems, Sunway University, Subang Jaya, Malaysia. He is also a Researcher, a Lecturer, and a Consultant in cognitive radio, wireless networks, applied artificial intelligence, applied deep learning, and reinforcement learning. He is a TPC Member and a Reviewer for major international conferences, including ICC, VTC, LCN, GLOBECOM, and AINA. He was the recipient of the 2007 Professional Engineer Board of Singapore Gold Medal for being the Best Graduate of the M.Sc. degree in 2006 and 2007. He was also the Vice General Co-Chair for ICOIN'18, the Co-Chair for the IET ICFCNA'14 and Organizing Committee for the IET ICWCA'12. He is the Editor of *KSII Transactions on Internet and Information Systems*, an Associate Editor for IEEE ACCESS, the Guest Editor for the Special Issues of IEEE ACCESS, IET *Networks*, IEEE *Computational Intelligence Magazine*, Springer *Journal of Ambient Intelligence and Humanized Computing*, and a Regular Reviewer for more than 20 journals, including the IEEE journals and magazines, *Ad Hoc Networks*, and *IET Communications*.

YUSHENG JI (Senior Member, IEEE) received B.E., M.E., and D.E. degrees in electrical engineering from The University of Tokyo, Tokyo, Japan. In 1990, she joined the National Center for Science Information Systems, Japan. She is currently a Professor with the National Institute of Informatics, Tokyo, Japan, and the Graduate University for Advanced Studies (SOKENDAI), Hayama, Japan. Her research interests include network architecture, resource management, and quality of service provisioning in wired and wireless communication networks. She is the Editor of IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, the Symposium Co-Chair of the IEEE GLOBECOM 2012 and 2014, and the Track Co-Chair of the IEEE VTC2016-Fall and VTC2017-Fall.