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A Relay Selection Protocol for UAV-Assisted VANETs

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Abstract: In this paper, we investigate the relay selection problem for the unmanned aerial vehicle (UAV)-assisted vehicular ad-hoc networks (VANETs). For the considered network, we first model and analyze the link quality of service (LQoS) from the source node (SN) to the neighbor node and the node forward capacity (NFC) from the neighbor node to the destination node (DN). Then, the relay selection problem is formulated as a multi-objective optimization problem by jointly considering the LQoS and the NFC. Afterward, we decompose the problem into two subproblems and propose a relay selection protocol with the storage-carry-forward (SCF) method. Moreover, we define a utility function with the node encounter frequency (NEF) and the message time-to-live (TTL) taken into account, based on which a redundant copy-deleting approach is devised. Furthermore, we analyze the security of the designed protocol. Finally, the simulation results demonstrate that the proposed relay selection protocol can improve the message delivery ratio, reduce the average end-to-end delay, and limit the overhead.

Keywords: relay selection; storage-carry-forward (SCF); unmanned aerial vehicle (UAV); vehicular ad-hoc networks (VANETs)

1. Introduction

Vehicular ad-hoc networks (VANETs) can provide users a safer and more pleasant driving experience through integrating wireless communication and informatics technologies into the intelligent transportation system (ITS) [1]. However, VANETs face the challenge of frequent connection disruptions due to highly dynamic network topologies, which significantly degrade the network performance [2]. To address this challenge, unmanned aerial vehicles (UAVs) can be considered as the suitable candidates to improve the connectedness of VANETs [3]. For example, UAVs can assist the ground vehicle in data transmission by the "storage-carry-forward" (SCF) method, which can effectively improve the message delivery ratio and reduce the end-to-end delay [4].

In UAV-assisted VANETs, UAVs and vehicles are network nodes that transmit messages to each other through multi-hop relays. To fully exploit the advantages of the UAV-assisted VANETs, some relay selection protocols have been proposed in recent years [5–12]. The works in [5,6] conceived efficient routing solutions based on the flooding technique to guarantee the robust path and to make the message delivery more reliable. In [7], the problem of relay transmission efficiency was studied by optimizing the transfer probability. Moreover, in our previous work in [8], we formulate the relay selection problem as a multi-objective optimization problem by jointly considering the the state transition probability (STP) of communication interruption and the transmission consumption (TC) including energy consumption and delay consumption. Furthermore, the researchers in [9–12] analytically derived the probability distribution of the vehicle-to-UAV (V2U) packet end-to-end delay, and used UAVs collaborative communication to decrease the V2U packet delay.

The above works have enhanced the communication capability of UAV-assisted VANETs, nevertheless, there are still some problems to be further investigated. Specifically, the authors in [5–8] improve the data delivery process by designing the routing strategy for the relay selection, but they assume that the link between the source node (SN) and the relay node (RN) is ideal. Although the works in [9–12] consider the link quality of service (LQoS), they do not take into account the node forward capacity (NFC), which has an important effect on the message delivery ratio and the average end-to-end delay. Moreover, all works in [5–12] neglect the optimization of the overhead, which is a significant factor that affects whether the relay selection can be successfully executed in practice.

Motivated by the above, we investigate the relay selection problem for UAV-assisted VANETs by jointly considering the LQoS and the NFC. Specifically, the LQoS is the ratio of the channel capacity to the delay, which reflects the reliability and stability of the link from the SN to the neighbor node. The NFC represents the delivery probability of the message from the neighbor node to the destination node (DN), which consists of the node activity (NA) and the node encounter frequency (NEF). The main contributions are summarized as follows.

- We formulate the relay selection problem as a multi-objective optimization problem. For the considered problem, we first model and analyze the LQoS from the SN to the neighbor node and the NFC from the neighbor node to the DN. Then, we decompose the primal problem into two subproblems and solve them by the graphical method.
- Considering the high mobility and cooperative data sharing of UAVs, we propose a relay selection protocol named LQFC with the SCF method. Furthermore, we jointly consider the NEF and the message time-to-live (TTL) to define a utility function to delete redundant copies. The simulation results indicate that our proposed protocol achieves significant performance superiority as compared with other schemes in terms of the message delivery ratio, the average end-to-end delay, and the overhead.

The rest of this paper is organized as follows. Section 2 overviews the related works on relay selections for VANETs. Section 3 introduces the considered network model and the problem formulation. In Section 4, we elaborate the proposed relay selection protocol. Simulation results are presented in Section 5. Finally, we conclude our paper in Section 6.

2. Related Works

In recent years, VANETs have gained popularity for various applications and services in the civilian domains [13]. Compared with the mobile ad-hoc networks (MANETs), the high mobility and wide range cause significant LQoS changes in VANETs [14]. Therefore, in order to realize efficient cooperation and information exchange among multiple network nodes, it is critical to design an efficient relay selection protocol for VANETs.

Many papers have proposed relay selection schemes in VANETs [15–18]. Specifically, based on the VANET-Cellular network architecture, authors in [15] proposed a safety message broadcast relay selection method. This method by jointly considered the cellular signal strength, the link stability, the channel quality, and the geographical location to select the best broadcast relay node. Mathematical analysis and simulations showed that the proposed relay selection method can improve the VANET resource utilization. In addition, Ma et al. [16] proposed a cross-layer relay selection scheme, which can reduce the end-to-end transmission delay. Moreover, Jeong et al. [17] proposed a data forwarding scheme based on trajectory, which was specially designed for roadside reports in sparse VANETs. Furthermore, He et al. [18] proposed an analytical framework for the path delay in bidirectional vehicular traffic. They used this analytical framework to select the relay node with the lowest expected delay. However, the above works [15–18] are based on fixed infrastructure road side units (RSUs) to relay selection. In the large space scale, the obstacle, the complex terrain, the severe weather, and other factors may lead to LQoS degradation or even unavailability. In particular, in some extreme environments, there is a lack of fixed infrastructure RSUs to assist vehicle communication. Thus, it is difficult to meet the demand solely relying on the ground-based VANETs.

To address the problem discussed above, the Consultative Committee for Space Data Systems (CCSDS) [19] proposed that ground nodes can communicate with space networks. However, the number of access network nodes in this method is limited, which cannot meet the demand for multi-vehicle simultaneous access in UAV-assisted VANETs. Recently, research works have also emerged that use UAVs in VANETs [20–28]. Specifically, Bor-Yaliniz et al. [20] studied the opportunistic utilization of UAV-base stations (BSs) in future VANETs and proposed the UAV stations that can be used in cellular wireless VANETs. Liu et al. [21] proposed a relay selection method in space information VANET environment, which can effectively reduce the network overhead while satisfying security constraints. Zhou et al. [22] proposed an aerial-ground cooperative vehicular networking architecture, in which UAVs can act as the relays when network partitions happen in the ground-based VANETs. Zhang et al. [23] proposed a software defined air-to-ground (A2G) network architecture for supporting diverse vehicular services in a seamless, efficient, and economical manner. Oubbati et al. [24] proposed an intersection UAV-assisted VANET relay selection protocol, which was beneficial in developing more intelligent connected network nodes. Lyu et al. [25] studied a wireless system consisting of distributed vehicles and UAVs and proposed the cyclical multiple access method, which can improve the network throughput. Shahidi et al. [26] calculated the probability distribution of the end-to-end information propagation delay of a message in UAV-assisted VANETs with the SCF method. Cheng et al. [27] proposed the task of using one or more UAVs to relay messages between two distant ground nodes by the SCF method. Wang et al. [28] devised an UAV-assisted VANET system, which utilized UAVs to boost vehicle-to-vehicle data message transmission under instructions conducted by their distributed vehicle location prediction algorithm.

Although the existing studies have promoted the development of UAV-assisted VANET, there are still some open issues that remain to be tackled. Firstly, the studies in [20–22] consider that the UAV flight height is constant in their simulations. Meanwhile, they ignore the impact of the UAV mobility model on the performance of a UAV-assisted VANET. Furthermore, the works in [23–25] do not take into account the links between UAVs and vehicles. Specifically, these relay selection protocols do not consider that the transmission of messages in VANETs can be opportunistic, and can increase the VANETs performance by the SCF method. Moreover, the authors of [26–28] perform simulations without considering the mobility of UAVs, and hence the accuracy of the simulation results needs to be further investigated.

Motivated by the aforementioned questions, in our work, we fully consider the cooperation among UAVs in flying, the A2G LQoS, and the network node mobility model for relay selection. For all we know, this has not been studied in the previous works. By making full use of the features of the LQoS and the NFC on the network performance, the proposed scheme achieves better performance than the traditional relay selection protocols in UAV-assisted VANETs.

3. System Model and Problem Formulation

In this section, we first introduce the concerned system model and definitions, and then we formulate the relay selection problem.

3.1. Network Model

This paper considers the UAV-assisted VANET, which consists of N network nodes (vehicles or UAVs). The network nodes adopt the shortest path map based movement (SPMBM) mobility model to plan the trajectory [29]. The nodes periodically interact with each other by the Hello message, which is used to discover available neighbor nodes.

As shown in Figure 1, when the SN N_a has the message to send, N_a can select the neighbor node N_j as the RN to deliver its message by the SCF method. As such, the end-to-end delay $T_{a,b}$ from the SN N_a to the DN N_b can be expressed as

$$T_{a,b} = \sum_{i=1}^{n} \left(T_{S_i} + T_{P_i} + T'_{P_i} + T_{Q_i}\right) + \sum_{i=1}^{n-1} T_{C_i}, \tag{1}$$

where i represents the i-th hop, n represents the total number of hops, T_{S_i}, T_{P_i}, T'_{P_i}, T_{Q_i}, and T_{C_i} represent the i-th hop sending delay, propagation delay, processing delay, queuing delay, and the carrying delay, respectively.

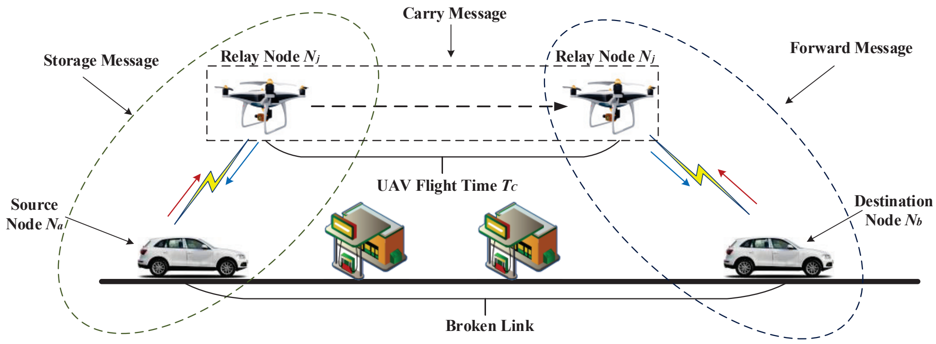


Figure 1. Unmanned aerial vehicle (UAV)-assisted vehicular ad-hoc networks (VANETs) architecture.

3.2. Link Quality of Service (LQoS) Model

According to the Shannon formula, the channel capacity $C_{a,j}$ between the SN N_a and the neighbor node N_j is

$$C_{a,j} = B\log_2 \left[1 + \frac{P\left(L_{a,j}\right)^{-\gamma}|h_{a,j}|^2}{n_0 B}\right], \tag{2}$$

where B represents the bandwidth, P represents the transmitting power of the SN, j represents the ID number of the neighbor node, $L_{a,j}$ represents the distance between the SN and the neighbor node, n_0 represents the noise power spectral density, γ represents the path loss factor, and $h_{a,j}$ represents the small scale fading between N_a and N_j, which follows the exponential distribution [30], i.e., $|h_{a,j}|^2 \sim E(\lambda)$. The probability density function of the exponential distribution can be expressed as

$$f\left(|h_{a,j}|^2\right) = \lambda e^{-\lambda|h_{a,j}|^2}, \tag{3}$$

where λ represents the rate parameter.

According to (2) and (3), we can get the probability of successful transmission $P_{a,j}$ from N_a to N_j is

$$\begin{aligned} P_{a,j} &= P\left(C_{a,j} \geq R\right) = P\left(|h_{a,j}|^2 \geq \frac{(2^{R/B}-1)n_0 B}{P\left(L_{a,j}\right)^{-\gamma}} = \omega\right) \\ &= \int_{\omega}^{\infty} f\left(|h_{a,j}|^2\right) d\left(|h_{a,j}|^2\right), \end{aligned} \tag{4}$$

where R represents the actual transmission rate of the SN N_a, and $d(\cdot)$ represents the variable of integration. When $C_{a,j} \geq R$, the message can be successfully forwarded.

In addition, the mobility of nodes can affect the LQoS in UAV-assisted VANETs. As discussed in [8], the LQoS model from the SN N_a to the RN N_j can be defined as

$$I_{a,j} = \frac{C_{a,j}}{T_{a,j}} = \frac{C_{a,j}}{T_{S_{a,j}} + T_{P_{a,j}} + T'_{P_{a,j}} + T_{Q_{a,j}}}, \tag{5}$$

where $I_{a,j}$, $T_{S_{a,j}}$, $T_{P_{a,j}}$, $T'_{P_{a,j}}$ and $T_{Q_{a,j}}$ represent the LQoS, the sending delay, propagation delay, processing delay, queuing delay from the SN N_a to the RN N_j, respectively.

3.3. Node Forward Capacity (NFC) Model

The NFC is the delivery probability of the message from the neighbor node to the DN, which consists of the NA and the NEF [31]. We divide the message TTL into l time intervals with τ as the time unit, the m-th time interval is τ_m ($m = 1, 2, \ldots, l$). The NA $D_j(\tau_m)$ is the frequency of a certain node N_j encountering other nodes in time τ_m, which is given by

$$D_j(\tau_m) = \frac{|S_j(\tau_m)| - |S_j(\tau_{m-1}) \cap S_j(\tau_m)|}{|S_j(\tau_{m-1}) \cup S_j(\tau_m)|}, \tag{6}$$

where $S_j(\tau_m)$ and $S_j(\tau_{m-1})$ represent the sets of the nodes that N_j encounters with in time τ_m and τ_{m-1}, respectively.

If N_j frequently encounters the N_b in time τ_m, N_j is preferred as the RN to assist the message transmission from N_a to N_b. Thus, the NEF $F_{j,b}(\tau_m)$ can be defined as

$$F_{j,b}(\tau_m) = \frac{E_{j,b}(\tau_m)}{E_{j,1}(\tau_m) + \ldots + E_{j,b}(\tau_m) + \ldots + E_{j,N}(\tau_m)} = \frac{E_{j,b}(\tau_m)}{\sum\limits_{k=1}^{N} E_{j,k}(\tau_m)}, \tag{7}$$

where $E_{j,b}(\tau_m)$ represents the number of encounters between N_j and N_b in time τ_m, and $E_{j,k}(\tau_m)$ represents the number of encounters between N_j and all nodes in time τ_m.

To sum up, the NFC $Q_{j,b}(\tau_m)$ from N_j to N_b in time τ_m can be defined as

$$Q_{j,b}(\tau_m) = D_j(\tau_m) F_{j,b}(\tau_m) = \frac{|S_j(\tau_m)| - |S_j(\tau_{m-1}) \cap S_j(\tau_m)|}{|S_j(\tau_{m-1}) \cup S_j(\tau_m)|} \times \frac{E_{j,b}(\tau_m)}{\sum\limits_{k=1}^{N} E_{j,k}(\tau_m)}. \tag{8}$$

3.4. Problem Formulation

In this paper, we investigate the relay selection problem by jointly considering the LQoS and the NFC. Specifically, the relay selection problem is formulated as the following multi-objective optimization problem.

$$\begin{aligned} &\max_{I,Q} E_j = I_{a,j} Q_{j,b}(\tau_m) \\ &\text{s.t.} C1.1 : P_{a,j} \geq \delta \\ &\quad C1.2 : 0 \leq T_{a,b} \leq M_{th}, \end{aligned} \tag{9}$$

where δ represents the minimum successful transmission probability and M_{th} represents the message TTL.

The objective of (9) is to improve the network performance comprehensively. In (9), maximization $I_{a,j}$ can effectively ensure the user QoS, while maximization $Q_{j,b}$ can improve the possibility of RNs encountering the DN, so as to successfully forward messages. In addition, C1.1 guarantees the transmission rate from the SN N_a to the neighbor node N_j and C1.2 ensures the validity of the message.

4. Description of Proposed Protocol

In this section, we decompose the problem in (9) into two subproblems, based on which we propose the relay selection scheme and design a redundant copy-deleting approach by defining a utility function.

4.1. Problem Decomposition

As can be seen in (9), C1.4 becomes a constraint on the objective function due to the SCF method, in which the carrying delay T_C can affect the message validity. Therefore, selecting the appropriate neighbor node N_j as the RN is in favor of ensuring the message validity and reducing the end-to-end delay. Motivated by this, the problem in (9) can be equivalently recast as the following two subproblems.

$$\begin{aligned} &\mathrm{P1}: \max_{I,Q} E_j = I_{a,j} Q_{j,b}\left(\tau_m\right) \\ &\mathrm{s.t.C2.1}: P_{a,j} \geq \delta, \end{aligned} \tag{10}$$

$$\begin{aligned} &\mathrm{P2}: \min_{T_C} T_{a,b} \\ &\mathrm{s.t.C3.1}: \Theta \\ &\quad \mathrm{C3.2}: 0 \leq T_{a,b} \leq M_{th}, \end{aligned} \tag{11}$$

where Θ represents the feasible solutions of (10).

4.2. Relay Selection

For the SN, the number of neighbor nodes is finite. Therefore, the problem (10) can be transformed into

$$\begin{aligned} &\max_{I,Q} E_j = \left[I_{a,j} Q_{j,b}\left(\tau_m\right)\right]_{1\times r}, j = 1, 2, \ldots, r \\ &\mathrm{s.t.C4.1}: P_{a,j} \geq \delta, \end{aligned} \tag{12}$$

where r represents the number of neighbor nodes, and E_j is the r-order matrix, i.e., $E_j = [I_{a,1}Q_{1,b}(\tau_m), I_{a,2}Q_{2,b}(\tau_m), \ldots, I_{a,r}Q_{r,b}(\tau_m)]_{1\times r}$. Thus, the problem (12) can be written as

$$\begin{aligned} &\max_{I,Q} E_j = \left[I_{a,1}Q_{1,b}\left(\tau_m\right), I_{a,2}Q_{2,b}\left(\tau_m\right), \ldots, I_{a,r}Q_{r,b}\left(\tau_m\right)\right]_{1\times r} \\ &\mathrm{s.t.C5.1}: P_{a,j} \geq \delta, \end{aligned} \tag{13}$$

which means that the neighbor node with the highest $I_{a,j}Q_{j,b}(\tau_m)$ is selected from the set of nodes satisfying C5.1.

In addition, for (13), the objective function is a discrete function, and C5.1 is the linear constraint. Therefore, based on the above analysis, we use the graphical method [32] to solve (13), we have

$$\Theta = x_j^* = \left[I_{a,j} Q_{j,b}\left(\tau_m\right)\right]_{1\times k}, j = 1, 2, \ldots, k \leq r, \tag{14}$$

where x_j^* is the feasible solutions of (13), which is the k-order matrix, and k is the number the feasible solutions.

According to (14), the problem (11) can be expressed as

$$\begin{aligned} &\min_{T_C} T_{a,b} \\ &\mathrm{s.t.C6.1}: x_j^* = \left[I_{a,j} Q_{j,b}\left(\tau_m\right)\right]_{1\times k} \\ &\quad \mathrm{C6.2}: 0 \leq T_{a,b} \leq M_{th}. \end{aligned} \tag{15}$$

The problem in (15) is a non-convex programming problem, which is very hard to tackle directly.

4.3. Relay Operation

In this paper, the UAV-Assisted VANETs can be regarded as the UAV-assisted VANETs can be regarded as the delay tolerant networks (DTNs). Therefore, UAV-assisted VANETs can use the SCF method for information transmission. Further, the UAV mobility is exploited to let mobile network nodes physically carry the message as the RN, and forward the message opportunistically upon contacts. Thus, how to determine an appropriate relay selection strategy and the message forwarding criteria is the key problem. Epidemic routing is one of the first message forwarding schemes, which copies the message to any newly encountered nodes in the network [33].

Motivated by the above "network-centric" idea, we adopt the flooding technique to make the message delivery timelier to minimize $T_{a,b}$. In other words, the SN adopts the multi-copy transmission scheme, which selects the neighbor nodes in x_j^* as the RN. However, increasing the number of copies can improve the network performance, but this leads to the increment of the overhead. Therefore, we conceive a utility function $\psi\left(x_j^*, N_b\right)$ by jointly considering the NEF and the message TTL to limit the overhead, which is defined as

$$\psi\left(x_j^*, N_b\right) = \frac{T_{a,j}}{M_{th}} F_{j,b}\left(\tau_m\right) = \frac{T_{a,j} E_{j,b}\left(\tau_m\right)}{M_{th} \sum\limits_{k=1}^{N} E_{j,k}\left(\tau_m\right)}, \tag{16}$$

where $\psi\left(x_j^*, N_b\right)$ represents the utility value of the message at the RN N_j (the DN of message is N_b), and $T_{a,j}$ represents the time taken for the message to be forwarded from N_a to N_j.

After receiving the message, N_j calculates the utility value according to (16). If (17) is satisfied, N_j stores the message, otherwise the message is discarded.

$$\psi\left(x_j^*, N_b\right) \geq D_j\left(\tau_m\right) E\left(\psi\right), \tag{17}$$

where $E\left(\psi\right)$ represents the average utility value of the cache messages, which is given by

$$E\left(\psi\right) = \sum_{i=1}^{\varphi} \psi\left(x_j^*, N_b\right)_i \Big/ \varphi, \tag{18}$$

where φ represents the number of messages cached at N_j.

4.4. The Overall Protocol

The proposed LQFC protocol is summarized in Algorithm 1. In detail, the network nodes first exchange the Hello message with each other in a cooperative manner to discover available neighbor nodes. Then, the SN calculates the LQoS from the SN to the neighbor node and the NFC from the neighbor node to the DN. Afterward, the SN selects the next-hop RNs (the neighbor vehicles or UAVs) according to the LQoS and the NFC for the message forwarding. Finally, the RN adopts the utility function to calculate the message utility value and decides whether to cache the message. This process continues until the DN receives the message.

Algorithm 1 The Proposed LQFC Relay Selection Protocol

Initialization
    Input N_a and N_b.
    Set R and M_{th}.
for $j = 1$ to N **do**
    Calculate $C_{a,j}$, $T_{a,j}$, $D_j\left(\tau_m\right)$, and $F_{j,b}\left(\tau_m\right)$.
end for
    $E_j \Leftarrow \left[I_{a,j} Q_{j,b}\left(\tau_m\right)\right]_{1\times r}$.
    Find the feasible solutions $x_j^* \Leftarrow \left[I_{a,j} Q_{j,b}\left(\tau_m\right)\right]_{1\times k}$.
    Select the neighbor nodes in x_j^* as the RN.
    Calculate $\psi\left(x_j^*, N_b\right)$ and $E\left(\psi\right)$.
if $\psi\left(x_j^*, N_b\right) \geq D_j\left(\tau_m\right) E\left(\psi\right)$ **then**
    Store the message.
else
    Discard the message.
end if

4.5. Security Analysis

In this section, we analyze the secrecy performance of the proposed scheme. For the proposed system, there is an eavesdropper, denoted as Eve, that will eavesdrop the transmitted information. We denote the channels between N_a and Eve and between N_j and Eve are $h_{a,e}$ and $h_{j,e}$, respectively. We assume that N_a and N_j utilize the different codebook. Therefore, the wiretap rates in the first and second hops are

$$C_{a,e} = B\log_2\left[1 + \frac{P(L_{a,e})^{-\gamma}|h_{a,e}|^2}{n_0 B}\right] \leq R_{a,e}^{th}, \tag{19}$$

and

$$C_{j,e} = B\log_2\left[1 + \frac{P(L_{j,e})^{-\gamma}|h_{j,e}|^2}{n_0 B}\right] \leq R_{j,e}^{th}, \tag{20}$$

where $R_{a,e}^{th}$ and $R_{j,e}^{th}$ represent the maximized permitted wiretap rates in the first and second hops, respectively.

Based on the above analysis, the security outage probability P_o is derived as

$$\begin{aligned} P_o &= 1 - \left(1 - \Pr\left(C_{a,e} \leq R_{a,e}^{th}\right)\right)\left(1 - \Pr\left(C_{j,e} \leq R_{j,e}^{th}\right)\right) \\ &= 1 - \exp\left(-\frac{\lambda\left(2^{\frac{R_{a,e}^{th}}{B}} - 1\right)n_0 B}{P\left(L_{j,e}\right)^{-\gamma}}\right)\exp\left(-\frac{\lambda\left(2^{\frac{R_{a,e}^{th}}{B}} - 1\right)n_0 B}{P\left(L_{j,e}\right)^{-\gamma}}\right). \end{aligned} \tag{21}$$

Therefore, we can make full use of the physical characteristics of wireless channels that enables messages to be transferred securely and prevents eavesdroppers from decoding confidential information.

5. Simulation Results

In this section, we use the opportunistic network environment (ONE) simulator to evaluate the performance of our proposed LQFC protocol. We compare it with the other nine schemes, namely the LQFC-G, the MTAP [6], the CORV [7], the First Contact [34], the Direct Delivery [35], the Epidemic [33], the Spray and Wait [36], the Prophet [37], and the MaxProp [38]. In the LQFC-G, the vehicle is selected as the RN. Moreover, the MTAP and the CORV are respectively proposed in [6,7]. Specifically, the MTAP uses the flooding technique for message delivery, and the CORV predicts the transfer probability based on the UAV course information for relay selection. Furthermore, other schemes are respectively proposed in [33–38]. The detailed simulation parameters are summarized in Table 1.

5.1. Metrics

We use the message delivery ratio M_s, the average end-to-end delay M_d, and the overhead M_o as metrics to evaluate performance. The metrics can be expressed as

$$M_s = \frac{m}{M} * 100\%, \tag{22}$$

$$M_d = \frac{1}{m}\sum_{k=1}^{m}\left[\sum_{i=1}^{n}\left(T_{S_i} + T_{P_i} + T'_{P_i} + T_{Q_i}\right) + \sum_{i=1}^{n-1} T_{C_i}\right]_k, \tag{23}$$

$$M_o = (H - \sum_{i=1}^{m} F_i) / \sum_{i=1}^{m} F_i, \tag{24}$$

where m represents the number of messages received by the DN, M represents the message generated by the SN, H represents the number of packets, and F_i represents the number of successfully transmitted packets.

Table 1. Simulation parameters.

Category	Parameter	Value
Node	Transmission mode	Wi-Fi
	Mobility model	SPMBM
	Vehicle transmission range	200 m
	UAV transmission range	1000 m
	Vehicle speed	0–50 km/h
	UAV speed	0–70 km/h
	UAV flight height	0–200 m
	Number of UAVs	20
Message	Hello message interval	0.1 s
	Message interval	25 s–35 s
	Message size	1 MB–5 MB
	Buffer	30 MB
	Time to Live (TTL)	5 h
Scenario	Longitude	[33.42° N−34.45° N]
	Latitude	[107.40° E−109.49° E]
	Simulation area size	45 km × 45 km
	Simulation times	1000

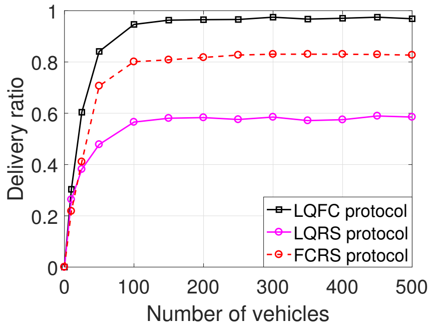
5.2. Impact of Components

In this section, to prove that our proposed construction ($E_j = I_{a,j}Q_{j,b}\left(\tau_m\right)$) is valid, we evaluate the performance of the proposed LQFC protocol via simulations. We compare it with two schemes, namely, the LQRS protocol and the FCRS protocol. In the LQRS protocol, RNs are selected based on the LQoS, and in the FCRS protocol, we select RNs based on the NFC.

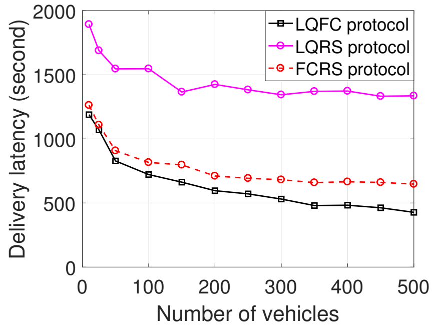
Figure 2a–d depict the network performance versus the number of vehicles. Specifically, it is observed that the LQRS protocol outperforms other protocols (the LQRS protocol and the FCRS protocol) in terms of the delivery ratio, the delivery latency, the overhead, and the hop count. This is because our designed LQRS protocol by jointly considering the LQoS and the NFC to make relay selection. If we only consider the influence of the NFC on relay selection, we can find that it is close to LQRS protocol in terms of the delivery ratio, the delivery latency, and the hop count. However, the overhead value of FCRS protocol increases significantly because the selected node may have poor LQoS and cannot accurately transmit the message. For the LQRS protocol, and the converse is also true. Therefore, based on the above analysis, we clearly know that our proposed construction is valid.

5.3. Network Performance Comparison

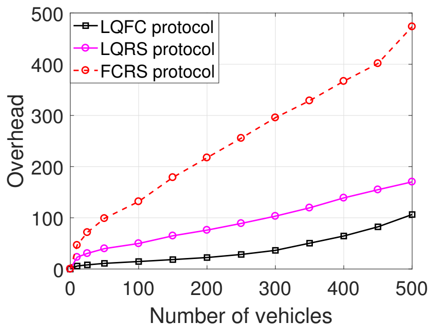
Figure 3a depicts the message delivery ratio versus the number of vehicles. It is observed that the proposed LQFC protocol outperforms other protocols in terms of the message delivery ratio, especially in comparison with the LQFC-G. This is because our designed LQFC protocol can take full advantage of the flexible deployment of UAVs to select the RN. It is worth noting that the delivery ratio of the LQFC protocol increases can achieve 96% when the number of vehicle nodes increases to 150. In this case, the LQFC-G protocol is only 60%. In addition, we find that the delivery ratio of all protocols increases with an increasing number of vehicles, because with the more the vehicles, the more chances for messages to be transferred. Unfortunately, relay nodes cannot be adaptively selected in the proposals of First Contact, Direct Delivery, Epidemic, Spray and Wait, Prophet and MaxProp, hence their delivery ratio increases slower than LQFC protocol. Hence, Figure 3 shows that in the scenario with massive connections, the LQFC protocol can provide reliable information transmission services for more users.



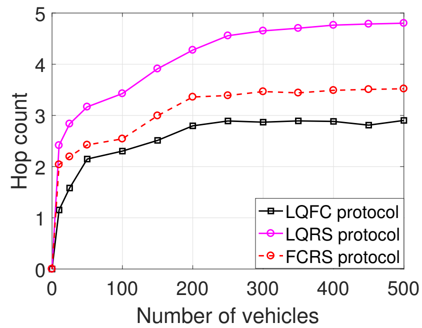
(**a**) Message delivery ratio.



(**b**) Average end-to-end delay.

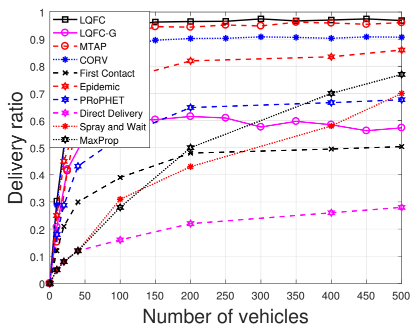


(**c**) Overhead.

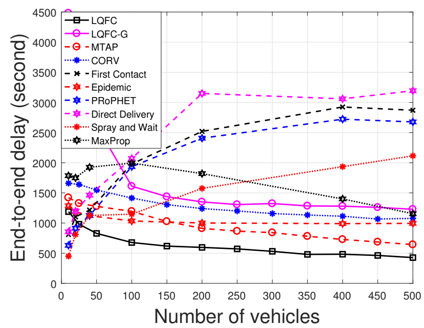


(**d**) Hop count.

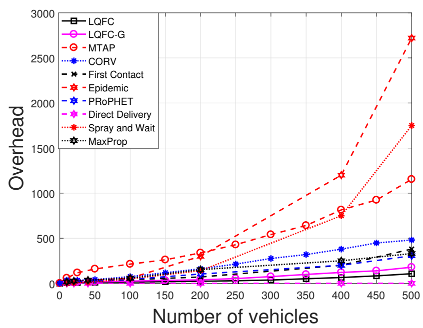
Figure 2. Network performance vs. number of vehicles.



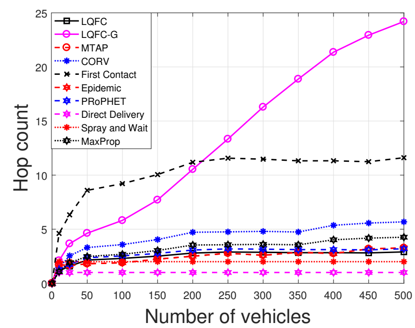
(**a**) Message delivery ratio.



(**b**) Average end-to-end delay.



(**c**) Overhead.



(**d**) Hop count.

Figure 3. Network performance vs. number of vehicles.

Figure 3b plots the average end-to-end delay versus the number of vehicles. From the simulation results, we can find that the LQFC-G protocol has the highest average end-to-end delay at the early stage and then it decreases as the number of vehicles increased. Therefore, when the number of network nodes is small, the network delay with the LQFC-G protocol will increase because no appropriate relay nodes can be selected; however, in the other three protocols, UAVs can improve VANETs connectivity and cooperate with VANETs to bypass obstacles and participate reliably in data transmission to reduce the average end-to-end delay. Therefore, the message can be successfully forwarded even if the number of network nodes is small.

Figure 3c illustrates the effect of the number of vehicles on the overhead. The simulation results indicate that although the message delivery ratio and average end-to-end delay of the MTAP protocol are close to those of our design protocol, the overhead of the MTAP protocol rapidly increases with the number of vehicles, because the MTAP protocol uses the multi-copy-based flooding technique for message delivery. Moreover, as expected, the overhead of Epidemic and Spray and Wait rapidly increases with the number of vehicles, because the schemes are based on flooding. In Spray and Wait, each message has a fixed number of copies, and hence the overhead is lower than that of Epidemic. Compared with other three protocols, the Direct Delivery has the lowest overhead ratio because it cannot select a relay node. Furthermore, in comparison with the MTAP protocol, our proposed LQFC protocol can effectively limit the overhead through deleting the redundant copies based on the designed utility function.

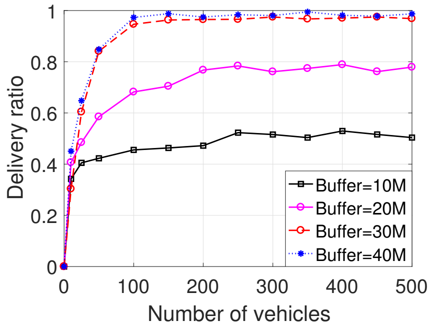
Figure 3d presents the hop count versus the number of vehicles. From this figure, we can observe that the hop count of the LQFC-G protocol far more than the other protocols. This is because in VANETs, all network nodes are vehicles, which have limited communication range and therefore require multiple hops for relay transmission. For UAV-assisted VANETs, UAVs are flexibly deployed and freely moved in three-dimensional (3-D) space, making it easier to convert multi-hop forwarding into single-hop relay, thus reducing communication delay and improving transmission reliability. Therefore, we can find that through a proper deployment of the UAV in VANETs, the path connectivity and the network comprehensive performance are improved, which can provide more users with the reliable QoS.

5.4. Impact of Buffer

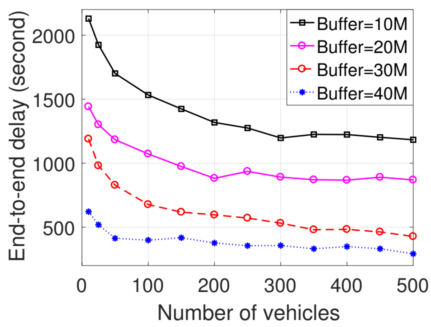
Figure 4a–d show the comparison in terms of network performance with respect to different buffers. From these figures, we can find that the network performance increases with the buffer. Specifically, as the buffer increases, the message delivery ratio increases, and the average delivery latency, the overhead, and the hop count decrease. This is because the LQFC protocol adopts the multi-copy transmission scheme, nodes transfer copies of all the messages they have to all the other nodes they become in contact. The message is discarded when it expires or a destination delivery acknowledgment is received. However, due to the limited buffer (storage space), the protocol performance (the message delivery ratio, the average end-to-end delay, and the overhead) degrades significantly when the number of nodes is large. In order to overcome this problem, the LQFC protocol define a utility function with the NEF and the message TTL taken into account, based on which a redundant copy-deleting approach is devised to limit the flooding of messages to a certain number of copies. Increasing the buffer allows for more messages to be stored, and therefore, appropriately increasing the node buffer can effectively improve the network performance of UAV-assisted VANETs.

5.5. Impact of Number of UAVs

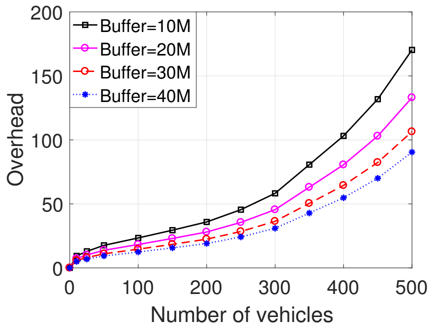
Figure 5a–d demonstrate the network performance versus the number of UAVs. These figures show that the increase in the number of UAVs can help to improve the UAV-assisted VANET performance, but it becomes with little help when the number of UAVs is increased to some extent, which is defined as the “threshold” of the protocol. For example, it does not improve the performance in terms of the message delivery ratio when the number of UAVs is over 30, thus the number of UAVs = 30 is the threshold of the LQFC protocol.



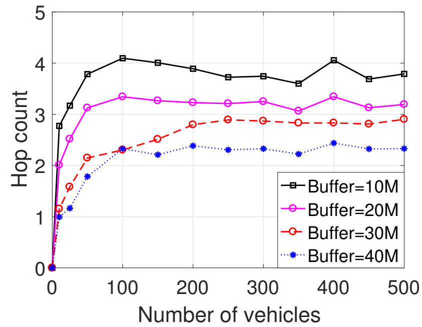
(**a**) Message delivery ratio.



(**b**) Average end-to-end delay.

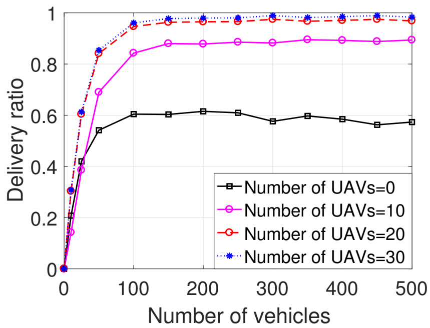


(**c**) Overhead.

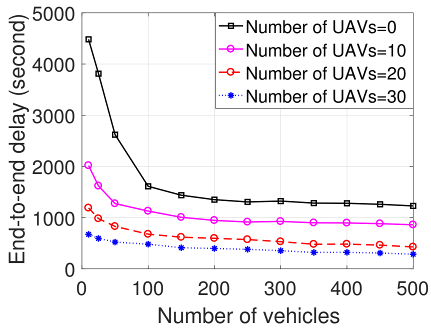


(**d**) Hop count.

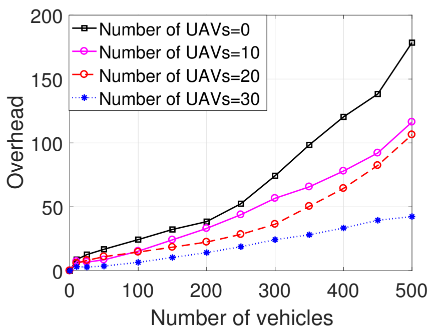
Figure 4. Network performance vs. buffer.



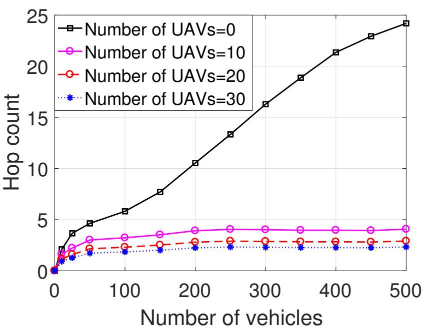
(**a**) Message delivery ratio.



(**b**) Average end-to-end delay.



(**c**) Overhead.

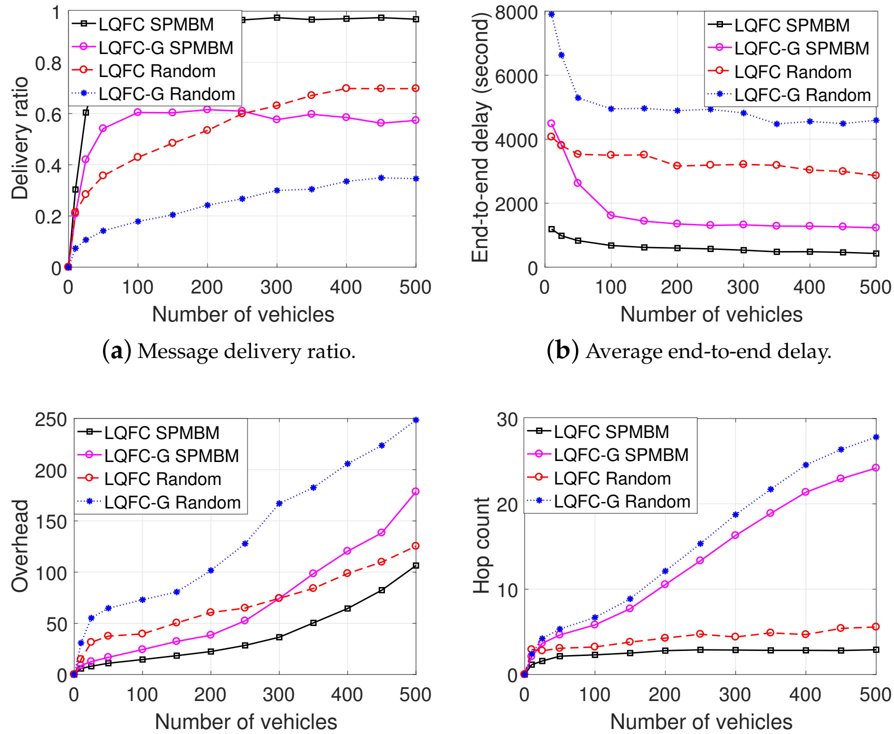


(**d**) Hop count.

Figure 5. Network performance vs. number of UAVs.

5.6. Impact of Mobility Model

Figure 6a–d show the effect of the mobility model on the network performance. According to the NFC model, we know that the node encounter probability depends highly on the mobility model of both the vehicles and the UAVs. It can be observed from these figures that the protocol performance is significantly reduced when the network nodes adopt the random movement mobility model to plan the trajectory. That is because in the random movement mobility model, the network nodes (UAVs and vehicles) move randomly and always follow the paths defined by the map data. However, in the SPMBM movement mobility model, the network nodes choose a random point on the map and then follow the shortest route to that point from their current location. This result indicates that optimizing the network node movement mobility model is more useful for improving the network performance comprehensively.



(**a**) Message delivery ratio. (**b**) Average end-to-end delay.

(**c**) Overhead. (**d**) Hop count.

Figure 6. Network performance vs. mobility model.

6. Conclusions

In this paper, we investigated the relay selection problem for UAV-assisted VANETs and proposed a relay selection protocol, namely LQFC. The LQFC protocol takes into full consideration the effect of the LQoS and the NFC on the network performance when making relay selection. For our proposed LQFC protocol, we define a utility function by jointly considering the NEF and the message TTL, based on which the LQFC protocol can effectively delete the redundant copies. Further, we analyze the security of our designed protocol. The simulation results have demonstrated that the LQFC protocol can achieve the significant performance gain in comparison with other schemes, which can be widely applied in smart city and Internet of Things (IoT) domains.

In addition to those listed in the previous sections, there are many research issues that need further study. In this paper, we investigated the relay selection problem by jointly considering the LQoS and the NFC, and the cooperative secure transmissions are ignored. We ignored the cooperative secure transmissions since some messages in the VANETs can be public. However, for some private applications, the security of message transmission is very important, which can be an interesting aspect for further investigation.

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