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MP-VRCR: A Multi-dimension and Priority-based Vehicle-Road Collaborative Routing Protocol

Yujie Song, Yue Cao, *Senior Member, IEEE*, Kai Jiang, *Student Member, IEEE*, Yuqing Li, Yuping Lai, *Member, IEEE*, Lixin Wang

***Abstract*—With the requirements of time-sensitive and highly reliable applications, it is difficult to implement emerging communication technologies in internet of vehicles. Literature works are dedicated to improving the reliability and efficiency of data delivery, to address problems such as high and unstable End-to-End (E2E) latency, high network overhead. This paper explores the routing protocol with assistance of core network to provide high-reliability and low-latency data delivery services. We propose a Multi-dimension and Priority-based Vehicle-Road Collaborative Routing (MP-VRCR) protocol to improve the efficiency and reliability of data delivery. Specifically, MP-VRCR utilizes multi-dimension indicators to evaluate the data delivery capability of candidate devices, considering trajectory similarity of data, predicted buffer time, buffer occupation and distance cost. Furthermore, MP-VRCR evaluates device priority based on geographical information, selects optimal next-hop device, and evaluates data priority to order data forwarding. Then, MP-VRCR updates the congestion status of network relay devices according to buffer occupation. Vehicles carry data bypass congested network relay devices to reduce the E2E latency. Extensive simulation results show that MP-VRCR significantly outperforms other baseline algorithms regarding delivery ratio, overhead, average delivery latency.**

***Index Terms*—Routing Protocol, IoVs, Trajectory, Traffic Management**

I. Introduction

In the wave of industry digitization, ‘5G + Industry’ instructs in typical scenarios with several characteristics, including large bandwidth, low latency, ubiquitous connectivities, mobility, and fast deployment [1]. For example, the mode of ‘5G + Internet of Vehicles (IoVs)’ promotes the innovation of communication and the digitalization process of IoVs, including vehicle-to-vehicle and Vehicle-to-Infrastructure (V2I) models [2]. Several international standards of 5G and IoVs are provided to normalize technologies for applications, such as, 3GPP R16 [3], [4]. It is necessary to orchestrate, schedule, and manage network service autonomously to support the requirements of fleet choreography, threat avoidance, autonomous driving, and in-vehicle virtual reality [5]–[7].

The implementation on above applications relies on the technologies of IoVs and Core Network (CN) to provide data delivery services [8]. Indeed, although recent works on IoVs provide delay tolerant and geographic data services for data delivery, they suffer from the dynamic network topology, intermittent connectivities, uncertain vehicular encounters. These problems prevent efficient data delivery especially for emerging real-time applications, e.g., autonomous and remote driving. In comparison, the assistance of CN improves the efficiency of data delivery thanks to the high bandwidth, reliable connectivities, robust computing, and storage capabilities. In particular, CN-assisted methods decrease the latency for delivering data to its destination, i.e., limiting the End-to-End (E2E) latency.

To overcome the intermittent connectivities in IoVs, recent works employ a store-carry-forward model and data copies[1] to improve the data forwarding reliability [9], [10]. BSaW [11] is the widespread improvement routing protocol of Epidemic [12] to control the data copies, reducing the network overhead and E2E latency in IoVs. Furthermore, trajectory-based routing protocols focus on the moving path of vehicles and the forwarding path of data without pre-processing, supporting real-time data transmission decisions [13]–[15]. However, they cannot adapt to the variable network status and fail to guarantee low E2E latency for several reasons: (i) the moving trajectory relies on the destination of vehicles, (ii) encounters between vehicles are uncertain, and (iii) limited bandwidths. Although above routing protocols fail to maintain the continuous E2E connectivities, they are with flexibility to establish connectivities through opportunistic nodal encounters thanks to the vehicle mobility.

The CN-assisted methods fulfill the requirements of high bandwidth, low delivery latency, and reliability of connectivities, including Time-Sensitive Network (TSN) and Deterministic Network (DetNet). TSN and DetNet are dedicate on implementing traffic-awareness, bandwidth management, and encoding, to reduce the end-to-end latency. Specifically, TSN provides high robustness while delivering data rapidly within strictly defined time window, covering bandwidth reservation, traffic shaping and scheduling [16]–[19]. DetNet covers architecture, data plane specification, data flow information model, and data encoding, etc., to deliver data within given delay requirements [20], [21]. Unfortunately, these routing protocols focus on traffic scheduling between network relay devices[2], but not upon the consideration of data forwarding with the assistance of IoVs. The local concentration on the

Y. Song, Y. Cao (corresponding author), K. Jiang, Y. Li and L. Wang are with the School of Cyber Science and Engineering, Wuhan University, Wuhan 430000, China. (e-mail: Y.Song@whu.edu.cn, yue.cao@whu.edu.cn, kai.jiang@whu.edu.cn, li.yuqing@whu.edu.cn, LixinWang517@163.com.).

Y. Lai is with the School of Cyberspace Security, Beijing University of Posts and Telecommunications, Beijing 100144, China. (e-mail: laiyp@bupt.edu.cn.)

[1]The data copies have the same content but are differentiated with different unique identifier flags.

[2]The network relay device is located in a fixed position and utilized to deliver and manage data, including Road Side Units (RSUs), routers, and base stations, etc.

CN gives unbalanced network load, network congestion, and unreasonable resource allocation when combining the CN with IoVs.

The necessaries of integration of IoVs and CN are illustrated as below: (1) satisfying the requirements of traffic prediction and scheduling in smart city, (2) improving the efficiency of data transmission for ultra-low latency applications (e.g., autonomous driving), (3) exploring the feasibility of vehicle-network integration [22]–[24]. Furthermore, IoVs and CN provide different advantages in terms of data delivery: (i) The data delivery methods of IoVs implement flexible networking and low power consumption. (ii) Routing protocols in CN provide bandwidth reservation and traffic scheduling for reliable data delivery within given delay requirements. Therefore, to further reduce the E2E latency and overhead, both CN and IoVs are considered as alternatives for data delivery.

Motivated by above considerations, we utilize the characteristic of flexible networking of IoVs, and gain the large bandwidth and high reliability of CN. Firstly, multi-dimension indicators are utilized to evaluate the data delivery capability of candidate devices, including trajectory similarity[3] of data, predicted buffer time, buffer occupation, and distance cost. Secondly, to ensure that data is forwarded in the direction of its destination, we evaluate the device priority for each data and select the device with geographical advantages.The data priority is considered to schedule data in a reasonable order and to improve data delivery efficiency. Thirdly, to overcome the weight offset problem (less weight produces more influence) occurred in traditional weighted methods, we propose a wave assimilation weighted method to achieve network load balancing. Based on the above, we propose a Multi-dimension and Priority-based Vehicle-Road Cooperative Routing protocol (MP-VRCR). The main contributions can be summarized as follows:

1) Previous works have ignored the complementary features of IoVs and CN. Therefore, we first integrate them as a holistic system to benefit both advantages, e.g., the flexible networking and low power consumption in IoVs, large bandwidth and reliable connectivities in CN. The CN performs the primary task of fast data delivery, while IoVs serves as a supplementary option in opportunistic way. Vehicles, as intermediates, temporally carry data and bypass congested network relay devices to reduce the E2E latency.
2) In addition, MP-VRCR considers multi-priority and spatio-temporal indicators to evaluate the data delivery capability of network relay devices. A wave assimilation weight method is proposed to overcome the weight offset problem. Moreover, the priority of devices for each data is dynamically adjusted, the priority of data is also changed to avoid the high E2E latency and buffer time. Then, the fast data re-delivery and trajectory reconstruction mechanisms are utilized to further reduce the E2E latency and overhead.

[3]The trajectory similarity of data measures the similarity of candidate forwarding path to data trajectory path. One of the candidate forwarding paths will be the channel to forward data. The data trajectory path is a set of network relay devices to guild forwarding to its destination.

The rest of this paper is organized as follows. Section II illustrates the related work and motivation. Section III establishes and quantifies the data delivery model. Then, the detailed algorithms of this routing protocol are described in Section IV. Section V evaluates the performance of proposed algorithms. Finally, Section VI concludes this paper.

II. Related Work

A. Data delivery in IoVs

The reliability of data delivery in IoVs can be improved thanks to the store-carry-forward model and data copies. Recent works focus on copy controlling, probabilistic forwarding, multi-queue prioritization, and data link layer technologies in spare and dense IoVs [11], [25]–[29]. Specifically, the conventional routing algorithm, e.g., DSRC [25], was employed for electronic toll collection, but limited by its communication distance. Similar to Epidemic [12], direct delivery [26] method transmitted data to encounters (vehicles). Furthermore, those based on copies controlling are proposed to reduce network overhead, i.e., SaW [27], BSaW [11], and SaF [29]. BSaW transmitted multi-copies to encounters, increasing the scattering speed of data exponentially. SaF evaluated data delivery capability and probability by utility functions, considering distance and transmission rate. Moreover, LADA [28] built the adaptive communication model according to the local graph information. Based on one-dimensional Markov chains, LADA derived the closed-form of delivery latency to minimize E2E latency of fleets (a sequence of vehicles). However, since data delivery in fleets cannot adapt the dynamic connectivity changes and the latency of control signaling synchronization, the data delivery suffers from the local optimal problem, i.e., the topology of fleets changed after the data delivery decision was made.

As a methodology closely associated with geographic and beacon-based routing, the nature of Trajectory-Based Forwarding (TBF) [30] is formulated as a sequence relay devices for data delivery. Specifically, TDOR [14] considered (i) the relationship between the vehicle and the data trajectory, (ii) the relationship between the vehicular movement trajectory and the data destination, and (iii) data delivery priority mechanism. These concerns support data delivery following a reference direction and avoiding a loop. TBHGR [15] was a probabilistic data delivery model based on geographic information, considering the moving speed of vehicles and data delivery latency. BETA [31] utilized the beacon mechanism to dynamically aware traffic. Its mathematical analysis has proved the feasibility of leveraging beacons to relay traffic information. The implementation of BETA demonstrates the advantage of beacon-based traffic-aware mechanism. However, since the moving trajectory of vehicles relies on vehicular destinations and dynamic encounters with other vehicles, recent routing protocols in IoVs cannot adapt to frequent network status changes and ensure low E2E latency.

B. Data delivery in vehicle-road cooperation

Vehicle-road cooperation-based methods are divided into two categories, including V2I-assisted scheduling and CN-

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assisted delivery. Specifically, V2I-assisted scheduling methods utilize RSUs to share data and improve the efficiency of data delivery. Luo *et al.* [32] presented a 5G-IoVs data sharing architecture based on Software Defined Network (SDN) to decouple the context-aware information sensing and data sharing. TRADING [33] illustrated a duple-aware traffic model to balance data traffic, including traffic of vehicles and data. To reorganize transmission channels and reduce the offloading cost for big data, this model balanced offloading data traffic among getaways, given vehicular traffic and network status. Based on traffic-aware technologies, ONES [34] was proposed to maximize the quality of experience according to the traffic type, cost, and reward. Its advanced algorithm (D-ONES) improves the convergence performance of ONES. ONES and D-ONES focus on calculating expected rewards of networks and switches a network for traffic between heterogeneous networks, but fail to explore how to forward traffic. The work [35] proposed a local traffic aware unicast routing scheme to deliver data by integrating the internet and IoVs. Its backup mechanism provides data relay and caching services to improve the traffic-aware capability. When a base station fails, a vehicle will work as the virtual base station in junctions to avoid network fragments with homogeneous network. However, those mechanisms rely on centralized scheduling, which cannot be employed in dense scenario (numerous data traffic) since center nodes[4] suffer from bottleneck problem.

In addition, the CN-assisted routing protocols with stable topology and high bandwidth, are typically distributed and express channels for data delivery. The single factor is frequently employed by traditional CN-assisted routing protocols to evaluate the data delivery capability of relay devices, i.e., hop count, distance, and bandwidth [12], [36]. The classical flooding-based routing protocol (Epidemic) [12] transmitted data to neighbor devices, suffering from numerous redundancy data. OSPF [36] maintained the state information about its neighbors to form a routing table for data transmission. STALB [37] focused on the multi-indicators and evaluated data delivery capability of devices by a weighted method in SDN.

Moreover, recent routing protocols in TSN/DetNet mainly overcome problems, i.e., high E2E latency, traffic scheduling, and network load [19], [38]. The work [18] illustrated a two-stage updating traffic scheduling model based on TSN and SDN to balance network load, including offline and online scheduling algorithms. To track multi-path of traffic in CN (a non-deterministic polynomial-hard problem), an Iterated Integer linear programming based Scheduling (IIS) model [39] was proposed. It employed graph-based degree of conflict sense traffic partitioning to improve the success rate and fault tolerance of IIS. However, the graph partitioning still incurs heavy computational overhead, and this model does not consider the effects of path cost and transmission delay.

The above works do not integrate IoVs and CN as a holistic ecosystem to improve data delivery efficiency, and only focus on the data scheduling problem in isolation. RCAS [40] improved the data sharing rate between vehicles with RSU as assistance. It centrally schedules data traffic after dividing clusters (a group of vehicles) to avoid data collision. The work [41] utilized a SDN-based multi-hops data delivery architecture to select multi-paths with low travel time and high reliability.

[4]Center nodes are network relay devices with the capability of data scheduling.

TABLE I
NOTATIONS AND SYMBOLS

Notations	Explanation
r_s	The origin device is a network relay device that stored data m
r_d	The destination of data
$T_{r,v,r}$	The time overhead of data being delivery from r_s to r_d via RAN
$T_{r,r,r}$	The time overhead of data being delivery from r_s to r_d via CN
$\xi_{m,r}$	The trajectory similarity of data m
θ_r	The ratio of free buffer size to the total buffer size
D_r	The distance cost between two network relay devices
T_r^{t+1}	The predicted buffer time
S_m	The size of data m
$\psi(\cdot)$	Normalization function
v_v	The candidate vector of data
v_m	(1) The reference vector formed of r_s and destination of data m. (2) The reference vector formed of r_s and the last network relay device in sliding window of data m
v_r	The vector formed of r_s and its neighbor device r_i
$\chi_{r,m}$	The size of the angle between v_r and v_m
τ	The congestion threshold of network relay device r_i

C. Motivation

Unfortunately, aforementioned works are limited in several aspects: (i) the difficulty in estimating the delivery latency for a hybrid of wireless and wired networks [33], [42], (ii) global load balancing without guarantees [12], [36], [39], and (iii) traffic scheduling limited by encounters [14], [15]. Based on above concern, we integrate the advantages of IoVs and CN to deliver data within given delay requirements, and propose a vehicle-road cooperative routing protocol. To improve the efficiency of data delivery and reduce interruptions of data transmission, we explore the data scheduling method based on the priority of devices and data. Multi-dimension indicators is utilized to evaluate the data delivery capability of network relay devices and vehicles. Vehicles can carry data and bypass the congested network relay devices.

III. System Model

Notations with their descriptions are listed in Table I.

A. Network Architecture

We premeditate an extended data delivery architecture that integrates the IoVs and CN, as shown in Fig. 1. This architecture consists of the edge layer, access layer, and core switch layer. Accordingly, vehicles are components of the edge layer. The n network relay devices ($\mathcal{R} = \{r_1, r_2, \ldots, r_n\}$) constitute the access layer, involving base stations, wireless devices, RSUs, and routers, etc. The switch layer consists of numerous network relay devices (routers) in CN. The CN is the infrastructure that connects together edge networks. Specifically, network relay devices establish fixed links with other network

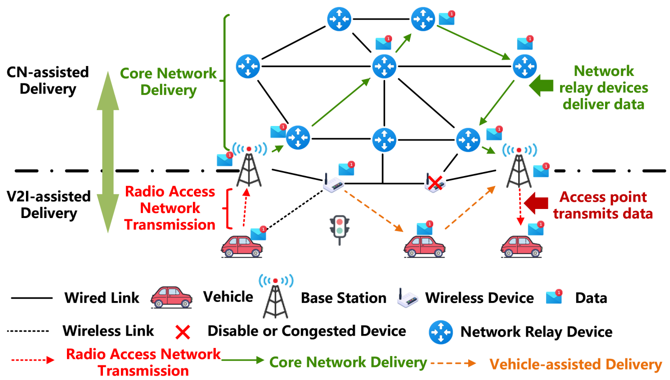

Fig. 1. System Architecture and Data Delivery Model integrated IoVs and CN.

relay devices to provide data delivery service through CN. As source device of data, l vehicles ($\mathcal{V} = \{v_1, v_2, \ldots, v_l\}$) with data delivery capability are distributed on digitally mapped streets. They move along the street at a constant speed and continuously establish/disconnect connectivities with network relay devices through RAN. Based on this, temporary data delivery services can be provided by vehicles to bridge network relay devices and avoid high E2E latency, average buffer time, and heavy overhead caused by network congestion in the CN.

B. Data Delivery Model

Based on the data generation mechanism, the system adopts a vehicle-road collaborative data delivery model. Specifically, this model first generates events and to trigger vehicles to create data (destination, Time-To-Live (TTL), and data size). The responsibility of network relay devices is not limited to managing buffer space, seeking next-hop device (the other network relay devices, vehicles), but also executing data aggregation.

In Fig. 1, firstly vehicles periodically generate multi-copies of data and deliver them to the non-congested network relay devices. Then, network relay devices collect and manage the information of vehicles within its communication range, such as moving direction, speed, and path. Meanwhile, k vehicles are selected as the potential mobile devices and denoted by a matching set ($\mathcal{V}^* = \{v_1, v_2, \ldots, v_k\}$). Secondly, the time overhead[5] is chosen as an indicator to evaluate the data delivery capability of vehicles. A vehicle with the minimum time overhead is selected as the optimal mobile device v_{op}. Here, multi-dimension indicators are considered to quantify the data delivery capability of network relay devices by a wave assimilation weighted method. The optimal set of network relay devices can be established after devices priority evaluating.

In addition, network relay devices periodically update a lightweight matrix, namely non-adjacent device delivery time overhead matrix[6]. According to this matrix, the time overhead between any two network relay devices ($a(i,j) = T_{r,r,r}$, where $i, j \in \{1, 2, \ldots, n\}$) can be immediately obtained. Similarly, the total time overhead $T_{r,v,r}$ of data delivered via v_{op} can be calculated, including the time overhead that data carried by v_{op} and delivered through CN, i.e., $t_{v,r}$ and $t_{r,r}$. In this, for any data, the next-hop device can be determined by comparing the values of $T_{r,r,r}$ and $T_{r,v,r}$. If $T_{r,r,r} > T_{r,v,r}$, the next-hop device is vehicle v_{op}. In contrast, a network relay device is considered as the next-hop device. Finally, according to the Table II, the data set ($\mathcal{M} = \{m_1, m_2, \ldots, m_o\}$, where o is the number of data.) is prioritized to arrange the delivery order of data.

C. Mathematical Model

1) Total Delivery Time of Data: To evaluate the data delivery capability of network relay devices and vehicles, we quantify indicators in temporal and spatial domain perspectives, and realize the syncretic multi-indicators evaluation problem by weighting. Here, trajectory similarity $\xi_{m,r}$, buffer occupation θ_r, and distance cost D_r are the indicators of spatial domain, and predicted buffer time T_r^{t+1} is the indicator of temporal domain. For network relay device r_s, j network relay devices and k vehicles serve as its neighbour devices, denoted as $\mathcal{N} = \{r_1, r_2, \ldots, r_j, v_1, v_2, \ldots, v_k\}$. The links between them and r_s are denoted by $\mathcal{C} = \{c_i | i \in [1, 2, \ldots, j+k]\}$. Furthermore, the simulation time is divided into a lot of fixed length of time slices (named period). The present period is represented as t, and the next period is denoted as $t+1$. We assume that h network relay devices along the moving path of vehicle v_i is predicted as they are fixed network entities along vehicular path, denoted as $\mathcal{R}_{v_i} = \{r_1, r_2, \ldots, r_h\}$. The distances between v_i and any network relay device in $\mathcal{R}_{v_i}$ is calculated, denoted as $\mathcal{D} = \{d_{1,t}, d_{2,t}, \ldots, d_{h,t}\}$, where $d_{i,t}$ is the sum of Euclidean distance that vehicle v_i moving along its path to the network relay device r_i. Therefore, the travel time for vehicle v_i to pass any network relay device r_i along its path is obtained as follows:

$$t_{v_i,r_i} = \frac{d_{i,t}}{v_{i,t}}, \tag{1}$$

where $d_{i,t}$ represents the distance between vehicle v_i and network relay device r_i at period t. $v_{i,t}$ is the moving speed of vehicle v_i at period t.

Meanwhile, to fairly evaluate the data delivery capability of vehicles and network relay devices, the time overhead required for data to reach its destination through IoVs and CN is considered. Therefore, if the next-hop device is a vehicle, the time overhead consists of two bullet points:

- (i) data m is delivered to the non-congested network relay device r_i along its moving path of vehicle v_i. The time overhead t_{v_i,r_i} is the cost for v_i to move within the communication range of r_i.

[5] Any vehicle v_i receives a data m from a network relay device r_s, v_i delivers m to another network relay device r_i. Then, the data m is delivered to its destination r_d through CN. The path of data m can be denoted by $\{r_s, v_i, r_i, \ldots, r_d\}$. The total time spent in this process is defined as time overhead.

[6] A two-dimensional matrix (denoted as $\mathcal{A}$) records the average time overhead of delivery between any two network relay devices, i.e., $a(1,2)$ represents the time overhead from r_1 to r_2.

TABLE II
PRIORITIZE RULE

Data Priority in Vehicles	
Match Items	**Priority**
The received data	high-priority
The generated data	medium-priority
Data Priority in Network Relay Devices	
Match Items	**Priority**
The next-hop device is vehicle	high-priority
The network relay device is destination of data	high-priority
The status of network relay device is non-congestion	medium-priority
The status of network relay device is congestion	low-priority
Device Priority	
Match Items	**Priority**
Non-congested network relay device and the angle $\chi_{r_i,m} \in [0, \pi/2] \cup [3\pi/2, 2\pi]$	high-priority
Non-congested network relay device and the angle $\chi_{r_i,m} \in [\pi/2, 3\pi/4] \cup [5\pi/4, 3\pi/2]$	medium-priority
The angle $\chi_{r_i,m} \in [3\pi/4, 5\pi/4]$	low-priority
The status of network relay device is congestion	low-priority

- (ii) data m is delivered to its destination r_d through CN by the non-congested network relay devices r_i, and its time overhead is denoted as t_{r_i,r_d}.

Then, the total time overhead of data m is calculated as follows:

$$T_{r,v,r} = t_{r_s,v_i} + t_{v_i,r_i} + t_{r_i,r_d}, \tag{2}$$

where t_{r_s,v_i} is the time overhead for delivering data m from origin device r_s (network relay device) to vehicle v_i. t_{v_i,r_i} is the travel time that vehicle v_i moving to non-congested network relay device r_i. t_{r_i,r_d} represents the time overhead for delivering data m from this non-congested network relay device r_i to its destination r_d. Notably, t_{r_s,v_i} is contained by t_{v_i,r_i} as vehicle v_i can receive data while moving. Therefore, Eq. (2) is simplified as follows:

$$T_{r,v,r} = t_{v_i,r_i} + t_{r_i,r_d}. \tag{3}$$

Similarly, the time overhead for delivering data m by network relay devices is shown as follows:

$$T_{r,r,r} = t_{r_s,r_i} + t_{r_i,r_d}, \tag{4}$$

where t_{r_s,r_i} is the time overhead for delivering data m from origin device r_s to a network relay device r_i. t_{r_i,r_d} represents the time overhead for delivering data m through CN while m is received by its destination r_d.

To evaluate the delivery capability of neighbor devices, the device-level prioritization of neighbor devices is required. Specifically, a network relay device may have different devices priority for two data. For example, two network relay devices (r_1 and r_2) are the neighbor devices of origin device r_s. data m_1 and data m_2 are stored in r_s, and priority sets of devices can be denoted as $\{m_1|r_1 : 0, r_2 : 1\}$ and $\{m_2|r_1 : 2, r_2 : 1\}$. The numbers (0, 1, and 2) represent high-priority, medium-priority, and low-priority, respectively. For data m_1, r_1 is high-priority, r_2 is medium-priority. For data m_2, r_1 is low-priority, r_2 is medium-priority. Moreover, four indicators are utilized to evaluate the data delivery capability of neighbor devices, classifying into temporal indicators and spatial indicators.

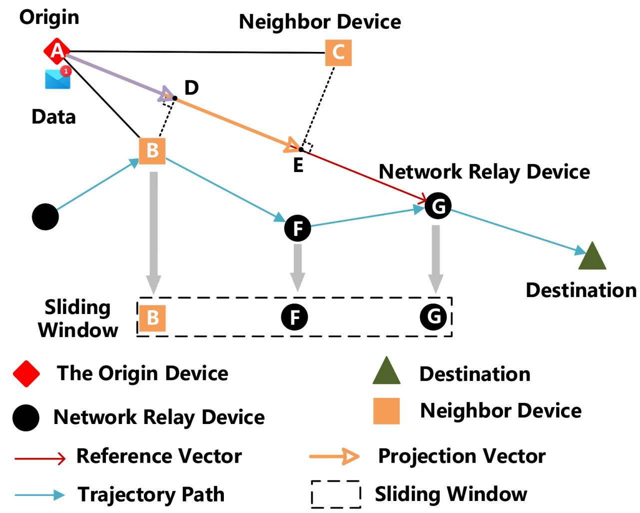

Fig. 2. An example of trajectory similarity of data.

2) Spatial Indicators: Assuming the candidate vector is formed by the origin device r_s and its neighbor device r_i, it can be denoted as v_r. The reference vector of data m is denoted as v_m.

Definition 1 ***Trajectory similarity:*** *It indicates the projected length of the candidate vector v_r on the reference vector v_m.*

$$\xi_{m,r} = \frac{v_{r,x} \cdot v_{m,x} + v_{r,y} \cdot v_{m,y}}{\sqrt{v_{m,x}^2 + v_{m,y}^2}}, \tag{5}$$

where $v_{r,x}$ and $v_{r,y}$ represent the X and Y axis coordinate values of the candidate vector v_r, respectively. Similarly, $v_{m,x}$ and $v_{m,y}$ are the X and Y axis coordinates values of the reference vector v_m, respectively.

An example is shown in Fig. 2, where data m is stored in origin device r_A. Two neighbor devices r_B and r_C connect with r_A are ready to receive data. The reference trajectory path[7] of data m is depicted as continuous blue arrows. Based on this, three network relay devices (r_B, r_F, and r_G) form a sliding window for generating the reference vector v_m of data m. Then, r_A and r_G consist of the reference vector v_m. To calculate the trajectory similarity of neighbor devices (r_B and r_C), two candidate vectors are obtained according to the position of neighbor devices, denoted as v_r^B and v_r^C. Then, two vertical points (D and E) of neighbor devices are utilized to generating the projection vectors of candidate vectors (v_r^B and v_r^C). Finally, the trajectory similarity $\xi_{m,r}$ is obtained by the projection vectors of v_r^B and v_r^C according to Eq. (5).

Definition 2 ***Buffer occupation:*** *It indicates the ratio of available buffer space to the total buffer space in a network relay device, denoted as θ_r.*

$$\theta_r = \frac{\kappa}{\kappa + \nu}, \tag{6}$$

[7]The reference trajectory path is a sequential network relay devices for delivering data.

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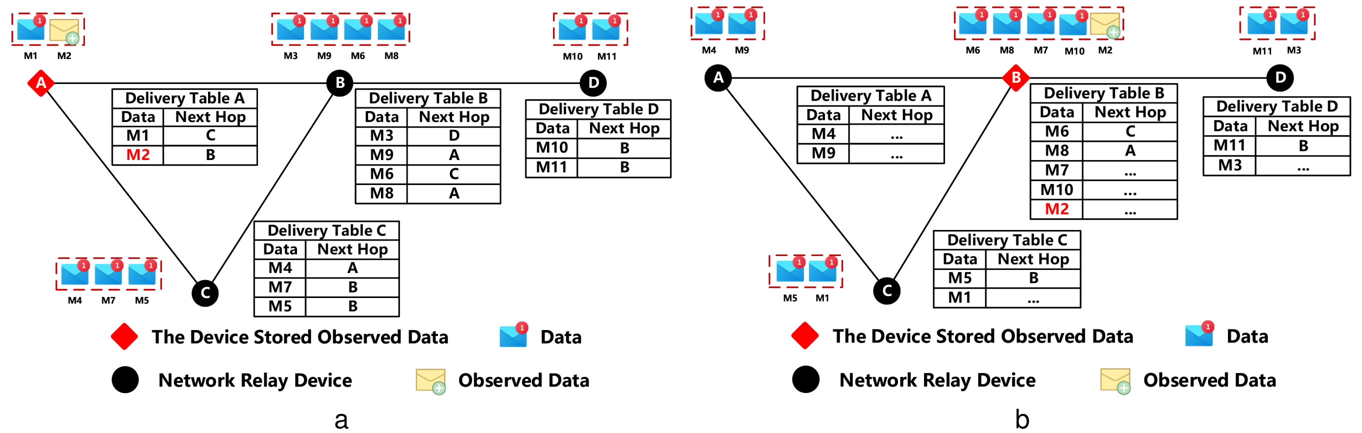

Fig. 3. An example of calculating predicted buffer time T_r^{t+1} in period t. (a) The data m_2 is in the origin device r_A. (b) The data m_2 is in the network relay device r_B.

where κ represents the free buffer size of network relay devices in period t. ν represents the occupied buffer size of network relay devices in period t.

Definition 3 ***Distance cost:*** *It indicates the total Euclidean distances for delivering data m to its destination via network relay device r_i, denoted as D_r.*

$$D_r = d_{r_s,r_i} + d_{r_i,r_d}, \tag{7}$$

where d_{r_s,r_i} and d_{r_i,r_d} are the Euclidean distance among origin device r_s, neighbor device r_i, and the destination (r_d) of data m.

3) Temporal Indicators: Assuming the period is t at present, the data m is stored in network relay device r_s, and the i-th data is denoted as m_i.

Definition 4 ***Predicted buffer time:*** *It indicates the time overhead of data m in buffer waiting for delivery at period $t+1$, denoted as T_r^{t+1}.*

$$T_r^{t+1} = \sum_{i=1}^{n} \frac{S_{m_i}}{v_{r_i}}, \tag{8}$$

where n is the number of data m_i before data m in the output queue of neighbor device r_i. S_{m_i} denotes the size of data m_i, and its unit is MB. v_{r_i} represents the transmission speed between origin device r_s and r_i. Furthermore, the following factors affect T_r^{t+1} in period $t+1$: (i) the data that r_i receives before data m arrives. (ii) the order of data m. (iii) the transmission speed between r_i and its neighbor devices. Specifically, the neighbor devices set of r_i is denoted by $\mathcal{R} = \{r_1, r_2, \ldots, r_j\}$, where j represents the number of r_i's neighbor devices. At period $t+1$, the network relay device r_i receives data from its neighbor devices, and the data set of its neighbors is denoted by $\mathcal{M}' = \{m_1, m_2, \ldots, m_o\}$, where o is the number of data. Then, r_i continuously receives the data until data m received, those data are stored in a list $\mathcal{M}^*$. Finally, the predicted buffer time is calculated after ordering $\mathcal{M}^*$ according to Eq. (8).

An example of calculating predicted buffer time T_r^{t+1} is shown in Fig. 3a. Each network relay device maintains a routing table for recording the mapping of data and next-hop device. Data is delivered from descending order in this routing table. Specifically, network relay device r_A has stored data m_1 and m_2 in period t. The observed data m_2 will be delivered to the neighbor device r_B. Then, the waiting time of m_2, denoted by T_r^t, can be calculated according to Eq. (8). At period $t+1$ in Fig. 3b, r_B receives several data (m_2, m_7, and m_{10}). Although both data m_5 and m_{11} are to be delivered to r_B, they will not affect the waiting time of m_2. Furthermore, the data set $\mathcal{M} = \{m_6, m_7, m_8, m_{10}, m_2\}$ of r_B is sorted according to TTL, denoted as $\mathcal{M}_{order}$. Thus, the predicted buffer time T_r^{t+1} of m_2 is calculated according to Eq. (8).

To reduce the calculating overhead of data delivery between network relay devices, a two-dimensional matrix $\mathcal{A}$ is utilized to record the time overhead. Assuming that there are n network relay devices, the size of the two-dimensional matrix $\mathcal{A}$ is $n \times n$. The row/column number indicates the corresponding network relay device, i.e., $\{i : r_i\}$ is the i-th network relay device. The values in this matrix represent the time overhead of data delivery between network relay devices. This matrix is shown as follows:

$$\mathcal{A} = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,n} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n,1} & a_{n,2} & \cdots & a_{n,n} \end{bmatrix}_{n \times n} \tag{9}$$

where $a_{i,j}, i, j \in \{1, 2, \ldots, n\}$ represents the time overhead that a data is delivered from network relay device r_i to another r_j. The value of the diagonal of $\mathcal{A}$ are all zero since r_i has stored the data, i.e, $a_{i,i} = 0$. Moreover, the $\mathcal{A}$ is updated periodically according to the Dijkstra algorithm [43] with the average buffer time calculated by r_i.

In addition, to comprehensively evaluate device performance, MP-VRCR adopts a weighted method to integrate multiple indicators. Combined with Eq. (5), Eq. (8), Eq. (6), and Eq. (7), the utility function for evaluating performance of

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network relay device is shown as follows:

$$Q(m,r,\alpha,\beta,\gamma) = \begin{cases} \alpha\psi(\xi_{m,r}) + \beta\psi(T_r^{t+1}) + \gamma\psi(\theta_r), & \xi_{m,r} \neq \emptyset, \\ \psi(D_r) + \psi(T_r^{t+1}) & , \quad \xi_{m,r} = \emptyset, \end{cases} \tag{10}$$

where $\psi(\xi_{m,r})$, $\psi(T_r^{t+1})$, $\psi(\theta_r)$, and $\psi(D_r)$ represent the normalized values of trajectory similarity $\xi_{m,r}$, predicted buffer time T_r^{t+1}, and buffer occupation θ_r, respectively. α, β, and γ are the weighted coefficients of $\psi(\xi_{m,r})$, $\psi(T_r^{t+1})$, and $\psi(\theta_r)$, respectively. Specifically, MP-VRCR divides network relay devices into three priorities, i.e., high, medium, and low-priority. When network relay devices with high-priority do not exist ($\xi_{m,r} = \emptyset$), D_r and T_r^{t+1} are utilized to evaluate the data delivery capability of network relay devices with medium-priority. Otherwise, we evaluate the data delivery capability of network relay devices with high-priority, considering $\xi_{m,r}$, T_r^{t+1}, and θ_r.

However, the above weighted method suffer from the weight offset problem, i.e., indicators with small weights have a significant impact on the utility function. To avoid this problem caused by data fluctuation, a wave assimilation weighted method is proposed as follows:

$$Q(m,r,\alpha,\beta,\gamma) = \begin{cases} \alpha\Delta T\Delta\theta\psi(\xi_{m,r}) + \beta\Delta\xi\Delta\theta\psi(T_r^{r+1}) + \gamma\Delta\xi\Delta T\psi(\theta_r) \\ \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad , \xi_{m,r} \neq \emptyset, \\ \Delta T\psi(D_r) + \Delta D\psi(T_r^{t+1}) \qquad\qquad\qquad , \xi_{m,r} = \emptyset, \end{cases}$$
$$s.t. \quad \alpha + \beta + \gamma \leq 1, \tag{11}$$

where $\Delta\xi$, ΔT, $\Delta\theta$, and ΔD are the Mean Square Error (MSE) of trajectory similarity $\xi_{m,r}$, predicted buffer time T_r^{t+1}, buffer occupation θ_r, and distance cost D_r, respectively. The weighted coefficients (α, β, and γ) are 0.3, 0.4, and 0.3, respectively. Specifically, the time overhead is utilized as the main evaluation indicator since the radical purpose is to reduce the E2E latency. The spatio-indicators (θ_r and $\xi_{m,r}$) are equally important. Therefore, the weighted coefficient of T_r^{t+1} is considered to be more important than other indicators ($\beta = 0.4$, $\alpha = \gamma = 0.3$).

Accurately, seeking the optimal next-hop device is an approximate optimization problem in spatio-temporal domain, which can be formulated as follows:

$$P1 : Q^*(m,r,\alpha,\beta,\gamma) = \max Q(m,r,\alpha,\beta,\gamma)$$
$$s.t. \begin{cases} C1 : \alpha+\beta+\gamma \leq 1, \\ C2 : 0 \leq Q(\cdot), \\ C3 : r \neq \emptyset, m \neq \emptyset, \end{cases} \tag{12}$$

where $C1$ restricts the weighted coefficient of indicators, and the upper limit of total coefficients equals 1. $C2$ indicates that the minimum values of utility function is 0. $C3$ ensures that network relay device r and data m exist.

IV. Spatio-temporal Vehicle-Road Collaborative Routing Protocol

A. Data Delivery Strategy in IoVs

MP-VRCR focuses on the V2I communication model. Specifically, vehicles play an essential role with two modes:

Algorithm 1: The data delivery strategy in IoVs

Input: Network relay device set $\mathcal{R} = \{r_1, r_2, \ldots, r_n\}$
Output: Sequential data output queue $\mathcal{M}_{order}$

```
priorityQueue ← Data received from network relay
  device;
midQueue ← Data generated by the vehicle;
for data m_i in priorityQueue do
    for non-congested network relay device r_i in R do
        c_i ← A link between r_i and the vehicle;
        d_{r_i} ← Calculating the distance cost;
    end
    c_op ← Finding the minimum distance cost;
    Binding link c_op with data m_i;
end
for data m_i in midQueue do
    for non-congested network relay device r_i in R do
        c_i ← Getting the corresponding link between
          r_i and the vehicle;
        if the number of copies > 1 then
            Binding link c_i with data m_i;
        end
    end
end
M_order ← Splicing priorityQueue and midQueue;
Return M_order;
```

- The detail of data priority is shown in Table II. In the data generation mode, vehicles periodically generate data with medium-priority. This is because the newly generated data with more copies has more opportunity to be transmitted than data received by vehicles. Each data has several copies with the unique identity [14], [15].
- In data delivery mode, vehicles transmit copies to non-congested network relay devices, or carry the received data for directly delivering this data to its destination. Vehicles set the received data to a high-priority, because data with high-priority should be forwarded preferentially to reduce the E2E latency. These data will be preferentially delivered.

Furthermore, the status of network relay devices is detected by vehicles to evaluate the capability of data delivery, including buffer space and distance cost. Network relay devices with two statuses cannot work as the ideal next-hop device: (i) congestion status, (ii) receiving/transmitting status. Moreover, when there are multiple non-congested network relay devices, vehicles deliver high-priority data to one of them with the minimum distance cost. The medium-priority data is delivered to them without considering distance cost.

The process of data delivery strategy in IoVs is shown in Algorithm 1. Firstly, vehicle v_i divides its data set into high and medium-priority queues based on whether the data is received or generated. Specifically, the high-priority queue $priorityQueue$ stores data received by vehicles. The data generated by vehicles is stored in the medium-priority queue $midQueue$. Secondly, the network relay device set $\mathcal{R}$ is searched to seek a non-congested network relay device r_i with

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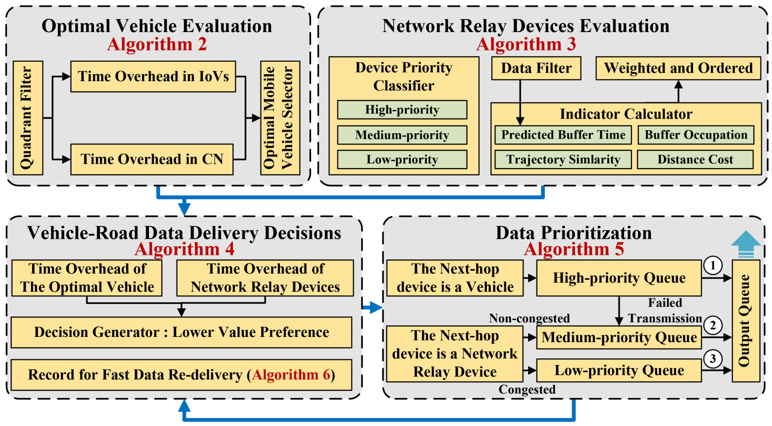

Fig. 4. The functions of network relay devices.

the minimum distance cost, as the next-hop device to deliver data. Then, the corresponding link c_{op} is obtained. Data m and link c_{op} are bound as a key-value pair $< m, c_{op} >$. Thirdly, the medium-priority data is restricted by the number of copies and the status of network relay devices. If the number of copies above 1, data will be delivered to a non-congested network relay device c_i. Otherwise, this data is carried by vehicle v_i and directly delivered to its destination. Finally, data in $priorityQueue$ and $midQueue$ is arranged sequentially and stored in the output queue $\mathcal{M}_{order}$.

B. Data Delivery Strategy in CN

Fig. 4 depicts the functions of network relay devices. Firstly, a network relay device calculates the data delivery capability of vehicles (Algorithm 2) and network relay devices (Algorithm 3). Secondly, the optimal relay device is selected for data delivery (Algorithm 4). Finally, the prioritization of data is implemented to reduce the interruption of transmission (Algorithm 5).

1) Optimal Vehicle Evaluation: Initially, according to the moving direction of vehicles, the origin device r_s periodically divides vehicles within its communication range into four quadrant collections. Furthermore, to avoid the high E2E latency caused via congested network relay devices, the origin device r_s selects a vehicle with the minimum time overhead[8] (Eq. (3)) as the optimal vehicle v_{op}.

The process of optimal vehicle evaluation is shown in Algorithm 2. Firstly, the origin device r_s filters out vehicles where the direction vector v_v and reference vector v_m are in four quadrant collections (similar to mathematics), while the candidate set $\mathcal{V}^*$ consists of the remained vehicles. Then, the total time overhead $T_{r,v,r}$ is calculated according to Eq. (3) for each vehicle in $\mathcal{V}^*$. The minimum time overhead is recorded and denoted as T_{op}. If $T_{r,v,r} < T_{op}$, T_{op} and the optimal mobile device v_{op} will be updated.

2) Network Relay Devices Evaluation: Initially, an example of priority evaluation for network relay devices is shown in Fig. 5. The reference vector v_m is defined in Definition 1.

[8]The minimum time overhead is that a vehicle carries data and moves into the communication range of the first non-congested network relay device.

Algorithm 2: Optimal Vehicle Evaluation

Input: Vehicles $\mathcal{V} = \{v_1, v_2, \ldots, v_n\}$, Data m
Output: The optimal mobile device v_{op}

```
v_m ← Calculating the vector from the origin device r_s
    to the destination r_d of m;
V* ← Getting vehicles from V that are in the same
    quadrant as v_m;
T_op = ∞, initializing earliest arrival time;
for vehicle v_i in V* do
    t_1 ← The time overhead that v_i moves to the
        communication range of the non-congested
        network relay device r_i;
    t_2 ← The time overhead from r_i to the destination
        r_d of m according to the matrix A;
    T_{r,v,r} = t_1 + t_2 ← Calculating the total time
        overhead;
    if T_{r,v,r} < T_op then
        T_op = T_{r,v,r} ← Updating the earliest arrivel
            time;
        v_op = v_i ← Updating the optimal mobile
            device;
    end
end
Return v_op;
```

The candidate vector v_r is formed of the origin device r_s (i.e., r_A) and one of its neighbor devices (r_B, r_C, r_D, and r_E). As shown in Table II. According to the angle between v_r and v_m (denoted as $\chi_{r_i,m}$), those neighbor devices are set to one of three priorities (high, medium, and low-priority), and the corresponding priority values are 0, 1, and 2, respectively. Specifically, several cases are shown as follows:

- If $\chi_{r_i,m} \in [0, \pi/2] \cup [3\pi/2, 2\pi]$, the neighbor device r_i will be set to high-priority value, i.e., $\{r_B : 0\}$.
- If $\chi_{r_i,m} \in [\pi/2, 3\pi/4] \cup [5\pi/4, 3\pi/2]$, it indicates that data may be temporarily delivered to the opposite direction of its destination. r_i is set to the medium-priority value, i.e., $\{r_E : 1\}$.
- If $\chi_{r_i,m} \in [3\pi/4, 5\pi/4]$, it represents that data is deliv-

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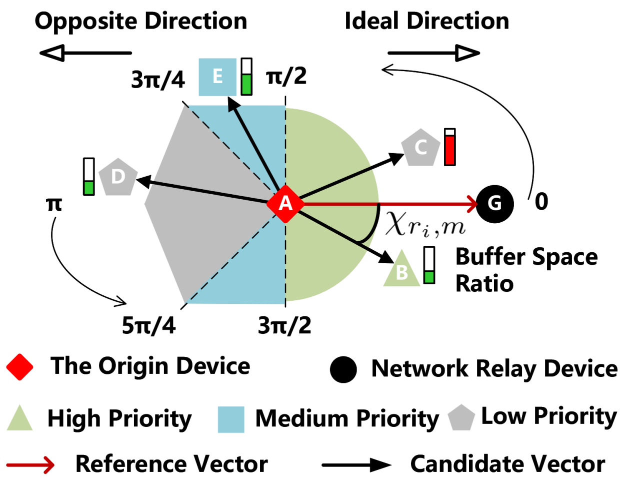

Fig. 5. An example of network relay devices priority evaluation.

ered to the opposite direction, and the priority value of r_i is 2, i.e., $\{r_D : 2\}$.

- If the buffer occupation of neighbor device is above 0.75 similar to HashMap management in java development kit v.1.8, this neighbor device is set to low-priority and congested, i.e., $\{r_C : 2\}$.

The process of network relay devices evaluation is shown in Algorithm 3. To alleviate data being delivered in the opposite direction, the origin device r_s customizes the priority of neighbor devices for each data, e.g., $\{m_1|r_1 : 0, r_2 : 1, \ldots, r_n : 2\}$, $\{m_2|r_1 : 1, r_2 : 2, \ldots, r_n : 1\}$. If high-priority devices exist ($r_i : 0$), they are considered candidate devices in CN, e.g., m_1. Otherwise, the medium-priority devices work as the candidate devices. Furthermore, the performance evaluation consists of four parts: (i) trajectory similarity $\xi_{m,r}$, (ii) predicted buffer time T_r^{t+1}, (iii) buffer occupation θ_r, and (iv) distance cost D_r.

- In the phase of trajectory similarity evaluation, the trajectory similarity $\xi_{m,r}$ is calculated for high-priority neighbor devices according to Eq. (5).
- In the phase of predicted buffer time evaluation, the buffer time of data in origin device r_s is denoted as T_r^t. It is utilized to calculate the predicted buffer time T_r^{t+1} according to Eq. (8).
- In the next two phases, the buffer occupation θ_r is calculated according to Eq. (6). The distance cost D_r is calculated according to Eq. (7).

Based on this, the MSE of $\xi_{m,r}$, T_r^{t+1}, θ_r , and D_r can be calculated, denoted as $\Delta\xi$, ΔT, $\Delta\theta$, and ΔD, respectively. Then, the performance evaluation $Q(\cdot)$ of each neighbor device $r_i \in \mathcal{R}$ is calculated according to Eq. (11), where '$\cdot$' is a shorthand representation of input parameters (m, r_i, α, β, and γ). Finally, the neighbor devices $\mathcal{R}$ are sorted in descending order according to the value of $Q(\cdot)$, and the sorted set is denoted as $\mathcal{R}_{order}$.

3) Vehicle-Road Data Delivery Decision: Based on the Algorithm 2 and Algorithm 3, the main problem becomes the optimal next-hop device decision. To fairly evaluate the data delivery capability of heterogeneous devices, MP-VRCR evaluates the time overhead of optimal mobile device v_{op} and the ordered set of network relay devices $\mathcal{R}_{order}$. Specifically, $T_{r,v,r}$ denotes the time overhead that a vehicle as one of the relay devices for data delivery, its value is calculated according

Algorithm 3: Network Relay Devices Evaluation

Input: Neighbor devices $\mathcal{R} = \{r_1, r_2, \ldots, r_n\}$, Data m, The threshold T_r^t
Output: The ordered neighbor devices $\mathcal{R}_{order}$
$v_m \leftarrow$ Calculating the reference vector for m by utilizing the sliding window;
for *neighbor device* r_i in $\mathcal{R}$ **do**
  $v_r \leftarrow$ Calculating the candidate vector formed of the origin device r_s and r_i;
  $\chi_{r_i,m} \leftarrow$ Calculating the angle between v_r and v_m;
  if $\chi_{r_i,m} \leq \pi/2$ or $\chi_{r_i,m} \geq 3\pi/2$ **then**
    r_i with high-priority ($\{r_i : 0\}$);
    $\xi_{m,r} \leftarrow$ Calculating trajectory similarity according to Eq. (5);
  else
    if $\pi/2 \leq \chi_{r_i,m} \leq 3\pi/4$ or $5\pi/4 \leq \chi_{r_i,m} \leq 3\pi/2$ **then**
      r_i with medium-priority ($\{r_i : 1\}$);
    else
      r_i with low-priority ($\{r_i : 2\}$);
    end
  end
  $\mathcal{R}^* \leftarrow$ Neighbor devices of r_i;
  $\mathcal{M}^* \leftarrow$ new list to store data;
  for r_j in $\mathcal{R}^*$ **do**
    $\mathcal{M}' \leftarrow$ the data set of r_j;
    for m' in $\mathcal{M}'$ **do**
      $t \leftarrow$ the buffer time of m' in r_j;
      if $\chi_{r_i,m} \leq \pi/2$ and $t \leq T_r^t$ **then**
        Adding m' to $\mathcal{M}^*$;
      end
    end
  end
  $T_{r_i}^{t+1} \leftarrow$ Calculating the predicted buffer time of m after ordering M^* by TTL according to Eq. (8);
  $\theta_{r_i} \leftarrow$ Calculating the buffer occupation of r_i according to Eq. (6);
  $D_{r_i} \leftarrow$ Calculating the distance cost of r_i according to Eq. (7);
end
$\Delta\xi$, ΔT, $\Delta\theta$, $\Delta D \leftarrow$ Calculating mean square errors of $\xi_{m,r}$, T_r^{t+1}, θ_r, and D_r, respectively;
$\psi(\xi_{m,r})$, $\psi(T_r^{t+1})$, $\psi(\theta_r)$, $\psi(D_r) \leftarrow$ Normalizing $\xi_{m,r}$, T_r^{t+1}, θ_r, and D_r, respectively;
for r_i in $\mathcal{R}$ **do**
  $Q(\cdot) \leftarrow$ Calculating the evaluation value of r_i according to Eq. (11);
end
$R_{order} \leftarrow$ Sorting $\mathcal{R}$ in descending order by $Q(\cdot)$;
Return R_{order};

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Algorithm 4: Vehicle-Road Data Delivery Decisions

Input: Candidate devices $\mathcal{R}_{order} = \{r_1, r_2, \ldots, r_n\}$, Data m, Optimal mobile device v_{op}
Output: The mapping of data and next-hop device $\mathcal{F} = \{m : next\_hop\}$

$\mathcal{R}^{'} \leftarrow$ Storing unselected network relay devices;
if v_{op} is $\emptyset$ **then**
  if $\mathcal{R}_{order}$ is $\emptyset$ **then**
    $next\_hop = null$;
  else
    $next\_hop = r_1$;
    $\mathcal{R}^{'} = \{\mathcal{R}_{order} - r_1\}$;
  end
else
  $T_{r,v,r} \leftarrow$ Calculating the time overhead for m through v_{op} according to Eq. (3).;
  if $\mathcal{R}_{order}$ is $\emptyset$ **then**
    $T^{*}_{r,r,r} = \infty$;
  else
    $T^{*}_{r,r,r} \leftarrow$ Calculating the time overhead for m through r_1 according to Eq. (4);
  end
  if $T_{r,v,r} < T^{*}_{r,r,r}$ **then**
    $\mathcal{R}^{'} = \mathcal{R}_{order}$;
    $next\_hop = v_{op}$;
  else
    $next\_hop = r_1$;
    $\mathcal{R}^{'} = \{\mathcal{R}_{order} - r_1\}$;
  end
end
Storing $\mathcal{R}^{'}$ in the isolated buffer;
Return $\mathcal{F} = \{m : next\_hop\}$;

to Eq. (3). Similarly, the time overhead of a candidate device $r_i \in \mathcal{R}_{order}$ is obtained according to the matrix $\mathcal{A}$, denoted as $T_{r,r,r}$. Furthermore, $T^{*}_{r,r,r}$ represents the time overhead of candidate device r_1, where r_1 represents the first network relay device in the ordered candidate set $\mathcal{R}_{order}$. If $T_{r,v,r} < T^{*}_{r,r,r}$, the optimal mobile device v_{op} is selected as the next-hop device. Otherwise, network relay device r_1 is selected. Finally, to support the fast data re-delivery mentioned later, the remaining network relay devices are stored in the isolated buffer[9].

The process of vehicle-road data delivery decision is shown in Algorithm 4. Firstly, the candidate table $\mathcal{R}^{'}$ is utilized to store unselected network relay devices for fast data re-delivery (Algorithm 6). According to whether the optimal mobile device v_{op} exists, MP-VRCR divides the solution into two parts:

- If the optimal mobile device $v_{op} = \emptyset$, data will be delivered by network relay devices. Specifically, if $\mathcal{R}_{order} = \emptyset$, the next-hop device will be set to $null$. Otherwise, the first device r_1 in $\mathcal{R}_{order}$ will work as the next-hop device, and the remaining candidate devices will be added to $\mathcal{R}^{'}$, denoted as $\mathcal{R}^{'} = \{\mathcal{R}_{order} - r_1\}$.
- When $v_{op} \neq \emptyset$, the optimal mobile device v_{op} has the probability becomes the next-hop device. Specifically, the time overhead $T_{r,v,r}$ is calculated according to Eq. (3). If $\mathcal{R}_{order} = \emptyset$, $T^{*}_{r,r,r}$ will be set to infinity. Otherwise, $T^{*}_{r,r,r}$ is set to the time overhead of r_1, where r_1 represents the first network relay device in $\mathcal{R}_{order}$. Additionally, if $T_{r,v,r} < T^{*}_{r,r,r}$, the optimal mobile device v_{op} is selected as the next-hop device, and network relay devices are added to $\mathcal{R}^{'}$. Otherwise, r_1 is selected as the next-hop device, and $\mathcal{R}^{'} = \{\mathcal{R}_{order} - r_1\}$.

Finally, $\mathcal{R}^{'}$ is stored in the isolated buffer. The mapping of data m and the next-hop device is obtained, denoted as $\mathcal{F} = \{m : next\_hop\}$.

4) Data Prioritization: The data prioritization mechanism orders data forwarding to reduce the E2E latency and buffer time.

The process of the prioritization of data is shown in Algorithm 5. Firstly, the set of mapping between data and the next-hop device is obtained ($\mathbb{F} = \{\mathcal{F}_1, \mathcal{F}_2, \ldots, \mathcal{F}_o\}$, where o is the number of data). According to the mobility and status of next-hop devices, a mapping $\mathcal{F}_i \in \mathbb{F}$ can be classified into one of three priority queues (high, medium, and low-priority queue, i.e., Q_h, Q_m, and Q_l). The detail cases are shown as follows:

- If data is delivered to a vehicle, the corresponding mapping $\mathcal{F}_i$ is added to the high-priority output queue Q_h thanks to the mobility of vehicles —— it is better for vehicles to finish data transmission within the communication range of receivers.
- If data is delivered to a network relay device, $\mathcal{F}_i$ is added to the medium/low-priority output queue according to the buffer occupation θ_r and congestion threshold $\tau \in [0, 1]$. Specifically, if $\theta_r \geq \tau$, $\mathcal{F}_i$ is added to the medium-priority output queue Q_m. Otherwise, $\mathcal{F}_i$ is added to the low-priority output queue Q_l.

However, data m may fails to be forwarded to a vehicle because of the disconnected vehicle. Its mapping $\mathcal{F}_i$ will be transferred from Q_h to Q_m, and the next-hop device will be replaced to the first network relay device r_1 in $\mathcal{R}_{order}$. Finally, an ordered list of mapping between data and the next-hop device is denoted as $\mathbb{F}_{order}$, splicing Q_h, Q_m, and Q_l sequentially.

C. Supervision and Handling

1) Fast Data Re-delivery: The data backhaul may occur during data delivery, i.e., data m is delivered to a network relay device that has already received m. To alleviate the high E2E latency and network congestion caused by data backhaul, MP-VRCR adopts a fast data re-delivery mechanism which is shown in Algorithm 6. Specifically, the the unique Identity (ID) of data m is first transmitted to the next-hop device r_i. Then, r_i checks this ID and the records (network relay device set $\mathcal{R}^{'}$) in isolated buffer. Furthermore, if $\mathcal{R}^{'} \neq \emptyset$, the network relay device r_1 will be selected as the next-hop device and removed. The mapping ($\mathcal{F} = \{m : r_1\}$) is generated and

[9]The isolated buffer is unused buffer space to store the mapping of data and its remaining candidate devices, e.g., $\{m | r_2, r_3, r_{10}\}$. When the buffer space is not enough to store the new data, the earliest mapping in the isolated buffer will be removed.

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Algorithm 5: Data Prioritization

Input: Mapping set $\mathbb{F} = \{\mathcal{F}_i = \{m : next\_hop\} \,|m \in \mathcal{M}, i \in \{1, 2, \ldots, o\}\}$
Output: Sequential Output Queue $\mathbb{F}_{order}$

Q_h, Q_m, Q_l ← The high, medium, and low-priority queue;
for $\mathcal{F}$ in $\mathbb{F}$ **do**
  if $next\_hop$ is v_{op} **then**
    Adding $\mathcal{F}$ to Q_h;
  else
    if $\theta_r \geq \tau$ **then**
      Adding $\mathcal{F}$ to Q_m;
    else
      Adding $\mathcal{F}$ to Q_l;
    end
  end
end
Return $\mathbb{F}_{order} = \{Q_h \cup Q_m \cup Q_l\}$, splicing Q_h, Q_m, and Q_l sequentially;

Algorithm 6: Fast Data Re-delivery

Input: Data ID id

m ← Obtaining the corresponding data according to id;
$\mathcal{R}^{'} = \{r_1, r_2, \ldots, r_n\}$ ← Getting candidate devices of m;
$next\_hop = r_1$, where r_1 is a next-hop device;
$\mathcal{F} = \{m : r_1\}$;
if $next\_hop$ is not $null$ **then**
  if $next\_hop$ is *congested* **then**
    Adding $\mathcal{F}$ to the low-priority queue Q_l;
  else
    Adding $\mathcal{F}$ to the medium-priority queue Q_m;
  end
  $\mathcal{R}^{'} = \{r_2, \ldots, r_n\} = \{r_1, r_2, \ldots, r_n\} - r_1$;
  Updating $\mathcal{R}^{'}$ to the isolated buffer;
end

updated. Moreover, the status of next-hop device decides the priority of $\mathcal{F}$. The mapping $\mathcal{F}$ is added to the low-priority queue Q_l because of the congestion status of r_1. Otherwise, $\mathcal{F}$ is added to the medium-priority queue Q_m.

2) Destination Monitoring and Trajectory Reconstruction: The destination monitoring mechanism detects whether data is close to its destination. The trajectory reconstruction mechanism constructs the shortest trajectory for data. Specifically, the process of destination monitoring and Algorithm 3 run synchronously. In the phase of trajectory similarity evaluation, MP-VRCR detects the destination of data m by checking the element of sliding window. If the destination of m is one of those elements, it indicates that data is close to its destination. To reduce the E2E latency and avoid data backhaul, m follows the shortest trajectory that is reconstructed by Dijkstra algorithm. Additionally, the trajectory reconstruction mechanism is triggered in the following cases: (i) Data is close to its destination. (ii) The next-hop device is $null$ or disabled.

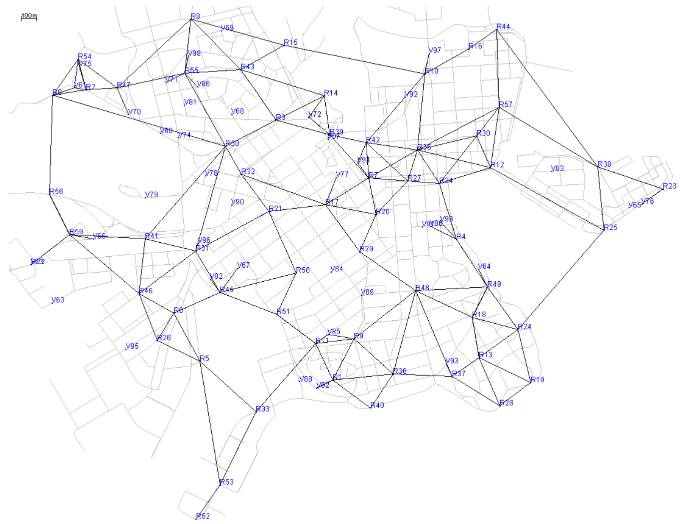

Fig. 6. The snapshot of network scenarios.

V. Performance Evaluation

A. Simulation Setup

The Opportunistic Network Environment (ONE) is utilized for evaluations. As shown in Fig. 6, to ensure the comparability and reliability of our simulation experiment, the road data from Helsinki city serves as the scenario similar to the baseline algorithms [11], [14], [15], [37], [44], [45]. We consider the simulation time set with $18,000s$, and the total number of network relay devices (denoted as R) and vehicles (denoted as EV) is set to 100. Additionally, vehicles and network relay devices are randomly deployed along the road on the digital map. Each vehicle follows the shortest path generated by Dijkstra algorithm [43], and its moving speed is randomly chosen from $[18 \sim 72]km/h$. Similar to [14], the vehicular communication technique is set with $200m$ transmission range and $500kbit/s$ bandwidth. According to the configuration in [15], [46], the communication range and bandwidth of network relay devices are set to $200m$ and $1Mbit/s$, respectively. Both the buffer size of vehicles and network relay devices are set to $1GB$.

Moreover, vehicles randomly generate data with 60 minutes TTL and $1MB$ size, and one of the network relay devices is selected as a destination for each data. According to [47], each data has 10 copies calculated by 10% of total number of nodes (network relay devices and vehicles). Furthermore, to distinguish the importance of different reference indicators of network status, the corresponding weighted coefficients (α, β, and γ) are set to 0.3, 0.4, and 0.3 similar to [37], respectively. The reason for setting these values is explained in Section III. Detailed parameters is listed in Table III.

Based on the above settings, we introduce six baseline algorithms with multi-copies (BSaW [11], TBHGR [15], TDOR [14], OSPF [44], STALB [37], and the method in [45] which named SDNBACKBONE) to evaluate the performance of MP-VRCR. Firstly, BSaW transmits half the number of copies to

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TABLE III
SIMULATION PARAMETERS

Parameters	Values
Simulation area	$4500 \times 3400m^2$
Simulation time	$18000s$
Number of repetition for each run	10
Number of devices	100
Velocity of vehicles	$18 \sim 72kmph$
Bandwidths in the RAN	$500kbps$
Bandwidths in the CN	$1Mbps$
Communication range	$200m$
Data size	$1MB$
Number of data	$3600 \sim 18000$

the next-hop device. Secondly, TDOR considers the vehicular trajectory, path of data transmission, and data priority. Thirdly, TBHGR is a probabilistic data delivery model based on geographic information, considering the moving speed of vehicles and data delivery latency. Fourthly, STALB considers the spatio-temporal indicators and utilizes the weighted method to select the next-hop device in SDN. Fifthly, SDNBACKBONE is an advanced Dijkstra algorithm thanks to the multiple shortest paths mechanism.

The main results of 10 runs show performance with the following indicators:

- **Delivery Ratio**: It is the ratio between the number of delivered data and the total number of data generated.
- **Overhead**: It is the ratio between the number of relayed data[10] (excluding the delivered data) and the number of delivered data.
- **Average Delivery Latency**: The average time it takes for data to be successfully forwarded from source to destination.
- **Average Buffer Time**: The average time that data is stored in a network relay device after it has been received.

B. Algorithm complexity and feasibility analysis

The time complexity of MP-VRCR is $O(n^3)$ according to the Algorithm 3 (network relay devices evaluation). The space complexity is $O(n^2)$. Firstly, assume the size of sets is n, i.e., $|\mathcal{R}|, |\mathcal{R}^*|, |\mathcal{M}^{'}|$ are set to n. Secondly, several lines are original operations (time complexity is $O(1)$), such as, lines 3,4,6,7,10,12,15,16. Thirdly, several control structures (sequence, branch, loop) are listed below: lines 2,17,19,32, etc. Fourthly, the first control structure (line 2) will be executed n times. So, original operations (lines 3,4,6,7,10,12,15,16) will be executed n times. Fifthly, the control structure (line 17) is nested in the control structure (line 2), so line 17 and the original operation (line 18) will be executed $n * n$ times. Sixthly, lines 19-22 will be executed n^3 times. Lines 26-29 will be executed n^2 times. Seventhly, the time complexity is expressed as $T(n) = 2n^3 + n^2 + 11n = O(n^3)$. Eighthly, the space complexity is expressed as $O(n^2)$.

Furthermore, we discuss the feasibility of algorithms.

[10]The relayed data is generated by receivers. For example, three network relay devices are connected in series, i.e., $r_1 \rightarrow r_2 \rightarrow r_3$. r_1 delivers a data to r_3, and it will generate two relayed data.

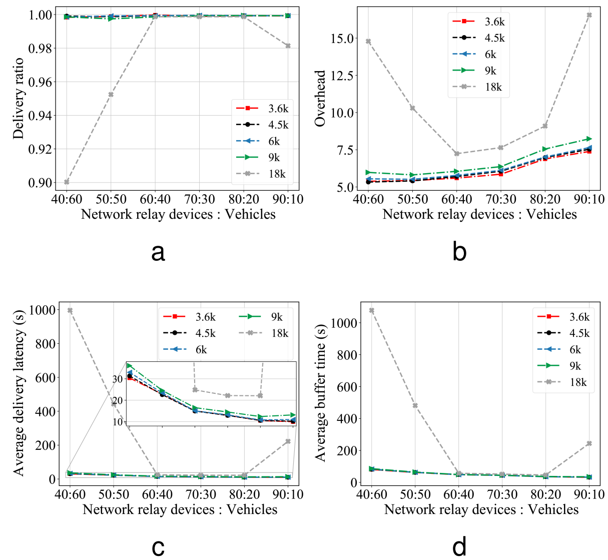

Fig. 7. (a) Delivery ratio versus device ratio (b) Overhead versus device ratio. (c) Average delivery latency versus device ratio. (d) Average buffer time versus device ratio.

- **Input and Output:** We input a configuration file to set the experiment scenario. The result file is generated following the end of simulation experiment, including delivery ratio, overhead, average delivery latency, and average buffer time.
- **Infinity:** Since the number of network relay devices, vehicles, and data is limited, the input and output of algorithms are limited (Algorithms 1-5). The fast data re-delivery (Algorithm 6) has no output because only the stored content needs to be read and updated, without interacting with other modules.
- **Determinism:** Each line of code does not have duality, i.e., same input, same output. Similarly, the same configuration file gives the same output.

C. Impact of devices ratio

In this section, the ratio formed by i network relay devices and j vehicles is denoted as $\varpi_{i,j}$, e.g., $\varpi_{70,30}$ represents that there are 70 network relay devices and 30 vehicles. Furthermore, the total number of devices is a constant (100), and $\varpi_{i,j}$ is changed from $\varpi_{40,60}$ to $\varpi_{90,10}$ with a gap of 10. Moreover, we consider a series of scenarios with different data volumes ($3.6k$, $4.5k$, $6k$, $9k$, and $18k$, where k represents $1,000$, i.e., $1,000$ equals $1k$).

Fig. 7a shows the tendency of delivery ratio. MP-VRCR maintains high delivery ratio in the case of $18k$ data volume, which reached a minimum of 99.74%. When the data volume is $18k$, the tendency of delivery ratio shows a concave function. Specifically, in the case of $\varpi_{40,60}$, there are only 90.05% of the data is delivered to its destination.

Fig. 7b depicts the tendency of overhead to vary with the proportion of devices (network relay devices and vehicles). Specifically, in the scenario with sparse data volume ($3.6k$, $4.5k$, $6k$, and $9k$), the overhead of MP-VRCR is increased with the devices ratio $\varpi_{i,j}$, and can be approximated as a downward convex function in the $18k$ data volume scenario.

Fig. 7c and Fig. 7d illustrate the tendency of average delivery latency and that of average buffer time, respectively. Specifically, in the scenario with data volume ($3.6k$, $4.5k$, $6k$, and $9k$), they decrease with the increase of device ratio $\varpi_{i,j}$. Furthermore, in the dense data volume scenario ($18k$), the tendency of average delivery latency and average buffer time show a downward convex function with different $\varpi_{i,j}$.

Several factors influence the above multi-dimension indicators, including the connectivities, hop count, and queue priority in CN. Firstly, when the device ratio is $\varpi_{40,60}$, a small number of network relay devices does not benefit to disseminate data, therefore data kept in buffer is with potential risks on buffer space exhaustion. Although vehicles assist network relay devices in delivering those data to their destinations, vehicles cannot satisfy the requirement of delivering a massive number of data. Since network relay devices with full buffer space cannot receive data, vehicles deliver data directly to its destination. Secondly, as the increase of $\varpi_{i,j}$, the CN provides additional connectivities for data delivery to deliver data through other non-congested network relay devices. Thirdly, when the number of network relay devices is excessively high, i.e., $\varpi_{90,10}$, abundant links established by network relay devices provide feasible delivery paths for data. Unfortunately, abundant links increase the hop count of data from source and destination. Data has to spend more time to through network relay devices, causing high overhead, E2E latency, and average buffer time. Some data are dropped because of expired TTL, the data delivery ratio is decreased.

D. Impact of data copies

In this section, we fix the proportion of devices $\varpi_{60,40}$. Then, the number of data copies is changed from 2 to 10. Other parameters are unchangeable.

Fig. 8a shows the variation of delivery ratio versus the number of data copies. The delivery ratio gradually increases as the number of data copies changes from 2 to 7. When the number of data copies exceeds 7, the delivery ratio is unchanged, i.e., 99.91%.

Fig. 8b shows the variation of overhead versus the number of data copies. As the number of data copies increases, the overhead of MP-VRCR increases. When the number of data copies exceeds 7, the overhead of MP-VRCR is unchanged, i.e., 7.19.

As shown in Fig. 8c and Fig. 8d, the tendency of average delivery latency and average buffer time is an upward concave function. The average delivery latency and average buffer time increase as the number of data copies increases. The maximum of average delivery latency is $24.68s$, the maximum of average buffer time is $57s$.

The reason for above tendency is redundant data copies enhance the probability that data will be delivered to its destination. Specifically, when the number of data copies is set to a smaller value (e.g., 2, 3), limited number of data copies is transmitted to CN. The CN with low overhead delivers data rapidly thanks to a limited amount of redundant data copies.

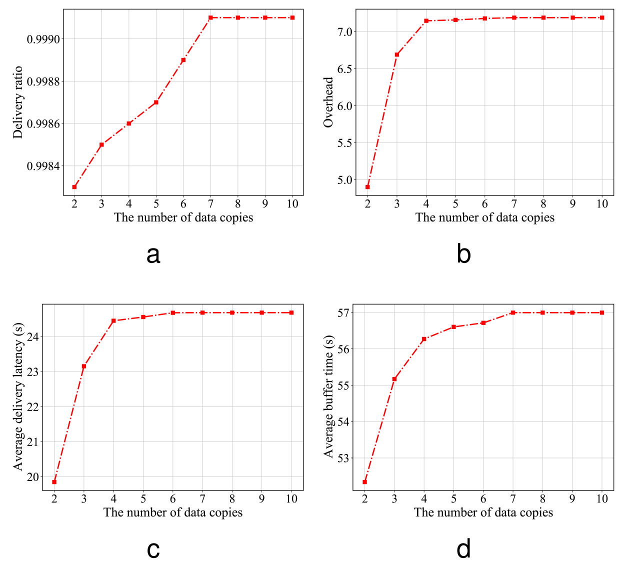

Fig. 8. (a) Delivery ratio versus the number of data copies. (b) Overhead ratio versus the number of data copies. (c) Average delivery latency versus the number of data copies. (d) Average buffer time versus the number of data copies.

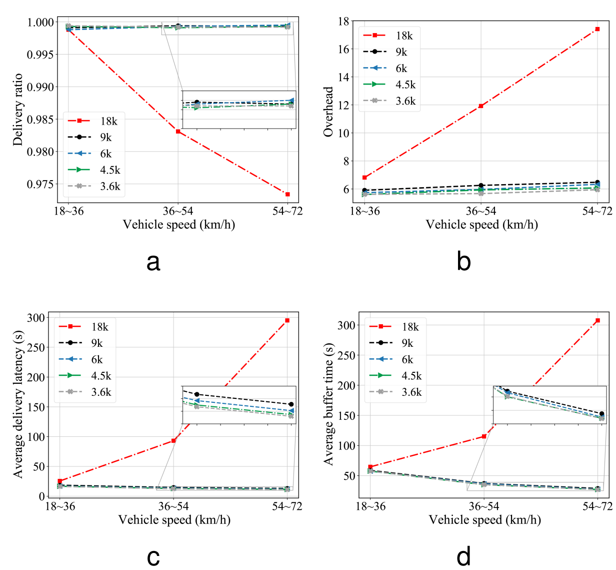

Fig. 9. (a) Delivery ratio versus vehicle speed. (b) Overhead ratio versus vehicle speed. (c) Average delivery latency versus vehicle speed. (d) Average buffer time versus vehicle speed.

Furthermore, as the number of data copies increases, abundant data copies are transmitted in CN, increasing the probability of data being delivered to its destination. Unfortunately, network congestion may occur because abundant data copies cause long queuing latency, increasing the E2E latency and overhead.

E. Impact of vehicle speed

In this section, we fix the proportion of devices $\varpi_{60,40}$. The number of data copies is set to 10. Then, the vehicle speed is changed from $18kmph$ to $72kmph$. Other parameters are unchangeable.

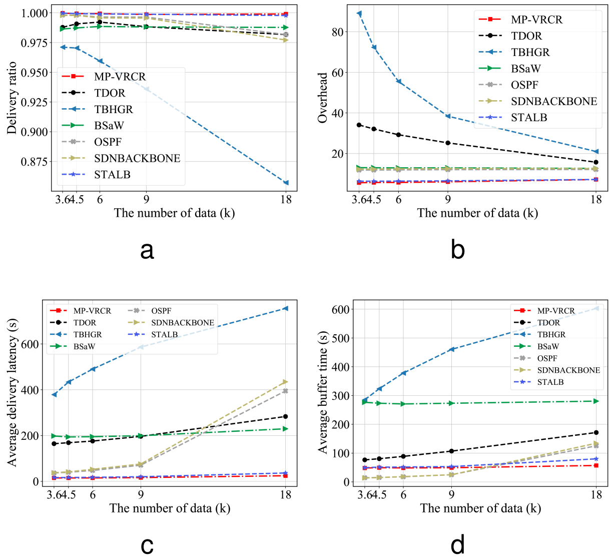

Fig. 10. (a) Delivery ratio versus the number of data. (b) Overhead ratio versus the number of data. (c) Average delivery latency versus the number of data. (d) Average buffer time versus the number of data.

Fig. 9a shows the tendency of delivery ratio versus vehicle speed. When the number of data is $18k$, the delivery ratio decreases as the vehicle speed increases. The tendency of delivery ratio in other scenarios is opposite to the tendency in the dense scenario of data.

As shown in Fig. 9b, the overhead increases as the vehicle speed increases in all data density scenarios. The higher the data density is, the higher the variation of overhead. For example, the slope of red line ($18k$ data) is greater than the slope of black line ($9k$ data).

The variations of average delivery latency and average buffer time are shown in Fig. 9c and Fig. 9d, respectively. Specifically, in the dense scenario ($18k$ data), the average delivery latency and average buffer time increase as the vehicle speed increases. However, their values decrease as the vehicle speed increases.

The fundamental reason is the data transmission from vehicles with high moving speeds is frequently interrupted. Specifically, the faster the vehicle moves, the shorter the time the vehicle is within the communication range of network relay devices. The number of data that can be fully transmitted to network relay devices by vehicles decreases. In the dense scenario, frequent data transmission interruptions increase the E2E latency of data. Furthermore, CN with low overhead has more data transmission capability in other scenarios. Vehicles carry data and transmit it to non-congested network relay devices, decreasing the E2E latency and average buffer time.

F. Impact of data volumes

In this section, we fix the proportion of devices $\varpi_{60,40}$. The number of data copies is set to 10. Then, the data volume is changed from $3.6k$ to $18k$. Other parameters are unchangeable.

Fig. 10a shows the tendency of delivery ratio with the variation of data volumes. MP-VRCR outperforms the other baseline algorithms in all scenarios, and its average delivery ratio is 99.92%. It provides the high reliability, i.e., the variance of delivery ratio is the minimum value 0.04%. BSaW and STALB provides the high reliability similar to MP-VRCR, and their variance of delivery ratio are 0.072% and 0.067%, respectively. However, TDOR, TBHGR, OSPF, and SDNBACKBONE have a downward trend with the increase of data volume.

Fig. 10b illustrates the variation of overhead versus different data volumes. The average overhead of MP-VRCR is 6.07, which is at least 7.75% lower than other baseline algorithms. The average overheads of STALB, OSPF, SDNBACKBONE, TDOR, TBHGR, and BSaW were 6.58, 11.97, 12.45, 27.29, 55.30, and 12.92, respectively. Furthermore, the overhead of TDOR and TBHGR decreases as the number of data increases. By contrary, the overhead on other algorithms shows a slow upward tendency.

It is seen from Fig. 10c that the experiment compared the average delivery latency in terms of various number of data. MP-VRCR, STALB, BSaW, and TDOR provide decent reliability of average delivery latency, while TBHGR, OSPF, and SDNBACKBONE did not. Furthermore, the average delivery latency of all the algorithms follows an increasing trend with the increasing number of data.

Fig. 10d depicts the tendency of average buffer time in various scenarios of data volumes. The average buffer time is increased as the data volume increased from $3.6k$ to $18k$. MP-VRCR with high reliability has a lower average buffer time than BSaW, TDOR, TBHGR, and STALB, but is higher than OSPF and SDNBACKBONE in the sparse data volume scenarios ($3.6k$, $4.5k$, $6k$, and $9k$).

The fundamental reason for the above differentiation is the difference in data delivery strategies, copy control strategies, and other supplement mechanisms.

- Firstly, MP-VRCR and STALB predict data trajectory in CN, while TDOR and TBHGR focus on the movement trajectory of vehicles. Thanks to the fixed connectivities in CN, the predicted data trajectory is more reliable than the movement trajectory of vehicles.
- Secondly, BSaW, TDOR, and TBHGR utilize vehicle-to-vehicle communication to deliver data, but are affected by the dynamic of vehicular mobility and uncertain vehicular encounters. Several data cannot be delivered to their destinations, limiting the delivery ratio and causing high average delivery latency.
- Thirdly, since the transmission trajectory of data cannot be changed in OSPF and SDNBACKBONE, the intersecting trajectory may cause network congestion. OSPF and SDNBACKBONE without copy controlling cannot alleviate overhead by dropping copies with the same content.
- Fourthly, MP-VRCR integrates IoVs and CN for data delivery. The vehicle-assisted method of MP-VRCR partially alleviates network congestion, so as to improve the probability of delivering data to its destination.
- Fifthly, MP-VRCR considers multi-dimension indicators and data delivery capability of candidate devices, e.g., trajectory similarity, predicted buffer time, distance cost,

buffer occupation, minimum time overhead, and movement direction of vehicles. The vehicle-assisted method enables vehicles to carry data and bypass the congested network relay device, while STALB does not.
- Sixthly, MP-VRCR has equipped several supplement mechanisms, i.e., the fast data re-delivery mechanism, device and data priority evaluation, and destination monitoring. Supplement mechanisms are utilized to improve the delivery ratio and avoid network congestion.

VI. Conclusion

In this paper, we proposed a Multi-dimension and Priority-based Vehicle-Road Collaborative Routing (MP-VRCR) protocol to improve the efficiency and reliability of data delivery. Specifically, MP-VRCR utilized multi-dimension indicators to evaluate the data delivery capability of candidate devices, considering trajectory similarity of data, predicted buffer time, buffer occupation and distance cost. Furthermore, MP-VRCR evaluated device priority based on geographical information, selected optimal next-hop device, and evaluated data priority to order data forwarding. Then, MP-VRCR updated the congestion status of network relay devices according to buffer occupation. Vehicles carried data bypass congested network relay devices to reduce the E2E latency. Extensive simulation results show that MP-VRCR significantly outperforms other baseline algorithms regarding delivery ratio, overhead, average delivery latency. The average delivery ratio of MP-VRCR can reach 99.9%, and the maximum of its average delivery latency is $24.7s$. The average overhead of MP-VRCR is 6.07, which is at least 7.75% lower than other baseline algorithms.

VII. Acknowledgement

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Yujie Song is currently pursuing the M. S. degree in cyberspace security at Wuhan University, China. His research interests include Internet of Vehicles, Networking Transmission, Space-ground Integrated Information Network, and Trust Management.

Yue Cao (M’16, SM’21) received the Ph.D. degree from the Institute for Communication Systems (ICS) formerly known as Centre for Communication Systems Research, University of Surrey, Guildford, U.K., in 2013. Further to his PhD study, he had conducted a Research Fellow with the University of Surrey, and academic faculty with Northumbria University, U.K., Lancaster University, U.K., and Beihang University, Beijing, China. He is currently a Professor with the School of Cyber Science and Engineering, Wuhan University, Wuhan, China. His research interests include intelligent transport systems, including E-Mobility, V2X, and edge computing.

Kai Jiang (S’20) received the M. S. degree from China Three Gorges University, China, in 2021. He is currently pursuing the Ph. D. degree in cyberspace security at Wuhan University, China. His research interests include Mobile Edge Computing, Deep Reinforcement Learning, and Internet of Vehicles.

Yuqing Li received the B.S. degree in Communication Engineering from Xidian University, Xi’an, China, in 2014, and the Ph.D. degree in Electronic Engineering from Shanghai Jiao Tong University, Shanghai, China, in 2019. She is currently an associate professor at the School of Cyber Science and Engineering, Wuhan University, China. Before this, she was a Researcher at Huawei Hong Kong Research Center from 2020-2022, and a Post-Doctoral Fellow in Hong Kong University of Science and Technology from 2019-2020. Her research of interests are in the area of data-intensive and machine learning systems, cloud and edge computing, data privacy and security.

Yuping Lai (M’18) received the Ph.D. degree in information security from Beijing University of Posts and Telecommunications, Beijing, China, in 2014. He is currently an associate professor in the School of Cyberspace Security at Beijing University of Posts and Telecommunications, Beijing, China. His current research interests include information security, machine learning, and data mining.

Lixin Wang received the undergraduate degree in cyberspace security at Wuhan University, China. Her research interests include Internet of Vehicles, Mobile Edge Computing, Machine Learning.