Traffic Differentiated Clustering Routing in DSRC and C-V2X Hybrid Vehicular Networks

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***Abstract*—Vehicles equipped with sensors can participate in mobile crowdsourcing applications. Vehicular Ad Hoc Networks (VANETs) based on Dedicated Short Range Communication (DSRC) are used to carry sensing data. However, multi-hop transmissions for gathering data to Road Side Units (RSUs) in VANETs suffer from low data rate and long end-to-end delay, which can hardly meet the QoS requirements of delay-sensitive services. This triggers the consideration of constituting a DSRC and Cellular-Vehicle-to-Everything (C-V2X) hybrid vehicular network. Nevertheless, using cellular links to carry traffic can cause high cellular bandwidth costs. In this paper, we propose a Traffic Differentiated Clustering Routing (TDCR) mechanism in a Software Defined Network (SDN)-enabled hybrid vehicular network. The proposed mechanism includes a centralized one-hop clustering approach and a data delivery optimization method. Particularly, the optimization is to make a tradeoff between cellular bandwidth cost and end-to-end delay, for Cluster Heads (CHs) delivering their aggregated data either by multi-hop Vehicle-to-Vehicle (V2V) transmissions or by cellular networks. Since the problem is proven to be NP-hard, a two-stage heuristic algorithm is designed. We carry out simulations to evaluate the performance of our data collection scheme and the results show that it performs better than traditional mechanisms.**

***Index Terms*—Dedicated short range communication, cellular-vehicle-to-everything, software defined vehicular networking, clustering, routing optimization.**

I. Introduction

IN VEHICULAR networks, various advanced applications such as autonomous driving, remote driving, in-vehicle entertainment, remote vehicle diagnostics, traffic monitoring, and road weather prediction are emerging, where the wireless communication technologies would no longer just provide road safety guarantee, but assist in better traffic management, cater car infotainment, and accomplish sensing tasks of deployers. Gathering sensed data from vehicles efficiently to a processing server is a key point to support these applications.

Dedicated Short Range Communication (DSRC) is a wireless communication technology designed for direct Vehicle-to-Vehicle (V2V) connections, which takes the IEEE 802.11p standard as its physical (PHY) and medium access control (MAC) layers currently. In Jan. 2019, a new IEEE study group proposed the 802.11bd as an evolution of radio access technology for DSRC, which supports higher relative velocities, shorter response time and longer communication range. The DSRC-based Vehicular Ad Hoc Networks (VANETs) with Road Side Unit (RSU) infrastructures are used to carry vehicular data. In particular, the multi-hop V2V communication can extend the range of an individual RSU indirectly. However, occupying a spectrum of 75 MHz at the 5.9 GHz frequency band, V2V links suffer from low data rates ranging from 6 to 27 Mbps [1]. Multi-hop transmissions for gathering data to RSUs cause long end-to-end delays, which can hardly meet the QoS requirements of delay-sensitive services. This triggers the consideration of constituting a DSRC and Cellular-Vehicle-to-Everything (C-V2X) hybrid vehicular network, where C-V2X allows vehicles to realize long-range uplink transmissions over Uu interface. Recently, the 3rd Generation Partnership Project (3GPP) is working to develop the 5G New Radio (NR)-V2X, in order to supplement Long Term Evolution (LTE)-V2X in advanced use cases. However, the cellular spectrum is licensed, which implies that it is controlled by an operator and can be costly to use. Especially in the Internet of Things (IoT) era, cellular networks are under tremendous traffic pressure and vehicular communications will preempt resources from other terminal users. Therefore, the cellular communication should be restricted to use only when needed. It is a big challenge to guarantee all QoS of different services while reducing cellular bandwidth cost for vehicular data transmission.

Some work on vehicular data transmission has been done, but there is still plenty of room for improvement. Firstly, some studies have been carried out to guarantee the QoS in VANETs, which mainly take the end-to-end delay [2] and packet dropping ratio [3] as metrics. However, most of them are designed for a single type of traffic [4]. Secondly, optimal methods to leverage the latency requirement and the cellular bandwidth cost were proposed in the DSRC and C-V2X hybrid vehicular network [5]. The multi-hop V2V route selection was not considered, which has a great influence on the latency performance. Finally, in

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order that the efficient use of heterogeneous technologies can be achieved by grouping vehicles into clusters, a wide range of clustering approaches have been presented. Reasonable clustering schemes can reduce control overhead, increase network scalability and also provide opportunities for data aggregation. The current clustering schemes mainly focus on improving clustering stability by considering metrics such as connectivity degree, link duration, etc. However, most of them have not considered how they perform in data collection applications, where the distance to the sink is of equal importance. In addition, the advanced vehicular applications have diverse QoS demands such as low communication latency and high reliability, which put forward higher requirements on the resource management efficiency and scalability of a vehicular network.

Compared to the traditional network paradigm, Software-Defined Networking (SDN) has great advantages. SDN realizes centralized network management by decoupling the control plane and the data plane, which contributes to optimized resource utilization, flexible network configuration and heterogeneous network integration. SDN enables network slices which are used to isolate network functions and resources. As a result, network functions are not tied to the hardware but run on different virtual platforms instead. Utilizing the advantages of SDN provides a way for a vehicular network to simultaneously handle traffic flows with different QoS requirements. Recently, the convergence of SDN with vehicular networks has gained significant attention from academia and industry. A Software-Defined Vehicular Network (SDVN) testbed on a campus was built in [6], based on which the advantages of SDVNs in resource management and network scalability have been verified. SDVNs provide better vehicular services, and also reduce the cost of hardware upgrades for On-Board Units (OBUs).

Further, multi-domain SDVN architecture can relieve pressure on the central controller. Specifically, the primary-domain controller offloads some tasks to the local controllers. Fig. 1 shows the multi-domain SDVN architecture, where an SDN controller controls RSUs and a Base Station (BS) in its domain in a centralized manner. Specifically, the SDN controller obtains vehicle state information to build a global network graph. Each RSU and BS, in turn, receive forwarding rules from the controller and then distribute to vehicles. The vehicles are connected in clusters. In each cluster, a single vehicle is elected as a Cluster Head (CH) to collect data from cluster members through direct short-range V2V links and aggregate this information. There are two alternatives for CHs delivering the aggregated data to the processing center: going through a BS over cellular links or through an RSU over multi-hop V2V links (since BSs and RSUs are connected to the processing center over fibers).

In this paper, to achieve a balance between end-to-end delay and cellular bandwidth cost, a Traffic Differentiated Clustering Routing (TDCR) mechanism is proposed for an SDVN. Firstly, a single-hop clustering strategy based on geographical locations is proposed. Vehicles moving in the same direction on a road segment within the one-hop range are grouped into one cluster, since clusters maintaining vehicles with low relative velocities are more stable. In each cluster, a CH is selected according to the link duration and the distance to the nearby RSU, so that

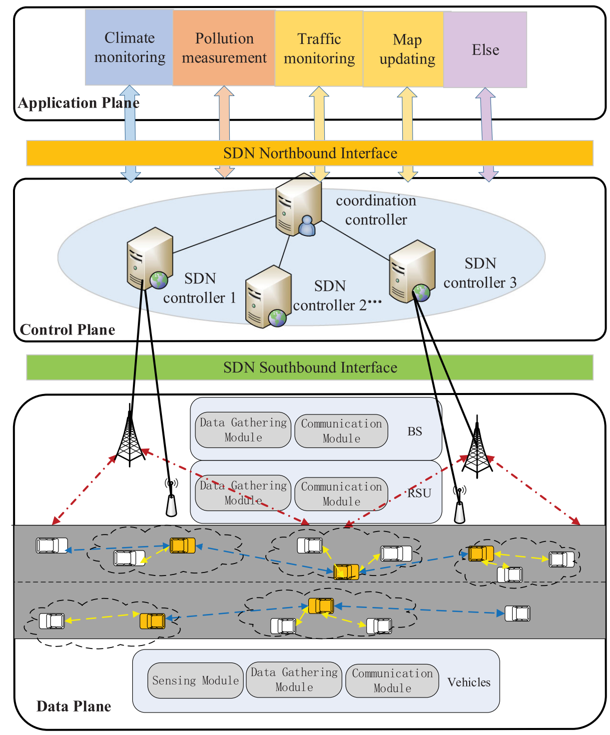


Fig. 1. Multi-domain SDVN architecture.

the head-to-sink hop count is minimized while guaranteeing the cluster stability. Secondly, Nonlinear Integer Programming (NLIP) is employed to formulate mathematically the joint optimization problem of access method (DSRC or C-V2X) selection and routing for CHs. The objective is to minimize the hop counts from CHs to the RSU under constraints including flow conservation, maximum link capacity, and maximum end-to-end delay. An optimal solution is obtained by solving the NLIP through CPLEX. We also propose a heuristic algorithm to obtain a near-optimal solution. The simulation results show that TDCR can effectively reduce the cellular bandwidth cost while guaranteeing the QoS. The key contributions are listed below:

- We design a centralized one-hop clustering approach. It takes data transmission among CHs into account, where adjacent CHs are reachable and hence the number of hops along routing paths to the RSUs are reduced.
- Based on an SDVN architecture, where two access technologies including DSRC and C-V2X are supported, a joint optimization problem of delivery method selection and routing is formulated. Through solving the problem by CPLEX and also our proposed heuristic algorithm, a tradeoff between cellular bandwidth cost and multi-hop end-to-end delay is realized.
- We carry out the performance evaluation of TDCR with simulations in different settings, and also compare our proposed TDCR with traditional methods. Results show that it performs better than traditional mechanisms.

The paper is organized as follows. In Section II, we review the state of art related to our work. In Section III, we give details of our proposed data collection scheme including the one-hop clustering strategy, optimization problem formulation and also a heuristic algorithm to solve the optimization problem. We evaluate our scheme in Section IV. Finally, we conclude in Section V.

II. Related Work

In this section, we first introduce the research status of SDVNs. Then, current sensing data collection schemes in vehicular networks are stated. Last, we discuss some work on clustering techniques in vehicular networks.

A. SDVN Architecture

As a promising paradigm to manage a network in a centralized way, SDN develops fast. Much work on the SDVN architecture has been done.

Combined with fog computing, a new SDVN architecture was designed for both safety and non-safety services [7]. Through resource management and fog coordination, this architecture can effectively reduce latency and improve resource utilization. To cope with connectivity loss with the SDN controller, S. Correia *et al.* [8] presented a hierarchical SDVN architecture with a central controller coordinating local controllers. Further, the authors in [9] considered the QoS of diverse applications in a proposed SDVN architecture, where low-delay and high-reliability communications can be achieved. Additionaly, some work on resource scheduling [10] and routing optimization [11] under the SDVN architecture has been done.

Moreover, to overcome the low channel capacity in VANETs, the authors in [12] combined cellular networks with VANETs under the SDN architecture. Further, in order to overcome the high dynamics of network topology, X. Duan *et al.* [13] presented an adaptive clustering scheme and also a beam-formed transmission method in cellular-VANETs.

Our work is inspired by these works and aims to optimize QoS and reduce communication budgets for the data collection problem.

B. Data Collection in Vehicular Networks

Numerous data collection solutions have been proposed in vehicular networks, most of which consider metrics such as end-to-end delay, collection ratio, and communication cost. Using dynamic programming, the authors in [14] constructed a data aggregation tree with a waiting time budget at each node, producing much lower transmission overhead while achieving the same QoS performance as other schemes. The delay-bounded routing protocols presented in [15] provided a routing scheme that satisfies user-defined delay requirements while maintaining a low level of channel utilization. The authors in [16] proposed optimization schemes that achieve tradeoffs between latency and delivery ratio.

Since clustering has been proven to be effective to overcome the high dynamics of mobile ad-hoc network topology, many researchers utilized clustering strategies in their vehicular data collection schemes. Clustering algorithms in vehicular networks are basically based on a weighted sum of network metrics including inter-vehicle distance, degree of connectivity, link stability, node uptime, etc. The Clustered Gathering Protocol (CGP) [17] and DIstance and MObility based Clustering (DIMOC) [18] are good examples. Moreover, based on DIMOC, a Compressive Sensing based Data Collection (CSDC) was proposed to collect spatially correlated data in VANETs. It successfully achieves the goal of effective communication with low computing and control overhead.

However, most current works use distributed mechanisms. Without a global view, it is difficult to maximize the utilization of network resources.

C. Clustering in Vehicular Networks

Many clustering methods were studied in Mobile Ad hoc Networks (MANETs) since a hierarchical network is more manageable. The popular lowest-ID and highest-degree clustering algorithms were proposed in [19] but without considering node mobility. The Mobility Based Clustering (MOBIC) method [20] is an attempt to introduce the distance between nodes into the CH selection process. Borrowing the idea from MANETs, many researchers have proposed clustering algorithms for VANETs. Most of them are based on a weighted sum of several network metrics such as connectivity degree, link stability, node uptime, etc.

However, different from MANET nodes which are distributed randomly in space, VANET nodes are subject to some mobility constraints since the road infrastructure follows a geographical direction. Except for the metrics at a network level, the special features of mobility should also be utilized to develop stable clusters. The BackBone Routing protocol proposed by Wu *et al.* [21] utilizes vehicle speed, traffic direction, and the quality of transmission, to generate a reliably connected network. Togou *et al.* [22] proposed the Connected Dominating Set-Stable Virtual Backbone (CDS-SVB) which uses vehicle speed, direction and relative distance for CH selection to stabilize the backbone structure. In [23], the authors proposed a multi-hop-cluster-based DSRC-C-V2X hybrid architecture for the first time. A CH is selected based on the metric of average relative speed to the neighboring vehicles. Velocities of vehicles are utilized to predict link durations, which are conducive to reduce network overhead.

However, the current clustering schemes seldom analyze how their algorithms perform in data collection. And also, without a global view from an SDN controller, cluster maintenance and updating become harder.

III. Proposed Scheme

To alleviate data overload, one-hop clustering aggregations and inter-cluster multi-hop V2V transmissions are adopted in the data plane. Hence we then give specific details on our proposed one-hop clustering approach and formulate the optimization problem for data collection from CHs. Last, to solve the problem, a heuristic algorithm is proposed.

A. Clustering Approach

1) Moving Cluster Formation: Vehicles report their position and speed to the BS periodically, hence the BS knows the vehicular network topology. Initially, the road is divided into

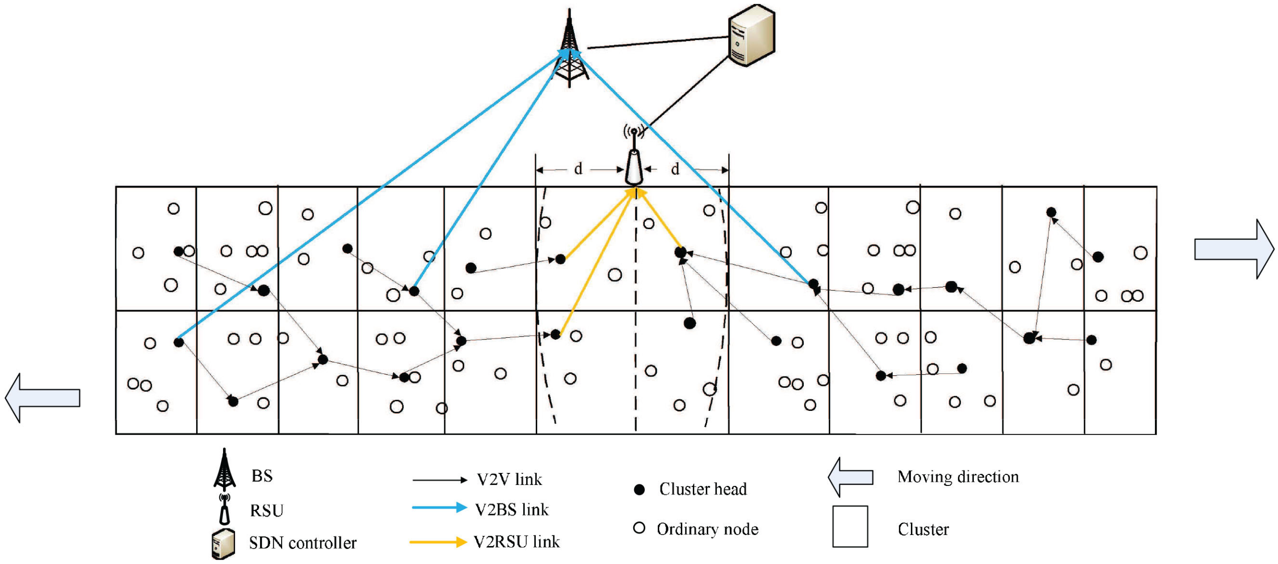


Fig. 2. Data collection from CHs to data center through BS or V2V+RSU.

fix-length rectangular road segments, in each of which a set of vehicles moving in the same direction are classified into a group. And then the grouping information is sent back to the vehicles. Note that the rectangular area exists only at the beginning of clustering and the vehicles in a group will not keep moving in a regular shape. The length of the road is generally not larger than the DSRC transmission range. An example of the initial grouping result is shown in Fig. 2. Based on the global view, the clustering algorithm will be executed in the SDN controller only when needed instead of periodically.

2) CH Selection: The duration of each link can be calculated by the controller based on the vehicles' moving speeds and inter-vehicle distances. Here we assume that all vehicles perform uniform motions in the cluster set-up phase. The link duration between node v_i to v_j is:

1) Case 1: two nodes are moving apart from each other:

$$T_{ij} = \left(\sqrt{R_t^2 - d_{vij}^2} - d_{hij}^2\right) \Big/ vel_{ij} \tag{1}$$

where R_t is the transmission range of DSRC. Notations d_{vij} and d_{hij} are the vertical and horizontal distances between nodes v_i and v_j, respectively. The velocity difference of nodes v_i and v_j is denoted by vel_{ij}. Note that vehicle velocity is denoted by a numerical value with sign which represents its moving direction. $\sqrt{R^2 - d_{vij}^2} \geqslant d_{hij}$.

2) Case 2: two nodes are moving close to each other:

$$T_{ij} = \left(\sqrt{R_t^2 - d_{vij}^2} + d_{hij}\right) \Big/ vel_{ij} \tag{2}$$

The link from node v_i to v_j is admitted as an edge in the topology graph only when its duration T_{ij} is equal to or greater than a threshold value:

$$T_{ij} \geq T_{set} \tag{3}$$

where T_{set} is a presetted link duration threshold.

For a certain node v_i, those nodes connecting with it in the graph are its neighbors and the node-set is denoted as N_i. In each cluster, a node which connects more than a predefined number of neighboring nodes with the minimum distance to a nearby RSU declares as a CH, so that the CH-to-sink hop count is minimized while the cluster stability is guaranteed. Intra-cluster data collection and aggregation are performed at each CH, through which all of the duplicate or invalid packets are dropped to save bandwidth. After performing adaptive and efficient clustering, flow rules are distributed to BSs by fiber links and then to vehicles by cellular links.

B. Optimization Problem

Based on the clustering strategy, the data generated by vehicles is aggregated to their own CHs. The details of the intra-cluster data aggregation process are beyond the scope of this paper. In this section, we formulate the problem of data collection from CHs as an optimization model. The main notations used in the paper are listed in Table I.

To save the deployment cost, RSUs are separated by an extended distance. Multi-hop V2V transmissions are utilized to compensate for the limited coverage of RSUs. We consider a rectangular area in which all moving vehicles have the same nearest RSU. In this large rectangular area, there are a certain number of clusters, each of which has a CH, as shown in Fig. 2. We use $G(S, E)$ to denote the skeleton topology graph. The notation $S = \{s_1, s_2, \ldots s_k, \ldots s_n, s_g\}$ is the set of CHs and an RSU node. $E = \{e(1,2), e(1,3), \ldots e(i,j), \ldots\}$ is the set of CH-to-CH or CH-to-RSU links, where $e(i,j)$ is a unidirectional link from CH s_i to s_j. Here Eq. (3) is also valid to judge whether link $e(i,j)$ exists. The vehicles keep moving and the topology $G(S, E)$ changes over time. Due to the predefined link duration threshold, the links we consider here remain valid for a certain period of time, providing reaction time for SDN controllers to perform re-clustering and re-routing. For simplicity, here we just consider the routing problem for a skeleton topology graph in one domain.

TABLE I
NOTATION LIST

bfNotation	bfDefinition
$G(S,E)$	Topology composed of CHs and an RSU in a road segment.
S	Set of CHs and an RSU in a road segment.
E	Set of links between CHs and the RSU.
s_k	A vehicle node in set S, where k is a variable.
s_g	The RSU node in set S, where g is a constant.
$e(i,j)$	A unidirectional link from node s_i to s_j.
l^c	Packet transmission delay over a cellular link.
l^a_{ij}	Packet transmission delay over V2V link $e(i,j)$.
α	Weighting factor.
$path^k$	An end-to-end path from node s_k to the RSU nearby.
f_k	Data rate of a traffic flow transmitted from node s_k.
η	Price of cellular bandwidth.
$SIZE$	Packet size.
c_k	Cellular bandwidth cost in unit time for data from node s_k.
C	Overall cellular bandwidth cost for all packets in unit time.
T	Overall delay for all packets generated in a unit time.
ω_k	Emergency degree of the traffic flow from node s_k.
T_w	Weighted overall delay for packets generated in a unit time.
C_a	V2V link capacity.
C_b	Cellular link capacity for vehicular traffic.
D_k	Delay constraint for the traffic flow from s_k.

For an aggregated data flow from CH s_k with the data rate of f_k and delay constraint of D_k, there are two optional ways for the delivery to the data processing center. First, it can be delivered to the nearest RSU through the multi-hop V2V transmission. However, it may incur large transmission delay especially for CHs which are far away from the RSU, which might be intolerant for some delay-sensitive services. Second, the traffic flow can be transmitted by a cellular link to the BS directly. Although this approach reduces transmission delay, it causes cellular bandwidth cost. Thus, there is a tradeoff between delay and cost during the scheduling of traffic flows. By considering both transmission delay and cellular bandwidth cost, we can decide whether it should be transmitted by a cellular link or delivered to an RSU by multi-hop V2V links, and also which path should be selected in the case of V2V+RSU. Before formulating the problem, we define two decision variables as follows:

$$x_k = \begin{cases} 1, & \text{if CH } s_k \text{ uses a cellular link.} \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

$$y^k_{ij} = \begin{cases} 1, & \text{if } x_k = 0 \ \&\ e(i,j) \in path(k) \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

where the notation $path(k)$ is a path which is selected in a VANET for the traffic flow from CH node s_k to its sink RSU. Obviously, the first variable decides if the traffic flow is transmitted over a cellular link or V2V links. The second variable decides the transmission path once V2V transmission paths have been chosen. Next, we utilize these two decision variables to describe the overall cellular bandwidth cost and end-to-end delay of all traffic flows.

First, we suppose that η is the price of cellular bandwidth (in dollar/MB) and if node s_k decides to transmit data through a BS, the cost c_k is as follows:

$$c_k = \frac{\eta}{8} \cdot f_k \tag{6}$$

The overall cellular bandwidth cost per second for all CH vehicles in the topology graph is as follows:

$$C = \sum_{s_k \in S} x_k \cdot \frac{\eta}{8} \cdot f_k \tag{7}$$

We use l^c to denote the transmission delay along cellular links and l^a_{ij} the delay along link $e(i,j)$ for one packet. The notation $SIZE$ is the the size of a packet which is in unit of byte. The overall delay of all packets generated per second is calculated as follows:

$$T = \sum_{s_k \in S} \left(x_k \cdot l^c \cdot \frac{1024^2 \cdot f_k}{SIZE} + \sum_{e(i,j)\in E} y^k_{ij} \cdot l^a_{ij} \cdot \frac{1024^2 \cdot f_k}{SIZE} \right) \tag{8}$$

where the first item corresponds to delivery delay of packets transmitted by cellular links and the second one is the total delivery delay of packets transmitted by multi-hop V2V links. Since different services have different delay requirements, which reflects the importance of messages, we define a weighted overall delay of all traffic flows as follows:

$$T_w = \sum_{s_k \in S} \omega_k \cdot \frac{1024^2 \cdot f_k}{SIZE} \cdot \left(x_k \cdot l^c + \sum_{e(i,j)\in E} y^k_{ij} \cdot l^a_{ij} \right) \tag{9}$$

where ω_k is a weighting factor reflecting the emergency degree of the traffic flow from node s_k. It is a comparative ratio based on priority-sorting and is specified by the service deployer according to the QoS requirements.

For the CH data collection problem, we consider both delay and cost, and the objective function can be formulated as follows:

$$\min \ln T_w + \alpha C \tag{10}$$

where α is a weighting factor.

$$x_k + \sum_{s_v : e(k,v)\in E} y^k_{kv} = 1,\ s_k \in S \tag{11}$$

$$\sum_{s_v : e(i,v)\in E} y^k_{iv} - \sum_{s_u : e(u,i)\in E} y^k_{ui} = 0, s_k, s_i \in S \setminus \{s_g\},\ i \neq k \tag{12}$$

$$x_k + \sum_{s_v : e(v,g)\in E} y^k_{vg} = 1, s_k \in S \setminus \{s_g\},\ s_g = RSU \tag{13}$$

$$\sum_{s_k \in S} y^k_{ij} \cdot f_k \leq C_a,\ e(i,j) \in E \tag{14}$$

$$\sum_{s_k \in S} x_k \cdot f_k \leq C_b \tag{15}$$

$$\sum_{e(i,j)\in path(k)} y^k_{ij} \cdot l^a_{ij} \leq D_k,\ s_k \in S \tag{16}$$

Single-path routing is adopted in this paper, hence each ordinary node must have one out-going link for one traffic flow. Constraints (11) and (12) ensure that the flows begin from their sources and end at the RSU, respectively. Flow conservation at relay nodes is guaranteed by (13). The amount of aggregated traffic carried by a link should not exceed its capacity. Capacity constraints C_a (14) and C_b (15) are for V2V links and cellular links, respectively. Each traffic flow has a delay constraint D_k which is reflected in constraint (16).

C. Heuristic Algorithm

Our proposed optimization problem in this paper is 0–1 Non-Linear Integer Programming (NLIP), we notice that x_k is opposite to y^k_{kj}, and this problem becomes a Multiple Objective Shortest Path (MOSP) problem with multiple conflicting objectives. The optimal solution for one objective is probably not for the other one and we can only obtain an equilibrium solution, which is called Pareto set. It is a classical NP-hard problem shown in [24]. An efficient heuristic algorithm with polynomial time complexity is then strongly required. In this section, we propose a centralized heuristic algorithm for this problem to find a suboptimal solution.

Instead of using y^k_{kj}, we intentionally introduce the binary variable x_k to denote whether the traffic flow from s_k is delivered by the cellular link, supporting us to solve our problem in two steps.

In the first step, imagine that all the traffic flows are taken by the VANET, that is, for all $s_k \in S$, $x_k = 0$, the algorithm finds a shortest-path tree whose overall weighted delay is minimized under the capacity and delay constraints. Specifically, the algorithm sorts the list of traffic demands in decreasing order of weights $\{\omega_k, s_k \in S\}$, which is referred to as a criticality list L_1. Then it picks each demand entry from L_1 and finds the shortest path with the minimum delay from its source node to the nearest RSU in the topology using the Dijkstra algorithm, after which, the residual capacity of the occupied link will be updated by subtracting the corresponding data rate. Note that if there is no available path satisfying the capacity constraint for the flow from s_k, x_k will be set to 1 directly.

In the second step which is called the post-processing step, the algorithm will iteratively select traffic flows to be delivered by cellular links and re-compute the routes for traffic flows travelling through the V2V network, aiming to improve the objective function value. We take it as a virtual flow migration process from VANET to cellular network.

By observation and analysis, we obtain that: 1) To reduce the overall weighted delay, one may prefer to allow the delay-sensitive flows with more V2V hops to be delivered by cellular links first. However, these flows may require quite some bandwidth, which will impact other flows' transmission opportunities through cellular links. 2) Because of the limited cellular bandwidth resources, one may select those flows requiring the least resource to be transmitted by cellular links first. However, flows with fewer bandwidth resources may be delay-tolerant services, or they are generated from CHs near the sink RSU.

To balance the total weighted delay and cost, a parameter ζ_k, as determined by Eq. (17), is assigned to a traffic demand from node s_k.

$$\zeta_k = \frac{1}{\omega_k \cdot f_k \cdot (l^a_k - l^c)} \cdot \daleth_{l^a_k > l^c} \tag{17}$$

Algorithm 1: Constrained Shortest Path Tree.

Input: $T_{ij}, T_{set}, C_a, \{f_k, s_k \in S\}$.
Output: $T_{\min}, \{y^k_{ij}, s_k \in S, e(i,j) \in E\}, \{l^a_k, s_k \in S\}$.
$T_{\min} = \varnothing, l^a_k = 0$;
for all $s_i \in S$ **do**
  for all $s_j \in S$ **do**
    if $T_{ij} \geqslant T_{set}$ **then**
      add $e(i,j)$ to E;
      estimate $\{l^a_{ij}$;
    end if
  end for
end for
sort the CHs $s_k \in S$ in decreasing order of weights ω_k to form criticality list L_1;
while $L_1 \neq \varnothing$ **do**
  pick the next source node s_k from L_1;
  find the shortest path $path(k)$ from the source s_k to the RSU using Dijkstra algorithm;
  $T_{\min} \leftarrow T_{\min} \bigcup path(k)$;
  if $e(i,j) \in path(k)$ **then**
    $y^k_{ij} \leftarrow 1$;
    $C_{ij} \leftarrow C_a - f_k$;
    $l^a_k \leftarrow l^a_k + l^a_{ij}$;
  end if
  $L_1 = L_1 - \{s_k\}$;
end while
Return $T_{\min}, \{y^k_{ij}, s_k \in S, e(i,j) \in E\}, \{l^a_k, s_k \in S\}$

where l^a_k is the delay from source node s_k to the sink RSU by path $path(k)$, which is obtained in the first step. $l^a_k - l^c$ denotes the delay saved if node s_k prefers to transmit data by a cellular link rather than V2V links. $\daleth_{\Omega}$ is an indicator function that takes value 1 when condition Ω is true, and 0 otherwise. Note that the parameter ζ_k is proportional to the cellular bandwidth consumed for saving per unit of delay if node s_k chooses to deliver its traffic flow by a cellular link. In our algorithm, the flow with smaller ζ_k should have a higher chance to be migrated to the cellular link.

We assume that cellular links are able to satisfy the delay requirements of all traffic demands, that is $l^c \leq D_k, \forall s_k \in S$. We compare l^a_k with D_k and l^c, respectively. If $l^a_k > D_k$, it is unwise for node s_k to transmit data by V2V links to an RSU, which will induce an intolerant latency. In this case, we will migrate the traffic flow generated by s_k to a cellular link. In another case, if $l^a_k < D_k$ and $l^c > l^a_k$, we will keep the traffic flow generated by s_k on the vehicular links.

Then the algorithm creates a priority list L_2 sorting all traffic demands whose x_k value has not been decided, in increasing order of $\{\zeta_k\}$. The algorithm picks the node $s_k \in S$ whose ζ_k is the smallest in L_2 and decides whether to migrate its traffic flow. Assuming that the overall weighted delay obtained from the first step is T_ω, the value of the objective function is $\ln T_\omega$ initially. If node s_k chooses to migrate its flow, the value of the objective function becomes $\ln(T_\omega - \omega_k \cdot f_k \cdot (l^a_k - l_c)) + \alpha c_k$. Hence, if $\ln(\frac{T_\omega - \omega_k \cdot f_k \cdot (l^a_k - l_c)}{T_\omega}) + \alpha c_k > 0$, node s_k will choose to migrate data to a cellular link, as it incurs a decrease of the objective

Algorithm 2: Post- Processing Step.

Input: $\{l_k^a, s_k \in S\}, l^c, \{D_k, s_k \in S\}$.
Output: $\{x_k, s_k \in S\}$
while stopping criteria not reached **do**
  for all $s_k \in S$ **do**
    if $l_k^a > D_k$ **then**
      $x_k \leftarrow 1$;
    else if $l^c - l_k^a \leq 0$ **then**
      $x_k \leftarrow 0$;
    else
      $\eta_k \leftarrow$ Equ. (17);
      sort s_k in increasing order of weights η_k to form criticality list L_2;
    end if
  end for
  while $L_2 \neq \varnothing$ **do**
    pick the next source node s_k from L_2;
    Calculate the function value;
    if $\ln(\frac{T_\omega - \omega_k \cdot f_k \cdot (l_k^a - l_c)}{T_\omega}) + \alpha c_k > 0$ **then**
      $x_k = 1$;
      $C_b \leftarrow C_b - f_k$;
    else
      $x_k = 0$;
    end if
    $L_2 = L_2 - \{s_k\}$;
  end while
  $\{l_k^a, s_k \in S\} \leftarrow$ Algorithm 1;
end while
Return $\{x_k, s_k \in S\}$

function. Otherwise, s_k will keep transmitting data over V2V links. After the decision process, the entry of s_k will be removed from L_2. The decision process will be executed repetitively for all nodes in L_2.

The connecting point of these two algorithms is that Algorithm 1 provides input information l_k^a to Algorithm 2, and Algorithm 2 determines the value of x_k which will affect Algorithm 1. Hence the two algorithms can be executed iteratively until the stopping criteria is reached.

1) Computational Complexity: In Algorithm 1, the process of topology generation takes $O(n^2)$ time, where n is the number of CHs. The time complexity of the recursive sorting algorithm is $O(nlogn)$. The Dijkstra algorithm is executed for all CHs, which requires $O(n^3)$ time since the time complexity of the Dijkstra method is $O(n^2)$. In Algorithm 2, we obtain a time complexity of $O(n + nlogn)$ through checking the number of loops. Therefore our algorithm takes $O(n^2 + nlogn + n^3 + nlogn + n) = O(n^3)$.

IV. Performance Evaluation

Based on the idea of the discrete event simulation, using the C++ programming language, we developed a simple and flexible wireless simulation platform, by which we verified our scheme. In this section, we introduce the simulation settings first. Then, we analyze our algorithm under different value settings and also compare it with other algorithms in terms of latency and bandwidth cost. The figures are plotted with 95% confidence intervals.

A. Simulation Settings

By default, we consider the length of the highway segment is 2000 meters and there are 3 lanes in each direction. We adjust the DSRC transmission range R from 200 to 400 meters in the simulations. The length of a cluster is set to $R/2$ which is 100 to 200 meters. Then we can obtain that the number of CHs ranges from 20 to 40 since two CHs are traveling in opposite directions on a road segment with a length of $R/2$. The vehicular speed is uniformly distributed between 18 and 28 meters per second. The current locations of nodes are independently chosen uniformly randomly in the network. We set the price that vehicles pay for cellular links is 1 yuan RMB (approximately equal to 0.15 dollar) per MByte of data. The latency of each cellular link is 0.5 s by default and we adjust it from 0.1 to 1 s to verify its effect on the system performance. The latency of V2V links is between 0.3 and 0.5 s. Here the size of each packet is assumed to be 512 byte and the V2V link capacity is 24 Mbps. Each CH node has a traffic flow demand. We consider that all traffic flows are with the same/different CBR data rates and QoS requirements. In the case of the same flows, the unified data rate is assumed to be 1 Mbps and the delay constraint is 2 s. The priority weight of each traffic flow ω_k is equally 1. For the case of different flows, their data rates are uniform random distributed between 0 and $Data_{\max}$ Mbps. The value of $Data_{\max}$ is variable from 1 to 8 and 2 by default. These CBR flows have their own QoS requirements, i.e., each flow has a delay constraint D_k which is between 0.5 and $Delay_{\max}$. Here the value of $Delay_{\max}$ is 2 by default and we adjust it from 0.5 to 3. The priority weight of each traffic flow ω_k is proportional to D_k. The value of ω_k is between 0 and 2, which is expressed as follows:

$$\omega_k = 2 \cdot \left(\frac{1}{D_k} - \frac{1}{Data_{\max}}\right) \Big/ \left(\frac{1}{0.5} - \frac{1}{Data_{\max}}\right) \tag{18}$$

The smaller ω_k is, the higher priority the flow is. The main parameters are summarized in Table II.

B. Simulation Results

1) Tradeoff Between Delay and Cellular Bandwidth Cost: We set the DSRC range to be 400 meters and study the impact of the parameter α on the tradeoff between overall weighted delay and cellular bandwidth cost. We change the parameter α from 0 to 0.3 in the step of 0.05. Fig. 3 shows the values of total weighted delay, total cellular bandwidth cost and also the objective function, under the cases of data flows being the same (solid lines) and different (dotted lines). We can observe that the cellular bandwidth cost decreases while the delay increases in both cases, along with the increase of α. This is because, when α increases, the cellular bandwidth cost contributes more to the objective. In this case, to reduce the objective function, more flows should choose to be transmitted by V2V links, increasing the delay. Particularly, when $\alpha = 0$, only the delay affects the

TABLE II
MAIN PARAMETERS USED IN THE SIMULATION

Parameters	Value Range	Default Value
Length of a road (m)		2000
Number of lanes per direction		3
DSRC transmission range R (m)	$200 \sim 400$	200
Number of CHs	$20 \sim 40$	40
Speed of vehicles (m/s)		$U[18, 28]$
Link duration threshold T_{set} (s)	$2 \sim 12$	6
Price of cellular bandwidth (($/MB)		1
Delay of cellular link l^c (s)	$0.1 \sim 1$	0.5
Delay of V2V link l_{ij}^a (s)		$U[0.3, 0.5]$
Packet size $SIZE$ (byte)		512
V2V link capacity		24
CBR data flow (Mbps) f_k (Mbps)	1	$U[0, Data_{max}]$
Maximum data rate $Data_{max}$	$1 \sim 8$	2
Delay constraint D_k (s)	2	$U[0.5, Delay_{max}]$
Maximum delay constraint $Delay_{max}$	$0.5 \sim 3$	2
Weight of each traffic flow ω_k	$0 \sim 2$	1

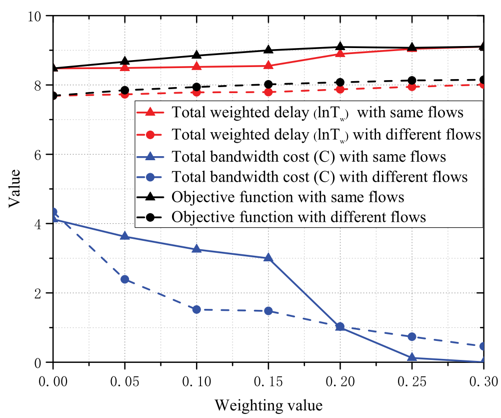


Fig. 3. Tradeoff between delay and cellular bandwidth cost.

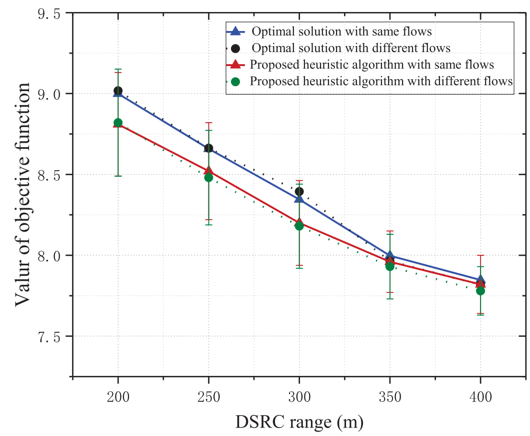


Fig. 4. Value gap between proposed heuristic algorithm and optimal ILP result by CPLEX.

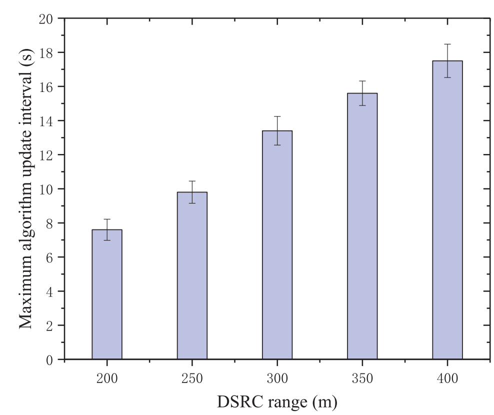


Fig. 5. Maximum algorithm update interval versus DSRC range.

objective function, and the objective should be reduced by transferring as many flows through cellular links as possible. Note that not all flows choose cellular links, because V2V links save both delay and cellular bandwidth cost for the CHs within the DSRC range of an RSU. When $\alpha = 0.3$, the impact of the cellular bandwidth cost is large enough, which results in as much traffic as possible being transmitted to the VANET. For the case of data flows being the same, the value of cellular bandwidth cost is 0, which means that the VANET carries all the traffic. However for the case of data flows being different, the value of cellular bandwidth cost is low but greater than 0, that is to say, there are still some flows being transmitted by the cellular network. The reason is that the delay constraints of some flows are very low and the multi-hop V2V transmissions cannot guarantee the QoS. Actually, for the same reason, the total bandwidth cost with different flows becomes larger than that with the same flows since $\alpha = 0.2$.

2) Effectiveness of the Proposed Heuristic Algorithm: We set the value of α to be 0.15 and compare the performance of the proposed heuristic algorithm with the optimal solution of the NLIP model in cases with the same flows (solid lines) and different flows (dotted lines). In the simulation, the optimal solution of the defined problem is solved by CPLEX Constraint Programming (CP) optimizer. As shown in Fig. 4, the value of the objective function decreases with the DSRC range since the number of CH nodes is reduced and the objective is the weighted sum of for all traffic flows. Additionally, we notice that the gap between our algorithm and the optimal solution becomes larger with more flows in the system, because it is more flexible to choose whether to use a cellular link or a V2V transmission. Nevertheless, the gap is very small, both in cases of the same and different flows, which verifies the effectiveness of our scheme.

3) Performance Analysis Under Different Parameters: We assume that a link exists only when its duration is larger than a threshold so that the sparseness of the generated topology is related to this threshold. The larger the threshold is, the sparser the topology is. The algorithm has to be updated at least when there is no end-to-end route between a CH and the RSU. The corresponding link duration threshold is defined as the maximum update interval here. To eliminate the effects from the properties of each traffic flow including QoS requirements and data rate, we set the delay constraint of each flow to be infinite and the data rate infinitesimal. Fig. 5 shows the results of maximum update interval under different DSRC ranges. We can see that along with the increase of the DSRC range, the maximum update interval becomes longer, which means that the link duration threshold for generating a connected graph can be larger. The reason is obvious that increasing the DSRC range will make vehicles

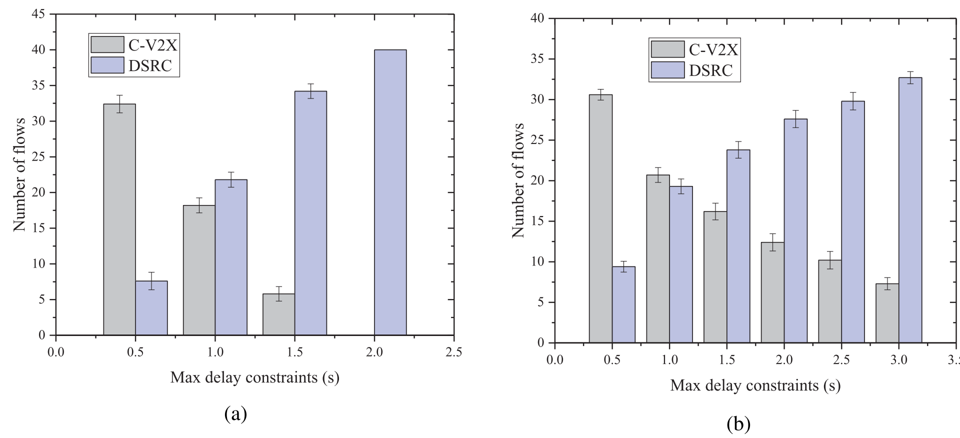


Fig. 6. Number of data flows delivered by cellular network and VANET along with delay constraint. (a) Same delay constraints. (b) Different delay constraints.

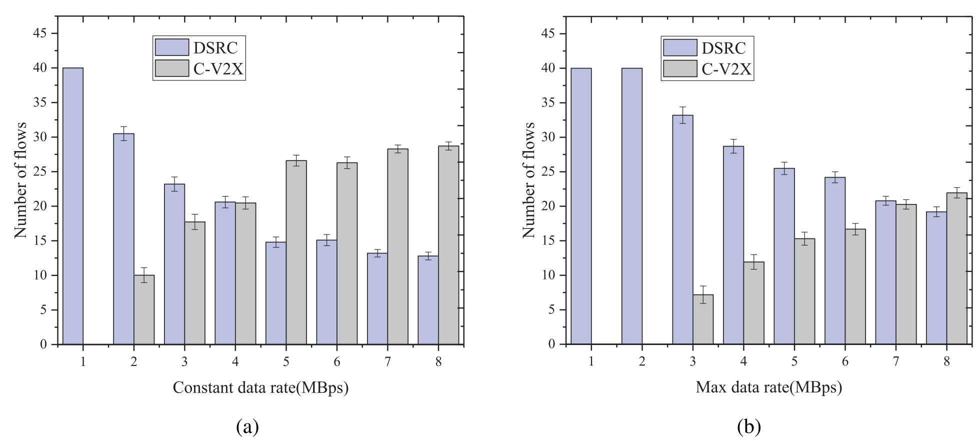


Fig. 7. Number of data flows delivered by cellular network and VANET along with flow data rate. (a) Same data rates. (b) Different data rates.

connected for a longer period when the velocities of vehicles are in the range of 18 to 28 m/s. On the other side, along with the increase of the DSRC range, the number of clusters decreases and so does the number of CHs. A topology with fewer nodes is easier to maintain, contributing to the extension of the algorithm update interval. In any case, we can conclude that the lifetime of clusters is long enough, saving overhead and leaving SDN controllers enough time for re-computing.

In a VANET, nodes within a multi-hop range of an RSU suffers from long delays. The QoS requirements (mainly refer to the end-to-end delay here) of traffic flows will influence nodes' selection of access technologies. We set $\alpha = 0.3$ here. Fig. 6 shows a trend in the number of data flows delivered by C-V2X (to a BS) and DSRC (to an RSU) along with the increase of the delay constraint. Fig. 6(a) is under the case of all flows have the same delay constraints. We can see that our hybrid TDCR scheme can make a growing number of flows choose DSRC with the increase of constant delay constraint, saving cellular bandwidth cost. When the delay constraints are equal to 2 s, the VANET definitely takes all the traffic. Fig. 6(b) is under the case that traffic flows have different delay constraints. We can see that more and more flows choose DSRC as the maximum delay constraint $Delay_{\max}$ increases. We also notice that when $Data_{\max}$ is as low as 0.5, there are still a certain number of flows being transmitted by the VANET. This is because a cellular link is always an unwise choice for nodes within the DSRC range of an RSU.

VANETs have low link capacity. When excessive traffic is injected, it is necessary to use a cellular network to share the load. Fig. 7 shows that our scheme can achieve this goal. As the constant data rate (a) or the maximum data rate $Data_{\max}$ (b) increases, a growing number of flows migrate to a cellular network for relieving the load in the VANET. Note that in the cases when the data rate is very low, the vehicles always choose DSRC and in this case, the error range becomes 0.

4) Performance Comparison With Different Schemes: The latency of the cellular link is set to 0.5 s. The DSRC range increases from 200 to 400 meters by 50 in each step. First, we compare our proposed TDCR under SDN architecture with a Center-Based Secure and Stable Clustering Algorithm (CBSC) [25] and a K-Means-Based method (KMB) [26] without SDN in the terms of average hop counts. CBSC uses the relative mobility metric which is related to the relative position, speed, and maximal acceleration differences between vehicles. KBM is done based on the distance between nodes. As shown in Fig. 8, we can see the average hop counts in the three schemes decrease as the

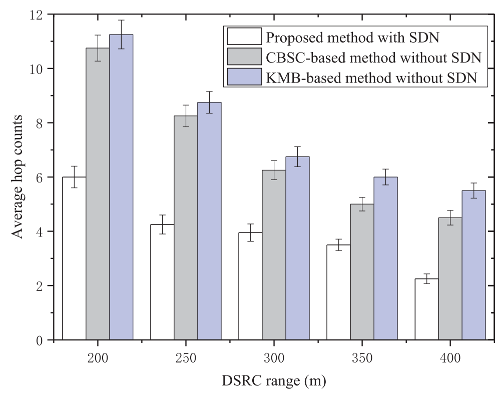


Fig. 8. Average hop counts versus DSRC range.

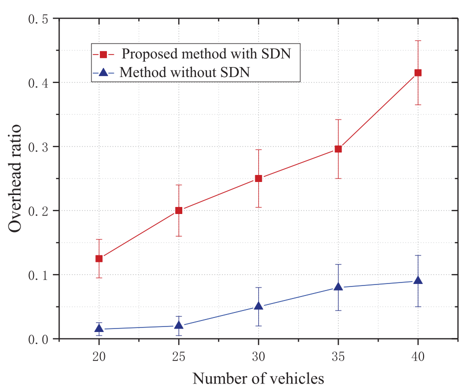


Fig. 9. Overhead ratio versus number of vehicles.

DSRC range increases. The reason is that the number of CHs become fewer as the DSRC range becomes larger and each CH needs fewer hops to reach the sink RSU. Our proposed TDCR scheme performs best because it divides the road into segments of equal length, which makes adjacent CHs reachable. In the CBSC and KMB methods, a relay node needs to be found when two CHs are out of communication range, which will result in aggregated data being sent back to a cluster member node.

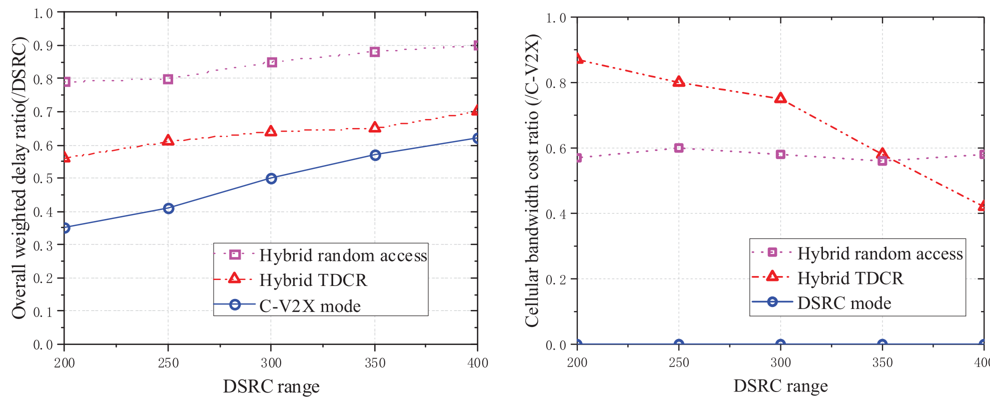
We define overhead ratio as the ratio of the number of control packets to the total number of packets in the network. The performance comparison between SDN-based and non-SDN-based approaches in terms of the overhead ratio is shown in Fig. 9. We can see that the overhead ratio increases as the number of vehicles increases. However, the SDN-based approach shows better performance than the non-SDN-based approach. This is because each node just communicates with the controller under the SDN architecture, while in the non-SDN-based approach, each node sends the beacon message about the current network state to all neighboring nodes for each update.

We then compare the performance of our hybrid TDCR scheme with a hybrid random access scheme and two single transmission modes: C-V2X mode and DSRC mode. In our proposed hybrid TDCR each CH delivers data based on the optimization result. While the hybrid random access scheme is a way where the C-V2X and DSRC are supported and each CH randomly selects one of the two access technologies for delivering data. As shown in Fig. 10(a), the delay ratio of the C-V2X mode to the DSRC mode is the lowest, which indicates that C-V2X performs much better than DSRC in terms of transmission delay. The delay in our hybrid TDCR scheme is also satisfying, especially when the DSRC range is small. The reason is obvious. When the DSRC range is 200 meters, it needs more hops to transmit data to the nearest RSU in DSRC mode. And the hybrid TDCR can use cellular links more frequently to reduce transmission delay and further satisfy the QoS requirement. But when the DSRC range is increased to 400 meters, fewer hops and less delay are needed for data transmission in DSRC mode, which results in the reduced benefit of hybrid methods. Our method has the performance closer to that of the C-V2X mode and much better than the hybrid random method. Because in our method, those CHs which are far away from RSUs or have high-priority traffic flows always select to deliver data through the cellular network, in order to obtain lower delay and satisfy those vehicular applications with strict delay constraints.

From the result shown in Fig. 10(b), in the DSRC mode, the cellular bandwidth cost, which is the access fee from the cellular network, is absolutely 0. And the curve in the hybrid random scheme is relatively smooth, which means that the DSCR range does not affect how much traffic goes to the cellular network. We notice that the superiority of our hybrid TDCR scheme over the C-V2X mode increases as the DSRC range grows. The reason is that our hybrid TDCR scheme can use V2V links more frequently to reduce the cellular access fee with a large DSRC range. When the DSRC range is 400 meters, the cost of our method is close to 42% of the C-V2X mode.

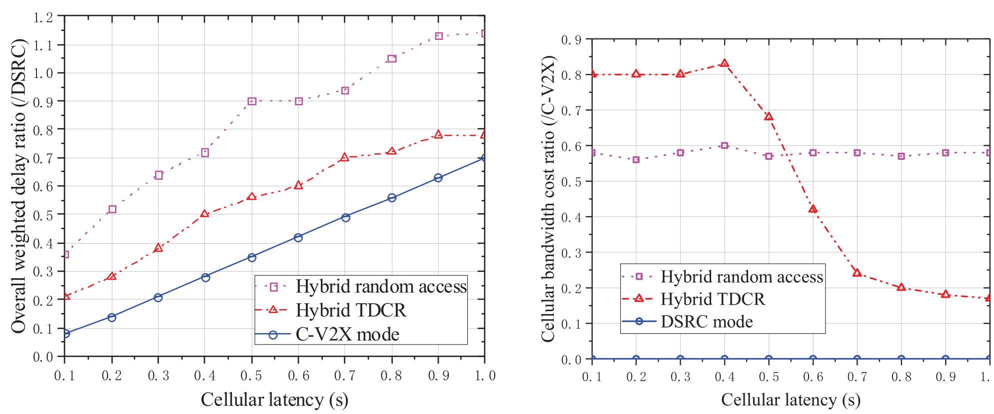
Then, we study the overall weighted delay with different cellular network performance. Specifically, we set the DSRC range to be 400 meters and adjust the latency of the cellular network from 0.1 s to 1 s. As shown in Fig. 11(a), for the C-V2X mode, the overall weighted delay increases linearly. The ratios of delay in the hybrid schemes and that in the DSRC mode also increase as the cellular latency becomes larger, which means that the benefit of the hybrid schemes drops off. The reason is that fewer hops are needed for most CHs to transmit data to the RSU, and it is wiser to deliver data using DSRC without cellular access fees. Nevertheless, our proposed TDCR scheme performs much better than the hybrid random access scheme and basically close to the C-V2X mode, since it allows high-priority data flows far away from the RSU to be delivered through C-V2X.

The cellular bandwidth cost is shown in Fig. 11(b), the DSRC mode and the hybrid random access scheme perform similarly to that shown in Fig. 10(b) due to the same reason. In our hybrid TDCR scheme, the cost ratio keeps stable at the beginning and rapidly descends when the cellular latency is larger than 0.4 s. This is because when the cellular latency is smaller than the latency of the multi-hop communication, more traffic flows will be arranged to the cellular network and its advantages of the hybrid TDCR in saving bandwidth cost will be diminished. When the cellular latency becomes larger, CH nodes near the RSU will choose DSRC mode. But for CHs far away from the RSU, C-V2X is still a better choice. This is why the cost value is greater than 0 when the cellular latency is large enough.



(a) (b)

Fig. 10. Performance comparisions along with DSRC range. (a) Overall weighted delay. (b) Cellular bandwidth cost.



(a) (b)

Fig. 11. Performance comparisions along with cellular latency. (a) Overall weighted delay. (b) Cellular bandwidth cost.

V. Conclusion

In this paper, we have designed a Traffic Differentiated Clustering Routing (TDCR) mechanism for vehicular data collection in an hybrid SDVN network, in order to guarantee QoS and reduce cellular bandwidth cost. The proposed mechanism includes a one-hop clustering approach and a CH data collection method. In the clustering approach, adjacent CHs are reachable and the number of hops along routing paths is hence reduced. In the CH data collection method, we have formulated an optimization problem which aims to achieve a tradeoff between cellular bandwidth cost and multi-hop V2V transmission delay. To solve the complicated NP-hard problem, a heuristic algorithm has been designed, and it has been shown to approach the optimal solution. The simulations have indicated that TDCR achieves low end-to-end delay for delay-sensitive traffic and low cellular bandwidth cost for high data-rate traffic.

References

[1] K. Dar, M. Bakhouya, J. Gaber, M. Wack, and P. Lorenz, "Wireless communication technologies for ITS applications [Topics in Automotive Networking]," *IEEE Commun. Mag.*, vol. 48, no. 5, pp. 156–162, May 2010.

[2] Y. Tang, N. Cheng, W. Wu, M. Wang, Y. Dai, and X. Shen, "Delay-minimization routing for heterogeneous vanets with machine learning based mobility prediction," *IEEE Trans. Veh. Technol.*, vol. 68, no. 4, pp. 3967–3979, Apr. 2019.

[3] W. L. Junior, D. Rosário, E. Cerqueira, L. A. Villas, and M. Gerla, "A game theory approach for platoon-based driving for multimedia transmission in VANETs," *Wireless Commun. Mobile Comput.*, vol. 2018, pp. 1–11, 2018.

[4] A. Patel and P. Kaushik, "Improving QoS of VANET using adaptive CCA range and transmission range both for intelligent transportation system," *Wireless Personal Commun.*, vol. 100, no. 3, pp. 1063–1098, 2018.

[5] H. Li, M. Dong, and K. Ota, "Control plane optimization in software-defined vehicular ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 10, pp. 7895–7904, Oct. 2016.

[6] G. Secinti, B. Canberk, T. Q. Duong, and L. Shu, "Software defined architecture for VANET: A testbed implementation with wireless access management," *IEEE Commun. Mag.*, vol. 55, no. 7, pp. 135–141, Jul. 2017.

[7] N. B. Truong, G. M. Lee, and Y. Ghamri-Doudane, "Software defined networking-based vehicular adhoc network with fog computing," in *Proc. IFIP/IEEE Int. Symp. Integr. Netw. Manage.*, 2015, pp. 1202–1207.

[8] S. Correia, A. Boukerche, and R. I. Meneguette, "An architecture for hierarchical software-defined vehicular networks," *IEEE Commun. Mag.*, vol. 55, no. 7, pp. 80–86, Jul. 2017.

[9] J. Liu, J. Wan, B. Zeng, Q. Wang, H. Song, and M. Qiu, "A scalable and quick-response software defined vehicular network assisted by mobile edge computing," *IEEE Commun. Mag.*, vol. 55, no. 7, pp. 94–100, Jul. 2017.

[10] Q. Zheng, K. Zheng, H. Zhang, and V. Leung, "Delay-optimal virtualized radio resource scheduling in software-defined vehicular networks via stochastic learning," *IEEE Trans. Veh. Technol.*, vol. 65, no. 10, pp. 7857–7867, Oct. 2016.

[11] K. L. K. Sudheera, M. Ma, and P. H. J. Chong, "Link stability based optimized routing framework for software defined vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 68, no. 3, pp. 2934–2945, Mar. 2019.

[12] X. Ge, Z. Li, and S. Li, "5G software defined vehicular networks," *IEEE Commun. Mag.*, vol. 55, no. 7, pp. 87–93, Jul. 2017.

[13] X. Duan, Y. Liu, and X. Wang, "SDN Enabled 5G-VANET: Adaptive vehicle clustering and beamformed transmission for aggregated traffic," *IEEE Commun. Mag.*, vol. 55, no. 7, pp. 120–127, Jul. 2017.

[14] Y. Zhu, Q. Zhao, and Q. Zhang, "Delay-constrained data aggregation in VANETs," *IEEE Trans. Veh. Technol.*, vol. 64, no. 5, pp. 2097–2107, May 2015.

[15] C. E. Palazzi, F. Pezzoni, and P. M. Ruiz, "Delay-bounded data gathering in urban vehicular sensor networks," *Pervasive Mobile Comput.*, vol. 8, no. 2, pp. 180–193, 2012.

[16] L. Yao, J. Wang, X. Wang, A. Chen, and Y. Wang, "V2X routing in a VANET based on the hidden Markov model," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 3, pp. 889–899, Mar. 2018.

[17] I. Salhi, M. O. Cherif, and S. Senouci, "A new architecture for data collection in vehicular networks," in *Proc. IEEE Commun.*, 2009, pp. 1–6, 2009.

[18] C. Liu, C. Chigan, and C. Gao, "Compressive sensing based data collection in VANETs," in *Proc. Wireless Commun. Netw. Conf.*, 2013, pp. 1756–1761.

[19] M. Gerla and J. T. Tsai, "Multicluster, mobile, multimedia radio network," *Wireless Netw.*, vol. 1, no. 3, pp. 255–265, 1995.

[20] P. Basu, N. Khan, and T. D. Little, "A mobility based metric for clustering in mobile ad hoc networks," in *Proc. Distrib. Comput. Syst. Workshop*, 2001, pp. 413–418.

[21] C. Wu, S. Ohzahata, and T. Kato, "Can we generate efficient routes by using only beacons? Backbone routing in VANETs," in *Proc. Pers. Indoor Mobile Radio Commun.*, 2013, pp. 2929–2934.

[22] M. A. Togou, A. Hafid, and P. K. Sahu, "A stable minimum velocity CDS-based virtual backbone for VANET in city environment," in *Proc. Local Comput. Netw.*, 2014, pp. 510–513.

[23] S. Ucar, S. C. Ergen, and O. Ozkasap, "Multihop-cluster-based IEEE 802.11 p and LTE hybrid architecture for VANET safety message dissemination," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2621–2636, Apr. 2016.

[24] P. Ngatchou, A. Zarei, and A. El-Sharkawi, "Pareto multi objective optimization," in *Proc. 13th Int. Conf., Intell. Syst. Appl. Power Syst.*, 2005, pp. 84–91.

[25] X. Cheng and B. Huang, "A center-based secure and stable clustering algorithm for VANETs on highways," *Wireless Commun. Mobile Comput.*, vol. 2019, pp. 1–10, 2019.

[26] Y. R. Zaydoun and M. Syed, "A novel algorithm to form stable clusters in vehicular ad hoc networks on highways," *EURASIP J. Wireless Commun. Netw.*, vol. 2012, no. 1, pp. 1–15, 2012.

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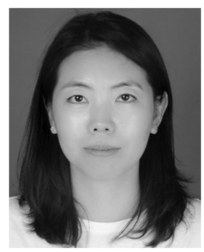

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