Control Plane Optimization in Software-Defined Vehicular Ad Hoc Networks

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He Li, Mianxiong Dong, and Kaoru Ota

***Abstract*—Vehicle ad-hoc network (VANET) is an emerging network technology that is expected to be, cost-effective, and adaptable, making it ideal for providing network connection service to drivers and passengers on today's roads. In the next generation of VANETs with 5G networks, software defined network (SDN) technology will place a very important role for the network management. However, for infotainment applications, high latency in VANET communication imposes a great challenge for the network management while direct communication through the cellular networks brings high cost. In this paper, we present an optimizing strategy to balance the latency requirement and the cost on cellular networks, in which we encourage vehicles send the SDN control requests through the cellular networks by rebating network bandwidth. Further, we model the interaction of the controller and vehicles as a two-stage Stackelberg game and analyze the game equilibrium. From the experiment results, the optimal rebating strategy provides smaller latency than other control plane structures.**

***Index Terms*—Software-Defined Network (SDN), vehicular ad-hoc network (VANET).**

I. Introduction

Vehicle ad-hoc networks (VANET) will playing an important role to provide network connection service for drivers and passengers [1][2]. Meanwhile, fifth generation (5G) cellular networks will improve existing vehiclular communications in performance, user experience, etc.[3][4]. In the development of 5G networks and VANETs, software defined networking (SDN) technology which decouples the network management from the data transferring will be an important approach to the network structure [5][6]. Therefore, a software defined VANET with 5G networks will be a potential network architecture for the next generation VANETs [7].

In the SDN structure, there are two different planes, namely the control plane and data plane. From some prospective works, software defined VANETs will have a similar structure. Usually, the data plane associates with the network devices for transferring network flows, which can be implemented by ordinary hardware with SDN interfaces. For example, in VANET, after adding support for some mature SDN protocols, the roadside units (RSUs), vehicles and cellular networks can be converted to SDN devices for the data plane. Considering unique features of VANETs, where the latency of packet forwarding brings less influence to the network performance in some applications, it is possible to use common memories instead of expensive special hardware, which is an important problem in the data plane [8].

However, with the different network architecture, the control plane especially in the control (management) communication between the controller and the data plane, has new problems to the network performance [9]. With existing technologies, there are three types of control communication structures, VANET based, cellular network based and hybrid structure. In VANET based structure or ad-hoc network based communication, all control events are transferred with network data in the ad-hoc network. In cellular network based structure, the control events will be transferred to the controller through the specific cellular network while hybrid structure combines two former methods where control communication links include both cellular links and the ad-hoc networks [10].

The hybrid structure can make a trade off between the uncertain latency in the ad-hoc networks and the expensive cost of the cellular networks, which is a potential solution of the control plane for the future software defined VANETs. The balancing between ad-hoc networks and cellular networks for transferring control events is an important problem to the hybrid structure. In this paper, we present an optimal method to leverage the latency requirement and the cellular network cost.

We design a rebating mechanism to optimize the southbound communication. In general, the rebating strategy is a type of sales promotion, which uses an amount paid by way of reduction, return, or refund on what has already been paid or contributed. In our mechanism, the controller assigns more network bandwidth to those vehicles which send network control events through the cellular network, in order to use cellular networks for the communication between the controller and the data plane, and then to minimize the network management latency. Therefore, we employ a game-theoretic analysis, and model the interaction between the controller and vehicles as a two-stage leader-follower (Stackel) game. In the first stage, the controller decides the rebated and assigned bandwidth for each vehicle. Accordingly, in the second stage, every vehicle decides how many event packets should be sent by the cellular network. We analyze the best decisions of both the vehicles and the controller, and find the game equilibrium. The game model with equilibrium analysis includes various system settings, including the scale of VANETs, and the bandwidth of the controller managed. As a result, it is possible to apply the derivation of the optimal decisions to other software VANET scenarios.

To evaluate our work, we implement a new application in popular VANET simulators to simulate both VANETs and

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the SDN structure. We use realistic maps, make extensive experiment, and comparing the performance of our solution and that of other solutions. From the simulation, we observe that the rebating strategy based control plane optimization makes a better trade off between the cost and latency than general software defined VANET solutions.

The main contributions of this paper are summarized as follows.

- We first introduce the hybrid control plane structure in software defined VANETs with 5G cellular networks. Based on this structure, we propose a rebating method to make a trade off between cellular network access cost and network control latency. Since the software defined VANET is a prospective technology, our work is the first work to optimize the performance of the control plane.
- We then design the optimal rebating strategy to balance the cost of the cellular network access cost and the SDN management latency, with a thorough understanding of the impact of rebating and assignment of bandwidth on the controller bandwidth management.
- We model the interaction of the controller and vehicles as a two-stage Stackelberg game, and analyze the game equilibrium. The analysis is generic and use variable system settings, which is applicable to different software defined VANET scenarios.
- We carry out the performance evaluation of the strategy with extensive simulations with realistic maps, and discuss the latency and cost in different settings. We also compare our rebating strategy with some other control plane structures and the results show our strategy performs better than others.

The rest of this paper is summarized as follows. Section II reviews the related work. Our network scenario and motivation are introduced in Section III. Section IV presents the problem formulation. An optimal rebating and assignment policy is proposed in Section V. Section VI presents the simulation results. Finally, Section VII concludes this paper and give the future work.

II. Related Work

In this section, we first brief some works to introduce basic knowledges of SDN in VANETs. Then, as a VANET is a type of wireless networks, we discuss some works on wireless southbound communications.

A. SDN in VANETs

Some researchers focus on deploying SDN technology to the wireless network environment, including ad-hoc networks. For example, M.Mendonca et al. [11] proposed an intermediary connection between the ad-hoc network and an infrastructure-based wireless access network to apply SDN in a heterogeneous network. In their work, they use leveraging SDN results in capability of automatically reconfigure for the intermediary communication.

As a VANET is a special ad-hoc network, it is hard to directly deploy general SDN structure for management in VANETs. Therefore, some researchers proposed specific structures of software defined VANETs. I. Ku et al. [6] introduced a SDN controller structure and a SDN-based VANET architecture. Since the network of VANET is different from the ordinary SDNs, they also discuss some potential operating modes and fallback mechanism which are feasible for the VANET environment. Of their design, they also used some simulations to evaluate their architecture by implementing some routing protocols. They also compared their work to the common VANET and the results show the benefits brought by SDN technology.

Moreover, researchers begin to add new components in software defined VANET to support new applications. M.A. Salahuddin et al. [12] proposed RSU cloud architecture in VANET environment by adding a component named RSU microdatacenter. The architecture of the RSU cloud consists of ordinary and SDN enabled RSU to support network virtualization and SDN technology. They also used a cloud controller, a SDN controller and resource manager to control their VANET architecture. Thus, they also leveraged the SDN programmability to support network applications and the network performance in the data plane. N. B. Truong et al. [13] proposed a VANET architecture named FSDN to add support of SDN and Fog computing to VANET. They designed the SDN-based VANET components with their functionality in their architecture. Meanwhile, they add Fog orchestration in the SDN controller to support Fog computing. They also chose a service-oriented sharing model from previous work to support the resource management. At last, they discussed two use cases of their work including data streaming and lane-change service.

B. Wireless Southbound Communication

Since wireless networks bring more latency and packet loss than the traditional SDNs, some previous works focus on control plane problems in wireless networks [14].

First, as wireless communications are different from data center networks, some works proposed specific models for southbound communications. The Open Networking Foundation (ONF) proposed OpenFlow protocol is a possible implementation of controller-switch interaction and also defined the southbound communication between the OpenFlow devices and the network controller [15]. OpenFlow provides support for encrypted Transport Layer Security communication and a certificate exchange between the devices and the controller. ONF also discussed an OpenFlow-enabled mobile and wireless networks structure to extend OpenFlow to the wireless network environment [16].

H. Ali-Ahmad et al. [17] proposed an architecture to support SDN for mobile networks with consideration with dense networks. They designed a southbound interface for managing different networks(e.g., LTE, Wifi, etc.). They focused on the design of the controller to support more network functions in their network architecture.

C. Guimaraes et al. [18] proposed SDN mechanisms with media independent handover services from the IEEE 802.21 standard. They implemented their framework over open-source software in a physical testbed and the results show their

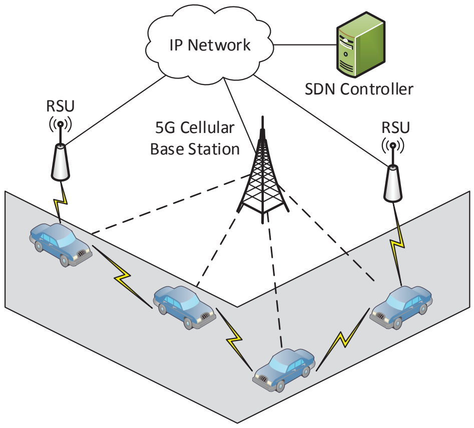


Fig. 1. Software defined VNAT with 5G cellular networks

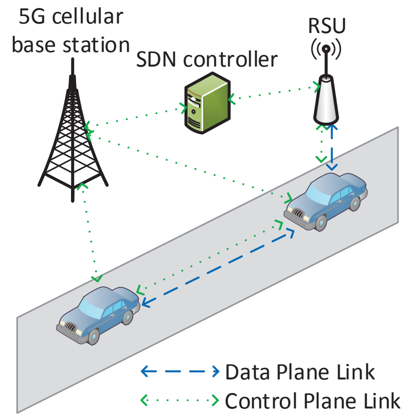


Fig. 2. Control and data planes in a software defined VANET with the 5G cellular network

solution brings in better performance and signaling overhead than some basic approaches.

In these structures, since the controller links the devices through wired connections, southbound communications barely influent the network performance.

Furthermore, more works proposed some solutions on wireless southbound communications. T. Luo et al. [19] proposed Sensor OpenFlow to enable SDN in wireless sensor networks (WSN). Since the TCP/IP connectivity is not available in WSN, they designed a SOF channel as an end-to-end connection to transmit control message between the controller and a sensor. They chose overlaying a WSN transport protocol for the non-IP solution as the southbound communication. For the IP solution, they just simply introduced some existing ready-to-use TCP implementations in WSN to support general OpenFlow protocol.

I. Ku et al. [20] proposed several designs for SDN-based mobile cloud architecture in ad-hoc networks. They designed some components to build their mobile cloud architecture, including variations to accommodate different wireless environment. They inserted an optional local SDN controller in each wireless node to support SDN protocols and communicate with the global controller. For the southbound communication, they assume each SDN-enabled wireless node has a LTE connection with the global controller for control message transmission.

However, in all of above works, there are few considerations on the latency issue in wireless southbound communications, which will seriously decrease the network performance because of large delay in network management.

III. Background and Motivation

In this section, we first present the scenario of software defined VANET with 5G cellular network. Then, we discuss the motivation of the control plane optimization.

A. Software Defined VANET with 5G

Software defined networking, which decouples the control and data planes of transitional networks, is an important technology for the next generation network [21]. Here, we present a scenario that merging the SDN technology into a VANET with 5G cellular networks.

As an example shown in Fig. 1, we assume that each vehicle has a 5G cellular network radio interface, and can connect to the IP network through the cellular base station. Meanwhile, in the VANET, vehicles uses RSUs to connect to the IP network. The SDN controller also connects to the same IP network to manage the VANET, including routing, access control, and flow control. The controller deploys the SDN rules to each RSU and vehicle to execute the forwarding strategies.

To leverage the cost and the performance for the southbound communication, consider the hybrid control network structure in which control events can be sent through either the 5G cellular network or the ad-hoc network. Therefore, for transmitting some emergence control messages, the latency is guaranteed by the high performance cellular network.

For example, if the network operator wants to add a new forwarding strategy in the VANET, it is convenient to insert this strategy to the controller. If a new packet in the corresponding flows comes to a vehicle in the network, the forwarding model can inform the controller for further processing. If the network operator has a low latency requirement, the notification event is sent through the cellular network otherwise the vehicle will send it through the ad-hoc network. After the controller receives this event, it will execute the forwarding strategy and deploy the forwarding rules to each vehicle through an updating event. Similar with the notification event, the controller can also choose the cellular network to send the updating event if the operator has low latency requirement. Then, a vehicle receives the updating event, and forwards the new packet to the next hop.

B. Motivation

In the software defined VANET scenario, since the controller use both the ad-hoc network and the cellular network to control the network, the control plane of this SDN is combined structure of both the 5G cellular network and the VANET.

As an example shown in Fig. 2, the data plane includes the communication modules in the vehicles, the links between vehicles, RSUs and the links between vehicles and RSUs. Different from the SDN structure in wired networks that the control plane only uses specific communication links, the

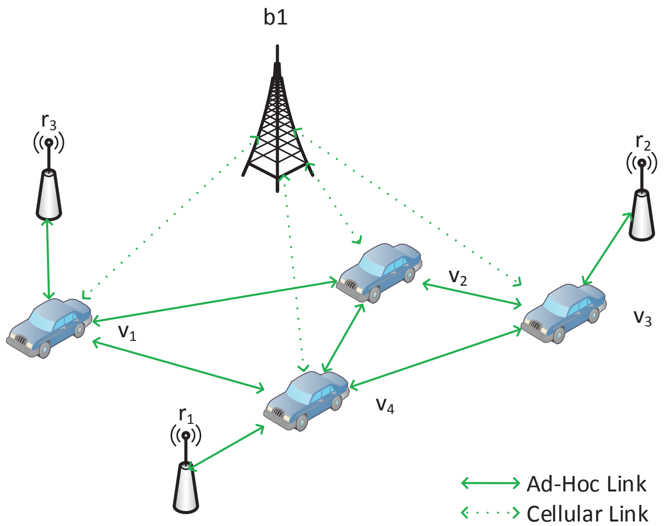


Fig. 3. Illustration of the control plane connections: Vehicles send the control events through both ad-hoc links and cellular links.

control plane in this scenario includes the 5G cellular links between base stations and vehicles and the parts in the data plane due to the hybrid mode in which the SDN controller can use both the 5G cellular network and the ad-hoc network to control the VANET.

Compared to the case that the controller only uses the 5G cellular network, the hybrid mode reduces the cost of the energy and radio spectrum access. Compared to the way without cellular network, the hybrid mode improves the stability of the control plane to guarantee the correctly execution of forwarding strategies.

However, the hybrid control plane brings some difficulty on the communication between the controller and vehicles. First, since the cellular network costs more energy and budget for the network management, it is necessary to use an efficient scheduler to arrange the SDN events to different links with their priority. Second, since a vehicle needs to absorb the cost brought by the 5G cellular network, it needs an incentive mechanism to encourage vehicles to transfer control events through the cellular links. In the following, we design a rebating mechanism that focuses on these two issues and present a two-level game model between the controller and vehicles.

IV. Problem Statement

In this section, we first model the control plane of software defined VANET with 5G cellular networks, then state the problem in the hybrid control plane.

The control plane connection model is shown in Fig. 3. We consider vehicles and RSUs from the ad hoc network and each vehicle has a cellular connection with the base station. The controller controls the ad-hoc network through these connections. For the issues mentioned in Section III-B, we design a rebating mechanism through adjusting the bandwidth of those vehicles who send control events with cellular links. We use set $V = \{v_1, v_2, ..., v_{|V|}\}$ to denote vehicles in the VANET. We also assume a time-slotted system to describe the different network packets transferring in the network and use $T = \{t_1, t_2, ..., t_{|T|}\}$ to denote the T time slots under consideration. The length of each time slot is normalized to unity.

As the VANETs are usually considered as non-profit services [22], we assume the cost of network maintenance in the scenario is paid by the provider and the cost of cellular network is afforded by vehicles. Additionally, we assume the network quality is good enough that the available radio resources of both the cellular network and the ad-hoc network are more than the required bandwidth. Thus, to maintain the VANET, the cost usually includes the energy consumption, and radio access fee from Internet service providers (ISP). To simplify this cost, we use a value c to denote cost per unit of the radio bandwidth. For each vehicle, the controller assigns a basic bandwidth b_i^s for each vehicle. Considering each vehicle has a different requirement of bandwidth, we use b_i to denote the bandwidth assigned to vehicle v_i in the entire time period, let with $b_i \geq b_i^s$. If the data traffic of a vehicle exceeds the assigned bandwidth, we assume the extra packets will be dropped by the VANET. Then, vehicles rent cellular networks from the mobile network operators to transfer the control events to the controller. We use r_i to denote the cost that vehicle v_i pays for cellular links per packet. Then, considering the energy cost from the network devices, we use e_i^c to denote the energy consumption that vehicle v_i uses for sending one packet through the cellular link and use e_i^a to denote the energy cost through the ad-hoc link.

The controller rebates the bandwidth to the vehicles which send network events to the controller to encourage them to send more. With more control events through cellular links, the latency brought by the communication between the control plane and the data plane can be decreased. Rebated bandwidth is not fixed but depends on the amount of the event packets sent by cellular networks. We use η_i to denote the rebated bandwidth per packet of vehicle v_i in time period T. When vehicle v_i sends one event packet with the cellular link, the controller will increase eta_i units of bandwidth. We consider the controller can provide different rebated bandwidth for vehicles according to the different weight of ad-hoc links in the VANET.

The strategy of the controller includes the bandwidth arrangement and the rebating ratio η_i. The value of η_i is come from the ratio of the cost of rebated bandwidth and the cellular data usage. If the cost of rebated bandwidth is more than cellular data usage, it is better to pay the cellular cost rather than bandwidth rebating. Thus, we assume the value of η_i is no more than 0.9. The objective of the controller is to decide the best strategy to minimize the latency. The bandwidth fee is stable during the entire time period, while the rebated bandwidth ratio eta_i and allocated bandwidth b_i remain unchanged in one time period of T slots, but may vary across different periods. Therefore, the controller is able to adjust the arranged bandwidth and the rebated bandwidth across the time period.

For vehicle v_i, we define a utility function $U_i(\cdot)$ to denote bandwidth needs. The utility function is defined to computes

TABLE I
NOTATIONS IN THE SOFTWARE DEFINED VANET MODEL

Notation	Description
V	Set of all vehicles
v_i	One vehicle in set V
T	Set of all time slots
t_j	One time slot in set T
c	Rate that the VANET rents bandwidth from ISP
b_i	Bandwidth arranged to vehicle v_i in time period T
r_i	Rate that vehicle v_i pays for cellular links
e_i^c	Energy consumption for vehicle v_i sending one packet through the cellular link
e_i^a	Energy consumption for vehicle v_i sending one packet through the ad-hoc link
η_i	Rebating ratio for vehicle v_i in time period T
k_{ij}	Number of packets that vehicle v_i want to transfer in time slot t_j
k_i	Vector of the number of packets sent by vehicle v_i in the entire time period
s_{ij}	Number of event packets transferred by vehicle v_i through the cellular links in time slot t_j.
s_i	Vector of s_{ij} in time period T
s_{ij}^t	Event packets to be sent by vehicle v_i in time slot t_j
l_{ij}^a	Latency of the vehicle v_i send one event packet in time t_j through the ad-hoc network
l_i^c	Latency of the vehicle v_i send one event packet in time period T through the cellular network

the utility of assignment bandwidth to vehicle v_i. As we seek an elastic model of the rebating strategy, user utility function is compatible with multiple previous models [23] [24]. We use k_{ij} to denote the number of packets that vehicle v_i can transfer in time slot t_j, and $k_i = (k_{ij},\ t_j \in T)$ as vector of the number of packets can be sent by vehicle v_i in the entire time period.

Each vehicle v_i can get the bandwidth from the controller in two different ways, including using the arranged bandwidth from the controller and getting the rebated bandwidth by sending control events through the cellular link. The cellular link brings additional cost including the access rate from the mobile network operators and the energy consumption. We use s_{ij} to denote the number of event packets transferred by vehicle v_i through the cellular links in time slot t_j, and s_i to denote the vector of s_{ij} in time period T. Thus, we use k_{ij}^r to denote the bandwidth from the rebating mechanism of vehicle v_i in time slot t_j and this part of bandwidth is given by

$$k_{ij}^r = \eta_i \cdot s_{ij}. \tag{1}$$

With k_{ij}^r and the bandwidth arranged by the controller, we get the total number of packets in time slot t_j as

$$k_{ij} = b_i + \eta_i \cdot s_{ij}. \tag{2}$$

The total cost for the needed bandwidth of vehicle v_i in time slot t_j is

$$r_{ij}^t = s_{ij} \cdot (r_i + e_i^c) + b_i \cdot e_i^a. \tag{3}$$

We list all notations used in the rebating strategy of the software defined VANET model in Table I. The system is assumed to be quasi-static, as some variables (i.e., those marked with the subscript j) may change in different time slots, while others are fixed in the entire time period.

We focus on interactions of the controller and vehicles, and formulate the process as a two-stage leader-follower (Stackelberg) game. A Stackelberg game is an economic model in which the leader moves before the follower. In the game terms, the game players are a leader and a follower and they compete on quantity. The game players are the controller and the vehicles in a VANET. In the first stage, the controller (leader) decides the arranged bandwidth and rebating ratio. The object of the controller is to maximize its payoff, which depends on network latency for SDN structure and the cost of purchasing bandwidth from ISPs. In the second stage, every vehicle v_i decides the number of control event packets to be sent via a cellular link. The object of each vehicle v_i is to maximize its payoff, which depends on the utility U_i from the number of packets to be sent, the payment and energy consumption on the cellular access, and the energy consumption for the ad-hoc links.

Specifically, given strategy (b_i, η_i) of the controller, the payoff of vehicle v_i, when choosing a strategy (s_i), is

$$J_i(s_i; b_i, \eta_i) = U_i(k_i) - \sum_{j=1}^{|T|} [s_{ij} \cdot (r_i + e_i^c) + b_i \cdot e_i^a]. \tag{4}$$

For the controller, since the latency is relevant to vehicle positions, we use l_{ij}^a to denote the latency when the vehicle v_i send one event packet in time t_j through the ad-hoc network. Assuming that latency does not change with the cellular link, we use l_i^c to denote the latency when the vehicle v_i sends one event packet through the cellular network in time period T. For simplifying the problem, each network flow only needs at maximum one control event packet for management and the dissipation is a latency summation of all network flows. Therefore, we use s_{ij}^t to denote the total packets to be sent by vehicle v_i in time slot t_j. We use l_{ij} to denote latency brought by the control events sent by vehicle v_i in time slot t_j, given by

$$l_{ij} = l_i^c \cdot s_{ij} + l_{ij}^a \cdot (s_{ij}^t - s_{ij}). \tag{5}$$

Then, let c_i^b denote the cost for purchasing bandwidth from ISPs for vehicle v_i in time slot t_j, given by

$$c_i^b = c \cdot (b_i + \eta_i \cdot s_{ij}). \tag{6}$$

Formally, the controller's payoff can be defined as

$$\begin{aligned} V(b, \eta; (s_i)_{v_i \in V}) = -\sum_{i=1}^{|U|} \sum_{j=1}^{|T|} [l_i^c \cdot s_{ij} + l_{ij}^a \cdot (s_{ij}^t - s_{ij}) \\ + c \cdot (b_i + \eta_i \cdot s_{ij})]. \end{aligned} \tag{7}$$

In the following, we find the game equilibrium in the arranging and rebating strategy with the controller and vehicle's payoff functions.

V. OPTIMAL ARRANGING AND REBATING STRATEGY

In this section, we study the controller-vehicle game under complete information, where both the controller and the vehicles know all system parameters. We solve the game by backward induction. First, we solve the vehicle's best cellular usage strategy in the second stage. Then, we study the controller's best arranging and rebating strategy in the first stage.

A. Best Decision of Vehicles in the Second Stage

We assume that the number of packets sent by the vehicles is elastic such that the analysis can be easily extended to other scenarios. Specifically, given the controller's bandwidth assignment and rebating strategy (b_i, η_i), vehicle v_i can derive the optimal scheduling strategy (s_i) by solving the problem,

$$\begin{aligned} &\max_{s_i} \quad J_i(s_i; b_i, \eta_i) \\ &s.t., \quad 0 \le s_{ij} \le s_{ij}^t, \quad i \in [1, |V|], j \in [1, |T|]. \end{aligned} \tag{8}$$

It is easy to check that (8) is a convex optimization. Hence, it has an optimal solution that can be characterized by the KKT conditions. We first study the optimal strategy (s_{ij}^*) in a particular slot t_j (fixed the scheduling decisions in other $T-1$ slots), and then study the optimal strategy $(s_i^*) = (s_{ij}^*)_{t_j \in T}$ of all T slots jointly, which is the solution of (8).

Now we consider the strategy in a single slot, t_j. We first use a strategy that converge to the optimal single-slot strategy. Then, we characterize the optimal scheduling step by step.

We use f_{ij} to denote the first-order derivatives of payoff $J_i(\cdot)$ for vehicle v_i with respect to s_{ij},

$$\begin{aligned} f_{ij} \triangleq \tfrac{dJ_i(s_{ij})}{ds_{ij}} = U_i'(k_{i,-j}^*, k_{ij}^*) - r_i - e_i^c = \\ U_i'(b_i + \eta_i \cdot s_{i,-j}^*, b_i + \eta_i \cdot s_{ij}^*) \cdot \eta_i - r_i - e_i^c. \end{aligned} \tag{9}$$

In (9), $k_{ij}^* = b_i + \eta_i \cdot s_{ij}^*$ and $k_{i,-j}^* = (b_{ik} + \eta_{ik} \cdot s_{ik}^*)_{t_k \in T, k \neq j}$. We can find that $f_{ij} = 0$ when $U_i'(s_{i,-j}^*, s_{ij}^*) = r_i + e_i^c$, the strategy in time slot t_j is optimal. We use s_{ij}' to denote the value that makes $f_{ij}(s_{ij}) = 0$. Then, we analyze the constraints of s_{ij}. When $s_{ij}' \notin [0, s_{ij}^t]$, the payoff function is monotonic. Thus, when $f_{ij}(s_{ij}^t) > 0$, since the payoff function is monotonic increasing, the optimal solution is s_{ij}^t. Otherwise, the optimal solution is 0, which means that the vehicle sends all event packets through the ad-hoc network.

Lemma 1: The optimal solution of (s_{ij}^*) for the single-slot strategy is given by

$$s_{ij}^* = \begin{cases} 0, & s_{ij}' \notin [0, s_{ij}^t], f_{ij}(s_{ij}^t) < 0 \\ s_{ij}^t, & s_{ij}' \notin [0, s_{ij}^t], f_{ij}(s_{ij}^t) > 0 \\ s_{ij}', & s_{ij}' \in [0, s_{ij}^t] \end{cases} \tag{10}$$

$$\text{where } s_{ij}' = [arg_{s_{ij}} U_i'(b_i + \eta_i \cdot s_{i,-j}^*, b_i + \eta_i \cdot s_{ij}) = \frac{r_i + e_i^c}{\eta_i}]_0^{s_{ij}^t}.$$

Since in a practical network, the number of packets forwarded by vehicles is an integer, the strategy from the Lemma 1 is not realistic. Therefore, we design an algorithm to decide the optimal event packets forwarded by vehicle v_i in time slot t_j as given in Algorithm 1. In this algorithm, we first set the s_{ij} to 0 and if $f_{ij}(0) < 0$, the solution is $s_{ij} = 0$. If the value of $f_{ij}(0)$ is larger than 0 , we use a loop to add the value of s_{ij} by one in each iteration until the $s_{ij} = s_{ij}^t$, or the value of $f_{ij} \le 0$.

Now we study the optimal strategy $(s_i^*) = (s_{ij}^*)_{t_j \in T}$ of the time period T. Since each vehicle will send all event packets in each time slot, there is no influence between neighboring slots. Therefore, we give the optimal solution in Lemma 2.

Algorithm 1 Single-Slot Strategy

```
Initialization: s_ij ← 0
while (s_ij ≤ s^t_ij) and (f_ij(s_ij) > 0) do
    s_ij ← s_ij + 1;
end while
```

Lemma 2: The optimal solution of (s_i^*) for the time period T in (8) is

$$s_i^* = \bigcup_{j=1}^{|T|} s_{ij}^*$$

$$\text{where } s_{ij}^* = \begin{cases} 0, & s_i' \notin [0, s_{ij}^t], f_{ij}(s_i^t) > 0 \\ s_{ij}^t, & s_{ij}' \notin [0, s_{ij}^t], f_i(s_i^t) < 0 \\ s_{ij}', & s_{ij}' \in [0, s_{ij}^t] \end{cases} \tag{11}$$

$$\text{and } s_{ij}' = [arg_{s_{ij}} U_i'(b_i + \eta_i \cdot s_{ij}) = \frac{r_i + e_i^c}{\eta_i}]_0^{s_{ij}^t}.$$

Thus, for less time complicity, we choose optimization learning from the binary search algorithm and propose an algorithm for the decision of vehicles as Algorithm 2.

Algorithm 2 Strategy for Time Period T

```
Initialization: s*_i ← ∅
for j ← 1 to T do
    if (f_ij(s^t_ij) > 0) then
        s*_ij ← s^t_ij;
    else
        s_b = s^t_ij;
        s_e = 0;
        while (s_b > s_e) do
            if (f_ij(s*_ij) > 0) then
                s*_ij ← s*_ij + (s*_ij + s_b)/2;
                s_e ← s*_ij;
            else if (f_ij(s*_ij) < 0) then
                s*_ij ← (s*_ij + s_e)/2;
                s_b ← s*_ij;
            else if (f_ij(s*_ij) = 0) then
                break;
            end if
        end while
    end if
    s*_i ← s_i ∪ {s*_ij};
end for
```

First, the algorithm sets s_i^* as an empty set and calculate each s_{ij}^* in different time slot t_j. For each s_{ij}^* in time slot t_j, we first check the value of $f_{ij}(s_{ij}^t)$ as one condition in (11). If the value is larger than 0, the solution of s_{ij}^* is s_{ij}^t else we choose the binary search to find the solution. In the binary search, we use s_b and s_e to denote highest and lowest inclusive values that are searched. After the binary search procedure, the solution of s_{ij}^* is put to the set of s_i^*. Finally, after solutions for all s_{ij}^* are calculated, the result of set s_i^* is the solution for vehicle v_i in time period T.

B. Best Decision of the Controller in the First Stage

Now we want to find the best decision of the controller to maximize its payoff. From the (7), since the result of the payoff function is negative where all b_i, η_i are nonnegative, we define the problem in the first stage is minimizing the negative value of the payoff function, i.e., the cost of the controller $V_i^c(\cdot) = -V_i(\cdot)$. Therefore, give the vehicle v_i's decision of the scheduling strategy (s_i), the controller can derive the optimal bandwidth assignment and rebating strategy (b_i, η_i) by solving the following problem:

$$\begin{aligned} \min_{b_i,\eta_i} \quad & V_i^c(b_i, \eta_i; s_i^*) \\ s.t., \quad & b_i \geq b_i^s, \\ & \eta_i \in [0, 0.9], \\ & s_i^* \text{ is solved in (8) }, \\ & i \in [1, |V|], j \in [1, |T|]. \end{aligned} \tag{12}$$

To simplify the problem, we only consider the solution where $s'_{ij} \in [0, s^t_{ij}]$. Therefore, it is easy to check that (12) is a convex optimization. Hence, it has an optimal solution that can be characterized by Fermat's theorem.

Let $g_i(\cdot)$ and $h_i(\cdot)$ denote the first-order derivatives of the controller's payoff from vehicle v_i with respect to b_i and η_i, given by

$$\begin{aligned} g_i(b_i, \eta_i) = \frac{\partial V_i^c}{\partial b_i} = \textstyle\sum_{j=1}^{|T|}[(l_i^c - l_{ij}^a + \eta_i \cdot c)\frac{\partial s_{ij}^*}{\partial b_i} + c] \\ h_i(b_i, \eta_i) = \frac{\partial V_i^c}{\partial \eta_i} = \\ \textstyle\sum_{j=1}^{|T|}[(l_i^c - l_{ij}^a + \eta_i \cdot c)\frac{\partial s_{ij}^*}{\partial \eta_i} + c \cdot s_{ij}^*]. \end{aligned} \tag{13}$$

When $g_i(b_i, \eta_i) = 0$ and $h_i(b_i, \eta_i) = 0$, the value of function $V_i^c(b_i, \eta_i)$ can get the extrema. However, from the solution in Lemma 2, since $U'_i(b_i + \eta_i \cdot s_{ij}) = \frac{r_i + e_i^c}{\eta_i}$, it is easy to get the value of $\frac{\partial s_{ij}^*}{\partial b_i}$ is 0. Therefore, the value of $g_i(b_i, \eta_i)$ is $c \cdot |T| \neq 0$, which means that $V_i^c(b_i, \eta_i)$ is monotone increasing with b_i. As a result, in the strategy of the controller, the value of b_i is always equal to the bandwidth for the basic service b_i^s.

Therefore, the problem of (12) can be simplified to one variable problem as

$$\begin{aligned} \min_{\eta_i} \quad & V_i^c(\eta_i; s_i^*) \\ s.t., \quad & \eta_i \in [0, 0.9], \\ & s_i^* \text{ is solved in (8) }, \\ & i \in [1, |V|], j \in [1, |T|], b_i = b_i^s. \end{aligned} \tag{14}$$

Similarly, we can get the value of $\frac{\partial s_{ij}^*}{\partial \eta_i}$ as

$$\frac{\partial s_{ij}^*}{\partial \eta_i} = -(\frac{e_i^c}{U''_i(b_i^s + \eta_i \cdot s_{ij}^*) \cdot \eta_i^3} + \frac{s_{ij}^*}{\eta_i}). \tag{15}$$

Then, $h_i(\cdot)$ can be derived as

$$\begin{aligned} h_i(\eta_i) = \\ \sum_{j=1}^{|T|}[(l_{ij}^a - l_i^c) \cdot (\frac{e_i^c}{U''_i(b_i^s + \eta_i \cdot s_{ij}^*) \cdot \eta_i^3} + \frac{s_{ij}^*}{\eta_i}) \\ - \frac{e_i^c \cdot c}{U''_i(b_i^s + \eta_i \cdot s_{ij}^*) \cdot \eta_i^2}]. \end{aligned} \tag{16}$$

Thus, we can get the optimal strategy η_i^* by solving equation $h_i(\eta_i) = 0$, where $h'_i(\eta_i^*) < 0$ and $\eta_i^* \in [0, 0.9]$.

Algorithm 3 Newton's method for solving the game equilibrium

1: Find $h'_i(\eta_i^0) < 0$ as a given guess;
2: $\eta_i \leftarrow \eta_i^0$;
3: $\eta'_i \leftarrow 0$;
4: **while** $\eta'_i - \eta_i > \Delta$ **do**
5: $\quad \eta_i \leftarrow \eta'_i - \frac{h_i(\eta'_i)}{h'_i(\eta'_i)}$;
6: $\quad \eta'_i \leftarrow \eta_i$;
7: **end while**
8: **if** $h'_i(\eta_i) < 0$ **then**
9: $\quad \eta_i^* \leftarrow \eta_i$;
10: **end if**

Since the game equilibrium needs a solution of a binary nonlinear equation set, we use Newton's method which is a popular iterative method to solve the nonlinear equation set. As shown in Algorithm 3, we first find η_i^0 as a given guess of the solution and assign this value to η_i. We use η'_i to store the temporary value in the iterations. Initially, the value η'_i is set to 0. The newton's iteration is shown in the while loop and we use a bound value Δ to describe the precision of the numeric solution. When the difference between solutions from two iterations is small than Δ, the algorithm stops the iteration. After that, if solution η_i meets the condition $h'_i(\eta_i^*) < 0$, the game equilibrium is solved. Otherwise, we try to find another value as initial guess and execute the algorithm again.

VI. Performance Evaluation

In this section, we evaluate the performance and cost of the southbound communication in the software defined VANET with the cellular network with simulations. First, we introduce the simulation settings and tools. Then, we discuss the latency and cost in different settings.

A. Simulation Setting

In our simulations, we use a simulator based method to evaluate our solution with a real world map and get more realistic latency in the ad hoc connections.

The simulation settings include two parts: the simulator and the networks. For simulations, we use an ordinary PC with Intel i7 4770 processor (8M Cache, up to 3.90 GHz), 16 GBytes RAM and 2 TBytes HDD. This simulator set includes SUMO [25], OMNeT++ [26], and Veins [27].

With these simulation applications, we introduce the map settings. We first use map data from OpenStreetMap (Higashi Muroran, Japan). After download the OSM data, we use the tool set provided by SUMO to transfer map data to the route data. Meanwhile, based on the route data, SUMO also generates vehicle data.

With map and traffic data, we add RSUs into the map for the VANET connections. We choose the RSU component provided by Veins and add some codes in the original wireless connection component to get the packet history and related latency. After that, simulator Veins connects the Map and route data in SUMO and network components in OMNeT++, and generates the dynamic VANET topology.

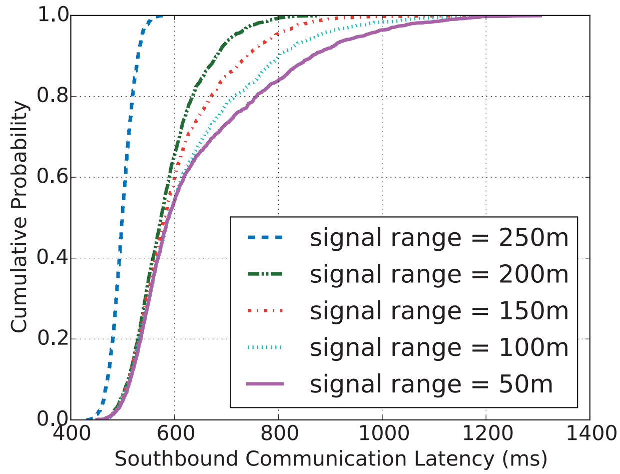


Fig. 4. Southbound communication latency with different signal range of RSUs

In all simulations, we set the time period is 1000 seconds and the time slot to 1 second. There are a total of 1000 vehicles in the whole time period and for each vehicle, the maximum speed is evenly distributed in [18, 28] meters per second. The length of each vehicle is evenly distributed in [1.5, 11] meters. Meanwhile, each vehicle begins its trip from random time with a random distance. The begin time is evenly distributed in the whole simulation time period and the running distance is evenly distributed in [10, 88] kilometers where 88 kilometers are total distance of map data.

With the map and traffic data, we use 20 RSUs in the simulation to connect the VANET. For each RSU, we use 802.11p WiFi components to connect RSUs and each vehicle. We adjust the transmission range from 50 to 250 meters in the simulations. Each vehicle has a cellular link for the southbound communication.

The network settings has two types of network communication. For the data plane, we adjust the number of flows from each vehicle from 5 to 25 and, for each flow, we set the number of packets per second is evenly distributed in [0, 600]. For the control plane, we set the number of packets for rule placement to evenly distributed in [1, 5]. To simplify the simulations, we consider that the controller only places rules when a new flow comes to the network.

We set the rate that the VANET rents bandwidth from ISP is 4 Japanese yens per Mbps which is an average rate in Japan. The rate that vehicle pays for cellular links is set to 1 yen per 1 mega byte. The size of each event packet is 1 kilobyte. The latency of the cellular links is adjusted from 100 milliseconds to 1 second.

For comparison, we use two simple pricing strategies,i.e., pay-as-use mode and long-term renting mode as follows.

(1) Cellular mode: There is no cellular link for the southbound communication. All event packets are sent by the ad-hoc network.
(2) Ad-hoc mode: All event packets are sent by the cellular network.

B. Result Analysis

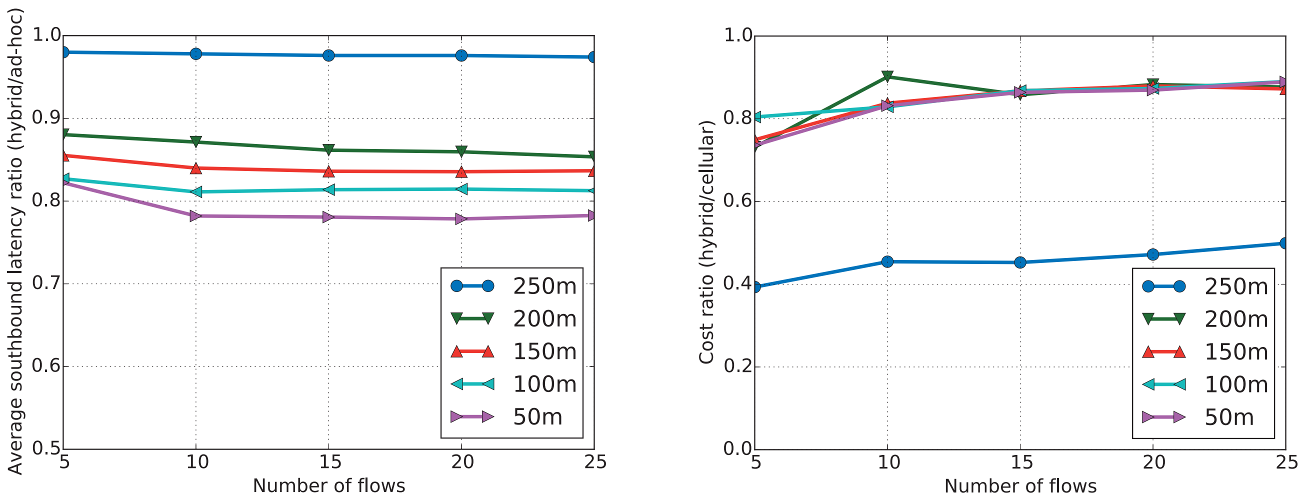
Before the performance evaluation, we first study the communication latency of the ad hoc network in our simulation environment. We adjust the signal transmission range from 50 meters to 250 meters and the signal range decreases by 50 meters in each step. Then, we calculate the cumulative distribution function of smallest latency between each vehicle and RSUs as shown in Fig. 4.

Obviously, the latency with a larger signal transmission range can reduce the latency in the ad-hoc connections. From the latency result, when the signal range is less than 100 meters, the latency will be much worse since ad-hoc communication needs more hops between vehicles and the nearest RSU. When the signal range is set to 250 meters, the latency is near 500 milliseconds when there is average one hop between each vehicle and the RSU, i.e., the signal covers the whole map. In the rest simulations, we test the performance with these five different latency sets.

We study the cost of the proposed rebating strategy under different numbers of network flows from each vehicle during its running in the VANET. The number of network flows increases from 5 to 25 and the number increases by 5 in each step. We set the latency of the cellular links to 500 milliseconds. As shown in Fig.5(a) , the average latency decreases as the number of flows increases. The hybrid mode performs better than the ad-hoc mode and has the performance very close to that of full cellular mode especially with more flows per vehicle. The latency of southbound communication increases as the signal range decreases. When the signal range is 250 meters, the latency with the hybrid mode is less than that of the cellular mode. When the signal range decreases, since the latency of ad-hoc connections is larger, the average latency of southbound communication also becomes larger with both hybrid and ad-hoc mode. However, compared to the latency of the cellular mode, latency of the hybrid mode increases by no more than 30 milliseconds while the latency with ad-hoc mode increases by 160 milliseconds when the signal range becomes 50 meters.

From the results shown in Fig. 5(b), the cost of the hybrid mode is similar with different signal range except the signal range of 250 meters. With large signal range, the hybrid mode can use ad-hoc connections more frequently to reduce the access fee from the cellular network and the latency also is better than that in the cellular network. While the signal range becomes smaller, as the number of flows of each vehicle increases, the cost increases linearly. When the signal range is no more than 200 meters, the cost of the hybrid mode is close to 89% of the cellular mode. However, the average latency only increases by less than 6%. Obviously, the cost efficiency of hybrid mode is better than cellular mode even with a small signal range.

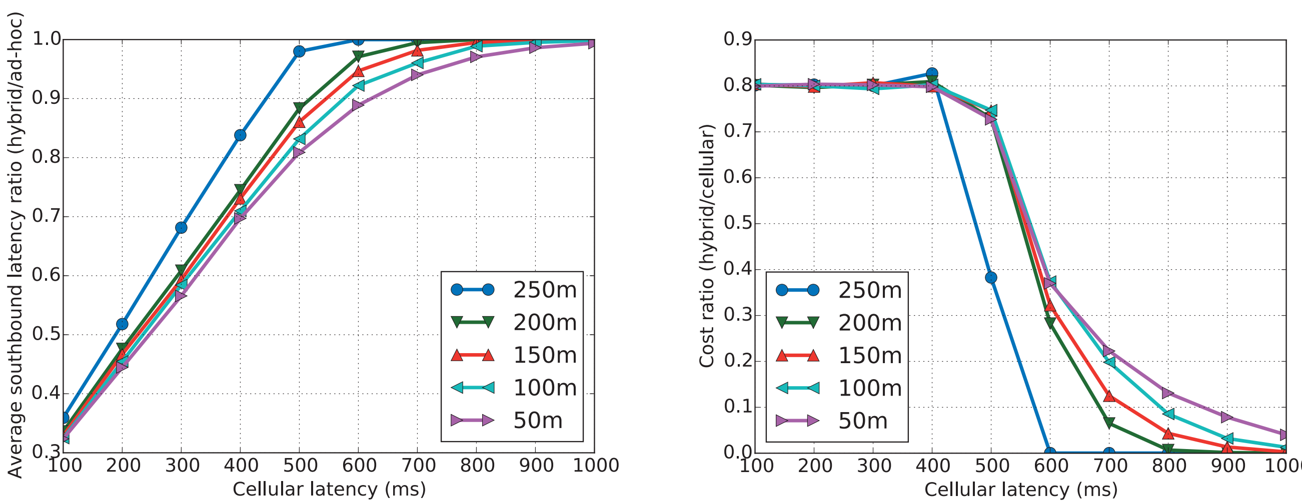
Then, we study the latency of southbound communication with different cellular network performance. We set the number of flows per vehicle to 5 and adjust the latency of the cellular network from 100 milliseconds to 1 second. As show in Fig. 6, the average latency of southbound communication with hybrid mode increases as the latency of the cellular



(a) Average southbound latency

(b) Cost

Fig. 5. Average latency of southbound communication and cost with different number of flows per vehicle



(a) Average southbound latency

(b) Cost

Fig. 6. Average latency of southbound communication and cost with different latency of the cellular connections

network increases. With different signal range of RSUs, the latency of the ad-hoc connections is also different. Since there is no influence from the cellular network, latency with the ad-hoc mode stays the same. When the latency of the cellular network increases to more than latency of the ad-hoc connections, the latency with hybrid mode does not increase any more. With a less signal range, the latency value with hybrid and ad-hoc modes becomes the same, and is larger with higher latency in the ad-hoc network.

From the result shown in Fig. 6(b), the cost of the hybrid mode varies when the ad-hoc network performs similarly with the cellular network. When the cellular network performs much better than the ad-hoc network, the cost of the hybrid mode is nearly the same. From the simulation result, the cost of high performance cellular network is less than 3 yen in 1000 seconds running period. When the performance of the cellular network become worse than the ad-hoc network, the cost of the hybrid mode dramatically decreases. The cost with hybrid mode is near 0 when the latency of the cellular network is more than 600 millisecond. With less signal range, since the average latency of the ad-hoc network becomes larger, the cost of the hybrid mode increases with the same latency of the cellular network.

As a result, from the plots of the average latency and cost with different latency of the cellular network, a very important message is that the performance of cellular networks will bring great influence to the software defined VANET. Even with weak ad-hoc network and sparse RSU coverage, the performance of the control plane in the software defined VANET is still satisfactory in the future 5G cellular network environment.

VII. Conclusion and Future Work

In this paper, we propose a scenario that uses hybrid mode for the southbound communication in the control plane of software defined VANET with 5G cellular networks. Since the ad-hoc connections bring higher latency than high performance cellular networks while cellular networks cost much more energy and budget than the ad-hoc network, we design a bandwidth rebating strategy to balance the cost and performance in the southbound communication. We formulate the bandwidth rebating problem as a two-stage leader-follower (Stackelberg) game, and analyze the game equilibrium. We also evaluate our hybrid mode with extensive simulations and compare its performance and cost with other southbound communication mode. From the result of performance evaluation, the hybrid southbound communication mode archives the balancing of the network cost and the network performance for the software defined VANET.

In the future, we plan to implement a complete software defined VANET in the simulator including a VANET controller and modified SDN protocols. Meanwhile, it is significant to build secure southbound communication between the vehicles and the controller. A deeper experiment with the real world testbed is also needed to evaluate the efficiency of the new software defined VANET with future 5G cellular networks.

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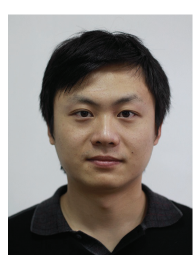

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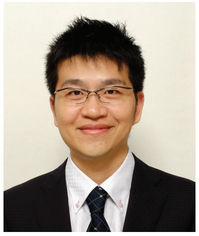

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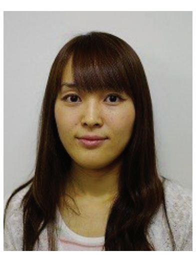

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