Adaptive Transmission Control for Software Defined Vehicular Networks

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***Abstract*—Efficient transmission control is an intricate issue in vehicular networks due to the inherent topology dynamics and unreliable link conditions. Leveraging flexible management in software-defined vehicular networks, we propose a Software-defined Adaptive Transmission Control Protocol (SATCP) for selecting various transmission control policies to adapt to the time-varying vehicular environment. We formulate the optimal transmission control problem, and develop a practical heuristic algorithm for adaptive transmission control. NS-3 based preliminary simulations are conducted to verify that SATCP achieves an improvement by 27.8% than TcpHtcp, and by 54.4% than TcpVegas in terms of average network throughput.**

***Index Terms*—adaptive transmission, protocol design, software-defined network, vehicular networks.**

I. INTRODUCTION

INTERNET of Vehicles (IoV) is emerging as a convergence of Internet of Things (IoT) and mobile vehicles. It greatly promotes information sharing on road conditions and surrounding environments among vehicles, roadside units, and other things. Currently, vehicle-to-everything (V2X) interaction and its enhancement (eV2X) have become key drivers for Fifth Generation (5G) mobile communications, and present great opportunities for new businesses in specific vehicular scenarios, *e.g.,* self-driving, traffic management, and automatic parking [1]. Although IoV has been extensively investigated, it inherits some limitations from the ossificated Internet architecture. Meanwhile, it faces enormous challenges arising from vehicular peculiarities, *e.g.,* dynamic topology, intermittent connectivity and frequent link interruptions [2]. Unfortunately, the current hardwired network is difficult to adapt to such high-dynamic IoV conditions and diversified service requirements [3].

Software defined networking (SDN) is an emerging networking paradigm, which enables rapid network innovation. Different from the "rigid" design of traditional network architecture, SDN decouples control and data planes to build a programmable and flexible network. Meanwhile, with a logically centralized controller, SDN can significantly simplify network management by removing a mass of inefficient distributed negotiation overhead, and manages network resources efficiently [4].

Recently, several researchers propose to enhance IoV by using SDN, referred to as software-defined vehicular networks (SDVN) [5]. Many important issues have been investigated in SDVN, including access control, edge computing, and resource management [6]–[9]. For instance, Quan *et al.* proposed an architecture to promote crowd collaboration for SDVN [6]; and Xu *et al.* proposed a game-theoretic stochastic learning algorithm for distributed decision-making in dynamic network access [8]. However, efficient transmission is still crucial to improve the end-to-end transmission in IoV [10]. Most of the existing transmission protocols, *e.g.*, TCP variants, were originally for the wireline networks, and their performance, such as in packet loss and delay, are greatly sensitive to the network environment, which makes them have difficulty to adapt to the dynamic IoV environment.

SDVN provides a potential solution to flexibly selected, configured and optimized the transmission protocol from a global view to improve the IoV flexibility and performance. However, to the best of our knowledge, there is few work focusing on the transmission control issue in SDVN. This letter is the first work to investigate on the practical issues in adaptive transmission control for SDVN. In particular, we focus on how a controller schedules different control policies to adapt to varying vehicular environments. The main contributions are summarized as follows:

- We propose a Software-defined Adaptive Transmission Control Protocol (SATCP) for vehicular networks, which details how an SDN controller selectively schedules different transmission control policies and then negotiates with the control units at the base stations to adapt to varying vehicular requirements.
- We formulate the transmission control optimization problem for the policy scheduling, and propose a practical heuristic algorithm in the transmission control engine. We conduct NS-3 based simulations to demonstrate how SATCP improves the performance by comparing with two other state of the art solutions.

II. SYSTEM MODELS AND ANALYSIS

A. Network Model

Each vehicle has multiple network access means including V2I with LTE, V2R with WiFi, and V2V with WAVE. Their respective link quality are denoted by q_I, q_R, and q_V. The vehicle can dynamically adjust its network access means according to the software defined access management [7]. Consider vehicles with various mobility statuses such as stationary, small-scale mobility and large-scale mobility, and each vehicle is initially located at an arbitrary location in a plane. Without loss of generality, we analyze the transmission control for one of these vehicles. An appropriate generic model

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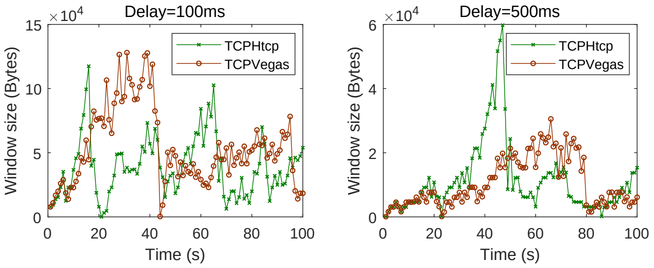

Fig. 1. Reactions (adjusting window size) of transmission control methods

is considered for the location of vehicles placed in a plane $\mathbb{R}^2$ according to a homogeneous spatial Poisson process with density λ [11]. Each vehicle can make connections with a certain server, which can be a remote cloud or a media server. Since vehicles are distributed according to a homogeneous spatial Poisson process, the number of vehicles within a targeted circle with a radius, r, follows a Poisson distribution with the parameter, $x = \lambda \pi r^2$. Thus, the probability of n vehicles in the targeted area is:

$$P\left(n \text{ vehicles with radius } r\right) = \frac{x^n}{n!} e^{-x}. \tag{1}$$

We assume the V2I access is stable in the targeted area, and thus q_I is a constant. The quality of V2R links varies with the capacity of the WiFi network and the number of associated vehicles. For example, the V2R rate can be calculated by $q_R = \frac{\eta R}{m}$, where η is a MAC throughput effective factor, R is WiFi network capacity, and m is number of vehicles within a WiFi coverage area. The quality of V2V links varies with the number of vehicles inside the target area. The more vehicles, the more available V2V links, then the better link quality. Thus, to be simple, we assume a relation $q_V = k \cdot n$, where n is the number of vehicles and k is a coefficient factor. Based on this, we can build a general network model for vehicular communication networks, but we should further clarify a clear transmission process.

B. Transmission Model

For the transmission model, we consider that the vehicle conducts a connection-oriented data retrieval. Transmission control works during the whole transmission to provide a reliable end-to-end data delivery over an unreliable link. A *window*-based transmission control can be used to model this transmission process [12]. Specifically, the sender keeps a variable window that determines the maximum number of packets allowed to be transmitted. When the window size is exhausted, the sender has to wait for new window space before sending a new packet.

Let $w(t)$ denote the window size of the sender at time t, and T denote the round-trip time (propagation plus queueing delay), which is assumed to be constant. Thus, $x(t) := w(t)/T$ is the sending rate at time t. Let $s(t)$ be the loss rate, which represents the end-to-end link quality. The key task is to model the sending rates $x(t)$ interacting with link status $s(t)$.

Consider that every packet is acknowledged when received. Each positive acknowledgement increases the window $w(t)$ by $1/w(t)$. Each negative acknowledgement (loss) halves the window. Hence, the dynamic of the window in period t is:

$$\dot{w} = x\left(t\right)\left(1 - s\left(t\right)\right)\frac{1}{w\left(t\right)} - x\left(t\right)s\left(t\right)\frac{w\left(t\right)}{2}. \tag{2}$$

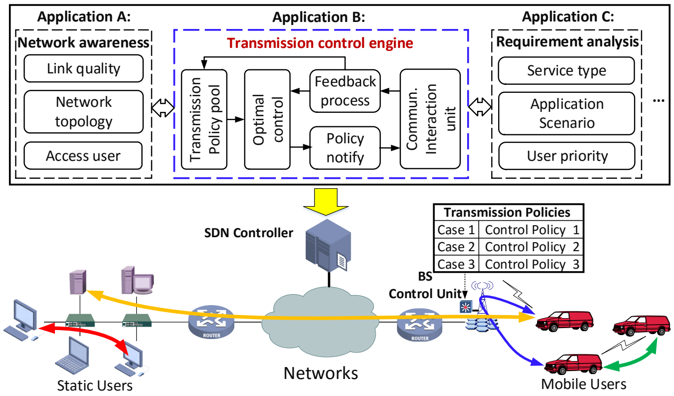

Fig. 2. Design of software defined transmission control in vehicular networks

The sending rate $x(t) := w(t)/T$ has the same dynamics as the window $w(t)$ except for a constant scaling. Hence, the sending rate can be calculated by:

$$\dot{x} = \left(\frac{1 - s\left(t\right)}{T^2} - \frac{1}{2}s\left(t\right)x^2\left(t\right)\right)^+_{x(t)}, \tag{3}$$

where the operation $(\cdot)^+_{x_i(t)}$ means it stays 0 when $x_i(t) = 0$ and the quantity in the bracket is negative, which ensures that $\dot{x}$ remains nonnegative.

There are many variants of this model, because different transmission control policies choose different algorithms to adapt the sending rate $x(t)$ to the network link status $s(t)$, including different metrics to measure congestion and different reactions taken to deal with the congestion. For example, TCP Reno and its variants use loss probability as the congestion metric, and TCP Vegas and its variants use the queueing delay. These tiny differences will make some kind of slight changes for the format of Eq. 3.

As an example, Fig. 1 shows a comparison between the reactions taken in different delay cases by two TCP variants, that are TCPHtcp and TCPVegas. It shows that reflection varies greatly in different methods. Therefore, software-defined transmission control is expected to optimally schedule multiple control methods according to the time-varying network situations to achieve the best performance.

III. SATCP SOLUTION

A. SATCP Design

To implement adaptive transmission control, a customized plug-and-play function and the corresponding protocols are required for the SDVN and its controller. Fig. 2 shows the design of software defined transmission control in vehicular networks. In this design, the SDN controller is logical and contains a set of following inter-connected control applications: *network awareness, requirement analysis, and transmission control engine*. The *network awareness* application collects network information from network elements in its area of network coverage, so that the logical SDN controller can have a global view of vehicular network status including access users, link quality, and network topology. The *service requirement analysis* application focuses on functions in application aspects, which include application scenario, user priority, and service type analysis. Both applications play basic supports to the transmission control engine.

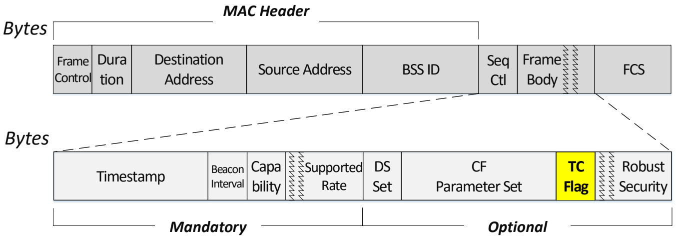

Fig. 3. Revised frame format supporting SATCP notification

The *transmission control engine* is installed in the SDN controller to optimize transmission control according to the current network status and service requirements. Specifically, it maintains a transmission policy pool, which includes the available transmission policies supported in the destination network. Its control optimization unit selects and schedules a suitable transmission policy for each case using a schedule algorithm to be explained in Section III-C. Then, the controller can distribute the scheduling choice to the corresponding base station (BS) through the policy notification and communication interaction units. In addition, policy feedback is handled online to revise and update the transmission policies.

At each base station, there is a control unit (BS-CU), which listens to the control policy notification and interacts with the transmission control engine in the controller. When the BS-CU receives the policy notification message, the BS can distribute (broadcast or unicast) to corresponding vehicular nodes in its control area through a beacon message carrying the recommended transmission policies. A revised frame format for SATCP is shown in Fig. 3, which takes 802.11 Mgmt as an example. This MAC message with a TC flag is sent from the BSs periodically at fixed intervals. When the vehicular nodes receive this message, they can start a transmission with the optimal transmission policy. Notice that the similar TC flag can be used for different wireless access, *e.g.,* cellular access, which is being suggested to add this flag into the standards.

B. Transmission Control Optimization

Control optimization is a key unit in our transmission control engine. It can dynamically select different congestion control methods to prevent or relieve congestions. These control methods are changeable during the entire transmission session, which can be split into a sequence of transmission subtasks. Each subtask is delivered with one kind of control policy, using the TC flag to indicate to the vehicles the use of which policy.

Without loss of generality, we consider a case that a vehicle downloads a large movie file from the server. Consider that there are L available control policies, and the file transmission contains M transmission subtasks (pieces of data chunks). The pair $\langle i,j\rangle$ denotes that control method, $j=1,\cdots,L$, is adopted for the subtask $i=1,\cdots,M$. Since different control methods take varied reactions to the network status, as was shown in Fig. 1, the network utility, $\mathcal{U}_{ij}$, varies with the pair of $\langle i,j\rangle$. More precisely, $\mathcal{U}_{ij}^t$ depends on whether the control policy j is adopted when the subtask i is conducted at time t. This decision needs some network status information, such as access mode, vehicle number and mobility.

Network status is time-varying. Once the network status of one vehicle changes, a new TC flag will trigger an adjustment of the control policy to adapt to the new network environment. However, each control policy adds an overhead to the network. The endpoints must reconfigure parameters and restart a transmission connection, resulting in an extra delay. Therefore, frequent transmission policy changes may result in inefficient transmission with significant delay caused by the frequent transmission interruptions. Consider the situation in a sequence of time $t=\{1,\cdots,T\}$, we model the overhead $\mathcal{H}_i$ of policy change for subtask i as follows:

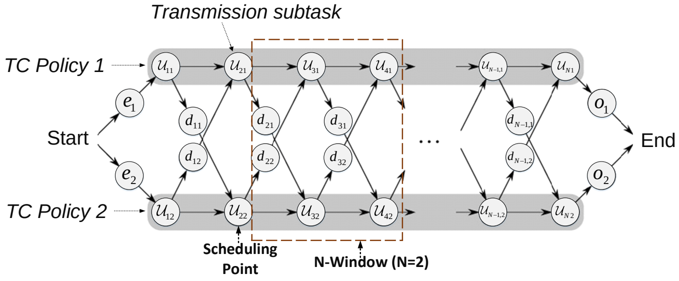

Fig. 4. Illustration of N-window transmission control process

$$\mathcal{H}_i^t=\sum_{j=1}^{L}\mathcal{H}_{ij}^t=\frac{1}{2}\cdot\sum_{j=1}^{L}\left|\alpha_{ij}^t-\alpha_{ij}^{t+1}\right|\cdot d_{ij} \tag{4}$$

where $\mathcal{H}_{ij}^t$ denotes the overhead of changing policy j at time t, $\alpha_{ij}^t\in[0,1]$ denotes whether i selects j at time t, and d_{ij} denotes the overhead if j is changed after the i-th subtask.

Then, the total performance for finishing the whole transmission can be evaluated by:

$$\mathcal{P}=\sum_{t=1}^{T-1}\sum_{i=1}^{M}\sum_{j=1}^{L}\left[\alpha_{ij}^t\cdot\mathcal{U}_{ij}^t-\mathcal{H}_{ij}^t\right] \tag{5}$$

Therefore, the transmission control optimization problem is:

$$\begin{aligned}\max_{\alpha}\quad & \frac{1}{2}\sum_{t=1}^{T\text{ - }1}\sum_{i=1}^{M}\sum_{j=1}^{L}\left[2\alpha_{ij}^t\cdot\mathcal{U}_{ij}^t-\left|\alpha_{ij}^t-\alpha_{ij}^{t+1}\right|\cdot d_{ij}\right]\\ \text{subject to}\quad & \alpha_{ij}^t\in\{0,1\},\ \forall i,j \text{ and } t;\\ & \sum_{j=1}^{M}\alpha_{ij}^t=1,\ \forall i \text{ and } t;\\ & i=1,\cdots,M;\\ & j=1,\cdots,L;\\ & t=1,\cdots,T.\end{aligned} \tag{6}$$

In Eq. 6, the objective is to maximize the network performance (throughput) by optimizing the variable α_{ij}^t with the parameters $\mathcal{U}_{ij}^t$ and d_{ij}. In practice, the values of $\mathcal{U}_{ij}^t$ and d_{ij} can be obtained from historical data analysis.

C. $\mathcal{N}$-window based Scheduling Algorithm

Fig. 4 shows the adaptive transmission control process. When the sender starts to send packets, a suitable control method is selected for each transmission subtask and can be switched to another one according to the network dynamics. This schedule repeats until all transmission tasks have finished. A greedy algorithm can choose the best available control in each subtask in the hope that this choice will lead to a globally optimal solution. However, as mentioned before, frequent policy change may result in inefficient transmission by introducing high overhead and jitter. To solve this problem, this letter

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Algorithm 1: $\mathcal{N}$-window based scheduling
Initialization: $\alpha[M] = 0$; $f_1 = 0$; $f_2 = 0$; flag=0;
$f_1 = e_1 + \mathcal{U}_{11}$, $f_2 = e_2 + \mathcal{U}_{12}$;
if $f_1 \leq f_2$ then flag=1;
    $\alpha[1]$ = flag;
for $i = 2 : M$ do
    for $k = 0 : \mathcal{N} - 1$ do
        $f_1 += \mathcal{U}_{(i+k)1}$, $f_2 += \mathcal{U}_{(i+k)2}$;
    end for
    if flag=0 then
        $f_2 += d_{(i-1)1}$;
    else if flag=1 then
        $f_1 += d_{(i-1)2}$;
    if $f_1 \leq f_2$ then flag=1;
    else flag=0;
    $\alpha[i]$ = flag;
end for
return $\alpha[M]$.
```

TABLE I
NETWORK PARAMETERS CONFIGURATION

Paramater	Packet loss	Bandwidth	Link Delay	Duration
Value	0∼10%	5 Mbps	45 ms	100 s

proposes an $\mathcal{N}$-*window* based quality-priority scheduling algorithm. Algorithm 1 shows the pseudocode of this algorithm. For each subtask, we make a scheduling decision on whether the policy changes based on the status in next $\mathcal{N}$ steps, that is, the $\mathcal{N}$-*window* status, instead of only the current status in the greedy algorithm. Once a subtask has finishes, the $\mathcal{N}$-*window* moves one step backward. Each status information can be used in several contiguous subtask decisions, and therefore, the policy selection will be more stable than the greedy algorithm. Besides, the value of $\mathcal{N}$ affects the performance, and the best value of $\mathcal{N}$ may depend on the specific network conditions. Comparing the performance with different values of $\mathcal{N}$ may help to search for the optimal value of $\mathcal{N}$.

IV. SIMULATION EVALUATION

We perform NS-3 based simulations to validate that the SATCP solution can improve the transmission throughput in vehicular networks. We simulate the vehicular network environment, where the link quality varies with time. Without loss of generality, we increase the link loss rate every 10 seconds under the same network of given raw bandwidth and physical one-way link delay (not counting resend). Table. I lists the main network configuration during our simulation. We compare SATCP with two traditional TCP variants, TcpHtcp and TcpVegas, in terms of network throughput.

Fig. 5 shows the throughput changes during 100-second transmission. Here, the throughput decreases with time in all three schemes. That is because packet loss rate increases with time in our simulation. Consequently, the high packet loss rate reduces the sending window size, and therefore lowers the throughput. SATCP outperforms the other two methods most of the time because SATCP can dynamically select the more efficient transmission control policy to adapt to the current network status. In terms of the average throughput, SATCP achieves 27.8% improvement over TcpHtcp, and 54.4% improvement over TcpVegas. It is noting that this simulation only takes an example to analyze the throughput optimization by the packet loss rate, but it can easily be extended to other metrics according to the specific requirements.

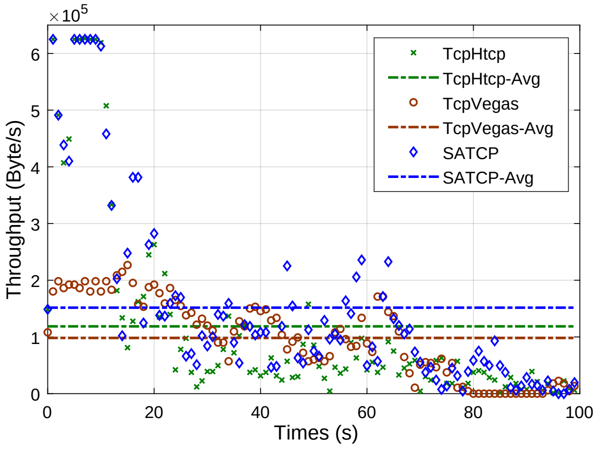

Fig. 5. Throughput comparisons

V. CONCLUSION

We have proposed a software-defined adaptive transmission control protocol (named SATCP) for vehicular networks, including the protocol design, transmission control optimization and a heuristic algorithm. Leveraging the software-defined networking peculiarity, SATCP can flexibly select different transmission control policies to adapt to varying vehicular environments. Simulation results have demonstrated that SATCP can improve transmission throughput significantly with respective to state-of-the-art solutions. In the future, we will adopt deep learning methods to enhance the transmission control functions to further improve the transmission efficiency.

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