Hybrid-Aware Collaborative Multipath Communications for Heterogeneous Vehicular Networks

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Abstract. With the large-scale deployment of wireless access technologies and infrastructures, heterogeneous vehicular networks have been widely studied in recent years. However, it produces unstable link reconstruction due to frequent switch among heterogeneous access networks. Multipath TCP (MPTCP) becomes a promising means to maintain link connectivity by using multiple access interfaces. How to efficiently collaborate multiple links is still a challenge. In this article, we propose Hybrid-Aware Collaborative Multipath Communications for Heterogeneous Vehicular Networks, named HCMC-V. First, we accurately evaluate the weights of different paths by real-time sensing the propagation delay, the packet drop rate, and the bottleneck link capacity. Then, we present a hybrid-aware multipath collaboration mechanism which considers path weights in its decision making process. HCMC-V provides transparent and effective vehicular services through multiple available wireless technologies. Finally, extensive simulations show that HCMC-V significantly reduces transmission delay and improves packet transmission reliability.

Keywords: Collaborative · Multipath · Heterogeneous vehicular networks

1 Introduction

Nowadays, vehicular networks have attracted extensive attention to improve traffic safety and efficiency. Traffic congestion and safety have become global issues. According to the research from the World Health Organization (WHO), more than 125 million people die in traffic accidents every year [1]. In vehicular networks, there are many wireless technologies and infrastructures have been deployed to support the vehicular applications. For instance, IEEE Dedicated Short-Range Communication (DSRC) enables efficient real-time information exchange among vehicles (V2V). Wireless Access for Vehicular Environment (WAVE) has been applied to the Vehicle-to-Infrastructure (V2I) communications. The Long Term Evolution (LTE) scheme has the ability to support vehicular applications [2].

Heterogeneous vehicular networks, which integrate the aforementioned wireless technologies, can completely satisfy unique requirements of the Intelligent Transport System (ITS). As mentioned above, DSRC, LTE, and WAVE are vital to support relevant applications for vehicular networks. However, with the explosive growth of

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vehicles, LTE networks are easily overloaded. Moreover, DSRC integrated with IEEE 802.11p presents poor performance in the wide coverage. Obviously, the single type of these access technologies is far from enough to satisfy all the requirements of vehicular services at the same time.

Currently, many research efforts have begun towards realize highly efficient heterogeneous vehicular communications in a cooperative manner. Zheng *et al.* presented a multi-layer and soft-defined HetVNET in detail, which enabled a far more flexible configuration capability [6]. Dong *et al.* analyzed and solved the issues of energy-efficient cluster management in heterogeneous vehicular networks [7]. However, the above newest researches concentrated on the global design of heterogeneous vehicular networks and failed to analyze its advanced execution mechanisms.

We investigated a new paradigm named Smart Identifier NETworking (SINET) and proposed a SINET customized solution enabling crowd collaborations for software defined Vehicular networks (SINET-V) [5]. Through the crowd sensing, network function slices are flexibly organized with a group of function-similar components. Different function slice(s) are further driven to serve various applications by using crowd collaborations. Extending SINET-V, a hybrid-aware multipath collaboration mechanism is proposed in this paper, named HCMC-V. We focus on the collaboration of heterogeneous vehicular networks at the transport layer. As a promising transport protocol, MPTCP is able to utilize multiple disjoint paths simultaneously and realize seamless vertical handover among multiple paths [6, 12]. The main contributions of this article are showed as follows:

(1) We make a comprehensive analysis of key challenges in heterogeneous vehicular communications and propose our considerations.
(2) We accurately evaluate the weights of different paths by real-time sensing the propagation delay, the packet drop rate, and the bottleneck link capacity.
(3) We present a hybrid-aware path collaboration mechanism according to the path weights, which provides transparent and effective vehicular services through multiple available wireless technologies.

The rest of this article is structured as follows. In the next section, we analyze the challenges in heterogeneous vehicular communications and propose our considerations. In Sect. 3, we describe the workflow of our proposal in detail. In Sect. 4, experimental results validate the benefits of the proposed HCMC-V. Finally, Sect. 5 makes a conclusion and proposes future work.

2 Our Considerations

A key challenge in heterogeneous vehicular networks is how to support a dynamic and instant composition of heterogeneous networks. Heterogeneous vehicular communications pose huge challenges in the deployment of vehicular networks, such as unbalanced link, inter-system handover, and big data processing. Here, we summarize the key challenges for the present limits of heterogeneous vehicular networking.

On the one hand, the hardware performances difference between the On-Board Unit (OBU) and the Roadside Unit (RSU) is great. Due to obviously different communication coverage, the unbalanced links arise. In particular, the reliable communication coverage of the RSU is about 1 km, nevertheless, that of the OBU is only 400 m. As a result, it may be too far for the OBU to receive information from RSU. Communication quality will deteriorate because of such unbalanced links.

On the other hand, there are a wide variety of services, such as real-time warning messages and various entertainment services. These services have different requirements, which require different vehicle-to-other connectivity, such as vehicle-to-vehicle (V2V), vehicle-to-Internet (V2I) and vehicle-to-road infrastructure (V2R) connectivity. Therefore, the collaboration among vehicles and others is challengeable.

As mentioned above, MPTCP efficiently pools the network resources and improves network throughput by enabling data transmission over multiple interfaces. Beyond that, MPTCP has the distinct advantages in heterogeneous vehicular networks [8, 10, 13]. MPTCP is a TCP extension being standardized by the IETF, and is backward compatible with TCP [9, 12]. Therefore, the aforementioned advantages can be obtained without modifying the applications and the existing network devices (*e.g.* firewall or middle box). Besides, MPTCP naturally implements make-before-break, so MPTCP can be incrementally deployed to support mobility.

However, enabling MPTCP in vehicular networks will not be feasible without resolving the above challenges. Kuhn *et al.* proposed Delay Aware Packet Scheduling (DAPS) which aims to reduce the receiver's buffer blocking time [3]. Zhu *et al.* proposed a mobility-aware multimedia data transfer mechanism using Multipath TCP in Vehicular Network [4]. However, they failed to sense the true link state. Based on the above analysis and considerations, we present our proposal HCMC-V in the following, which provides transparent and effective vehicular services through multiple available wireless technologies.

3 Solution: HCMC-V

HCMC-V is proposed to address multipath collaboration caused by heterogeneous wireless networks, as shown in Fig. 1. First, through crowd sensing, SINET-V controller can obtain the real link quality in real time. Then, through HCMC-V mechanism, the available paths are utilized according to the path weight ζ. As illustrated in Fig. 2, the main workflow of HCMC-V includes Hybrid Aware, Path Scheduling, and Packets Management. In the initial phase, the statuses of available paths are sensing through Hybrid Aware, and the key parameters mentioned earlier are recorded and passed to Path Scheduling model. In the path scheduling phase, the path weight will be calculated and used to schedule the available paths. It should be noted that the Hybrid Aware model will dynamically monitor the statuses of available paths and pass valid parameters to the Path Scheduling model. In the following, we described the model of Path Weight and the multipath collaboration policy in detail.

3.1 Model of Path Weight

To get a reasonable Path Weight, we redesign the definition of the weight. The path weight of each path relies on three link parameters: the propagation delay (RTT), the

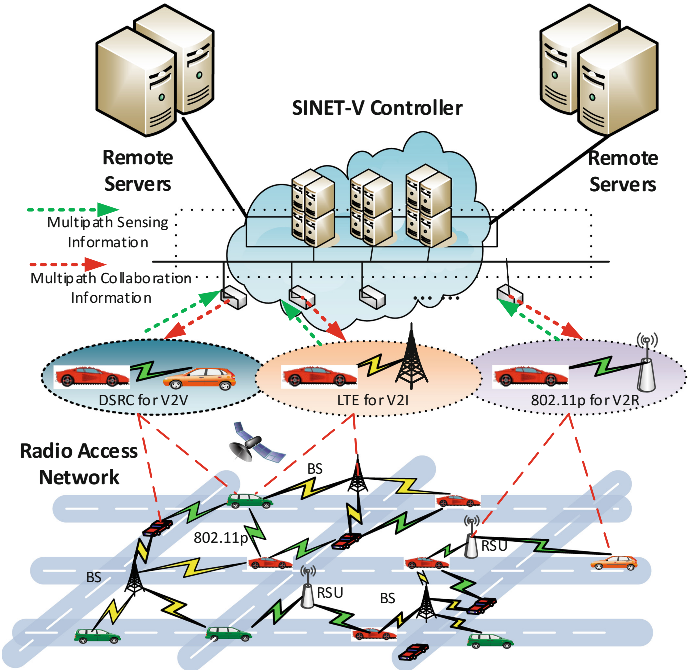

Fig. 1. This figure shows the architecture of SINET-V.

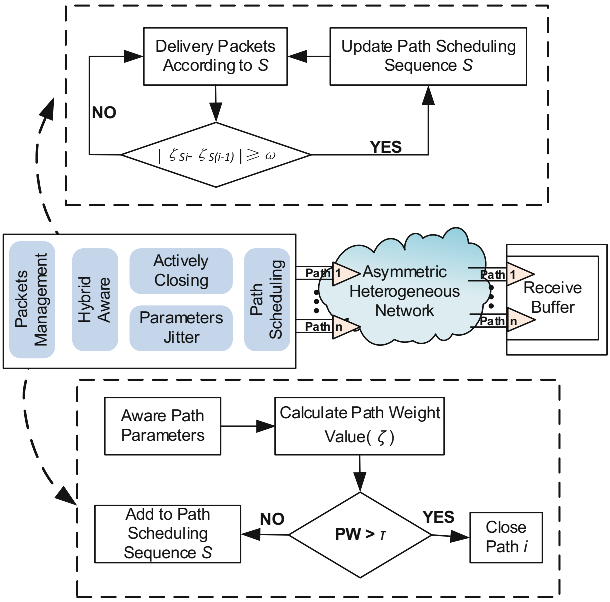

Fig. 2. This figure shows the workflow of HCMC-V.

packet drop rate (LOSS), and the bottleneck link capacity (Cap). We know the throughput formula based on traditional TCP [11] as shown in formula (1).

$$\text{Throughput} \propto 1 \Big/ \text{RTT}\sqrt{\text{LOSS}} \tag{1}$$

Similarly, the throughput of multiple subflows also meets the above relationship. Not only RTT but also LOSS needs to be considered when we evaluate link quality. Besides, there is a close connection between the bottleneck link capacity and the throughput. The bottleneck link capacity reflects the maximum throughput that the link can achieve within a unit time. In summary, only by considering the above factors comprehensively can we correctly reflect the actual situation of the paths.

In the following, we take PATH as a group of available paths between the vehicular users and the services providers, as shown in formula (2). We define ζ_i as the path weight of P_i, as shown in formula (3) and (4). In general, the better the path quality is, the smaller the path weight value is.

$$\text{PATH} = \{\text{P}_1, \text{P}_2, \ldots, \text{P}_\text{i}, \ldots, \text{P}_\text{n},\ \text{n} > = 2\} \tag{2}$$

$$\zeta_i = \alpha * \text{RTT}_i + \beta * (1/\text{Cap}_i) + \theta * \text{Loss}_i \tag{3}$$

$$\alpha + \beta + \theta = 1 \tag{4}$$

In the formula (3), RTT_i represents the Round Trip Time of P_i, Cap_i is the bottleneck link capacity of P_i, and Loss_i is the packet loss rate of P_i. The above three parameters are normalized by Min-Max Normalization as shown in formula (5). α, β and θ are all positive constants less than 1 determined by the jitter of each parameter as shown in formula (7–9). Standard deviation factor ε is used to indicate the degree of fluctuation among corresponding parameters as shown in formula (6). σ represents the standard deviation of the parameter and μ is defined as the mean value. For example, if the RTT of each path is more different than two extra parameters, α will be accounted for the largest proportion compared with β and θ. Algorithm 1 describes how to calculate the path weight.

$$\overline{\text{X}} = \text{X} - \text{X}_{\text{MIN}}/\text{X}_{\text{MAX}} - \text{X}_{\text{MIN}} \tag{5}$$

$$\varepsilon_X = \sigma_X/\mu_X \tag{6}$$

$$\alpha = \varepsilon_{RTT} \Big/ \varepsilon_{RTT} + \varepsilon_{Cap} + \varepsilon_{Loss} \tag{7}$$

$$\beta = \varepsilon_{Rate} \Big/ \varepsilon_{RTT} + \varepsilon_{Cap} + \varepsilon_{Loss} \tag{8}$$

$$\theta = \varepsilon_{Loss} \Big/ \varepsilon_{RTT} + \varepsilon_{Cap} + \varepsilon_{Loss} \tag{9}$$

HCMC-V will constantly monitor and update available radio interfaces. If there are packets needed to be sent, available paths will be scheduled according to the above Path Weight. In the following, the detailed scheduling policy will be presented.

Algorithm 1: Path weight calculation method

```
path weight (Output)
  {getSD is the function of calculating standard
deviation factor; getC is the function of calculating
weight coefficient α, β and θ; getPW is the function of
calculating path weight value ζ_i };
  for each Pi∈PATH do
  begin
    ε_RTT  := getSD(Pi);
    ε_Rate  := getSD(Pi);
    ε_Loss := getSD(Pi);
  end.
  α := getC(ε_RTT);
  β := getC(ε_Rate);
  θ = getC(ε_Loss);
  for each Pi∈PATH do
  begin
    ζ_i = getPW(α,β,θ);
  end.
```

3.2 Multipath Collaboration Policy

The vehicle users select suitable paths according to the multipath control information from SINET-C controller. The above information includes the sequence of available paths and the path weights of these paths. The ζ_i of Pi is calculated based on Algorithm 1. According to the path weight value, available paths list S can be obtained. In the following, we take S = {S1, S2… Sj… Sm, $n \geq m \geq 2$} as a group of available paths. The ζ_i value of Si is smaller than S_{i+1}. Because the better the path quality is, the smaller the path weight value is. It should be noted that the poor paths will not be selected temporarily.

Algorithm 2: Multipath collaboration policy

```
the list of available pahts(Output)
  { Sort(PiPi, ζi Pi,ζiPi,ζi) is to sort PiPi based on ζi in
ascending.};
  for each Pi∈PATH do
  begin
    if ζi ≤ τ;
      S.append(Pi);
  end.
  S = Sort(Pi, ζi);
  for each Pi∈PATH do
  begin
    if|ζSi − ζSi−1| ≥ ω;
      S = Sort(Pi, ζi);
  end.
  for each Si∈S do
  begin
    while unacki<cwndi do
      begin
        transmit packets on Si.
      end.
  end.
```

In HCMC-V, the parameter τ is proposed as path selection threshold. On the one hand, paths with $\zeta_i \leq \tau$ can be treated as available paths. In other words, Paths with $\zeta_i > \tau$ will be abandoned temporarily to ensure that packets are able to be sent quickly via good paths. On the other hand, ζ_{S_i} is dynamic with the links quality. But only when $\left|\zeta_{S_i} - \zeta_{S_{i-1}}\right| \geq \omega$, path scheduling list S will change. The parameter ω works as the switching threshold of path weight. If the link quality changes little ($\left|\zeta_{S_i} - \zeta_{S_{i-1}}\right| < \omega$), path scheduling sequence will not change which is able to minimize the number of link switching and ensure the stability of path scheduling. The specific algorithm to implement path scheduling is shown in Algorithm 2.

It should be noted that τ and ω can be obtained by a large number of experiments. Before the data sending, the multipath scheduling policy will select the paths according to the order of the array S. The first one in the array will be the best path. HCMC-V can select a ‘fastest’ path based on not only its RTT but also its real link quality, and avoid blind roll polling compared with Round Robin or Lowest RTT First [9].

4 Evaluation

We conducted a group of experiments to verify the feasibility and efficiency of HCMC-V. We performed the experiments under the NS-3 open source network simulator. In our experiments, we used the Routes Mobility Model in NS-3 to simulate the vehicular networks. The Routes Mobility Model can generate realistic mobility traces by querying the Google Maps Directions API. The information, obtained from the Google Maps services, allows the simulator to generate realistic mobility traces based on real-world locations and road networks. We analyzed the performance of HCMC-V from two aspects, the packet transmission reliability and transmission delay.

Obviously, the efficiency of HCMC-V relies on τ and ω. We usually set $\tau = 0.85$ to ensure using all of subflows as much as possible. We further evaluated the throughput according to the switching threshold ω. We can see that different thresholds will affect the performance of HCMC-V. On the one hand, if ω is too large, HCMC-V will become insensitive to severe fluctuation, and perform as well as traditional scheduling policies. On the other hand, if ω is too small, it will result in frequent path switching. We can set different threshold values according to path jitter. For example, we can set a larger threshold for the paths with frequency fluctuation and set a smaller threshold for the smooth paths.

We assessed the performance of the proposed paths scheduling policy by comparing with the state-of-the-art multipath scheduling mechanisms, including the Delay-Aware Packet Scheduling (DAPS) and mobility-aware MPTCP scheduling (MA-MPTCP). We set paths parameters according to Table 1. Figure 3 is a snapshot of the total throughput on all paths, and we can see that the throughput of HCMC-V is significantly better than those of other scheduling policy. The throughput of HCMC-V with $\omega = 0.3$ is 30% higher than that of MA-MPTCP. The throughput of DAPS is far lower than that of HCMC-V. The main reason is that MA-MPTCP is failed to sense the paths statuses, and DAPS only focus on the transmission delay. HCMC-V can dynamically sense and schedule the best path(s) using hybrid aware policy.

Table 1. Path characteristics

Path	RTT/ms	Rate/Mbps	Loss
Path 1	20	8	5%
Path 2	150	2	2%
Path 3	100	4	3%
Path 4	50	6	4%
Path 5	150	1	1%
Path 6	50	5	2%
Path 7	100	3	1%

We performed another set of experiments with varying the number of subflows, as shown in Table 1, and we also fixed $\tau = 0.85$. By comparing these results, we can see RTT based on HCMC-V has an obvious decreasing trend, compared with other strategies, as shown in Fig. 4. For example, when there are five subflows, the delay of HCMC-V is reduced by 20% compared with DASP, and it is reduced by 40% compared with MA-MPTCP. The main reason is that HCMC-V is able to dynamically sense and adjust multiple paths in real time. Hence, it can flexibly call up the better paths through multipath collaboration mechanism.

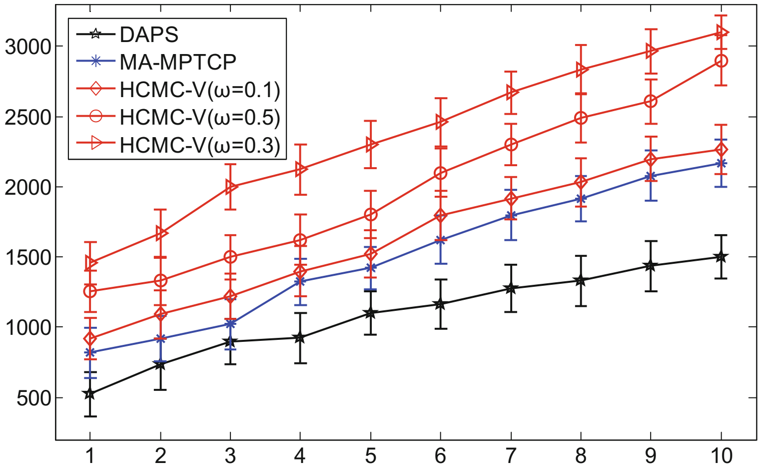

Fig. 3. This figure shows the total throughput with different policies during 10 s.

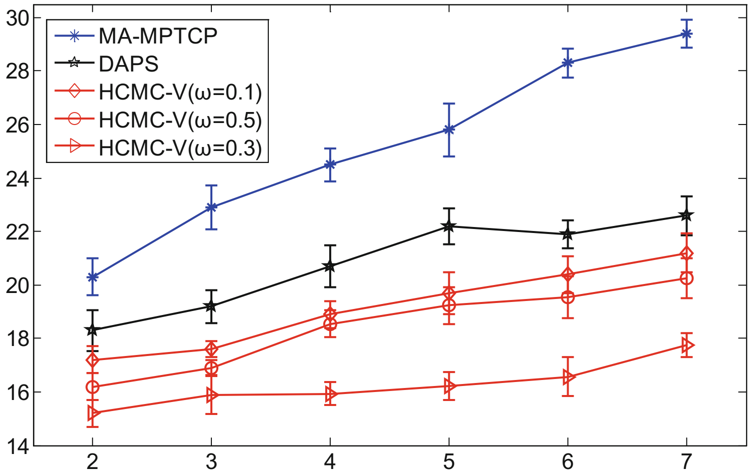

Fig. 4. This figure shows transmission delay of different subflows.

5 Conclusion and Future Work

This article presents a MPTCP communication architecture and proposes an innovative HCMC-V solution for heterogeneous vehicular networks. Specifically, we accurately evaluate the weights of different paths by real-time sensing the propagation delay, the packet drop rate, and the bottleneck link capacity. Then, we present a hybrid-aware path collaboration mechanism according to the path weight, which provides transparent and effective vehicular services through multiple available wireless technologies. Extensive simulations show that HCMC-V significantly reduces transmission delay and improves the packet transmission reliability. In our future work, we plan to implement HCMC-V in Linux implementation of MPTCP to evaluate the performance gain in realistic network conditions.

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References

1. Zheng, K., et al.: Heterogeneous vehicular networking: a survey on architecture, challenges, and solutions. IEEE Commun. Surv. Tutor. **17**(4), 2377–2396 (2015)
2. Zhang, H., Dong, P., Quan, W., et al.: Promoting efficient communications for high-speed railway using smart collaborative networking. IEEE Wirel. Commun. **22**(6), 92–97 (2015)
3. Kuhn, N., et al.: DAPS: intelligent delay-aware packet scheduling for multipath transport. In: IEEE International Conference on Communications, June 2014, pp. 1222–1227 (2014)
4. Zhu, D., et al.: Mobility-aware multimedia data transfer using multipath TCP in vehicular network. In: International Wireless Communications and Mobile Computing Conference, June 2017, pp. 1041–1046 (2017)
5. Quan, W., et al.: Enhancing crowd collaborations for software defined vehicular networks. IEEE Netw. **30**(4), 10–15 (2016)
6. Zheng, K., et al.: Soft-defined heterogeneous vehicular network: architecture and challenges. IEEE Netw. **30**(4), 72–80 (2016)
7. Dong, P., et al.: Energy-efficient cluster management in heterogeneous vehicular networks. In: IEEE INFOCOM 2016 - IEEE Conference on Computer Communications Workshops, April 2016, pp. 644–649 (2016)
8. Paasch, C., et al.: Exploring Mobile/WiFi handover with multipath TCP. In: ACM SIGCOMM, August 2012
9. Ford, A., et al.: TCP extensions for multipath operation with multiple addresses. RFC6824, January 2013
10. Yang, L., et al.: Multi-copy data dissemination with probabilistic delay constraint in mobile opportunistic device-to-device networks. In: IEEE, International Symposium on IEEE Computer Society, June 2016, pp. 1–9 (2016)

11. Sarwar, G., et al.: Mitigating receiver's buffer blocking by delay aware packet scheduling in multipath data transfer. In: IEEE WAINA, March 2013
12. Paasch, C., et al.: Experimental evaluation of multipath TCP schedulers. In: ACM SIGCOMM, August 2014
13. Xu, C., et al.: Congestion control design for multipath transport protocols: a survey. IEEE Commun. Surv. Tutor. **18**(4), 2948–2969 (2016)