GCH-MV: Game-enhanced Compensation Handover Scheme for Multipath TCP in 6G Software Defined Vehicular Networks

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***Abstract*—The latest developments in terms of self-driving technologies have increased the demand for high quality data transmission in vehicular networks. However, frequent handover among the Road Side Units (RSUs) causes degradation of data transmission performance, especially in the context of high-speed mobility. In order to address this problem, a novel game-enhanced compensation handover scheme (GCH-MV) for multipath TCP in 6G software defined vehicular networks is proposed. An innovative system architecture which integrates 6G communication solutions, SDN and multipath techniques is presented. GCH-MV redesigns the fluid model of Multipath TCP (MPTCP) to compensate for the declining throughput by using multiple paths. GCH-MV transfers traffic quickly between different paths, adapting the transmission to path quality and maintain high throughput. In addition, an innovative game-based optimal candidate RSU selection algorithm, employed by GCH-MV during the handover process, is also introduced. GCH-MV uses these solutions to achieve its goal to mitigate the negative impact of handover as much as possible and make the handover process smooth and transparent. Experimental results show how GCH-MV outperforms the existing solutions in terms of several quality of service (QoS) metrics, addressing efficiently the data transfer quality problem during handover in highly mobile vehicular networks.**

***Index Terms*—MPTCP, Handover, Game theory, SDN, Vehicular networks, Compensation.**

I. INTRODUCTION

RECENTLY several countries and organizations have focused their attention to the sixth generation (6G) communication systems [1][4] due to the limitations of the fifth generation networks (5G). Letaief et al. [3] and Gui et al. [5] discuss the roadmap of 6G, core services and potential key technologies and contribute to a better understanding of the progress towards 6G communications. Although the 5G communication systems [7][8] have just been deployed on large scale by operators, they do not deliver the support which was originally expected. In general 5G achieves limited technical improvements, especially in relation to intelligent driving, joint design of end-to-end communication, full ubiquitous mobile network coverage and so on [1]. Therefore, the support for the next generation vehicular networks should be included early in the design of the future 6G systems. This includes machine learning approaches, presented by Tang et al. [2] as potential development avenues for the future 6G vehicular network solutions and Software Defined Networking (SDN) solutions. SDN [9] is believed to remain a key technology in the 6G communication systems, as it has the advantage of enabling centralized and scalable control, sensing and computing [1][6]. Therefore software defined vehicular networking [10][12] is expected to attract increasing interest from researchers from both academia and industry.

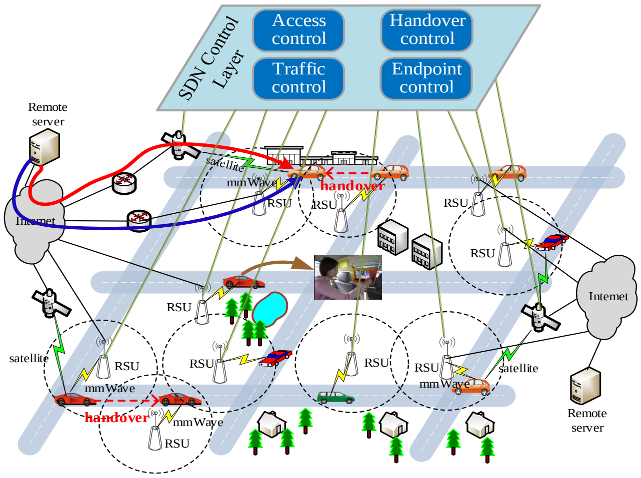

Fig. 1: Game-based MPTCP compensation handover architecture in 6G software defined vehicular networks

At the same time, the current widespread heterogeneous wireless network paradigm has determined most mobile devices, including vehicular ones, to be equipped with multiple network interfaces [14]. Hence, end-to-end multiple transmission protocols, for instance, Multipath TCP (MPTCP)

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[11][19] can be applied to vehicular networks to support their associated services. Finally, with the rapid development of diverse technologies related to autonomous vehicles for instance, there is a stringent need for solutions to support high-quality communications demands in vehicular networks. Due to high-speed mobility, frequent handovers between Road Side Units (RSUs)[1] have a strong impact on the quality of experience (QoE) levels for users in the vehicles [13]. Consequently, full coverage is necessary to be introduced in vehicular networks, for instance by using solutions such as space-terrestrial integrated networks [1]. Fig. 1 shows how a vehicle performs multiple handovers between different RSUs in a vehicular network environment. However, performing handover efficiently is the most challenging problem. In order to address this problem, SDN, multipath techniques and innovative communication solutions need to be leveraged in the next generation vehicle network context.

The vehicular networks can employ two communication modes: vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). This paper focuses on V2I communications and therefore all communications involving vehicles are performed via RSUs. Once driving away from the coverage area of a RSU, vehicles have to perform handover to another RSU to be able to communicate. Although a *make-before-break* approach can be employed for handover, any throughput fluctuation may degrade the transmission performance. The goal of this work is to propose innovative solutions to make the handover process transparent for users and achieve high QoS levels. Dedicated short range communication (DSRC) [43] is beneficial for V2V, especially in downtown scenarios with a high vehicle density. This will be the focus of our future work.

MPTCP has attracted much attention from researchers in heterogeneous wireless network environments [15][16]. MPTCP-based solutions can aggregate bandwidth, balance load and improve robustness, as multiple paths can backup each other. MPTCP can be employed to help address the handover problem in vehicular networks, as it can support handover by making use of different network interfaces simultaneously.

Taking advantage of global view, SDN is able to control the whole network. Decoupling the control and data planes, SDN can configure the network function and manage the network traffic flexibly in the control layer. SDN control layer makes intelligent decisions to provide good network services. In the context of handover, the problem is how to choose an optimal RSU among candidate RSUs and values of the network parameters monitored by the SDN control layer. Inspired by [17][18], the decisions of choosing optimal RSUs can be made by employing game theory in the SDN control layer. The SDN control layer can then inform the vehicles about the decisions, so they can follow them.

By combining these innovative techniques, this paper proposes a novel **G**ame-enhanced **C**ompensation **H**andover scheme for **M**ultipath TCP in 6G software defined **V**ehicular networks (GCH-MV). To the best of our knowledge, this is the first paper to employ MPTCP and SDN technologies in a 6G-based vehicular network context.

GCH-MV utilizes a multipath compensation method to make the handover process seamless and transparent. This method makes innovative use of original and handover paths via RSUs, employing high data transmission rate *6G mmWave* communication links, and a *6G satellite*-based compensation path, covering a wide area. GCH-MV introduces a novel fluid-based compensation handover solution which considers the variation of signal strength (SS) to enable fast transfer of transmission data between original, handover and compensation paths. GCH-MV uses game theory to evaluate the candidate RSUs and select the optimal RSU for handover.

The major contributions of this work are summarized next:

- A novel multipath transmission architecture in a 6G-based software defined vehicle network which includes fluid based multipath compensation handover model and optimal candidate RSU selection game mechanism.
- A fluid-based multipath compensation handover method which can achieve fast transfer of data traffic during handover.
- A game-based optimal candidate RSU selection mechanism which selects the best quality RSU for the handover decision and feeds this decision back to the vehicles.
- The handover process is composed of a compensation stage and a handover stage, in which the vehicles are able to make dynamic data transmission control decisions.

The rest of this paper is organized as follows. Section II discusses related works and Section III presents the overall system architecture and specific design of GCH-MV. Experimental results are provided and discussed in Section IV. Finally, conclusions are drawn and future research directions are indicated in Section V.

II. RELATED WORKS

A. Multipath TCP in Vehicular Networks

Diverse researchers have designed solutions which employ multipath TCP in vehicular networks. In CAIA technical report [20], Williams et al. have assessed MPTCP performance in V2I communications. The authors have compared the throughput and RTT of single-path, 2-path and 3-path MPTCP when using IEEE 802.11p, Wi-Fi wireless broadband and 3G cellular solutions, respectively. The results showed how MPTCP has outperformed TCP in most cases. The authors have indicated handover between RSUs as an important direction to explore as further work, and this is the significant problem addressed in this paper.

Mena et al. [21] have studied the performance of multipath TCP in vehicular ad-hoc networks (VANET) in both V2I and V2V scenarios. The problem identified is that MPTCP does not perform very well at high speeds. Therefore, in this paper optimization will be employed to improve the transmission quality while also considering mobility.

Rene et al. [22] have proposed a transport-layer solution to address communication interruption when moving between RSUs while employing MPTCP. The authors have used an additional satellite interface and a global access technique for

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[1] Although a RSU may include a base station (BS) or an access point (AP), in this paper these acronyms will be used interchangeably when referring to network connectivity.

communications. They also used Deep Packet Inspection rules to guarantee multimedia QoS. However, the researchers did not consider any traffic distribution when performing handover between different paths for load balancing.

Li and her team [25] performed performance measurements for MPTCP with multiple networks operators on high speed railways. Due to the frequent handovers, the performance of single path transmission degraded significantly. The authors have developed and used a tool *MobiNet* to measure the performance of handover of a mobile equipment. They have analysed flow competition time, subflow establishment, average rate for mice flows and elephant flows, respectively. The results have indicated that the MPTCP performance is not good and therefore, there is a need to optimize MPTCP in order to improve the transmission quality in high speed vehicular networks. This paper focuses on this performance aspect.

B. Fluid Model for Multipath TCP

In [26], Peng et al. have presented a fluid model for Multipath TCP, which is shown in eq. (1) and eq. (2).

$$\dot{x}_r = k_r(X_S)(\phi_r(X_S) - \frac{1}{2}\mathrm{q}_r)^+_{x_r} \tag{1}$$

$$\dot{p}_l = \gamma_l(y_l - c_l)^+_{p_l} \tag{2}$$

In the fluid model, x_r denotes the transmission rate of subflow r and p_l represents packet loss probability for link l. Detailed explanations of the other components are presented in [26]. The authors have used these equations to model existing MPTCP solutions and analyze them comparatively in terms of three key performance indicators: window fluctuation, fairness and responsiveness. Finally, they have designed a new MPTCP algorithm which focuses on achieving trade-off between these three indicators.

Focusing on fairness, Zhao et al. [27] have proposed a new fluid model for MPTCP. The authors have recomputed the aggressiveness factor and introduced a congestion balance factor to satisfy the design goal of MPTCP. Similarly, Melki et al. [28] extended the fluid model and focused on designing new MPTCP congestion control solutions. The authors have modified the two variables presented in eq. (3) to consider a new set of parameters $(\{\beta_1, \beta_{2,...,}\beta_M\}, \eta, n)$ and a constant gain C. The positive gain variable $k(x)$ controls algorithm responsiveness and variable $\varphi(x)$ controls its fairness. By choosing these parameters and *M*, the authors have proposed a fairness-based congestion control algorithm.

$$\begin{cases} k(\mathbf{x}) = \frac{1}{2}C[x_r(x_r + \eta(\|x\|_\infty - x_r))] \\ \varphi(\mathbf{x}) = \frac{2\prod_{m=1}^{M}[x_r + \beta_m(\|x\|_n - x_r)]}{C\tau_r^2 x_r^M \|x\|_1^2} \end{cases} \tag{3}$$

Dong et al. [29] have designed mVeno, a new algorithm for MPTCP which distinguishes between congestion loss and random wireless transmission loss. Based on the fluid flow model, mVeno distributes different weights for subflows to adjust adaptively the sending rate. The results showed that mVeno has not only improved the throughput dramatically, but also has balanced load and maintained TCP friendliness.

C. Handover Schemes in Heterogeneous Wireless Networks

There are two major handover modes MPTCP can employ: horizontal and vertical [30]. Horizontal handover refers to performing the handover process while retaining the same network type e.g. Wi-Fi 802.11g/n/ac. Vertical handover involves handover between different network types, for example, 4G/5G cellular, Wi-Fi wireless broadband, satellite networks, etc.

Paasch et al. [23] have studied vertical handover from wireless broadband to cellular and have performed many experiments to demonstrate the feasibility of employing MPTCP. The authors have mainly compared and analyzed three MPTCP modes: *Full-Path*, *Backup-Path* and *Single-Path* in terms of download goodput, application delay and energy consumption. They have performed basic research work which is progressed from in this paper.

The authors of [24] have proposed a new solution which takes advantage of MPTCP for vertical handover. The solution can switch between two modes *Full-Path* and *Single-Path*. Additionally, the authors have used a predictive mobility model to inform the decisions made. Similarly, Sinky et al. [30] have presented a proactive and seamless handover solution which maintains the total throughput unchanged. The authors have designed a cross-layer optimization algorithm which is based on the bandwidth delay product (BDP). They have utilized a linear equation system to balance Wi-Fi throughput and cellular throughput. However, these solutions have limited applicability in other handover scenarios and do not perform an optimal selection of candidate access points (AP).

Finally, Croitoru et al. [31] have utilized a MPTCP horizontal handover method in a multiple Wi-Fi AP-based environment. They have also proposed a novel estimation technique for AP downlink and used ECN marking to find the best AP. However, the researchers have not considered that fluctuations of transmission quality during the handover process can degrade user Quality of Experience (QoE).

D. SDN in Vehicular Networks

Increasing number of researchers have considered that applying SDN in vehicular networks is not only very promising, but also effective. Ge et al. [7] have utilized SDN to design a new vehicular network architecture which can decrease transmission delay and improve throughput. They have also integrated fog cells to avoid frequent handover between vehicles and RSUs. Similarly, Zhang et al. [9] have provided a great platform by using fog computing and SDN in order to satisfy the requirements of next generation vehicular networks. Furthermore, Correia et al. [10] have extended SDN and proposed a hierarchical SDN-based vehicular architecture to guarantee high reliability for vehicular user services. All these solutions have enhanced the vehicular network architecture with SDN and have added new useful solutions. However, none of these researchers have considered to include an end-to-end transmission protocol to the new architecture and improve fundamentally the transmission performance. Therefore, this paper fills this gap and integrates SDN and MPTCP into vehicular networks.

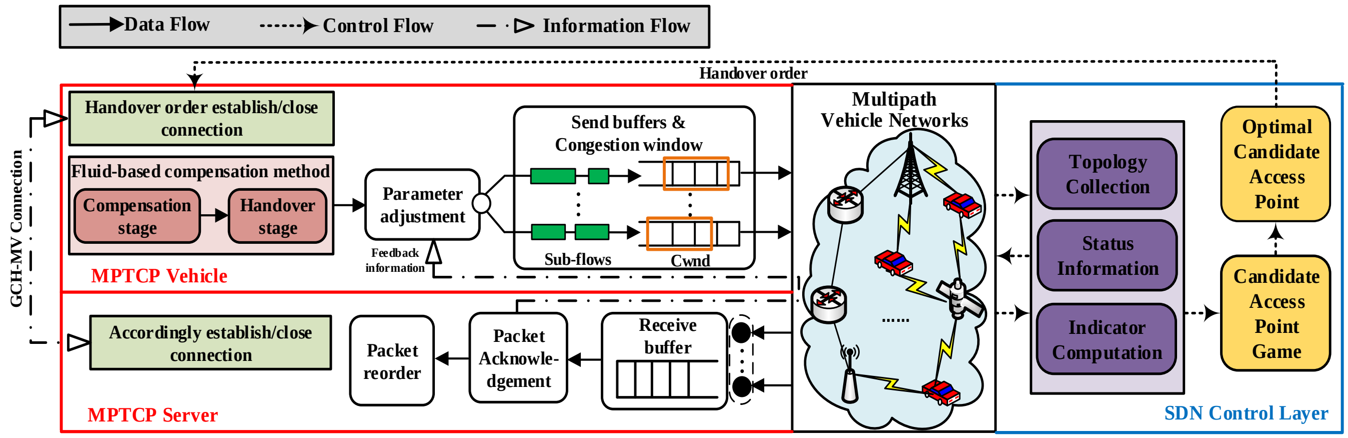


Fig. 2: Overall design of proposed GCH-MV

III. GAME-BASED MULTIPATH COMPENSATION HANDOVER SYSTEM DESIGN

A. Game-based Multipath Compensation Handover Architecture

During communications in multipath vehicular networks, vehicles have to perform frequent handovers between different RSUs due to their high speed mobility. There are many candidate RSUs around any vehicle. How to select the best one and how to define the assessment criteria are major problems to be solved. In the handover process, data transmission sometimes breaks and requires connection re-establishment. Although a *make-before-break* approach is employed, the fluctuation of total throughput is so great that user QoE is poor. In order to address this issue and improve user QoE, the game-based compensation handover for MPTCP in vehicular networks solution (GCH-MV) and its architecture are designed.

In a future 6G vehicular network context, this paper considers a handover scenario from the perspective of transport layer. We focus on taking advantage of some of 6G core requirements such as ultrareliable and low-latency communications (uRLLCs) and ubiquitous always-on broadband global network coverage, mentioned in [1][2]. As far as we know, space-terrestrial integrated network is our best choice to achieve the target of full coverage in the handover process. Related to the ultrareliable transmission requirement, not only there is a need to guarantee that the connections do not break, but also to make sure high transmission throughput is maintained. With respect to low-latency communications, the end-to-end delay is set as a control variable in our GCH-MV handover mechanism, so it is well considered.

Fig. 1 illustrates the scenario of GCH-MV, which includes vehicles, remote servers, SDN control layer and two 6G communication paths employing *mmWave* and *satellite* links. For instance when considering one of the vehicles, the red line represents the *satellite* path and the blue line indicates the *mmWave* path. The vehicles communicate with remote servers and each other via RSUs. To maintain communication, when mobile, the vehicles perform handover between RSUs. As the handover process involves the same $mmWave$ interface, the handover type is horizontal [30]. While performing handover between RSUs, vehicles employ the *satellite* link as an additional communication path to compensate for the degrading performance associated with basic handover. GCH-MV employs MPTCP to support this multi-path data transfer.

Furthermore, an extended fluid model is introduced to achieve fast load transfer among these paths. In a SDN-based control approach, the control layer performs access control, handover control, traffic control and endpoint control.

Fig. 2 presents the GCH-MV detailed design with specific modules, which abstract its major architecture components: a *MPTCP Vehicle*, a *MPTCP Server*, *SDN Control Layer* and *Multipath Vehicle Network* environment. The SDN control layer consists of a series of controllers such as SDN controllers, RSU controllers, satellite controllers or satellite control centers [9]. These controllers can collect information and monitor state of vehicles and transmission links via RSUs or satellites by taking advantage of the OpenFlow protocol [7]. In this manner, information about the available bandwidth, current packet loss and other indicators can be collected, as described in details in our previous works [16] [32]. Additionally, Signal Strength (SS) is measured using a computation method described in section III.D. Based on this collected information, the control layer employs game theory to select the optimal candidate RSU for handover. Later on, the control layer sends the order to perform the handover to the optimal RSU to the vehicle via the extended OpenFlow protocol [33][34] which makes vehicles support the SDN function. Once the vehicle receives the handover order, it establishes a connection with the remote server. Then, the vehicle executes the fluid-based compensation method to adjust the parameters of different paths. The compensation method aims at offsetting the declining throughput and achieving fast transfer of data traffic between the two paths. Moreover, the server can assist to set the compensating parameters according to the feedback information from packet acknowledgements. The detailed design principles of the proposed solution and the primary architectural modules are presented next.

B. Fluid-based Multipath Compensation Handover Mechanism

RFC 6356 [39] describes MPTCP's coupled congestion control mechanism which has three major goals related to throughput, TCP friendliness and data transfer. This paper extends these goals to consider the handover process and proposes a novel fluid-based MPTCP handover compensation algorithm which meets these goals. The compensation goals are as follows.

1) Maintain Throughput: The total throughput of multiple subflows in the handover process is close to the throughput of the single path before the handover.

2) Achieve TCP Friendliness: Multiple subflows should not take up more bandwidth resources than a single path when they are on a shared bottleneck.

3) Enable Fast Transfer: The original subflow traffic should transfer to the compensation subflow as soon as possible.

The use case involving the MPTCP handover compensation algorithm considered in this paper is described as follows. First, the vehicle communicates with the remote server by using the *mmWave* interface (initial subflow) via current RSU. When noting SS is lower than a compensation threshold, the vehicle initiates a new subflow using the *satellite* interface and makes use of it. When SS reaches the handover threshold, the vehicle performs handover from current RSU to the best candidate RSU. In the handover process, the total throughput of *mmWave* and *satellite* subflows should be as close as possible to that of *mmWave* before the handover. However, the multiple *mmWave* and *satellite* subflows should keep fair their throughput with regard to those of other TCP flows. Finally, the traffic of *mmWave* should transfer quickly to the *satellite* link.

It is assumed that there are m vehicles moving on the road. The sources set is denoted $S = \{1, ..., s, ..., m\}$. Each vehicle (source) s can communicate with remote servers through multiple subflows r. The set of subflows can be defined as $R= \{r|r \in s, s \in S\}$. Let $g_{lr} \in \{0,1\}^{|m|\times|R|}$, $g_{lr} = 1$ if link l is used by subflow r and 0 otherwise. Actually, a subflow r contains a set of links l. c_l is the capacity of link l. Let $x_r(t) = w_r(t)/\tau_r$ denote the transmission rate of subflow r at time t, where $w_r(t)$ is the congestion window (cwnd) of subflow r and τ_r is the round trip time (RTT) of subflow r. As both delay variation and delay difference between different paths can influence the transmission quality, GCH-MV employs delay as a control variable to adjust the sending rate and responsiveness for each subflow. For improving the time precision in a generic setup, a clock synchronization method [35] such as Network Time Protocol, Precision Time Protocol, etc. can be used. However, as 6G integrates space-terrestrial networks, clock synchronization will be guaranteed on the different transmission links. Therefore, we can assume that different subflows have the same clock in a 6G vehicular network.

The proposed fluid model of MPTCP for handover is presented in eq. (4) and eq. (5).

$$\dot{x}_r(t) = k_r(\mathbf{x}_s)(h_r\varphi_r(\mathbf{x}_s) - \frac{1}{2}q_r\sigma_r)^+_{x_r} \tag{4}$$

$$\dot{p}_l = \beta_l(y_l - c_l)^+_{p_l} \tag{5}$$

where q_r is the packet loss rate of subflow r and p_l is the packet loss rate of link l. σ_r is the packet-loss indicator which is designed in the handover stage. $\varphi_r(\mathbf{x}_s)$ and β_l are the positive gains. We define $K_s(\mathbf{x}_s) := (k_r(\mathbf{x}_s), r \in s)$ and $\Psi_s(\mathbf{x}_s) := (2q_r\varphi_r(\mathbf{x}_s), r \in s)$. $h_r = H_r/\sum_r H_r$, H_r is the handover transfer factor which is defined as follows:

$$H_r(k) = \frac{SS_r(k)}{\log(1 + s\tau_r(k))} \tag{6}$$

where $SS_r(k)$ is the signal strength of subflow r received from corresponding RSU/AP on the sample cycle k. $s\tau_r(k)$ is the smooth RTT of subflow r on the sample cycle k. An equilibrium point of eq. (4) and eq. (5) should satisfy the following formulas:

$$k_r(\mathbf{x}_s)(h_r\varphi_r(\mathbf{x}_s) - \frac{1}{2}q_r\sigma_r)^+_{x_r} = 0$$

$$\beta_l(y_l - c_l)^+_{p_l} = 0$$

Therefore, we can get

$$\begin{aligned} h_r\varphi_r(\mathbf{x}_s) &< \frac{1}{2}q_r\sigma_r \Rightarrow x_r = 0 \\ and \quad x_r &> 0 \Rightarrow \varphi_r(\mathbf{x}_s) = \frac{q_r\sigma_r}{2h_r} \end{aligned} \tag{7}$$

$$y_l < c_l \Rightarrow p_l = 0 \quad and \quad p_l > 0 \Rightarrow y_l = c_l \tag{8}$$

According to the result of eq. (7) and eq. (8), we need to redesign $\varphi_r(\mathbf{x}_s)$ in the handover process under the following utility function:

$$\max \sum_{s\in S} U_s(\mathbf{x}_s) \quad s.t. \quad y_l \le c_l \quad l \in L \tag{9}$$

where $U_s(\mathbf{x}_s) \in R^{|s|} \to R$ is a concave function. We regard $x_r(t)$ as primal variable. According to the constraint condition, the Lagrangian of problem from eq. (9) can be expressed as follows [26]:

$$\begin{aligned} L(\mathbf{x}, p) &= \sum_{s\in S} U_s(\mathbf{x}_s) - \sum_{l\in L} p_l(y_l - c_l) \\ &= \sum_{s\in S} U_s(\mathbf{x}_s) - \sum_{l\in L} p_l(\sum_{r\in R} g_{lr}x_r - c_l) \\ &= \sum_{s\in S} (U_s(\mathbf{x}_s) - \sum_{r\in s} x_r q_r \sigma_r) + \sum_{l\in L} p_l c_l \end{aligned} \tag{10}$$

where $p(t)$ is dual variable. The dual problem of eq. (9) is:

$$D(p) = \sum_{s\in S} \max_{x_s > 0} (U_s(\mathbf{x}_s) - \sum_{r\in s} x_r q_r \sigma_r) + \sum_{l\in L} p_l c_l \tag{11}$$

The Karush-Kuhn-Tucker (KKT) condition [26] results in the following equations:

$$\begin{aligned} \frac{\partial U_s(\mathbf{x}_s)}{\partial x_r} &< q_r\sigma_r \Rightarrow x_r = 0 \\ and \quad x_r > 0 &\Rightarrow \frac{\partial U_s(\mathbf{x}_s)}{\partial x_r} = q_r\sigma_r \end{aligned} \tag{12}$$

$$y_l < c_l \Rightarrow p_l = 0 \quad and \quad p_l > 0 \Rightarrow y_l = c_l \tag{13}$$

Comparing with eq. (7) and eq. (8), we get eq. (14):

$$\frac{\partial U_s(\mathbf{x}_s)}{\partial x_r} = 2h_r \varphi_r(\mathbf{x}_s) \tag{14}$$

Referring to Theorem 1-5 in [26], we summarize the conditions to satisfy the existence, uniqueness, stability and friendliness of system equilibrium, which is expressed in Theorem 1 as follows:

Theorem 1. The handover fluid model of eq. (4) and eq. (5) has an unique stable equilibrium and achieves utility maximization if and only the following conditions C1-C5 hold.

C1: For all $s \in S$, the Jacobians of $\Psi_s(\mathbf{x}_s)$ are symmetric in order to guarantee $U_s(\mathbf{x}_s)$ has a twice continuously differentiable solution, *i.e.*

$$\frac{\partial \Psi_s(\mathbf{x}_s)}{\partial \mathbf{x}_s} = \left[\frac{\partial \Psi_s(\mathbf{x}_s)}{\partial \mathbf{x}_s}\right]^T$$

C2: For all $s \in S$ and $l \in L$, there is a solution $\mathbf{x}_s := \mathbf{x}_s(p)$ about the relations between traffic and congestion price:

$$\frac{\partial y_l^s(p)}{\partial p_l} \leq 0, \lim_{p_l \to \infty} y_l^s(p) = 0$$

where $y_l^s(p) := \sum_{r \in s} g_{lr} x_r(p)$, which denotes the aggregate traffic.

C3: For all $s \in S$, the Jacobians of $\frac{\partial U_s(\mathbf{x}_s)}{\partial x_r}$ is negative definite and continuous.

C4: For all $r \in R$, $\lim_{x_r \to \infty} \varphi_r(\mathbf{x}_s) = \infty$ which represents that the data rate on subflow r is zero if and only if congestion price is infinite.

C5: To achieve the TCP friendliness goal, $\varphi_r(\mathbf{x}_s) \leq \frac{1}{(x_r \tau_r)^2}$. The reason is that for TCP, $\varphi_r(\mathbf{x}_s) = \frac{1}{(x_r \tau_r)^2}$. A MPTCP flow should not be more aggressive than a TCP flow.

Based on the analysis of three performance indicators made in Section II.B, it can be seen that there is not any existing algorithm which achieves superior results for all of them. At the same time, [37] has demonstrated that existing MPTCP algorithms are conservative when no shared bottlenecks. Because our designed transmission architecture is in heterogeneous wireless networks, the situation of shared bottlenecks will occur rarely. Therefore, we place emphasis on responsiveness rather than fairness.

To satisfy conditions C1-C5 in Theorem 1, we redesign $\varphi_r(\mathbf{x}_s)$ in order to meet the fast handover responsiveness goal:

$$\varphi_r(\mathbf{x}_s) = \frac{\theta}{x_r} \tag{15}$$

where θ is a handover responsiveness factor.

Based on the analysis in [26], we know that the performance of TCP friendliness depends on the value of $\varphi_r(\mathbf{x}_s)$. The values of $k_r(\mathbf{x}_s)$ and $\frac{\partial \varphi_r(\mathbf{x}_s)}{\partial x_r}$ determine the responsiveness characteristic. As window fluctuation (one of three performance indicators) depends on the value of $\|K_s(\mathbf{x}_s)\|_1$, it is not possible that a newly designed MPTCP algorithm is better than all other algorithms for all performance indicators. Therefore, there is a need to do a trade-off between the three properties. In a handover scenario, we focus more on the responsiveness which makes the traffic transfer faster. As transmission paths are distributed across heterogeneous networks, there are few shared bottlenecks. Hence, the requirement of friendliness is relatively less important. According to the prior MPTCP algorithm, we set $k_r(\mathbf{x}_s) = x_r^2$. Therefore, the responsiveness characteristic mainly depends on $\frac{\partial \varphi_r(\mathbf{x}_s)}{\partial x_r}$.

TABLE I: Meaning of GCH-MV parameters

Parameters	**Description**
SS_{om}	Signal strength of orignal RSU
SS_{hm}	Signal strength of handover RSU
T_c	Compensation threshold
T_h	Handover threshold
om	Original $mmWave$ subflow
cs	Compensation $satellite$ subflow
hm	Handover $mmWave$ subflow

We define x_r^{TCP} as the throughput of a TCP flow on path r. In the fluid model of TCP-NewReno, we can get $\varphi_r^{TCP}(\mathbf{x}_s) = \frac{1}{\tau_r^2 (x_r^{TCP})^2}$ and $\frac{\partial \varphi_r^{TCP}(\mathbf{x}_s)}{\partial x_r} = -\frac{2}{\tau_r^2 (x_r^{TCP})^3}$. In terms of responsiveness, TCP is better than any MPTCP algorithm. For our handover algorithm, we can get the following formula to meet the compensation goal 3):

$$\frac{\partial \varphi_r(\mathbf{x}_s)}{\partial x_r} = -\frac{\theta}{x_r^2} = -\frac{2}{\tau_r^2 (x_r^{TCP})^3}. \tag{16}$$

To meet the compensation goal 1), we obtain $\sum_{r \in s} x_r = \max_{r \in s}(x_r^{TCP})$. Furthermore, we can get:

$$\max_{r \in s} (x_r^{TCP})^3 = (\sum_{r \in s} x_r)^3 = \max_{r \in s} \frac{2x_r^2}{\theta \tau_r^2}. \tag{17}$$

Therefore, the handover responsiveness factor can be denoted as follows:

$$\theta = \frac{2 \max_{r \in s} x_r^2}{\tau_r^2 (\sum_{r \in s} x_r)^3} \tag{18}$$

Next we relate the proposed fluid model to the Additive Increase Multiplicative Decrease (AIMD) algorithm of MPTCP. Once receiving an ACK on the subflow r, I_r is the increment of cwnd. D_r is the decrement of cwnd when a packet drops. Without loss of generality, let $D_r = \frac{w_r}{2} = \frac{x_r \tau_r}{2}$. We define Δw_r as the window size change of cwnd on subflow r during each RTT, which is denoted as follows.

$$\Delta w_r = (I_r - q_r \sigma_r D_r) w_r = \dot{w}_r \tau_r = \dot{x}_r \tau_r^2 \tag{19}$$

Like previous MPTCP algorithms, we still keep $k_r(\mathbf{x}_s) = x_r^2$. Combining eq. (4) with eq. (15) and eq. (18), we obtain:

$$I_r = h_r \frac{2 \max_{r \in s} x_r^2}{\tau_r (\sum_{r \in s} x_r)^3}. \tag{20}$$

Based on the proposed fluid model, the compensation handover scheme contains two stages for a running vehicle: compensation stage and handover stage. We define the parameters and present their corresponding descriptions in Table I.

Algorithm 1 : Fluid-based Multipath Compensation Handover Algorithm

```
input: all sub-path $r$, congestion window $w_r$, RTT $\tau_r$, signal
  strength $SS_r$, compensation threshold $T_c$, handover threshold $T_h$
  and packet-loss indicator $\sigma_r$;

1:  for each path $r$ in $s$ do
2:      if $T_h < SS_r < T_c$ then
3:          enter into compensation stage;
4:          establish the satellite path;
5:          calculate the handover transfer factor $H_r$;
6:          increase the cwnd $w_r$ according to Eq.(20);
7:          adjust the transmission rate $x_r = w_r/\tau_r$;
8:      end if
9:      else if $SS_r < T_h$ then
10:         enter into handover stage and do the handover between RSUs;
11:         do step (5);
12:         let $\sigma_r = 0$ and do not decrease cwnd when packet-loss occurs;
13:         do step (7);
14:     end else if
15:     else $SS_r > T_c$ then
16:         execute the default MPTCP AIMD algorithm;
17:     end else
18: end for
```

1) Compensation Stage: In the compensation stage, vehicle i moves away from current RSU (initial subflow: original mmWave om). The compensation decision is made through the initiative prediction method. Once SS decreases to the compensation threshold T_c, the vehicle i establishes the second compensation subflow cs via *satellite* interface. At the same time, the vehicle i starts to scan the surrounding RSUs in order to get the best candidate RSU using the optimum method described in section III.C.

2) Handover Stage: In the handover stage, vehicle i has to break the original $mmWave$ subflow om and reconnect with the optimal RSU. Once SS of original RSU reaches the handover threshold T_h, the vehicle i makes the handover decision. After that, SS of the new RSU will gradually increase. Accordingly, the throughput of handover $mmWave$ subflow hm will also increase.

In the handover process, the reason of packet loss is mainly handover between RSUs rather than network congestion. Therefore, we add another indicator SS_r to link congestion signal with packet loss. Let $\sigma_r = 0$ if $SS_r < T_h$ and 1 otherwise. The overall compensation handover algorithm is shown in Algorithm 1.

The goal of the two stage Algorithm 1 is to maintain high throughput for vehicles, making the handover process better for vehicles. In the compensation stage, once detecting that the SS decreases to a compensation threshold, the vehicle establishes a second subflow to compensate for the degrading throughput. In the handover stage, the vehicle performs a handover decision, transferring from the original RSU to the optimal candidate RSU which has been selected based on the algorithm described in Section III.C. Note that the data traffic is transferred very fast between the two subflows in order to respond to variations in the handover scenario. All this process is set to support high QoE for vehicles, which is in fact our very important objective.

C. Game-based Optimal Candidate RSU Selection Mechanism

(1) Candidate RSU-related Game Model

We consider there are m vehicles in some area and their set is denoted $I = \{1, 2, ..., i, ..., m\}$. Each vehicle can communicate with the remote server through a RSU. Vehicle i needs to perform handover when it will drive out of range of current RSU. There are n candidate RSUs and their set is denoted $J = \{1, 2, ..., j, ..., n\}$ when the vehicles are ready to perform the handover process. We denote $d_i \in D_i = \{0, 1, ..., j, ..., n\}$ the handover decision of vehicle i. $d_i > 0$ means vehicle i will do the handover from current RSU to the next RSU. $d_i = 0$ means vehicle i maintains the connection with current RSU. We also denote the strategy profile of all vehicles as $\mathbf{d} = (d_1, d_2, ..., d_i, ..., d_n)$.

The ***handover quality of RSU selection*** is defined by formula from eq. (21). $Q_i^j(t)$ refers to the receiving transmission ability of vehicle i in relation to RSU j. This transmission ability is evaluated in terms of three indicators: signal strength, available bandwidth and packet loss. For each vehicle, the different handover decision D_i will result in a different handover quality of RSU selection. The total handover quality is defined as the sum of handover quality values for all vehicles.

$$Q_i^j(t) = \frac{S_i^j(t) BW_i^j(t)}{PL_i^j(t)} \tag{21}$$

where $S_i^j(t)$ is the signal strength of RSU j that vehicle i can receive. $BW_i^j(t)$ is available bandwidth which RSU j can assign to vehicle i. $PL_i^j(t)$ is the packet loss of RSU j for vehicle i to transmit data. The computation of the three indicators has been described in Section III.A.

Similarly, the quality of current RSU is defined as follows:

$$Q_i^{org}(t) = \frac{S_i^{org}(t) BW_i^{org}(t)}{PL_i^{org}(t)} \tag{22}$$

According to the above-described process, it can be noted that if too many vehicles do the handover process and connect to the same RSU, the link containing this RSU will cause congestion and increase loss, affecting transmission quality. Additionally, the bandwidth allocated to each vehicle will also be lower, leading to poor transmission performance and lower QoE.

The quality evaluation of vehicles in the strategy profile $\mathbf{d}$ is performed based on the following quality function:

$$Q(t) = Q_i^{org} F(d_i, 0) + \sum_{j \in J} Q_i^j F(d_i, j) \tag{23}$$

where $F(d_i, j)$ is an indicator function which is introduced in eq. (24):

$$F(d_i, j) = \begin{cases} 1, if\ d_i = j \\ 0, otherwise \end{cases} \tag{24}$$

(2) Problem Formulation and Game Properties Analysis

The target of vehicle i is to determine whether to do handover and which candidate RSU to select. The decision of each vehicle not only depends on the variation of SS, but also on the strategies of other vehicles. This is because the quality of transmission link is related to handover distribution of candidate RSUs. Let $d_{-i} = (d_1, ..., d_i, ..., d_n)$ be the handover decisions of all other vehicles except vehicle i. If

Algorithm 2 : Game-based Optimal Candidate RSU Selection Algorithm

```
input: vehicle $i$, current RSU $org$, candidate RSU $j$, current quality $Q_i^{org}$ ;
initialization: $d_i(t) = 0$, $Q(t) = \sum_{i \in I} Q_i^{org}$;
repeat $\forall i \in I$ in parallel;
    while ($d_i{}^* = \mathrm{argmax}_{d_i \in D_i} Q_i(d_i, d_{-i})$ and $Q_i(d_i^{'}, d_{-i}) > Q_i(d_i, d_{-i})$) do
        update the handover quality $Q(t)$ according to eq. (23) and (24);
        if $d_i{}^*$ satisfies the potential function from eq. (25) do
            execute the strategy $d_i{}^*$;
            select the optimal RSU until achieve NE;
        end if;
    end while
send the selection result to vehicle $i$.
```

other vehicles' decision d_{-i} is given, vehicle i can make an appropriate decision d_i, using the current RSU or the candidate RSU to maximize the quality of handover, namely finding a strategy: $d_i{}^* \in \mathrm{argmax}_{d_i \in D_i} Q_i(d_i, d_{-i})$.

Thus we can consider the problem as a strategic game $\Gamma =< I, (D_i)_{i \in I}, (Q_i)_{i \in I} >$, in which the set of vehicles I are the players. We regard the game as a *multi-candidate RSU selection game*. We are concerned about whether the vehicles can get a decision profile in which no vehicle can further improve its handover quality when changing its strategy, namely there is a pure Nash equilibrium (NE) of game Γ.

Definition 1. *Given a strategy profile* (d_i, d_{-i})*, if there is a strategy profile* d^* *can satisfy* $Q_i(d_i{}^*, d_{-i}{}^*) \geq Q_i(d_i, d_{-i}{}^*), \forall d_i \in D_i$*,* d^* *is a NE of the game* Γ*.*

According to the analysis above, we get that the multi-candidate RSU selection game is a potential game. Then we can construct one potential function as follows [36][38]:

$$\phi(d) = \frac{1}{2} \sum_{k=1}^{n} \sum_{k \neq l} \frac{s_k}{pl_k} b_{k,R} \frac{s_l}{pl_l} b_{l,R} G_{\{d_k = d_l\}} G_{\{d_k > 0\}} + \sum_{k=1}^{n} \frac{s_k}{pl_k} b_{k,R} G_{\{d_k = 0\}} \tag{25}$$

where $b_{k,R}$ is the available bandwidth between vehicle k and RSU R, $b_{l,R}$ is the available bandwidth between vehicle l and RSU R, and $G_{\{event\}}$ is an indicator function.

Theorem 2. *The multi-candidate RSU selection game with the potential function denoted in eq. (25) is a potential game which can reach a Nash equilibrium.*

Proof. If vehicle i changes its current handover decision d_i to a better one $d_i^{'}$, then it may increase its handover quality function, namely $Q_i(d_i^{'}, d_{-i}) > Q_i(d_i, d_{-i})$. Based on the property of potential game, the potential function will increase accordingly, namely $\phi(d_i^{'}, d_{-i}) > \phi(d_i, d_{-i})$. Therefore, we consider two situations: (1) $d_i > 0$ and $d_i^{'} > 0$; (2) $d_i = 0$ and $d_i^{'} > 0$.

For situation (1), from the eq. (21) we can get that $Q_i(d_i^{'}, d_{-i}) > Q_i(d_i, d_{-i})$ is equivalent to:

$$\sum_{k \in I \setminus \{i\} : d_k = d_i^{'}} \frac{s_k}{pl_k} b_{k,R} > \sum_{k \in I \setminus \{i\} : d_k = d_k} \frac{s_k}{pl_k} b_{k,R} \tag{26}$$

From eq. (25) and eq. (26), we derive that:

$$\begin{aligned} \phi(d_i^{'}, d_{-i}) - \phi(d_i, d_{-i}) = & \frac{s_i}{pl_i} b_{i,R} \sum_{k \neq i} \frac{s_k}{pl_k} b_{k,R} G_{\{d_k = d_i^{'}\}} \\ & - \frac{s_i}{pl_i} b_{i,R} \sum_{k \neq i} \frac{s_k}{pl_k} b_{k,R} G_{\{d_k = d_i\}} > 0 \end{aligned} \tag{27}$$

The proof for situation (2) is similar with that for situation (1), which can also derive $Q_i(d_i^{'}, d_{-i}) > Q_i(d_i, d_{-i})$. According to the above proof, the multi-candidate RSU selection game is a potential game. Additionally, we get that this potential game can achieve a NE from Theorem 2. Algorithm 2 details the selection game process of optimal candidate RSUs.

D. Signal Strength Accurate Evaluation Model

Each vehicle can measure SS from the received signal strength indicator (RSSI). Because of the high-speed mobility of vehicles, SS of current RSU changes. Any vehicle can make handover decisions according to the variation of the received signal. In order to obtain accurate received signal strength values, we use the Kalman filter to estimate the difference among candidate and current RSUs. The Kalman filter estimation contains two stages: a time update stage and a measurement update stage. The time update stage is used for prediction as follows:

$$SS_{prev} = SS \tag{28}$$

$$ER_{prev} = ER_{post} + V \tag{29}$$

where SS is the evaluation value in the last round and SS_{prev} is the previous signal strength. ER_{prev} and ER_{post} are the a-priori and posteriori evaluation error covariance, respectively. V is the process noise covariance.

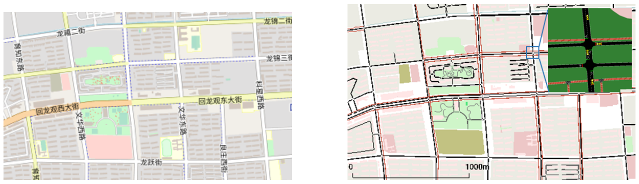
The measurement update stage is used for correction as follows:

$$KG = ER_{prev} / (ER_{prev} + NR) \tag{30}$$

$$SS = SS_{prev} + KG \times (SS_{cur} - SS_{prev}) \tag{31}$$

$$ER_{post} = (1 - KG) \times ER_{prev} \tag{32}$$

where KG is the Kalman Gain and NR is measurement noise covariance. SS_{cur} is the sample value of current round. Time update and measurement update stages can be inputs for each other. Finally, an accurate SS value can be obtained and used in the handover process.



(a) (b)

Fig. 3: A snapshot of the simulated area in Beijing, China: (a) The real map. (b)The SUMO map.

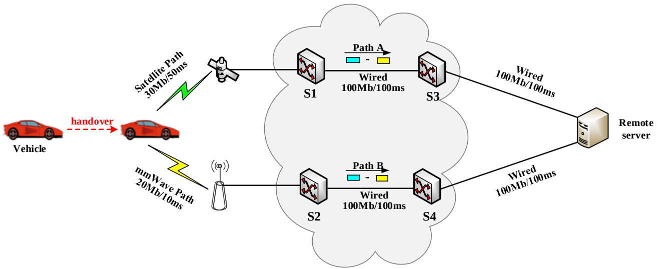


Fig. 4: The simulation topology

IV. PERFORMANCE EVALUATION

In this section, we evaluate our proposed handover scheme GCH-MV on a testbed which involves both Simulation of Urban MObility (SUMO) simulator [42] and Network Simulator NS-3.29 [40]. First, a part of the real road map of Beijing, China is obtained from OpenStreetMap, as shown in Fig. 3. Next, the traffic of vehicles on the map is generated by the SUMO simulator. The number of vehicles is 50 and the speed of each vehicle ranges from 0m/s to 30m/s. The mobility file is then imported into NS-3.29 which contains the latest MPTCP module [41] in order to simulate the moving track. We also perform numerical simulations in Matlab. We have deployed the experimental topology illustrated in Fig. 4. Each vehicle is equipped with two network interfaces mmWave and satellite. The parameter values used in simulations are listed in Table II.

The performance of handover is evaluated in terms of two aspects. The first aspect is ***transmission performance*** during the handover process, with focus on the following QoS metrics: throughput, end-to-end delay, retransmission number and loss rate. The detailed design mechanism corresponding to this aspect is described in Section III.B. In terms of evaluation, we compare GCH-MV with CLA-MPTCP [30] and MPTCP-LIA [25] in a vehicle network context. We have also designed a compensation handover algorithm for multipath TCP to mitigate the negative effects of handover, including for example, connection-break, throughput-degradation, etc. The goal of this compensation algorithm is not only to retain connectivity, but also to maintain high throughput by making use of multiple subflows for data transmission, improving the handover process for vehicles. The second aspect is the ***quality of transmission support*** provided by RSU to vehicles after handover. We have considered three indicators: signal strength, available bandwidth and packet loss and based on these we select the best-quality candidate RSU when performing handover decisions. The corresponding selection mechanism is detailed in Section III.C. For evaluation, we compare GCH-MV with two alternative handover methods: random selection and SS-based selection [30]. About the comparative evaluation, we mainly refer to handover quality of RSU selection in terms of vehicle number, RSU number and so on.

TABLE II: Parameter Configurations of Simulation

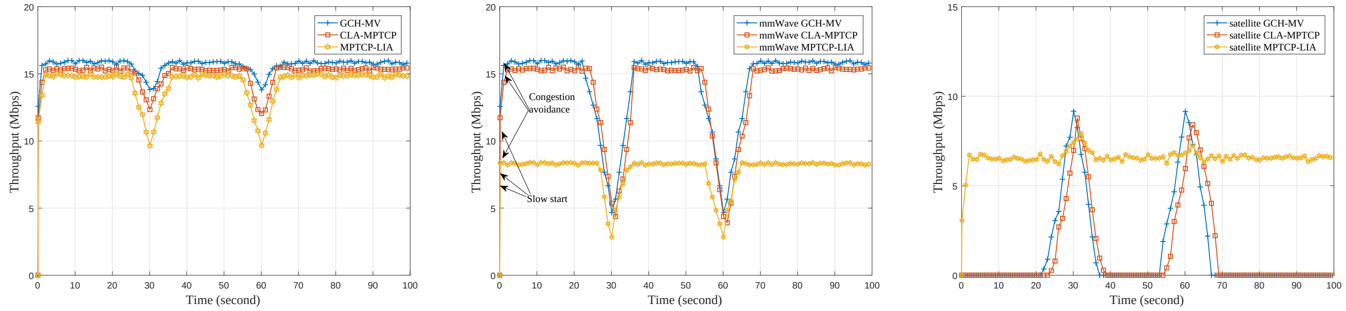
Parameters	**Original Path**	**Compensation Path**	**Handover Path**
Wireless technology	mmWave communication	Satellite communication	mmWave communication
Access bandwidth	20Mbps	30Mbps	20Mbps
Access link delay	10ms	50ms	10ms
Wired link bandwidth	100Mbps	100Mbps	100Mbps
Wired link delay	100ms	100ms	100ms
Loss rate	0∼0.15	0∼0.05	0∼0.15

A. *Handover Evaluation of Fluid Compensation Method*

The experimental environment is set up as in Fig. 4. The simulation time is 100s and handover is executed at 30s and 60s, respectively.

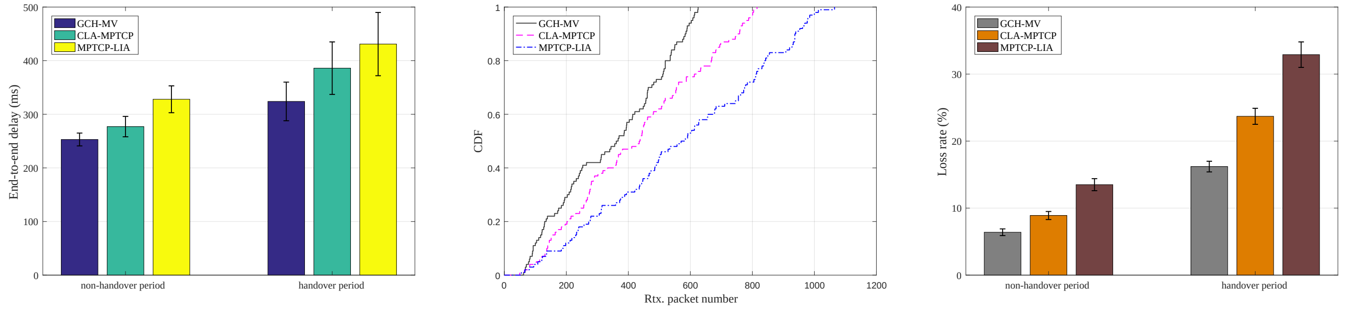
Fig. 5 shows the throughput variation for one of the vehicles in terms of total and sub-path throughput, respectively. Fig. 5(a) illustrates the comparison results of total throughput as the simulation time increases. It can be seen that GCH-MV performs better than CLA-MPTCP and MPTCP-LIA during the experiments, especially in the handover process. In vehicle networks with frequent handovers, the more varied transmission quality of different paths is, the faster responsiveness is required to maintain high level of transmission service. By making use of the fluid-based compensation method, GCH-MV can transfer much of the data traffic over the compensation path ($satellite$ subflow), achieving its overall goal of maintaining high throughput. At the same time, MPTCP-LIA mainly focuses on fairness and CLA-MPTCP considers the bandwidth delay product (BDP) only to maximize the amount of data transferred. However, in heterogeneous wireless networks, a situation with shared bottleneck happens rarely. Therefore, when facing sharp varying network conditions in the handover process, our proposed GCH-MV copes better than both CLA-MPTCP and MPTCP-LIA. As Fig. 5(a) shows, GCH-MV improves much the overall throughput, as it benefits from fluid-based multipath compensation handover mechanism.

We have also measured the throughput of each subflow. In Fig. 5(b), we compare the throughput of the $mmWave$ subflow among GCH-MV, CLA-MPTCP and MPTCP-LIA. During non-handover period, GCH-MV mainly transmits data via the $mmWave$ subflow, while MPTCP-LIA uses both $mmWave$ and $satellite$ subflows. Hence, the throughput of $mmWave$ subflow with GCH-MV outperforms that of MPTCP-LIA. However, during the handover period, the throughputs experienced by both methods degrade radically. The major difference is that the throughput of mmWave GCH-MV drops earlier than that of MPTCP-LIA. The reason is



(a) Total throughput variations (b) Throughput variations of mmWave sub-path (c) Throughput variations of satellite sub-path

Fig. 5: Comparison of throughput when GCH-MV, CLA-MPTCP and MPTCP-LIA are employed



(a) End-to-end delay (b) Retransmission number (c) Packet loss rate

Fig. 6: Comparison of other performance parameters when using GCH-MV, CLA-MPTCP and MPTCP-LIA

that GCH-MV proactively transfers traffic from the $mmWave$ subflow to the $satellite$ one in the compensation stage. Instead, MPTCP-LIA adjusts passively the cwnd in the handover process. Additionally, the responsiveness of CLA-MPTCP is slower than that of GCH-MV. Fig. 5(c) shows the comparative throughput variation of the $satellite$ subflow for GCH-MV, CLA-MPTCP and MPTCP-LIA. It is obvious that the compensation effect of GCH-MV is prominent. Similar with Fig. 5(a), it can be seen how the $satellite$ subflow when GCH-MV is employed compensates the decreasing throughput of the $mmWave$ subflow in advance due to the design of GCH-MV handover. The increase in the throughput on the $satellite$ subflow of CLA-MPTCP and MPTCP-LIA is hysteretic due to the lack of advance awareness of handover.

In addition to evaluating the throughput, we have also measured the end-to-end delays, retransmission numbers and packet loss rates for the three compared methods. Fig. 6(a) shows the end-to-end delay for the reference methods in the non-handover and handover periods, respectively. As a rule of thumb, larger end-to-end delays are associated with lower throughputs, and the results from Fig. 6(a) are consistent with those illustrated in Fig. 5(a). The benefit of GCH-MV in comparison with the other methods becomes larger during the handover period due to the smart use of the multiple subflows for data transmission. Fig. 6(b) plots the cumulative distribution functions (CDF) of the number of retransmissions for GCH-MV, CLA-MPTCP and MPTCP-LIA, respectively. It can be noted how GCH-MV well outperforms the other solutions in terms of number of packet retransmissions, indicating it supports a significantly higher transmission performance for vehicles than those solutions. Fig. 6(c) plots the packet loss rates for all the competing methods both during normal operation and during handover. Noteworthy is that GCH-MV outperforms the other methods in both situations, due to its superiority to handle the transmission. GCH-MV adaptation helps mitigate packet loss and guarantees high transmission performance.

B. Quality Evaluation of Optimal Candidate RSU Selection

In this subsection, the handover quality of the candidate RSU selection mechanism is evaluated. First, we introduce the setup of the experimental environment. We consider there are 10, 15, 20, 25, 30, 35 vehicles and 4, 5, 6, 7, 8 RSUs, respectively. Let the current signal strength of vehicles obey an uniform distribution of [-95dBm, -85dBm]. The current bandwidth that vehicles can obtain from current RSU obeys an uniform distribution of [1Mbps, 5Mbps]. The packet loss rate of current RSU obeys an uniform distribution of [0.5, 0.9]. Next, we set the index parameters of candidate RSUs. Each vehicle will have one to three candidate RSUs. The signal strength that each vehicle receives from candidate RSUs obeys an uniform distribution of [-90dBm, -75dBm]. The bandwidth that each vehicle obtains from candidate RSUs obeys an uniform distribution of [3Mbps, 10Mbps]. The packet loss

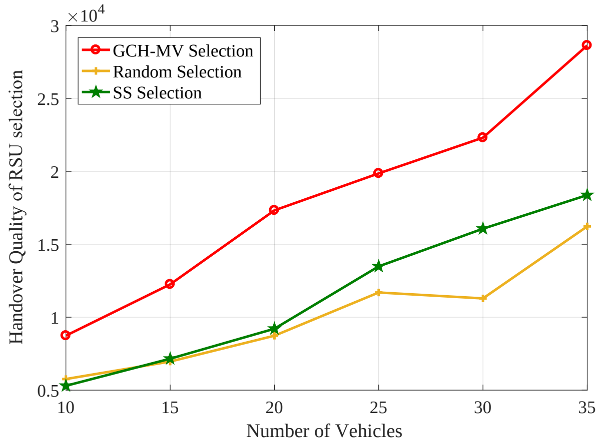


Fig. 7: Handover quality of RSU selection variation with increasing vehicle number

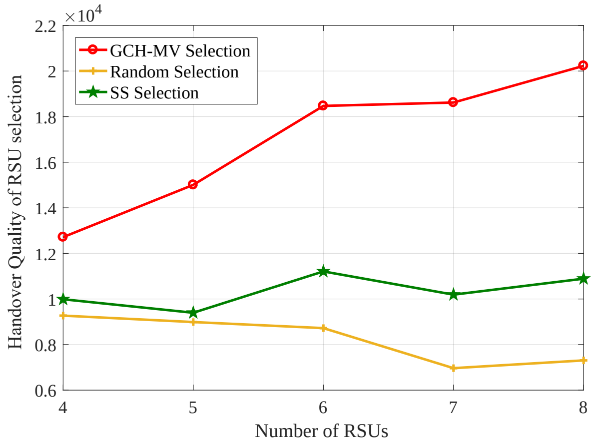


Fig. 8: Handover quality of RSU selection variation with increasing RSU number

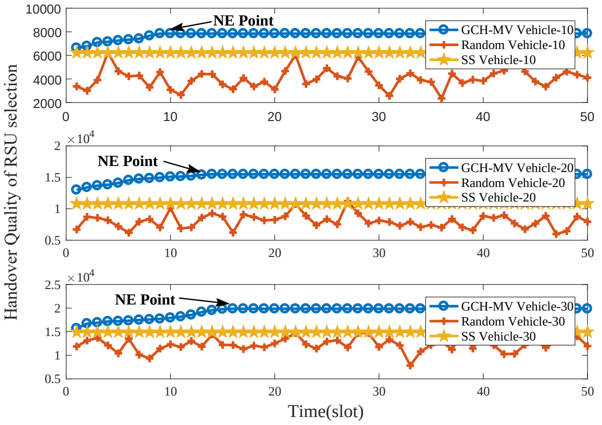


Fig. 9: Comparison of handover quality of RSU selection with different vehicles and 5 RSUs

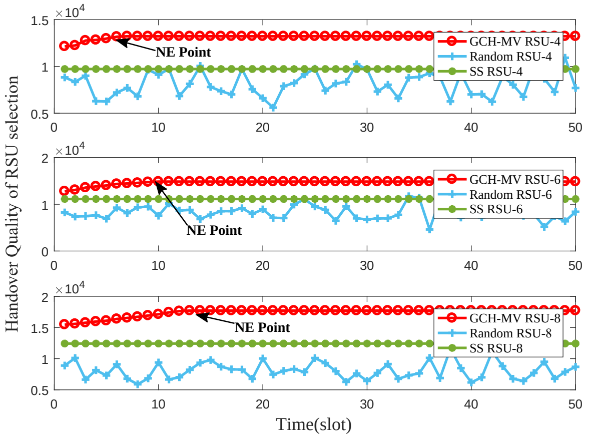


Fig. 10: Comparison of handover quality of RSU selection with 20 vehicles and different RSUs

rate of candidate RSU obeys an uniform distribution of [0.1, 0.6]. We compare our proposed GCH-MV selection with two other methods: Random Selection and SS Selection. Random Selection is designed to choose a candidate RSU for each vehicle randomly. SS Selection chooses the candidate RSU which can provide the highest signal strength to the vehicle.

Fig. 7 shows the variation of handover quality of RSU selection with three methods when the number of vehicle is set to 10 to 35 and the number of RSU is set to 5. As the figure shows, handover quality of RSU selection improves with the increase of vehicle number by using GCH-MV and SS Selection. When there are 30 vehicles with Random Selection, handover quality of RSU selection suddenly declines. The reason is that Random Selection does not consider any performance index of candidate RSU. This also causes Random Selection performs the worst among the three methods. In contrast, our proposed GCH-MV Selection can evaluate the candidate RSUs from signal strength, bandwidth and packet loss rate comprehensively. Noteworthy is that GCH-MV performs the best comparing with the other three methods.

Fig. 8 also shows the comparison results of handover quality of RSU selection as the number of RSU increases from 4 to 8 when the number of vehicle is set to 20. The performance of GCH-MV Selection outperforms the other two methods. Generally speaking, the more the number of RSU is, the more the candidate RSU choices the vehicles have. Therefore, handover quality of RSU selection of GCH-MV is increasing with the increase in number of RSUs. On the contrary, handover quality of RSU selection of SS Selection and Random Selection is fluctuant, even declining. The main reason is the same with Fig. 7. This result indicates that SS Selection and Random Selection can not guarantee the handover quality of vehicles.

Next, we will demonstrate the specific variation of the three methods within the simulation time. As shown in Fig. 9, from the top down, we can see the handover quality of the three methods when the number of vehicle is 10, 20 and 30, respectively. It is evident that our proposed GCH-MV can reach the NE point after limited slots. And the handover quality is better than the other two methods. It is worth noting that Random Selection is so fluctuant that we can not control the handover quality. Relatively speaking, SS Selection is definite to choose the RSU with highest signal strength. The strategy of SS-based selection will not change in the current handover phase. Similarly, Fig. 10 illustrates the handover quality of the three methods when the number of RSUs is 4, 6 and 8, respectively. Noteworthy is that GCH-MV selection reaches the NE point through the strategy game and GCH-MV performance is superior to those of the other two methods.

V. CONCLUSIONS AND FUTURE WORKS

This paper puts forward a novel game-enhanced compensation handover solution for Multipath TCP-based high-quality transmission service in 6G software defined vehicular networks. GCH-MV relies on two new mechanisms: fluid-based multipath compensation handover model and game-based optimal candidate RSU selection mechanism and involves two stages: compensation and handover. Through these mechanisms and stages, GCH-MV prepares for handover in advance in order to realize a transparent and performance-focused handover. In the compensation stage, GCH-MV analyzes original path status and establishes the compensation path to maintain the throughput. In the handover stage, GCH-MV selects the optimal candidate RSU by using potential game theory for vehicles to realize a Nash equilibrium. The experimental results indicate that our proposed GCH-MV outperforms other existing solutions in different conditions, demonstrating that it can address handover intelligently and effectively.

In our future work, we will consider employing V2V communications in downtown scenarios, especially involving dedicated short range communications. In addition, we plan to design a specific scheduler for MPTCP aiming to achieve fine-grained transmission control.

REFERENCES

[1] B. Zong, C. Fan, X. Wang, X. Duan, B. Wang and J. Wang, “6G Technologies: Key Drivers, Core Requirements, System Architectures, and Enabling Technologies,” in IEEE Vehicular Technology Magazine, vol. 14, no. 3, pp. 18-27, Sept. 2019.

[2] F. Tang, Y. Kawamoto, N. Kato and J. Liu, “Future Intelligent and Secure Vehicular Network Toward 6G: Machine-Learning Approaches,” in Proceedings of the IEEE, vol. 108, no. 2, pp. 292-307, Feb. 2020.

[3] K. B. Letaief, W. Chen, Y. Shi, J. Zhang and Y. A. Zhang, “The Roadmap to 6G: AI Empowered Wireless Networks,” in IEEE Communications Magazine, vol. 57, no. 8, pp. 84-90, August 2019.

[4] W. Saad, M. Bennis and M. Chen, “A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems,” in IEEE Network, vol. 34, no. 3, pp. 134-142, May/June 2020.

[5] G. Gui, M. Liu, F. Tang, N. Kato and F. Adachi, “6G: Opening New Horizons for Integration of Comfort, Security and Intelligence,” in IEEE Wireless Communications, vol. 27, no. 5, pp. 126-132, October 2020.

[6] P. Yang, Y. Xiao, M. Xiao and S. Li, “6G Wireless Communications: Vision and Potential Techniques,” in IEEE Network, vol. 33, no. 4, pp. 70-75, July/August 2019.

[7] X. Ge, Z. Li and S. Li, “5G Software Defined Vehicular Networks,” in IEEE Communications Magazine, vol. 55, no. 7, pp. 87-93, July 2017.

[8] G. Luo et al., “Software Defined Cooperative Data Sharing in Edge Computing Assisted 5G-VANET,” in IEEE Transactions on Mobile Computing, Early Access, 2019.

[9] Y. Zhang, H. Zhang, K. Long, Q. Zheng and X. Xie, “Software-Defined and Fog-Computing-Based Next Generation Vehicular Networks,” in IEEE Communications Magazine, vol. 56, no. 9, pp. 34-41, Sept. 2018.

[10] S. Correia, A. Boukerche and R. I. Meneguette, “An Architecture for Hierarchical Software-Defined Vehicular Networks,” in IEEE Communications Magazine, vol. 55, no. 7, pp. 80-86, July 2017.

[11] C. Xu, J. Zhao and G. M. Muntean, “Congestion Control Design for Multipath Transport Protocols: A Survey, in IEEE Communications Surveys & Tutorials, vol. 18, no. 4, pp. 2948-2969, Apr. 2016.

[12] G. Luo, J. Li, L. Zhang, Q. Yuan, Z. Liu and F. Yang, “sdnMAC: A Software-Defined Network Inspired MAC Protocol for Cooperative Safety in VANETs,” in IEEE Transactions on Intelligent Transportation Systems, vol. 19, no. 6, pp. 2011-2024, June 2018.

[13] L. Yan, X. Fang and Y. Fang, “A Novel Network Architecture for C/U-Plane Staggered Handover in 5G Decoupled Heterogeneous Railway Wireless Systems,” in IEEE Transactions on Intelligent Transportation Systems, vol. 18, no. 12, pp. 3350-3362, Dec. 2017.

[14] C. Xu, Z. Li, L. Zhong, H. Zhang and G. M. Muntean, “CMT-NC: Improving the Concurrent Multipath Transfer Performance Using Network Coding in Wireless Networks,” in IEEE Transactions on Vehicular Technology, vol. 65, no. 3, pp. 1735-1751, Mar. 2016.

[15] K. Xue et al., “DPSAF: Forward Prediction Based Dynamic Packet Scheduling and Adjusting With Feedback for Multipath TCP in Lossy Heterogeneous Networks,” in IEEE Transactions on Vehicular Technology, vol. 67, no. 2, pp. 1521-1534, Feb. 2018.

[16] K. Gao, C. Xu, J. Qin, L. Zhong and G. Muntean, “A Stochastic Optimal Scheduler for Multipath TCP in Software Defined Wireless Network,” 2019 IEEE International Conference on Communications (ICC), Shanghai, China, 2019, pp. 1-6.

[17] L. Xiao, T. Chen, G. Han, W. Zhuang and L. Sun, “Game Theoretic Study on Channel-Based Authentication in MIMO Systems,” in IEEE Transactions on Vehicular Technology, vol. 66, no. 8, pp. 7474-7484, Aug. 2017.

[18] F. Tang, Z. M. Fadlullah, N. Kato, F. Ono and R. Miura, “AC-POCA: Anticoordination Game Based Partially Overlapping Channels Assignment in Combined UAV and D2D-Based Networks,” in IEEE Transactions on Vehicular Technology, vol. 67, no. 2, pp. 1672-1683, Feb. 2018.

[19] C. Xu, P. Wang, C. Xiong, X. Wei and G. Muntean, “Pipeline Network Coding-Based Multipath Data Transfer in Heterogeneous Wireless Networks,” in IEEE Transactions on Broadcasting, vol. 63, no. 2, pp. 376-390, June 2017.

[20] N. Williams, P. Abeysekera, N. Dyer, H. Vu and G. Armitage, “Multipath TCP in Vehicular to Infrastructure Communications, Technical Report 140828A Swinburne University of Technology Melbourne, 2014.

[21] J. Mena, P. Bankole and M. Gerla, “Multipath tcp on a vanet: A performance study, ” 2017 ACM SIGMETRICS Performance Evaluation Review, Urbana-Champaign, 2017, pp. 39-40.

[22] S. Rene, E. Exposito, M. Gineste, J. Alins and O. Esparza, “Multipath TCP Architecture for Infotainment Multimedia Applications in Vehicular Networks,” 2015 IEEE 81st Vehicular Technology Conference (VTC Spring), Glasgow, 2015, pp. 1-5.

[23] C. Paasch, G. Detal, F. Duchene, et al, “Exploring mobile/WiFi handover with multipath TCP, ” 2012 ACM SIGCOMM workshop on Cellular networks: operations, challenges, and future design, 2012, pp. 31-36.

[24] A. Frmmgen, S. Sadasivam, S. Mller, A. Klein and A. Buchmann, “Poster: Use your senses: A smooth multipath tcp wifi/mobile handover”, ACM 21st Annual International Conference on Mobile Computing and Networking, Paris, France, 2015, pp. 248-250.

[25] L. Li, K. Xu, T. Li, K. Zheng, et al, “A measurement study on multipath TCP with multiple cellular carriers on high speed rails,” 2018 Conference of the ACM Special Interest Group on Data Communication (SIGCOMM ’18), Budapest, 2018,pp. 161-175.

[26] Q. Peng, A. Walid, J. Hwang and S. H. Low, “Multipath TCP: Analysis, Design, and Implementation,” in IEEE/ACM Transactions on Networking, vol. 24, no. 1, pp. 596-609, Feb. 2016.

[27] J. Zhao, C. Xu, J. Guan and H. Zhang, “A fluid model of multipath TCP algorithm: Fairness design with congestion balancing,” IEEE International Conference on Communications (ICC), London, UK, 2015, pp. 6965-6970.

[28] R. Melki, M. M. Mansour and A. Chehab, “A fairness-based congestion control algorithm for multipath TCP,” 2018 IEEE Wireless Communications and Networking Conference (WCNC), Barcelona, 2018, pp. 1-6.

[29] P. Dong, J. Wang, J. Huang, H. Wang and G. Min, “Performance Enhancement of Multipath TCP for Wireless Communications With Multiple Radio Interfaces,” in IEEE Transactions on Communications, vol. 64, no. 8, pp. 3456-3466, Aug. 2016.

[30] H. Sinky, B. Hamdaoui and M. Guizani, “Proactive Multipath TCP for Seamless Handoff in Heterogeneous Wireless Access Networks,” in IEEE Transactions on Wireless Communications, vol. 15, no. 7, pp. 4754-4764, July 2016.

[31] A. Croitoru, D. Niculescu and C. Raiciu, “Towards wifi mobility without fast handover,” 2015 12th USENIX Symposium on Networked Systems Design and Implementation (NSDI), 2015, pp. 219-234.

[32] K. Gao, C. Xu, J. Qin, S. Yang, L. Zhong and G. Muntean, “QoS-driven Path Selection for MPTCP: A Scalable SDN-assisted Approach,” 2019 IEEE Wireless Communications and Networking Conference (WCNC), Marrakech, Morocco, 2019, pp. 1-6.

[33] F. Meneses, D. Corujo, C. Guimaraes and R. L. Aguiar, “Extending SDN to End Nodes Towards Heterogeneous Wireless Mobility,” 2015 IEEE Globecom Workshops, San Diego, CA, USA, 2015, pp. 1-6.

[34] Rodriguez-Natal, Alberto, et al, “SDN for End-Nodes: Scenario Analysis and Architectural Guidelines,” arXiv preprint arXiv:1803.06294, 2018.

[35] M. Koivisto et al., “Joint Device Positioning and Clock Synchronization in 5G Ultra-Dense Networks,” in IEEE Transactions on Wireless Communications, vol. 16, no. 5, pp. 2866-2881, May 2017.

[36] S. Joilo and G. Dn, “A game theoretic analysis of selfish mobile computation offloading,” IEEE INFOCOM 2017 - IEEE Conference on Computer Communications, Atlanta, GA, 2017, pp. 1-9.

[37] S. Ferlin, O. Alay, T. Dreibholz, D. A. Hayes and M. Welzl, Revisiting congestion control for multipath TCP with shared bottleneck detection,” IEEE INFOCOM 2016 - The 35th Annual IEEE International Conference on Computer Communications, San Francisco, CA, 2016, pp. 1-9.

[38] Y. Liu, S. Wang, J. Huang and F. Yang, “A Computation Offloading Algorithm Based on Game Theory for Vehicular Edge Networks,” 2018 IEEE International Conference on Communications (ICC), Kansas City, MO, USA, 2018, pp. 1-6.

[39] C. Raiciu, M. Handley and D. Wischik, “Coupled congestion control for multipath transport protocols,” IETF RFC 6356, Oct, 2011.

[40] Network Simulator (NS-3.29), https://www.nsnam.org/releases/ns-3-29/.

[41] NS-3 MPTCP Kashif Nadeem Model, https://github.com/Kashif-Nadeem/ns-3-dev-git.

[42] Simulation of Urban MObility, https://sumo.dlr.de/docs/index.html.

[43] K. Ji, Y. Dong, J. Chen, T. Mao and Z. Wang, “Delay-Minimization Link Selection for Heterogeneous VLC-DSRC VANETs,” 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), Antwerp, Belgium, 2020, pp. 1-5.

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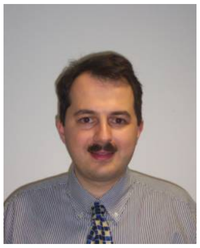

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