URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

A Cooperated Approach Between V2I and V2V for High Definition Map Dissemination in Automated Driving

Xinze Wu*, Xiangming Wen, Luhan Wang, Wei Zheng, Zhaoming Lu and Luning Liu
(1) Beijing Laboratory of Advanced Information Networks, BUPT, Beijing 100876, China
(2) School of Information and Communication Engineering, Beijing 100876, China

Abstract

Vehicle-to-everything (V2X) communication technology has been steadily developed and recently it has played an important role in automated driving technology. In order to achieve safe and reliable automated driving, high definition (HD) map-assisted high-precision positioning becomes more inevitable to provide vehicles with the ability of recognizing and perceiving. However, due to the bottleneck of wireless bandwidth and the delay constraint, efficient data dissemination scheme for HD map is a challenging task. In this paper, we investigate the policy for jointly power control and spectrum assignment with the purpose of guaranteeing the strictly reliable requirement of HD map transmission while maximizing the sum data rate of overall network. Simulation results demonstrate the effectiveness of the proposed scheme in terms of the system capacity and the probability of successful transmission.

1 Introduction

High definition (HD) map is a critical part of highly automated driving (HAD) technology and shows high possibility of supporting very high accuracy vehicle localization and navigation ability for automated driving. To our best knowledge, it is still an open problem to support automated driving with higher completeness by HD map transmission. The target vehicle needs to receive complete up-to-date map within given delay before roaming into the next region. V2X is considering as a promising technology to meet the communication requirement of automated driving[1], especially in disseminating time-sensitive and large volume contents.

Sidelink and shared channel communication are two major categories of V2V communication specified in 3GPP according to the co-existence mode with V2I links [2], between which shared channel V2V draws more attention due to its high spectrum efficiency. Since the shared channle mode use the same radio resources with multiple V2I links, interference control is a major issue in shared channel V2V communication, and plenty of studies have focus on these apsects[3, 4]. However, HD map dissemination tasks are quite different from other scenarios, as they have rigorous requirements of the transmission, including high throughput and real-time update, etc.. Therefore, it is distinctly important to design an efficient and robust HD map dissemination scheme for V2X-assisted automated driving.

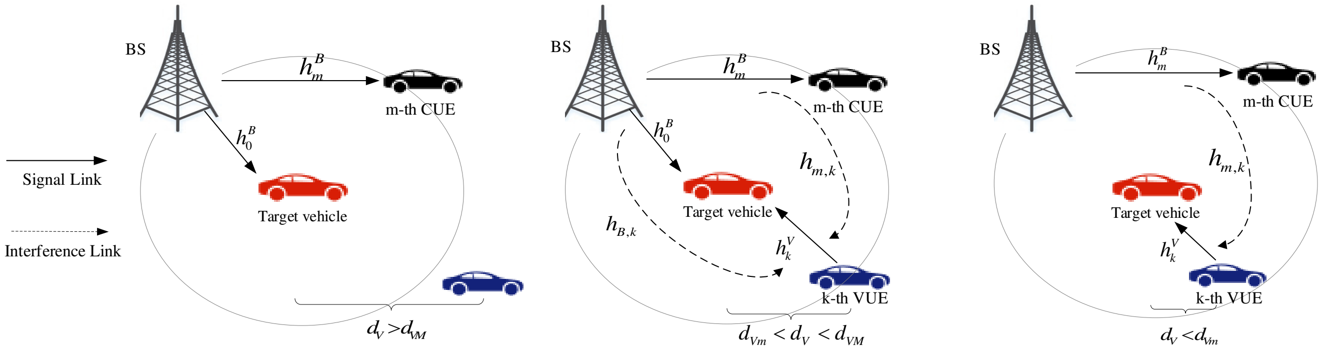
In this paper, we propose an HD map dissemination scheme based on cooperative V2X. Considering both the resource utilization and communication efficiency, we present a joint mode selection, power control and spectrum assignment scheme to maximize the overall network capacity while satisfying the reliability requirement of the HD map dissemination. The main contributions of this paper lie in the following aspects:

(1) A practical model is formulated to describe the interference control problem in V2X enabled HD map dissemination, in which HD map are divided into many data blocks based on data volume and infrastructure environment, and can be delivered to the target vehicle through cooperated V2I and V2V communications. (2) A Contact Duration model is introduced to model the delay satisfying probability, and a two-step solution is designed. Firstly, the optimal power allocation model with delay-satisfying probability, and the pairing model based on optimal power allocation. (3) We evaluate and analyze the performance of the proposed approach from the extensive simulations, and the results prove that the proposed approach can promote the overall throughput and gurantee the delay constraints of HD map dissemination.

2 System Model and Problem Formulation

2.1 Scenario

Consider a vehicular communication network as shown in Fig. 1, where the blue vehicle group, denoted as vehicular users (VUEs) et as $\mathscr{K} = \{1, 2, ..., K\}$, have stored the required HD map data in the forward direction of the red vehicle, the red one is considered as the target vehicle of the HD map request. Moreover, M vehicles are performing V2I communications, which may increase system interference to V2V users, denoted as cellular users (CUEs) set as $\mathscr{M} = \{0, 1, 2, ..., M\}$. Since the up-to-date map should be obtained by the target vehicle completely within given delay, the BS and each VUEs can simultaneously transmit different data blocks of the original content according to the network condition. To improve the spectrum efficiency of the considered vehicular network, we propose a bandwidth multiplexing communication mode in which different V2I and V2V communication links are permitted to access the same downlink resources for their individual data transmission. As shown in Fig.1, three cases of transmission modes will be discussed in detail later based on the position relationship of the two vehicles.



(a) Mode 1 : V2I transmission only (b) Mode 2 : cooperative V2X transmission (c) Mode 3 : V2V transmission only

Figure 1. An illustration of interference between V2I link and V2V link

In this paper, we focus on spectrum and power allocation in a resource block by optimizing P_k^V, P_m^B and $x_{m,k}$, which denote the transmit power of the k-th VUE, the transmit power of the BS, and the spectrum reusing indicator respectively. In particular, $x_{m,k}=1$ when the k-th VUE reuses the spectrum of the V2I links, and $x_{m,k}=0$ otherwise. We assume that d denotes the distance between the two vehicles, d_{VM} and d_{vm} indicate the maximum V2V communication range and threshold, respectively. And the channel power gain are denoted by h_m^B, h_k^V, $h_{B,k}$, $h_{m,k}$, respectively.

2.2 Transmission Model

The system performance can be directly impacted by V2I/V2V communication contact in the automated driving system. And the time of communication contact is known as contact duration, so that we define the V2I/V2V contact duration as $\mathrm{T}_{V2I/V2V}$ based on the location relationship between the target vehicle and the communication coverage. It is demonstrated that the probability density function of T_{V2I} and T_{V2V} follows the exponential distribution, which can be written as

$$f_{\mathrm{T}_{V2I}}(x)=\lambda_{V2I}e^{-\lambda_{V2I}x}, \quad f_{\mathrm{T}_{V2V}}(x)=\lambda_{V2V}e^{-\lambda_{V2V}x}, \tag{1}$$

where λ_{V2I} and λ_{V2I} are the average contact duration.

We assume the size of the original HD map data is L, and each data block has the same size. Fig. 1 illustrates possible interference case for three transmission mode during HD map delivery. We use Mode 2 to explain the meaning of each parameter in detail:

In Mode 2, HD map data is divided into k+1 data blocks, which have the same size $s^{(2)}=\frac{L}{k+1}$. Those data blocks are transmitted by both BS and k VUEs simultaneously in order to enhance communication efficiency. When the k-th VUE reuses the downlink spectrum resource of the m-th CUE, the interference between V2V pair and the CUE is incurred. Simultaneously, the V2V pair also suffer the interference from the link between the BS and the target vehicle. The SINR of the target vehicle is given by $\rho_{Vk}^{(2)}$, caused by V2V pairs, and $\rho_B^{(2)}$, caused by BS. The instantaneous downlink SINR received by the m-th CUE is given by $\rho_c^{(2)}$. Then, the transmission rates $r_B^{(2)}$, $r_{Vk}^{(2)}$ and the transmission delay $t_{V2I}^{(2)}$, $t_{V2V}^{(2),k}$ for BS and V2V pair can be calculated respectively.

In Mode 1, HD map information is only transmitted by BS. Under this case, when the CUEs spectrum resource is not currently reused by any other V2V pairs, it will not suffer the interference from V2V pairs. And in Mode 3, $d \le d_{vm}$ so that HD map data blocks are transmitted only by k VUEs.

Then, the sum data rate of CUE m and V2V pair k over their allocated spectrum resource can be given respectively by

$$\begin{aligned} R_m^c =&\eta_1 \log_2(1+\rho_c^{(1)})+\eta_2 \sum_{k\in\mathscr{K}} x_{m,k}^{(2)}\log_2(1+\rho_c^{(2)}) \\ &+\eta_3 \sum_{k\in\mathscr{K}} x_{m,k}^{(3)}\log_2(1+\rho_c^{(3)}), \end{aligned} \tag{2}$$

$$R_k^V=\eta_2\sum_{m\in\mathscr{M}} x_{m,k}^{(2)}\log_2(1+\rho_{Vk}^{(2)})+\eta_3\sum_{m\in\mathscr{M}} x_{m,k}^{(3)}\log_2(1+\rho_{Vk}^{(3)}). \tag{3}$$

where η_i denote the mode selection indicators, η_i=1 when Mode i was chosen.

2.3 Problem Formulation

Based on the proposed cooperative V2X transmission scheme, the objective of this paper is to maximize the overall network capacity while ensuring the reliability requirement of the HD map transmission.

We assume that the V2I/V2V contact duration is T_{V2I}^i/$\mathrm{T}_{V2V}^{i,k}$, where i denote mode selection parameter. According to the above analysis about contact patterns, we can obtain the successful transmission probability of the BS and the k-th VUE, which can be expressed as $P_{V2I}^i=P(\mathrm{T}_{V2I}^i \ge t_{V2I}^i)$ and $P_{V2V}^{i,k}=P(\mathrm{T}_{V2V}^{i,k} \ge t_{V2V}^{i,k})$.

Therefore, the resource management (joint mode selection, spectrum assignment, and power control) problem can be mathematically formulated as

$$\max_{x_{m,k},P_m^B,P_k^V} \{\sum_{k\in\mathscr{K}} R_k^V + \sum_{m\in\mathscr{M}} R_m^c\} \tag{4a}$$

$$s.t. \quad \eta_1+\eta_2+\eta_3=1,\ \eta_1,\eta_2,\eta_3\in\{0,\ 1\} \tag{4b}$$

$$0\le P_m^B \le P_{max}^B, 0\le P_k^V \le P_{max}^V, \tag{4c}$$

$$\sum_{k\in\mathscr{K},m\in\mathscr{M}} x_{m,k}\le 1,\ x_{m,k}\in\{0,\ 1\}, \tag{4d}$$

$$\eta_1 P_{V2I}^1+\eta_2\prod_{k\in\mathscr{K}} P_{V2I}^2\cdot P_{V2V}^{2,k}+\eta_3\prod_{k\in\mathscr{K}} P_{V2V}^{3,k}\ge 1-\varepsilon. \tag{4e}$$

where constraint (4b) is to ensure that only one mode is selected based on distance. Besides, (4d) are the matching constraints implying that the spectrum allocated to a CUE can be only reused by at most one VUE, which moderate the complexity of the interference management and serve as a reasonable starting point for the resource allocation. Constraint (4e) describes the outage probability requirement of HD map transmission and ε is the maximum violation probability.

3 Resource Management

Since interference exists only within each spectrum reusing pair consisting of a VUE and a CUE, we can decompose the problem (4) into two sub problems, i.e., power control and pairing optimization, which can be addressed in sequence. First, we design the optimal power allocation for each possible spectrum reusing pair to maximize the overall network capacity while guaranteeing the reliability requirement of the HD map transmission, which is the main contribution of this paper. Then, we optimize the spectrum reusing pattern based on the optimal power allocation of all possible reusing pairs.

3.1 Optimal Power Allocation

(4e) has different expressions in different situations, i.e.

$$P^{1}_{V2I} \geq 1-\varepsilon, \tag{5}$$

$$\prod_{k\in\mathscr{K}} P^{2}_{V2I}\cdot P^{2,k}_{V2V} \geq 1-\varepsilon, \tag{6}$$

$$\prod_{k\in\mathscr{K}} P^{3,k}_{V2V} \geq 1-\varepsilon. \tag{7}$$

We will solve the problem in (4) under the conditions (5)-(7), respectively.

We use *Mode 2* as an example to illustrate the process of solving the optimal power allocation problem: In Mode 2, the corresponding problem is formulated as

$$\max_{P^B_m, P^V_k} \{ \sum_{k\in\mathscr{K}} R^V_{k,m} + \sum_{m\in\mathscr{M}} R^c_{m,k} \} \quad s.t. \quad (4c),(6). \tag{8}$$

Consider a particular spectrum reusing pair of the k-th VUE and the m-th CUE, which implies that the k-th VUE suffers interference only from the m-th CUE, and vice versa. The SINR of the k-th VUE ($R^V_{k,m}(P^V_k, P^B_m)$) and the m-th CUE ($R^c_{m,k}(P^V_k, P^B_m)$) are then functions of P^B_m and P^V_k.

The problem (8) can be addressed by solving two one-dimensional optimization problems, i.e., optimizing P^V_k to maximize $R(P^V_k, P^B_{max})$ with P^B_m fixed as $P^B_m = P^B_{max}$, and optimizing P^B_m to maximize $R(P^V_{max}, P^B_m)$ with P^V_k fixed as $P^V_k = P^V_{max}$, whose optimal solutions are denoted by P^{V*}_k and P^{B*}_m, respectively. We set the optimal objective values of the two single-variable problems, denoted by $R^*(P^V_k, P^B_{max})$ and $R^*(P^V_{max}, P^B_m)$ correspondingly, to be $-\infty$ in case of infeasibility. Then, the optimal value of the problem (8) is $R^* = \max\{R^*(P^V_k, P^B_{max}), R^*(P^V_{max}, P^B_m)\}$. For the case $R^* > -\infty$, the optimal solution to the problem (8) is

$$\begin{cases} P^{V*}_k = P^V_k, P^B_m = P^B_{max} \;\; if \;\; R^*(P^V_k, P^B_{max}) \geq R^*(P^V_{max}, P^B_m) \\ P^{B*}_m = P^B_m, P^V_k = P^V_{max} \quad otherwise, \end{cases} \tag{9}$$

In the following, we discuss the optimization of the two single variable problems.

1) P^V_k optimization: the corresponding P^V_k optimization problem can be formulated as

$$\max_{P^V_k} R^*(P^V_k, P^B_{max}) \quad s.t. \quad (4c)\;,\;(4e). \tag{10}$$

The outage probability constraint can be transformed into

$$\frac{L}{k+1}\{\frac{\lambda_{V2I}}{B_B \log_2(1+\rho^{(2)}_B)} + \sum_{k\in\mathscr{K}} \frac{\lambda_{V2V}}{\sum_{m\in\mathscr{M}} B_V \log_2(1+\rho^{(2)}_{Vk})}\} \geq -\ln(1-\varepsilon) \tag{11}$$

If the constraint (11) holds, overall network capacity in (10) is monotonically increasing with P^V_k, we can find the optimal solution by Interpolation Search.

2) P^c_m optimization: the corresponding P^c_m optimization problem is similiar to 1), then we can obtain the optimal solution and the optimal value, denoted by P^{c*}_m and $R^*(P^V_{max}, P^c_m)$, respectively. By now, we have solved the problem (8), and derive the optimal power allocation scheme in Mode 2.

By comprehensively considering the three cases, the optimal power allocation can be expressed by

$$R^*(P^V_k, P^B_m) = \mathrm{argmax}\{R^*_{\eta_i}, i\in\{1,2,3\}\}. \tag{12}$$

3.2 Pairing optimization

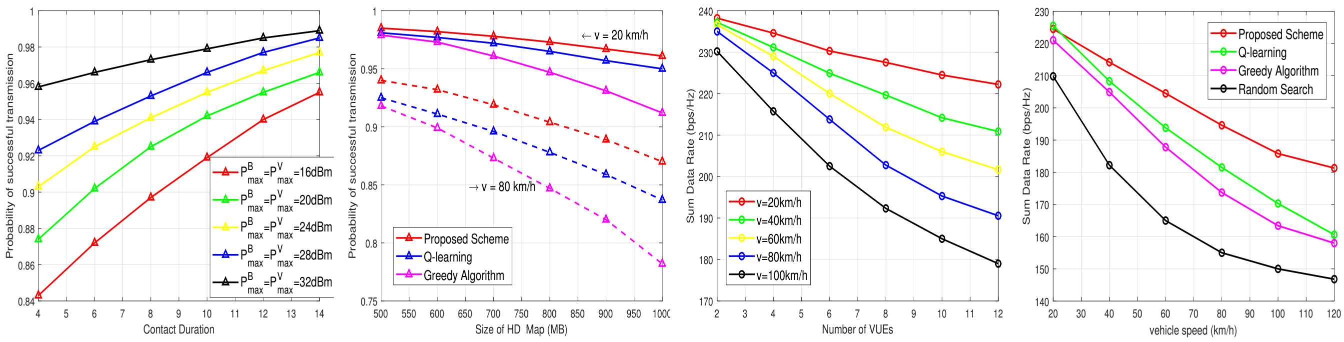
From the previous subsection, we have derived the optimal power allocation for all possible spectrum reusing pairs.The remaining work is to find the optimal spectrum reusing combination by determining $x_{m,k}$, which can be formulated as a linear assignment problem given by

$$\max_{x_{m,k}} \sum_{m\in\mathscr{M}, k\in\mathscr{K}} R^*(P^{V*}_k, P^{B*}_m), \tag{13}$$

which turns out to be a best matching problem with weighted bipartite graph and can be efficiently solved by the Kuhn-Munkras (KM) method in polynomial time. By combining the graph theory and the duality theory of linear programming, the KM Algorithm can yields the global optimum under perfect matching, as a sequential combinatorial optimization algorithm. After obtaining the optimal spectrum sharing pattern $x^*_{m,k}$, we can derive the optimal overall network capacity given as

$$x^*_{m,k}(\sum_{k\in\mathscr{K}} R^{*V}_{k,m} + \sum_{m\in\mathscr{M}} R^{*c}_{m,k}). \tag{14}$$

As the KM method solves the problem (13) with complexity $\mathscr{O}(M^3)$ and the Interpolation Search solves the problems (4g) with complexity $\mathscr{O}(\log\log(1/\varepsilon))$, the overall complexity of the proposed algorithm is $\mathscr{O}(M^3 + 2KM\log\log(1/\varepsilon))$, where ε is the error tolerance of the Interpolation Search.



(a) Probability of successful transmission with varying Contact Duration (b) Probability of successful transmission with varying size of HD map (c) Sum data rate with varying number of VUEs (d) Performance comparison of four different schemes

Figure 2. Performance comparison

4 NUMERICAL RESULTS

In this section, numerical results and analysis are provided to show the performance of the proposed cooperative V2X resource management scheme. It is assumed that a single cell outdoor scenario with a carrier frequency of 2 GHz and that RB has a bandwidth of 180 kHz for downlink communication. Some parameters are set as $d_{VM} = 150$m, $\sigma^2 = -114$dBm, Number of CUEs is 20.

As can be seen in Fig 2.(a), with the increasing average CD, the latency requirement of the HD map transmission becomes less stringent, so that the probability of successful transmission increases. It is also observed that the data reception of the target vehicle is less sensitive to CD when P^V_{max} , P^B_{max} increases, which can guarantee the requisite low-latency information transmission.

From Fig 2.(b), we can see that the performance of all approaches reduces as the increase size of HD map. This is because HD map with smaller size can be allocated more flexibly with the same number of vehicles. In addition, the topology of the vehicular network becomes more stable with reducing vehicle speed, and thus the probability of successful transmission increase.The high probability indicates that the proposed scheme can effectively guarantee the transmission reliability requirements and has higher performance than Greedy Algorithm and Q-learning.

From Fig 2.(c), we can see that the sum data rate performance reduces as the increase number of VUEs in. Because more V2V links aim to share the fixed radio resource as the increase number of VUEs, consequently leading to the growing amount of generated interference to V2I links and V2V links, hence the sum rate performance reduces. It is worth noting that faster speeds has a more significant impact on performance. Such the performance degradation results from the lower received desired power in cooperative V2X links due to the average increase inter-vehicle distance when the higher movement speed induces sparser traffic.

Fig 2.(d) evaluates the sum data rate performance of four schemes with different vehicle speed. From the figure, the sum data rate performance reduces due to the increase of vehicle speed, especially when the random search approach has the worst performance. The higher speed results in the high dynamic vehicular environment, resulting in the high observation uncertainties, which decreases the Q-learning efficiency. However, as the vehicle speed increases with high uncertainties, our proposed approach can still maintain the sum data rate at a considerable level and outperforms Greedy Algorithm which lack of global cosiderations.Hence, the proposed approach are more stable and robust in high dynamic IoV networks.

5 Acknowledgment

This work is supported by the NSFC project, under grant 61801047, the Beijing Municipal Education Commission Funding Project "5G Connected Autonomous Driving Technology and Applications", and the 111 project B17007.

References

[1] D. Hetzer and M. Muehleisen and A. Kousaridas and J. Alonso-Zarate, “5G Connected and Automated Driving: Use Cases and Technologies in Cross-border Environments,” *2019 European Conference on Networks and Communications (EuCNC)*, vol. 1, no. 1, pp. 78–82, 2019.

[2] X. Wang, S. Mao, M. Gong, “An overview of 3GPP cellular vehicle-to-everything standards,” *GetMobile: Mobile Computing and Communications*, vol. 21, no. 3, pp. 19–25, 2017.

[3] Y. Liu, H. Zhang, K. Long, A. Nallanathan, and V. C. M. Leung, “Energy-efficient subchannel matching and power allocation in noma autonomous driving vehicular networks,” *IEEE Wireless Communications*, vol. 26, no. 4, pp. 88–93, August 2019.

[4] C. Guo, L. Liang, and G. Y. Li, “Resource allocation for low-latency vehicular communications: An effective capacity perspective,” *IEEE Journal on Selected Areas in Communications*, vol. 37, no. 4, pp. 905–917, April 2019.