

# Toward Multi-Radio Vehicular Data Piping for Dynamic DSRC/TVWS Spectrum Sharing

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**Abstract**—Enabling high-throughput and cost-effective vehicular communications is important for many emerging vehicular applications, such as safety applications, traffic management, and mobile Internet access. However, dedicated short-range communications (DSRC), as the sole solution so far, would meet significant challenges in the foreseeable future for supporting diverse vehicular applications simply due to the spectrum scarcity. To address this issue, in this paper, we propose an adaptive vehicular data piping framework, which is assisted by a geolocation database, for the joint utilization of DSRC and TV white space (TVWS) spectrum; in this framework, three types of vehicular data pipes (DSRC, TVWS, and cellular) are considered, while the cellular data pipe is only used as a control-plane link in coordinating the dynamic DSRC and TVWS spectrum sharing happened in the data-plane operations. In order to guarantee the optimal dynamic vehicular access to the geolocation database, we first propose a log-sum-exp (LSE) approximation-based TVWS geolocation database access approach, named LSE-WS algorithm. We formulate the adaptive vehicular data piping problem for dynamic DSRC/TVWS spectrum sharing as a coalitional formation game, and it is shown that the proposed coalitional formation approach reaches the optimal and Nash-stable vehicular data pipe selection partition in a distributed way. Through extensive simulations, we demonstrate that not only the proposed LSE-WS algorithm satisfies the dynamic vehicular geolocation database access requirement but also the adaptive multi-radio vehicular data piping approach for dynamic DSRC/TVWS spectrum sharing significantly outperforms the traditional DSRC solution.

**Index Terms**—TV white space, DCF, geolocation database, dynamic spectrum sharing, Markov approximation, coalition game.

## I. INTRODUCTION

NOTICEABLE advance of wireless communications and pervasive use of mobile electronics have made connected vehicles no longer a futuristic promise but rather an attainable

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technology to improve road safety and provide in-car entertainment and mobile Internet access [1]. Vehicular users increasingly expect the connected services in their vehicles, and it is estimated that more than 75% of vehicles sold worldwide in 2020 will be connected, either by embedded, tethered or smartphone integration. Motivated by the increasing vehicular applications and tremendous market demands of in-vehicle communications, such as online media streaming, vehicular social networking, and real-time traffic information sharing etc., it is critical to enable high-rate and reliable vehicular wireless access in a scalable and cost-effective manner [2].

The IEEE Standard Working Group has developed a set of vehicular access standards for vehicular communications [3], such as Dedicated Short Range Communications (DSRC), IEEE 802.11p, and IEEE 1609.x WAVE standard. On one hand, it is still a challenging task to achieve the high-throughput and reliable vehicular communications in highly mobile, often densely populated, and frequently non-line-of-sight vehicular environments [4]. On the other hand, with the proliferation of medium-rich vehicular applications, the allocated 75 MHz 5.9 GHz licensed spectrum for DSRC would become even more crowded in the foreseeable future. Spectrum is the fundamental foundation of modern wireless networks; allowing vehicular communication to available licensed/unlicensed spectrum and supporting seamless interworking between these licensed/unlicensed bands is a simple – yet effective – idea with immense benefits, addressing many technical challenges that vehicular network researchers are facing. Given that both Industrial, Scientific and Medical (ISM) band and licensed cellular spectrum have already been facing an uphill battle against the phenomenal growth of mobile data traffic [5], [6], there are very few options remaining on the table. One such good opportunity is the abundant unlicensed spectrum resource at VHF/UHF bands, referred to as TV White Space (TVWS) [7], [8]. With the superior propagation characteristic of TVWS spectrum, TVWS-enabled vehicular access could provide a wide-coverage, high-rate, yet cost-effective connectivity by leveraging the Geolocation database [9], [10] or Radio Environment Maps (REM) technology [11], [12] for diverse vehicular applications.

Modern vehicles feature multiple wireless access techniques that are operating separately on different spectrum bands, e.g., WiFi, LTE, DSRC etc. To enable the dynamic DSRC/TVWS spectrum sharing for high-throughput and to support seamless internetworking between the licensed and unlicensed bands, research community needs to address two

major research challenges. The first major challenge is how to design a joint optimization mechanism for performance improvement when multiple wireless access techniques of different nature are present; in particular, it still remains unclear to the research community, at this moment, whether the introduced opportunistic TVWS dynamic sharing in joint optimization framework could co-exist with existing wireless access techniques, such as Distributed Coordination Function (DCF)-featured DSRC. The second major challenge that we have to address is how to well utilize the TVWS spectrum and maximize the TVWS enabled vehicular network capacity by jointly considering the TVWS availability and vehicular mobility. To address these two challenges, in this paper, we design a geolocation database assisted multi-radio vehicular data piping framework for dynamic DSRC/TVWS spectrum sharing, allowing an adaptive interworking for seamless flow of vehicular data between DSRC data pipe and TVWS data pipe. We then investigate the communication performance of DSRC data pipe applying DCF scheme within the vehicular carrier sensing range and TVWS data pipe with dynamic white space spectrum sharing in the TVWS-wide range, respectively. Thereafter, we formulate the adaptive data piping process for dynamic DSRC/TVWS spectrum sharing as a coalition formation game. The vehicular coalitional players could maximize its own payoff and form two coalitions of vehicular data pipe selection with Nash stability and individual stability. To optimize the cellular-supported vehicular access to the TVWS geolocation database, we apply the log-sum-exp (LSE) approximation technique and thus find an optimal channel assignment result for the TVWS utilization among vehicular users. The adaptive multi-radio data piping approach for dynamic DSRC/TVWS spectrum sharing mechanism explicitly considers the distributed feature, in order to be compatible with the IEEE 802.11 DCF based vehicular access. As a result, all the vehicles achieve a stable data piping equilibrium, maximizing the throughput of the entire vehicular network.

We highlight our contributions in three-fold in the light of previous literature works:

- *Geolocation database assisted dynamic DSRC/TVWS spectrum sharing:* To enable high-throughput and cost-effective vehicular communications by jointly utilizing the DSRC and TVWS spectrum, we design the geolocation database assisted vehicular data piping framework for seamless flow of data between the 802.11 DCF based DSRC data pipe and dynamic TVWS spectrum sharing based TVWS data pipe.
- *Optimal white space geolocation database access approach:* Explicitly taking into account both TVWS availability and vehicular mobility, we propose a TVWS geolocation database access approach that leverages a Log-Sum-Exp approximation method. It is shown that such a solution quickly finds the optimal channel assignment for vehicular users.
- *Adaptive data piping approach for dynamic high-throughput data pipe selection:* Applying the coalition formation game, we propose an adaptive vehicular data pipe selection approach for dynamic DSRC/TVWS

spectrum sharing, which allows the tightest possible interworking for seamless and high-throughput data flow between DSRC and TVWS data pipes. The adaptive data pipe selection approach with distributed feature is fully compatible with the IEEE 802.11 DCF based vehicular access technique.

The remainder of this paper is organized as follows. Section 2 introduces the related works. Section 3 describes the system model. Section 4 introduces vehicular data piping model. Section 5 presents the multi-radio data piping solution for dynamic DSRC/TVWS spectrum sharing. Section 6 gives the simulation results, and Section 7 concludes the paper.

## II. RELATED WORKS

DSRC standard is developed to provide both vehicular safety applications and commercial services [13]. However, how to achieve the high-rate and reliable vehicular access performance using DSRC in high-speed, and often densely populated and non-line-of-sight vehicular environments is very challenging [4]. For example, channel congestion in densely deployed environment would be severe for potential safety applications in DSRC systems, which will lead to the significantly degraded vehicular communication performance. To address this issue, Sahoo *et al.* [14] proposed a coordinator-based Medium Access Control (MAC) protocol for congestion control. Bansal and Kenney [15] presented a conceptual approach for DSRC congestion control, including the desired network behaviors, the preferred control variables, and requirements for an algorithm. With the maturity of multimedia processing and network technologies, more and more research attentions have been attracted into the medium-rich vehicular applications in DSRC-based vehicular networking [16], which will further aggravate the current busy DSRC channel, and need the support of additional spectrum resource, such as cellular spectrum. To further investigate the cellular network supported vehicular applications, such as vehicular medium streaming and Internet-based vehicular content distribution by leveraging the DSRC technology, Lee *et al.* [17] proposed a cooperative media streaming protocol over the  $k$ -hop hybrid vehicular networks which consist of cellular network and DSRC ad-hoc network. Xu *et al.* [18] presented a cellular/DSRC-combined hybrid vehicular networks framework. In addition, Liang and Zhuang [19] introduced a cellular/Infostation integrated networking framework for on-demand data service delivery.

There have been active research works on vehicular TV White Space utilization. Jiang *et al.* [20] proposed a spectrum resource allocation framework to effectively utilize the TV white space for high-speed vehicles. Fadda *et al.* [21] analyzed the coexistence problem of DVB-T2 broadcasting and IEEE 802.11p transmission over TVWS. Han *et al.* [22] considered the TVWS access in multi-channel vehicular networks and addressed the channel allocation problem with the objective of system-wide throughput maximization. Due to the superior propagation characteristic of TVWS spectrum, the utilization of abundant VHF/UHF bands becomes an attractive solution to complement and extend wireless networks in diverse vehicular applications and settings, including

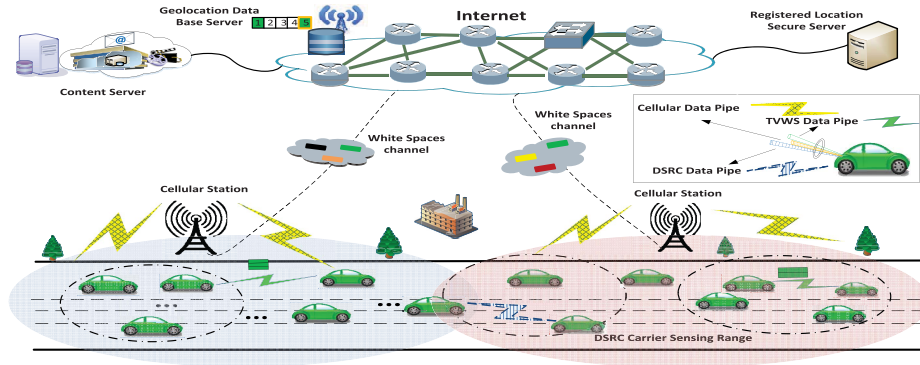


Fig. 1. Geolocation database assisted vehicle-to-vehicle communications using both DSRC data pipe and TVWS data pipe.

the vehicular content distribution and safety application [23]. Yu *et al.* [24] studied bandwidth efficient and rate-adaptive video delivery by using dynamically sensed TVWS channels. By fully considering the spatial spectrum reuse of TVWS, Chen *et al.* [8] introduced a vehicular Infotainment service provisioning approach to maximize the content delivery throughput and enhance the spectrum efficiency. Ding *et al.* [25] studied the systematic approach by leveraging the TVWS for Device-to-Device (D2D) communications. Lim *et al.* [26] exploited the advantages of DSRC and TVWS bands for Emergency Safety Message (ESM) dissemination and considered the delay-sensitive ESM dissemination applications by utilizing the TVWS channels. In addition, by leveraging the availability of TVWS channels, the performance of vehicular networks can be improved as well. Jiang *et al.* [27] proposed to optimize the vehicular users throughput through the route selection in cognitive vehicular networks. Pan *et al.* [28] introduced a Cognitive Vehicular Ad hoc NETWORKS (CVANETS) solution, in which vehicles can sense the vacant spectrum and temporally/geographically use these licensed bands to increase the Vehicle-to-Vehicle (V2V) link throughput.

### III. SYSTEM MODEL

We consider a  $D \times D$  squared coverage region of V2V communication scenario with  $N$  vehicular users, in which each vehicle can independently employ multiple data pipes in vehicular communications for dynamic spectrum sharing. There are three types of data pipes: cellular data pipe (cellular band utilization), DSRC data pipe (5.9 GHz channel contention) and TVWS data pipe (opportunistic TVWS spectrum sharing). For the high service cost of cellular communications, we assume the introduced cellular data pipe is only functioned as the domain control link in coordinating the dynamic DSRC/TVWS spectrum sharing within the cellular-wide coverage of V2V communications. Denote the vehicular user set utilizing DSRC data pipe and TVWS data pipe by  $\mathcal{A}_d$  and  $\mathcal{A}_w$ , respectively. The general DSRC 5.9 GHz channel can severely suffer from the performance deterioration in high-density vehicular traffic scenario due to the channel contention. By leveraging the spatial-temporal variability of TVWS channels, a portion of vehicles can dynamically shift and share the same set of white space channels by utilizing TVWS data pipes.

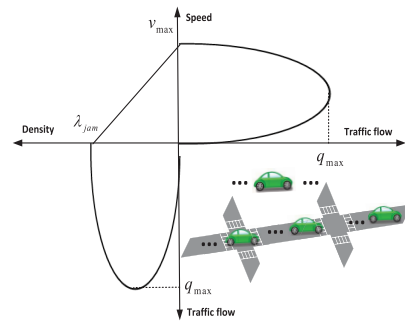


Fig. 2. Vehicular speed-flow-density relationship diagram.

As shown in Fig. 1, in specific, we assume that the Geolocation Data Base Server (GDDBS) can connect with cellular networks which perform the local vacant white space channel query to the geolocation database via Internet. Once part of vehicles apply the dynamic white space access by sending the TVWS channel applications to the Registered Location Secure Server (RLSS), cellular networks calculate vehicular transmit power parameters and coordinate the optimal dynamic white space spectrum assignment to minimize the co-channel interference among vehicle users. To better investigate the introduced geolocation database assisted V2V communication scenario, in what follows, we introduce the vehicle mobility model and wireless channel fading model, and the summary of important symbols in system model is given in Table I.

#### A. Vehicular Mobility Model

We target to establish the theoretical relationship between traffic flow and V2V communication performance in DSRC/TVWS interworking framework. We can track the vehicle  $i$ 's velocity  $v_i(t)$  and location  $L_i(t)$  at time  $t$ ,  $\forall i \in \mathcal{N}$ . The trajectory of vehicle  $i$  is a sequence of positions, denoted by  $\mathbb{L}_i = \langle L_i(0), L_i(1), \dots, L_i(t) \rangle$ . Based on the wide field observations, the vehicular speed-flow-density relationship can be shown in Fig. 2. Denote by  $\lambda$  and  $q$  the vehicle density and vehicle flow, respectively, where  $q = \lambda v$ . We consider different traffic flow conditions, ranging from the low density to high density traffic, as shown in Table II [29]. The relation between

TABLE I  
SUMMARY OF IMPORTANT SYMBOLS IN SYSTEM MODEL

Symbols Associated with System Model	
$v_i(t)$	Vehicle $i$ 's velocity at time $t$ .
$\mathcal{L}_i(t)$	Vehicle $i$ 's location at time $t$ .
$\mathbb{L}_i$	Vehicle $i$ 's trajectory.
$\mathcal{H}_{i,j}$	The distance headway between vehicle $i$ and vehicle $j$ .
$\lambda, q$	Vehicle density and vehicle flow, respectively.
$f_{\mathcal{H}}(x)$	The probability density function.
$\mathcal{R}$	The length of road segment.
$\text{Pr}(N)$	The Poisson distribution of the number of vehicles $N$ .
$(\mu, \Omega)$	The Nakagami-m distribution.
$(\gamma_1, \sigma_1)$	The exponent deviation parameters of path loss.
$(\gamma_2, \sigma_2)$	The standard deviation parameters of path loss.
$\Gamma(\mu, \frac{\mu}{\Omega} \lambda \varphi)$	The upper incomplete gamma function.
$\pi_k$	The modulation rate.
Symbols Associated with Problem Formulation	
$\mathcal{A}_d(t), \mathcal{A}_w(t)$	The set of DSRC data pipe and TVWS data pipe.
$C_r$	The vehicular carrier sensing range.
$\mathcal{N}$	The number of vehicles in the contention domain.
$T_f$	The average frame transmission time.
$\mathcal{T}_{A_d}^j$	The MAC transmission throughput of vehicle $j$ applying CSMA/CA protocol.
$E_{A_d}^j$	The mean MAC transmission throughput if vehicle $j$ applies the DSRC data pipe
$\mathcal{S}$	The set of white space channels.
$\mathcal{S}_F, \mathcal{S}_{II}, \mathcal{S}_I$	The three-type white space channels.
$\mathcal{L}_i(t)$	The vehicle $i$ arriving at the location at time $t$ .
$\mathcal{P}_i^F, \mathcal{P}_i^{II}, \mathcal{P}_i^I$	The sets of allowed transmission power.
$\text{SINR}_j$	The signal-to-interference-plus-noise ratio (SINR) at vehicle $j$ .
$N_0$	The noise power at the receiver.
$I_{pu}$	The interference power from the primary transmitter on channel.
$\Upsilon(\kappa)$	The piecewise constant auto-rate function.
$\mathcal{T}_{A_w}^j$	The white space link throughput of vehicle $j$ .
$E_{A_w}^j$	The the mean white space link throughput if vehicle $j$ applies the TVWS data pipe

TABLE II  
TRAFFIC FLOW CONDITION FOR DIFFERENT VEHICLE DENSITIES

Flow density	Density value (veh/km)	Flow operations
Low density	0 – 8	Free-flow
	9 – 13	Reasonable free-flow
	14 – 19	Stable
	20 – 27	Borders on unstable
Intermediate density	28 – 42	Extremely unstable flow
High density	43 – 63	Forced or breakdown

the vehicle density  $\lambda$  and speed  $v$  is given by the following equation,

$$v = v_{\max} (1 - \lambda/\lambda_{\max}) \quad (1)$$

Through the microscopic vehicular mobility tracking on the road, we can get the distance headway  $\mathcal{H}_{i,j}(\Delta t \cdot k)$  of any vehicle  $i$  to vehicle  $j$  after driving for  $\Delta t \cdot k$ -th time interval, and denote  $\mathcal{H}_{i,j} = \{\mathcal{H}_{i,j}(\Delta t \cdot k), k = 0, 1, 2, \dots\}$  by the set of distance headway distribution at different time points. The distance headway expression can be presented as  $\mathcal{H}_{i,j}(t) = |\mathcal{L}_i(t) - \mathcal{L}_j(t)|$ . Fig. 3 and Fig. 4 show the vehicular number distribution and headway distance for different traffic densities, respectively. Based on wide experimental study [29], the inter-vehicle distances  $\mathcal{H}_{i,j}$  at each time step are i.i.d. with an exponential Probability Density Function (PDF)  $f_{\mathcal{H}}(x)$ , which

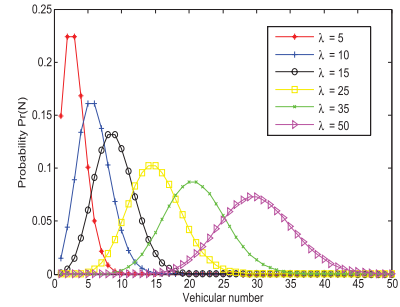


Fig. 3. The vehicular number distribution under different traffic densities.

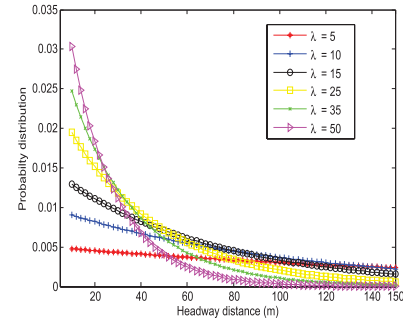


Fig. 4. The headway distance under different traffic densities.

can be generally expressed as

$$f_{\mathcal{H}}(x) = (e^{-x/\theta})/\theta, \quad x \geq 0 \quad (2)$$

where  $\theta$  and  $\delta$  are the mean and standard deviation of the distance headway, respectively,  $\theta = 1000/\lambda$ . Given the traffic

density  $\lambda$  and the length of road segment  $\mathcal{R}$ , the number of vehicles  $N$  follows the Poisson distribution, i.e.,

$$\Pr(N) = e^{(-\lambda\mathcal{R})}(\lambda\mathcal{R})^N/N! \quad (3)$$

### B. Wireless Channel Fading Model

It is essential to have full knowledge of statistical V2V channel fading properties in evaluating the dynamic physical layer transmission rates of V2V communications. According to the results report of real-world measurement, we can get that the received signals amplitude distribution in a mobile vehicle receiver gradually transits from Rician distribution to Rayleigh distribution as the inter-vehicle distance is increased. We model the V2V fast-fading channel environment using the Nakagami-m distribution, where the signal amplitude PDF can be represented by the Nakagami  $(\mu, \Omega)$  distribution,

$$\mathfrak{S}(x, \mu, \Omega) = \frac{2\mu^\mu}{\Gamma(\mu)\Omega^\mu} x^{2\mu-1} \exp\left(-\frac{\mu}{\Omega}x^2\right) \quad (4)$$

where  $\mu$  is a shape parameter related to the environment and the distance headway between any two connected vehicles, i.e.,  $\mathcal{H}_{i,j}(t)$ . For example, according to the vehicular mobility and measurement result in [3], if  $90.5 \text{ meter} \leq \mathcal{H}_{i,j}(t) \leq 230.7 \text{ meter}$ ,  $\mu = 0.74$ ; if  $230.7 \text{ meter} < \mathcal{H}_{i,j}(t) \leq 588.0 \text{ meter}$ ,  $\mu = 0.84$ , and  $\Gamma(\mu)$  can be calculated by  $\Gamma(\mu) = \int_0^\infty e^{-x}x^{\mu-1}dx$ , and  $\Omega$  is an average received power in the fading envelop and  $\Omega = E(P(d))$  can be accurately represented by using the introduced dual-slope piecewise-linear model in [3],

$$P(d) = \begin{cases} P(d_0) - 10\gamma_1 \log_{10}\left(\frac{d}{d_0}\right) + X_{\sigma_1} & \text{if } d_0 \leq d \leq d_c \\ P(d_0) - 10\gamma_1 \log_{10}\left(\frac{d_c}{d_0}\right) - & \text{if } d > d_c \\ 10\gamma_2 \log_{10}\left(\frac{d}{d_c}\right) + X_{\sigma_2} & \end{cases} \quad (5)$$

where  $d = |\mathcal{H}_{i,j}(t)|$ ,  $P(d_0)$  is the referenced signal strength at the distance  $d_0$ ,  $(\gamma_1, \sigma_1)$  and  $(\gamma_2, \sigma_2)$  are different path loss exponent and standard deviation parameter, respectively, which are related to the critical distance  $d_c$ , and  $d_c = \frac{4h_T h_R}{\lambda}$ ,  $h_T$  and  $h_R$  are the antenna heights of connected vehicles, respectively,  $X_{\sigma_1}$  and  $X_{\sigma_2}$  are the zero-mean normal distribution variables with the standard deviations  $\sigma_1$  and  $\sigma_2$ , respectively.

With (4), we have the probability that the current signal to noise ratio at the receiver is larger than a fixed threshold as

$$\Pr\left\{\frac{\Omega}{\lambda} > \wp\right\} = \frac{\Gamma(\mu, \frac{\mu}{\Omega}\lambda\wp)}{\Gamma(\mu)} \quad (6)$$

where  $\lambda$  denotes the thermal noise power at the receivers,  $\wp$  is a constant threshold,  $\Gamma(\mu, \frac{\mu}{\Omega}\lambda\wp)$  is the upper incomplete gamma function, denoted by  $\Gamma(\mu, \frac{\mu}{\Omega}\lambda\wp) = \int_{\frac{\mu}{\Omega}\lambda\wp}^\infty t^{\mu-1}e^{-t}dt$ .

We assume the single-antenna DSRC wireless transceivers in vehicles can be adapted to support up to  $H$  discrete modulation rates based on the current V2V link SNR, denoted by  $\mathbf{W} = \{\pi_1, \pi_2, \dots, \pi_H\}$  with  $\pi_1 < \pi_2 \dots < \pi_H$ . Specifically, if the current SNR is above the threshold  $\wp_k$  and

TABLE III  
THE DSRC DATA RATE AND SNR THRESHOLD SETTING

SNR Threshold (dB)	5	6	8	11	15	20	25	$\infty$
Date Rate (Mbps)	3	4.5	6	9	12	18	24	27

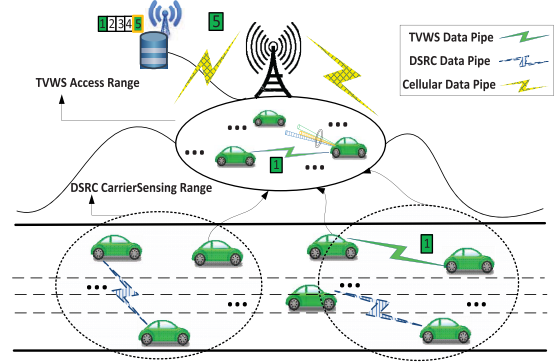


Fig. 5. The adaptive vehicular access selection between IEEE 802.11 DCF based DSRC data pipe and TVWS data pipe.

smaller than  $\wp_{k+1}$ , the modulation rate is set to as  $\pi_k$ , where we set  $\wp_{H+1}$  as  $\infty$ . As such, based on (6), the probability that the selected transmission rate  $C = \pi_k$  for the current V2V link can be expressed as,

$$\begin{aligned} \Pr\{C = \pi_k\} &= \Pr\left\{\wp_k < \frac{\Omega}{\lambda} < \wp_{k+1}\right\} \\ &= \begin{cases} \frac{\Gamma(\mu, \frac{\mu\lambda\wp_k}{\Omega}) - \Gamma(\mu, \frac{\mu\lambda\wp_{k+1}}{\Omega})}{\Gamma(\mu)}, & k = 1, \dots, H-1 \\ \frac{\Gamma(\mu, \frac{\mu\lambda\wp_k}{\Omega})}{\Gamma(\mu)}, & k = H \end{cases} \quad (7) \end{aligned}$$

## IV. VEHICULAR DATA PIPING MODEL

The performance of vehicular communications with DSRC data pipe highly depends on the channel contention status and vehicular fast-fading channel environment [15], while the performance of vehicular communication with TVWS data pipe is closely related to the interference management for the utilization of available of TVWS channels among in-motion vehicular users [21]. As shown in Fig. 5, we consider vehicles can be self-organized to apply either DSRC data pipe or TVWS data pipe for real-time vehicular communications, depending on the current traffic status and the availability of TVWS channels. For specific, we define two types of adaptive vehicular data piping model, and let  $\mathcal{A}_d(t)$  and  $\mathcal{A}_w(t)$  be the set of vehicles utilizing DSRC data pipe within the carrier sensing range and the set of vehicles utilizing TVWS data pipe within the  $D \times D$  squared coverage region at time  $t$ , respectively, where  $|\mathcal{A}_d(t)| + |\mathcal{A}_w(t)| \leq N$ .

### A. Vehicular Access With DSRC Data Pipe

We consider the performance analysis of DSRC data pipe applying IEEE 802.11 DCF basic access scheme [30].

We assume that there are  $|\mathcal{A}_d^{C_r}|$  vehicles within the carrier sensing range  $C_r$ . We focus on the vehicular transmission between a given pair of vehicles, i.e., vehicle  $i$  and vehicle  $j$ , and each packet is transmitted by means of the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). We consider a contention window size  $CW$  for counting the backoff time, and let  $\tau$  denote the average transmission probability of each vehicle, and  $\tau = 2/(CW + 1)$ . Let  $p_{suc}$  be the probability that any single vehicle within the carrier sensing range transmits data on the channel successfully in the considered slot, and  $p_{suc} = |\mathcal{A}_d^{C_r}| \tau (1 - \tau)^{|\mathcal{A}_d^{C_r}| - 1}$ . Let  $p_{tr}$  be the probability that there is at least one transmission in the considered slot duration, and  $p_{tr} = 1 - (1 - \tau)^{|\mathcal{A}_d^{C_r}|}$ . We denote  $T_e$ ,  $T_s$ , and  $T_c$  by the duration of an empty slot time, the average time that the channel is sensed busy, and the average time that the channel is sensed busy by each vehicle during a collision, respectively. In IEEE 802.11 standard,  $T_e = \sigma$ , and for a basic access scheme, the successful frame transmission  $T_s$  and the collided transmission time  $T_c$  can be given as follows:

$$\begin{cases} T_s = H + E[P] + SIFS + 2\sigma + ACK + DIFS \\ T_c = H + E[P^*] + DIFS + \sigma \end{cases} \quad (8)$$

where  $H = PHY_{hdr} + MAC_{hdr}$  is the package header size,  $E[P^*]$  is the average length of the longest packet payload involved in a collision,  $SIFS$  is a period of time equal to a Short Interframe Space (SIFS), and  $DIFS$  is a period of time equal to a Distributed Interframe Space (DIFS).

The average frame transmission time can be denoted by  $T_f$ , and  $T_f$  can be estimated by the ratio of the average frame length including the header package and payload to the average transmission rate at physical layer:

$$T_f = \frac{\mathbf{E}(P)}{\mathbf{E}(C)} = \frac{P_j / |\mathcal{A}_d^{C_r}| + \left( |\mathcal{A}_d^{C_r}| - 1 \right) \widetilde{P} / |\mathcal{A}_d^{C_r}|}{C / |\mathcal{A}_d^{C_r}| + \left( |\mathcal{A}_d^{C_r}| - 1 \right) \widetilde{C} / |\mathcal{A}_d^{C_r}|} \quad (9)$$

where  $C$  is the current transmission rate of vehicle  $j$ ,  $\widetilde{C}$  is the average transmission rate of the all other vehicles using the DCF based data pipe within the vehicular carrier sensing range, and  $\widetilde{C}$  can be estimated as  $\left( \frac{1}{C_r} \int_0^{C_r} \pi_m \Pr(C = \pi_m) dx \right)$ , where  $\Pr(C = \pi_m)$  can be calculated by (7). Here, we consider the same frame length of each vehicular transmission, hence, we can get that  $\mathbf{E}(P) = P$ .

Applying the results in [31], we can now evaluate the MAC transmission throughput  $\mathcal{T}_{A_d}^j$  of DSRC data pipe applying CSMA/CA protocol within the carrier sensing range of vehicle  $j$ ,  $j \in \mathcal{A}_d$ , which can be expressed as follow:

$$\mathcal{T}_{A_d}^j = \frac{\tau p_{suc} P_j}{(1 - p_{tr}) T_e + p_{suc} T_s + (p_{tr} - p_{suc}) T_c} \quad (10)$$

We can calculate the mean MAC transmission throughput  $E_{\mathcal{A}_d}^j$  if vehicle  $j$  applies the DSRC data pipe, which is expressed as follow:

$$E_{\mathcal{A}_d}^j = \sum_{j \in \mathcal{A}_d} \mathcal{T}_{A_d}^j / |\mathcal{A}_d|, \quad j \in \mathcal{A}_d \quad (11)$$

## B. Vehicular Access With TVWS Data Pipe

For the TVWS data pipe utilization within the TVWS-wide white space access range, according to the FCC rules and particularly the transmission power limitation, we consider two types of TVWS channels for vehicular access, i.e., mode-II device channel and mode-I device channel, which are denoted by  $S_{II}$  and  $S_I$ , respectively. According to the FCC regulation rule, let  $S = \{\mathcal{W}_1, \mathcal{W}_2, \dots, \mathcal{W}_{51}\}$  denote the set of all available 51 TVWS channels, and  $S_I = S_{II} \triangleq \{\mathcal{W}_n | n = 21 : 1 : 51 \setminus \{37\}\}$ , respectively. The allowed power window of available TVWS channels for mode-II devices and mode-I devices are  $(0, 100mW]$ , and  $(0, 40mW]$ , respectively. Specifically, for vehicle  $i$  arriving at the location  $\mathcal{L}_i(t)$  at time  $t$ , the set of available white space channels can be denoted by  $S_{\mathcal{L}_i(t)}$ . We denote the set of vehicles which will use white space data pipes in a given cellular-wide coverage range at time  $t$  by  $A_w(t) = \{1, 2, \dots, M(t)\}$ , and  $(t)$  may be dropped for simplicity. The set of vehicular location distribution of  $M$  vehicles is denoted by  $\{\mathcal{L}_1(t), \dots, \mathcal{L}_M(t)\}$ , and the inter-vehicle distance between any vehicle  $i$  to  $j$  can be calculated as  $d_{i,j} = |\mathcal{L}_i(t) - \mathcal{L}_j(t)|$ . For simplicity, we assume that the required transmission power for each pair of connected vehicles is given, which can be calculated according to the FCC rules and the proposed dual-slope piecewise-linear path loss model in (5), and denote  $\mathbf{P} = (P_1, P_2, \dots, P_M)$  as the transmission power allocation profile of the  $M$  vehicles using white space data pipe. We considered the set of available white space channels for each vehicle  $j$ ,  $j \in \mathcal{A}_w$ , is  $S_{\mathcal{L}_j(t)}$ , and  $S_{\mathcal{L}_j(t)} \in S$ .

To improve the vehicular transmission throughput by maximizing the TVWS utilization, we consider that vehicles can apply multiple TVWS channels with channel aggregation approach [21]. We denote  $W_j^K(t) \in S_{\mathcal{L}_j(t)}$  as the K-channel selection strategy at time  $t$  by vehicle  $j$ , where  $(t)$  may be dropped for simplicity. We denote  $\mathbf{W}^K = (W_1^K, \dots, W_M^K)$  as the channel selection profile of all  $M$  vehicles. To calculate the mean white space link throughput of each vehicle using TVWS data pipe, the interferences from other co-channel vehicles in the whole TVWS-wide range is considered. For the transmission between vehicle  $j$  and given destination vehicle, the signal-to-interference-plus-noise ratio (SINR) at vehicle  $j$  using K-channel configuration can be given by

$$SINR_j(\mathbf{W}^K) = \frac{\sum_{m \in \mathcal{W}_j^K} P_m / d_j^\phi(P_m)}{IN_0 + \sum_{m \in \mathcal{W}_j^K} \sum_{k \in S_{\mathcal{L}_j} \setminus \{j\} : \mathcal{W}_k = \mathcal{W}_j} P_m / d_{j,k}^\phi} \quad (12)$$

where  $IN_0$  is the sum of noise power at the receiver and interference power from primary transmitter on channel  $n$ , the constant conservative setting is  $I = -87.5dBm$ ,  $d_n^\phi$  denotes the transmission range of vehicle  $j$ ,  $P_j$  is the transmission power of vehicle  $j$ ,  $\phi$  is the pass loss parameter.

We introduce the piecewise constant auto-rate function  $\Upsilon(\kappa)$  which maps the given minimum received SINR to a white space channel enabled raw bit rate, shown in Table IV [32]. We consider if portion of vehicles in the

TABLE IV

 DEFINITION OF AUTO-RATE FUNCTION  $\Upsilon(\kappa)$ . (IN UNIT OF Mbps)

SINR (dB)	4	7	9	12	16	20
8 MHz TVWS	2.4	4.8	7.2	9.6	14.4	19.2
16 MHz TVWS	4.8	9.6	14.4	19.2	28.8	38.4
24 MHz TVWS	7.2	14.4	21.6	28.8	43.2	57.6

TVWS-wide range apply the white space channel and form a larger vehicular group to share the same set of white space channels, the white space link throughput  $\mathcal{T}_{\mathcal{A}_w}^j$  of vehicle  $j$ ,  $j \in \mathcal{A}_w$ , can be expressed as follow:

$$\mathcal{T}_{\mathcal{A}_w}^j(\mathbf{W}^K) = \Upsilon(\text{SINR}_j(\mathbf{W}^K)) \quad (13)$$

Similarly, we can calculate the mean white space link throughput  $E_{\mathcal{A}_w}^j$  if vehicle  $j$  applies the TVWS data pipe, which is expressed as follow:

$$E_{\mathcal{A}_w}^j = \sum_{j \in \mathcal{A}_w} \mathcal{T}_{\mathcal{A}_w}^j / |\mathcal{A}_w|, \quad j \in \mathcal{A}_w \quad (14)$$

## V. MULTI-RADIO DATA PIPING FOR JOINT DSRC/TVWS DYNAMIC SPECTRUM SHARING

In this section, we first propose an optimal TVWS geolocation database access approach when utilizing the TVWS data pipe. Then, we introduce a coalitional formation game based multi-radio data piping scheme for joint DSRC/TVWS dynamic spectrum sharing.

### A. Optimal TVWS Geolocation Channel Access

When a portion of vehicles in the TVWS-wide range apply to share the same set of TVWS channels by leveraging the geolocation database, i.e., TVWS data pipe utilization, the optimal geolocation TVWS channel allocation objective is to maximize the summary throughput  $\mathcal{T}_{\mathcal{A}_w}^j(\mathbf{W}^K)$  of  $|\mathcal{A}_w|$  vehicles within the TVWS-wide range and can be calculated as follows

$$\begin{aligned} & \max_{\mathbf{W}^K \in \Theta \triangleq \prod_{j \in \mathcal{A}_w} S_{L_j}} \sum_{j \in \mathcal{A}_w} \mathcal{T}_{\mathcal{A}_w}^j(\mathbf{W}^K) \\ & \text{s.t. } \mathcal{W}_j \in S_{L_j}, \quad j \in \mathcal{A}_w \end{aligned} \quad (15)$$

The geolocation TVWS channel allocation formulation (15) is a combinatorial optimization problem for finding the optimal channel assignment profile over the discrete solution space  $\Theta \triangleq \prod_{n=1}^M S_{L_n}$ , which is very challenging to solve exactly especially in TVWS-wide scenario with high-density traffic (i.e., very large  $\Theta$ ). We can apply the Log-Sum-Exp (LSE) approximation technique to provide a good approximation, which is widely used in optimal resource allocation algorithms like [33] and [34].

*Proposition 1:* The problem of (15) can be well solved by LSE approximation with an approximation gap  $\frac{\log|\Theta|}{\alpha}$ , and the optimal solution of (15) is

$$\psi_{\mathbf{W}^K}^* \triangleq \frac{\exp\left(\alpha \sum_{j \in \mathcal{A}_w} \mathcal{T}_{\mathcal{A}_w}^j(\mathbf{W}^K)\right)}{\sum_{(\mathbf{W}^K)' \in \Theta \triangleq \prod_{j \in \mathcal{A}_w} S_{L_j}} \exp\left(\alpha \sum_{j \in \mathcal{A}_w} \mathcal{T}_{\mathcal{A}_w}^j((\mathbf{W}^K)')\right)} \quad (16)$$

### Algorithm 1 LSE-WS Algorithm

**Input:**  $A_w = \{1, 2, \dots, M\}$ ,  $\{\mathcal{L}_1, \dots, \mathcal{L}_M\}$ ,  $\mathbf{P} = (\mathcal{P}_1(\mathcal{T}_1), \dots, \mathcal{P}_M(\mathcal{T}_M))$ ,  $S_{L_j(t)}$ ,  $\mathcal{W}_j$ ,  $j \in A_w$ .

**Output:**  $\mathbf{W}^{K*} = (W_1^K, \dots, W_M^K)$ .

- 1: **Initialize:**  $\Theta$ ,  $\mathbf{W}^{K*} \leftarrow \mathbf{W}^{K^0} = (W_1^{K^0}, \dots, W_M^{K^0})$ .
- 2: **Loop** Iteration  $i$ :
- 3: Randomly select vehicle  $j$ ,  $j \in A_w$ , to update  $\mathcal{T}_j$ ;
- 4: **If** vehicle  $j$  is selected, **Do**
- 5: **Calculating**  $\sum_{j \in A_w} \mathcal{T}_{\mathcal{A}_w}^j(\mathbf{W}^K)$ ;
- 6: Vehicle  $j$  selects  $\mathcal{T}_j$  with probability: **Calculating** Eq. (16);
- 7: **Then**  $\mathbf{W}^{K*} \leftarrow \mathbf{W}^{K^i}$ ,  $i = i + 1$ ,
- 8: **End if**
- 9: **End Loop**
- 10: Return  $\mathbf{W}^{K*} = (W_1^K, \dots, W_M^K)$ .

*Proof:* The problem of (15) has the same optimal solution as the following problem [33]:

$$\begin{aligned} & \max_{\psi_{\mathbf{W}^K} \geq 0} \sum_{\mathbf{W}^K \in \Theta \triangleq \prod_{j \in \mathcal{A}_w} S_{L_j}} \psi_{\mathbf{W}^K} \sum_{j \in \mathcal{A}_w} \mathcal{T}_{\mathcal{A}_w}^j(\mathbf{W}^K) \\ & \text{s.t. } \sum_{\mathbf{W}^K \in \Theta \triangleq \prod_{j \in \mathcal{A}_w} S_{L_j}} \psi_{\mathbf{W}^K} = 1 \end{aligned} \quad (17)$$

where  $\psi_{\mathbf{W}^K}$  is the channel selection probability for profile  $\mathbf{W}^K$ , and we can get  $\mathbf{W}^K \in \Theta \triangleq \prod_{j \in \mathcal{A}_w} S_{L_j}$ . It is known from [33] that the approximated optimal solution of problem (15) by applying the convex LSE approximation can be obtained, i.e.,

$$\begin{aligned} & \max_{\psi_{\mathbf{W}^K} \geq 0} \sum_{\mathbf{W}^K \in \Theta} \psi_{\mathbf{W}^K} \sum_{j \in \mathcal{A}_w} \mathcal{T}_{\mathcal{A}_w}^j(\mathbf{W}^K) - \frac{1}{\alpha} \sum_{\mathbf{W}^K \in \Theta} \psi_{\mathbf{W}^K} \log \psi_{\mathbf{W}^K} \end{aligned} \quad (18)$$

where  $\sum_{\mathbf{W}^K \in \Theta \triangleq \prod_{j \in \mathcal{A}_w} S_{L_j}} \psi_{\mathbf{W}^K} = 1$ ,  $\alpha$  is the approximation control parameter, and easily, when  $\alpha \rightarrow \infty$ , we can get that the approximated value of problem (18) is the exact optimal solution of problem (15). By applying the Karush-Kuhn-Tucker (KKT) condition, we can get the optimal solution of problem (15), and prove the lemma. ■

To better elaborate the LSE approximation based optimal white space allocation approach in the TVWS-wide access range to share the same set of white space channels, we proposed the geolocation database assisted White Space database access approach in Algorithm 1, namely, LSE-WS algorithm.

*Theorem 1:* The computational complexity of LSE-WS Algorithm is  $\Theta(MC_Z^K \Phi)$ . When the radio number  $K = 1$ , the computational complexity is  $\Theta(MZ\Phi)$ .

*Proof:* The LSE-WS Algorithm is performed with the unit of iteration. For each iteration, one vehicular user with the TVWS channel access requirement will be selected to update the TVWS channel configuration. Line 5 involves the summation of the capacities of  $M$  vehicular users. Since individual vehicular user has  $C_Z^K$  channel selection choices, where  $Z$  is the available TVWS channel selection size, this step

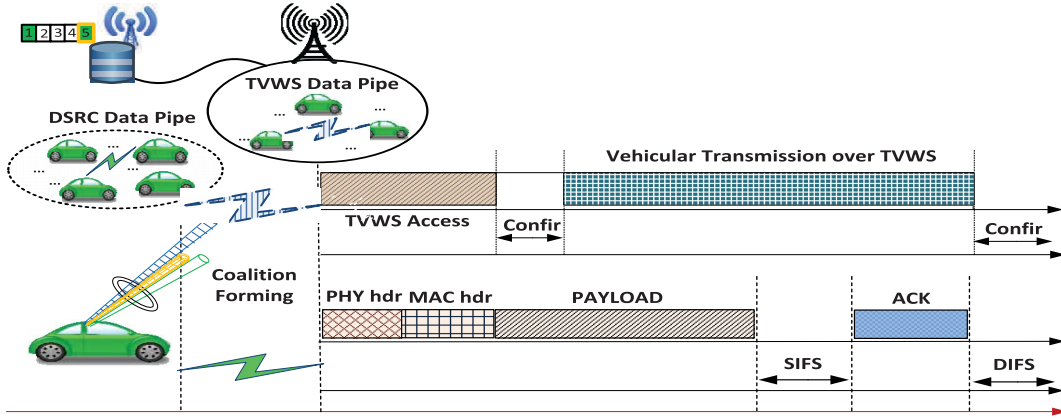


Fig. 6. The illustration of adaptive data pipe selection for geolocation database assisted vehicle-to-vehicle communications.

has the complexity of  $\Theta(MC_Z^K)$ . Line 6 involves at most  $C_Z^K$  summation and division operations and hence has a complexity of  $\Theta(C_Z^K)$ . Line 7 has a complexity of  $\Theta(1)$ . Suppose that the LSE-WS algorithm takes  $\Phi(\alpha)$  iterations to converge, which is related to the optimization approximation ratio  $\alpha$ . Then total computational complexity of LSE-WS algorithm is  $\Theta(MC_Z^K\Phi)$ . When  $K = 1$ , we can calculate the computational complexity as  $\Theta(MZ\Phi)$ . Hence, we can prove the theorem. ■

### B. Coalition Formation Game for Adaptive Data Piping

Coalition formation games have been widely explored to study the behavior of rational players when they cooperate to form groups referred to as coalitions [35], [36]. We formulate the adaptive multi-radio data piping for DSRC/TVWS dynamic sharing problem as a coalition formation game. As shown in Fig. 6, each vehicle can independently employ both DSRC data pipe and TVWS data pipe for vehicle-to-vehicle communications. The DSRC data pipe adopts the IEEE 802.11 DCF basic access scheme while TVWS data pipe can dynamically share the TVWS channels by leveraging the geolocation database assisted TVWS database access approach in Algorithm 1. Using the terminology of coalitional game theory, we refer to set  $\mathcal{A}_i$  as coalition  $i$ , and the coalition number  $CN$  equals  $CN = 2$ . The basic elements of coalition formation game are given as follows:

- Player: The player set of the coalition formation game are the  $N$  vehicle users, i.e.,  $|\mathcal{N}| = N$ .
- Strategies: The strategy of each vehicle  $j$  is to decide which data pipe can be selected in the cellular-wide access range, i.e.,  $i \in \mathcal{A}_d$  or  $i \in \mathcal{A}_w$ .
- Utilities: The utility of each vehicle depends on which coalition it belongs to, and we adopt the equal fair equation rule, in which the payoff of any vehicle  $i \in \mathcal{A}$ , denoted by  $\Phi_i^{\mathcal{A}}$  is given as following,

$$\Phi_i^{\mathcal{A}} = \mathcal{U}(\mathcal{A})/|\mathcal{A}|, \quad i \in \mathcal{N} \quad (19)$$

where we have  $\mathcal{U}(\mathcal{A})/|\mathcal{A}| = E_{A_d}^i$  under the condition of  $i \in \mathcal{A}_d$ , and  $\mathcal{U}(\mathcal{A})/|\mathcal{A}| = E_{A_w}^i$  under the condition of  $i \in \mathcal{A}_w$

Generally, with the assistance of wide-coverage cellular control link, we assume the vehicle users in vehicle set  $\mathcal{N}$  are allowed to autonomously form coalitions in the two types of data pipe selections in order to achieve higher utilities. We first present some basic definitions which are commonly used in the coalition formation games.

**Definition 1 (Coalition Structure):** A vehicular coalition structure for multi-radio data piping is defined as the set  $\Pi = \{\mathcal{A}_1, \mathcal{A}_2\}$  which partitions the vehicle players set  $\mathcal{N}$ , i.e.,  $\forall j, \mathcal{A}_j \subseteq \mathcal{N}$  are disjoint coalitions satisfying the condition that  $\bigcup_{j=1}^2 \mathcal{A}_j = \mathcal{N}$  and  $\mathcal{A}_i \cap \mathcal{A}_l = \emptyset, i \neq l$ .

**Definition 2 (Coalition Formation):** Given a partition  $\Pi$  of vehicle players set  $\mathcal{N}$ , for each player  $j \in \mathcal{N}$ , we denote the coalition that player  $j$  belongs to as  $\mathcal{A}_{\Pi}(j)$ , and coalition  $\mathcal{A}_{\Pi}(j) = \mathcal{A}_k \in \Pi, j \in \mathcal{A}_k$ .

For the in-motion vehicles communicating with each other on the road, each vehicle must have preferences over its own set of possible coalitions for data pipe selection. That is, each vehicle can compare the coalitions for data pipe selection and make an order based on which data pipe coalition that the vehicle player prefers being a member of. For evaluating these preferences of the vehicle players over the coalitions, we define the concept of a preference relation as follows:

**Definition 3 (Coalitional Preference):** For any vehicle  $j \in \mathcal{N}$ , a data piping selection preference relation  $\succeq_j$  is defined as a complete, reflexive and transitive binary relation over the set of all data piping coalitions that vehicle  $j$  can possibly form, i.e.,  $\{\mathcal{A}_k \subseteq \mathcal{N} : j \in \mathcal{A}_k\}$ .

We consider vehicles can autonomously form the coalitions in the two types of data piping modes. The above definitions are used to compare the preference of vehicle  $j$  over two different coalitions. For example, for vehicle  $j \in \mathcal{N}$ , given two coalitions  $\mathcal{A}_1 \subseteq \mathcal{N}$  and  $\mathcal{A}_2 \subseteq \mathcal{N}$ ,  $\mathcal{A}_1 \succ_j \mathcal{A}_2$  indicates that vehicle  $j$  strictly prefers to be a member of coalition  $\mathcal{A}_1$  over to be a member of coalition  $\mathcal{A}_2$ . For evaluating the preferences of data pipe selection for any vehicle player, we define the operation of two types of data pipe selection. Since the preference relationship of data pipe selection is common for all vehicle players, i.e.,  $\succeq_j = \succeq_M, \forall j \in \mathcal{M}$ , the general

operation expression is given as follows:

$$\mathcal{A}_1 \succeq_{\mathcal{M}} \mathcal{A}_2 \Leftrightarrow \mathcal{E}_j(\mathcal{A}_1) \geq \mathcal{E}_j(\mathcal{A}_2) \quad (20)$$

where the vehicle player's data pipe selection preference function  $\mathcal{E}_j : 2^{\mathcal{N}} \rightarrow \mathbb{R}$  is defined as follows:

$$\mathcal{E}_j(\mathcal{A}) = \begin{cases} \Phi_j^{\mathcal{A}}, & \text{otherwise} \\ 0, & \text{if } \mathcal{A} \in h(j) \end{cases} \quad (21)$$

where  $\Phi_j^{\mathcal{A}} = \mathcal{U}(\mathcal{A})/|\mathcal{A}|$ , and  $h(j)$  is the history set of vehicle player  $j$  that contains the coalitions that vehicle player  $j$  was a part of during anytime in the past.

We consider each vehicle can maximize the payoff  $\Phi_j^{\mathcal{A}}$  by adaptively selecting either DSRC data pipe or TVWS data pipe and forming coalitions for current vehicular communication. For general modeling, the coalition formation among any vehicle  $j$  follows the switch rule, shown as follow:

*Definition 4 (Switch Rule):* Given a partition  $\Pi = \{\mathcal{A}_1, \mathcal{A}_2\}$  of the set of vehicle player  $\mathcal{N}$ , vehicle player  $j$  decides to leave its current coalition  $\mathcal{A}_{\Pi}(j) = \mathcal{A}_m$ ,  $m = \{1, 2\}$ , and join another coalition  $\mathcal{A}_k \in \Pi \cup \{\phi\}$ ,  $\mathcal{A}_k \neq \mathcal{A}_{\Pi}(j)$ , if and only if  $\mathcal{A}_k \cup \{j\} \succ_j \mathcal{A}_{\Pi}(j)$ . Hence,  $\{\mathcal{A}_m, \mathcal{A}_k\} \rightarrow \{\mathcal{A}_m \setminus \{j\}, \mathcal{A}_k \cup \{j\}\}$ , where  $\rightarrow$  is the transition symbol.

Through the proposed switch rule made by any vehicle player  $j$ , the current partition  $\Pi$  of  $\mathcal{N}$  is transformed into  $\Pi' = (\Pi \setminus \{\mathcal{A}_m, \mathcal{A}_k\} \cup \{\mathcal{A}_m \setminus \{j\}, \mathcal{A}_k \cup \{j\}\})$ . For every partition  $\Pi$ , the switch rule provides a mechanism through which any vehicle player can leave the current data piping selection coalition  $\mathcal{A}_{\Pi}(j)$ , and join another coalition  $\mathcal{A}_k \in \Pi$  based on the introduced preference relationship in Eq. (20) and Eq. (21). Furthermore, we consider that whenever a vehicle player decides to switch from one coalition to another, and vehicle updates its history set  $h(j)$ . Hence, given a partition  $\Pi$ , whenever a vehicle  $j$  decides to leave current coalition  $\mathcal{A}_m \in \Pi$  to join a different coalition, coalition  $\mathcal{A}_m$  is stored in its history set  $h(j)$  by vehicle player  $j$ .

*Theorem 2:* Starting from any initial data piping selection partition  $\Pi_{ini}$ , the switch rule based coalition formation process always finally converges to a data piping selection partition  $\Pi_f$  which is composed of a number of disjoint coalitions.

*Proof:* We first denote  $\Pi_{nq}^q$  as the partition formed during the  $q$ -th time point when player  $\forall j \in \mathcal{N}$  decides to act after  $nq$ -th switch operations of all vehicle players. Given any initial starting partition  $\Pi_{ini} = \Pi_1^1$ , the coalition formation process consists of a sequence of switch operations. Based on the switch rule in Definition 4, a sequence of switched partitions can be obtained as follows:

$$\Pi_{ini} = \Pi_1^1 \rightarrow \Pi_2^2 \rightarrow \dots \rightarrow \Pi_{nq}^q \rightarrow \dots \rightarrow \Pi_{n\Delta}^{\Delta} \quad (22)$$

where the symbol  $\rightarrow$  is the switch operation. According to the introduced preference relationship in Eq. (20) and Eq. (21), every single switch operation will generate a new partition that has not yet been visited. Hence, for any two coalitions  $\Pi_{nq}^q$  and  $\Pi_{n_l}^l$  in the transformations of Eq. (22), where  $n_q \neq n_l$ , after  $|n_l - n_q|$  rounds of switch operations, we have  $\Pi_{nq}^q \neq \Pi_{n_l}^l$  for any of two turns  $k$  and  $l$ . Given that the number

of partition of a set and the vehicle player number is finite, the transformation number in Eq. (22) is finite. Hence, the switch rule based coalition formation process always finally converges to a final data piping selection partition  $\Pi_f$  which is composed of a number of disjoint coalitions.  $\Delta$  can also be considered as the convergence speed performance indicator of the adaptive selection process to the final Nash equilibrium. We can prove the theorem. ■

Next, we will prove that the switch rule based multi-radio data piping selection process will finally converge to a stable partition in the data piping selection coalition formation game. Before the presentation of the proof, we first introduce two types of stability concepts as follow:

*Definition 5 (Nash Stability):* An adaptive data piping coalition partition  $\Pi^* = \{\mathcal{A}_1, \mathcal{A}_2\}$  is Nash-stable if  $j \in \mathcal{N}$ ,  $\mathcal{A}_{\Pi^*}^*(j) \succeq_j \mathcal{A}_k \cup \{j\}$  for all  $\mathcal{A}_k \in \Pi^* \cup \{\phi\}$ .

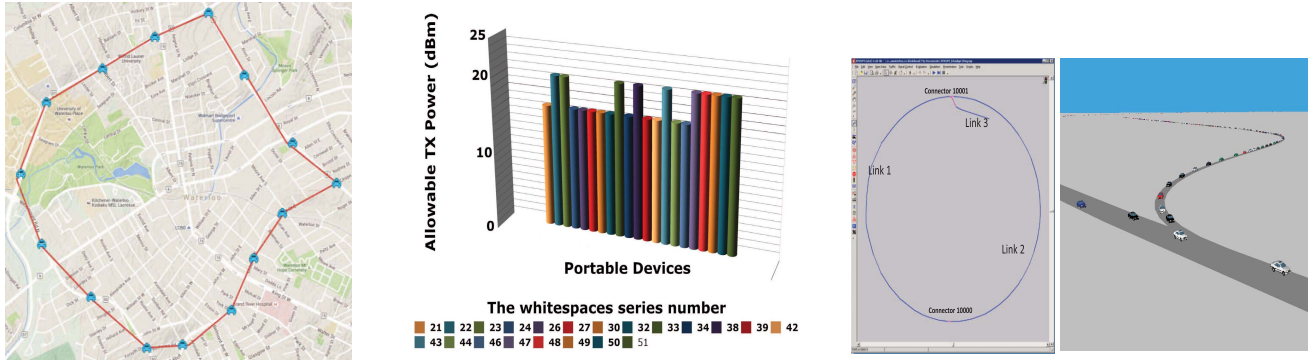
In other words, an adaptive data piping coalition partition  $\Pi^*$  is stable if no vehicular player has an incentive to move from its current data pipe selection partition to another data pipe selection partition in  $\Pi^*$  or to deviate and act alone to maximize the own payoff of any vehicle  $j \in \mathcal{N}$ . Furthermore, a Nash-stable partition  $\Pi^*$  indicates that there does not exist any coalition  $\mathcal{A}_k \in \mathcal{N}$  such that a vehicular player  $j$  strictly prefers to be a part of  $\mathcal{A}_k$  over being part of its current coalitions, while all vehicular players of  $\mathcal{A}_k$  do not get hurt by forming  $\mathcal{A}_k \cup \{j\}$ . This is the concept of individual stability as well, which is defined as follow:

*Definition 6 (Individual Stability):* An adaptive data piping coalition partition  $\Pi^* = \{\mathcal{A}_1, \mathcal{A}_2\}$  is individually stable if there do not exist  $j \in \mathcal{N}$ , and a coalition  $\mathcal{A}_k \in \Pi^* \cup \{\phi\}$  such that  $\mathcal{A}_k \cup \{j\} \succ_j \mathcal{A}_{\Pi^*}(j)$  and  $\mathcal{A}_k \cup \{j\} \succ_i \mathcal{A}_k$  for all  $i \in \mathcal{A}_k$ .

*Proposition 1:* Any data piping coalition partition  $\Pi^*$  resulting from the proposed coalition formation algorithm is both Nash and individually stable.

*Proof:* For any data piping coalition partition  $\Pi^*$ , no player  $j \in \mathcal{N}$  has incentive to leave its current coalition. Assume that the data piping coalition partition  $\Pi^*$  resulting from the proposed algorithm is not Nash stable, there exists a vehicular player  $j \in \mathcal{N}$ , and a coalition  $\mathcal{A}_k \in \Pi^*$  such that  $\mathcal{A}_k \cup \{j\} \succ_j \mathcal{A}_{\Pi^*}(j)$ . Hence, player  $j$  can perform a switch operation which contradicts with the fact that  $\Pi^*$  is the result of the convergence of the proposed algorithm. We prove that any data piping coalition partition  $\Pi^*$  resulting from the proposed coalition formation algorithm is both Nash and individually stable. ■

*Remark 1:* Seen from Eq. (11), we can get that the mean MAC transmission throughput  $E_{\mathcal{A}_d}$  of DSRC data piping is linearly decreasing with the vehicular contention number  $|\mathcal{A}_d|$  in the carrier sensing range due to the nearly fair channel allocation in CSMA/CA scheme. While seen from Eq. (12), with the increased vehicular number for the optimal white space utilization by leveraging the LSE-WS Algorithm, the interferences from other co-channel vehicles, i.e.,  $\sum_{k \in \mathcal{N}_{\mathcal{F}_j}} P_k / d_{n_i, n_k}^{\phi}$  will be increased significantly, therefore mean white space link throughput  $E_{\mathcal{A}_w}$  of TVWS data piping will be reduced accordingly. We consider that part of vehicles with the portion value  $\mathcal{F}$  in  $D \times D$  squared coverage region will apply the



(a) The location of TV white space data collection. (b) The available TV white space for portable devices. (c) The collected vehicular traces from VISSIM scenario.

Fig. 7. The collected empirical data for simulation.

TVWS data pipe and  $1 - \mathcal{F}$  part of vehicles will apply the DSRC data pipe accordingly, there are three types of application cases for the switch rule based coalition formation game, shown as follows:

- Case 1, ( $E_{A_w} > E_{A_d}, 0 < \mathcal{F} \leq 1$ ): The mean white space link throughput  $E_{\mathcal{A}_w}$  of TVWS data piping is always larger than the mean MAC transmission throughput  $E_{\mathcal{A}_d}$  of DSRC data piping, no vehicles have incentive to choose DSRC data pipes, and will form a stable grand TVWS data pipe selection set. This case occurred when enough TVWS resource can be fully utilized for VANET.
- Case 2, ( $E_{A_w} < E_{A_d}, 0 < \mathcal{F} \leq 1$ ): The mean white space link throughput  $E_{\mathcal{A}_w}$  of TVWS data piping is always less than the mean MAC transmission throughput  $E_{\mathcal{A}_d}$  of DSRC data piping, no vehicles have incentive to choose TVWS data pipe, and will form a stable grand DSRC data pipe selection set. This case occurred when limited TVWS resource can be utilized for VANET.
- Case 3, ( $E_{A_d} \leq E_{A_w}, 0 < \eta^* \leq \mathcal{F}; E_{A_d} > E_{A_w}, \mathcal{F} < \eta^* \leq 1$ ):  $\eta^*$  is a Nash equilibrium point, i.e., the ratio that vehicles will choose the TVWS data pipes satisfying the  $E_{A_d} = E_{A_w}$  and forming the two stable data pipe selection coalitions.

The proposed Adaptive Data Pipe Selection (ADPS) algorithm is summarized in Algorithm 2. Since the data pipe selection switch rule based coalition formation process can always finally converge to a data piping selection partition  $\Pi_{\mathcal{F}}$  after  $\Delta$  iterations, and considering there are total  $N$  vehicular users for adaptive data pipe selection, we have the overall computational complexity of the proposed adaptive data pipe selection algorithm is  $\Theta(N\Delta)$ .

## VI. SIMULATION RESULTS

We conduct simulations to evaluate both the performance of LSE-WS algorithm for optimal white space allocation and the performance of coalition formation game based multi-radio vehicular data piping approach for dynamic DSRC/TVWS spectrum sharing using Matlab. The settings of important simulation parameters are specified in Tables V.

### A. Empirical Data Specification for Simulation

To make the evaluation of our joint DSRC/TVWS dynamic spectrum sharing scenario practical, we collect the real-world

### Algorithm 2 ADPS Algorithm

**Input:**  $\mathcal{N}, \{\mathcal{L}_1, \dots, \mathcal{L}_M\}$

**Output:**  $\Pi^* = \{\mathcal{A}_d^*, \mathcal{A}_w^*\}$

- 1: **Initialize:**  $\Pi_{init} = \{\mathcal{A}_d, \mathcal{A}_w\}$ , where  $\mathcal{A}_d = \mathcal{N}, \mathcal{A}_w = \emptyset$
- 2: **Repeat**  $a(t)$  is not a Nash equilibrium **Do**
- 3:   **For** Vehicle  $j = 1$  to  $\mathcal{N}$ , given any current coalition partition  $\Pi_{current}$  **Do**
- 4:     **1)** Vehicle  $j$  investigates the possible switch operations using the preferences given by Eq. (20).
- 5:     **2)** After the payoff evaluation in Eq. (19), vehicle  $j$  performs a switch operation as follows:
  - 6:       2.1) Vehicle  $j$  updates its partition history  $h(j)$  by adding coalition  $\mathcal{A}_{\Pi_{current}}(j)$ , before leaving it.
  - 7:       2.2) Vehicle  $j$  leaves its current coalition  $\mathcal{A}_{\Pi_{current}}(j)$ .
  - 8:       2.3) Vehicle  $j$  joints the new coalition that improves its payoff.
- 9: **Until** convergence to final Nash-stable partition  $\Pi^*$
- 10: **Return**  $\Pi^* = \{\mathcal{A}_d^*, \mathcal{A}_w^*\}$

TABLE V  
SETTING OF IMPORTANT SIMULATION PARAMETERS

Parameters	Value	Parameters	Value
$\lambda$	15/35/50 veh/km	$K$	1/2/3
$\alpha$	0.01/0.03/0.05 ms	$B_w$	8 MHz
$R$	500 m	$\sigma$	50 $\mu$ s
$SIFS$	28 $\mu$ s	$DIFS$	128 $\mu$ s
$ACK$	37 $\mu$ s	$CW$	32, 64

TVWS data and traffic data generated from VISSIM simulation software for the performance evaluation of our proposed DSRC/TVWS dynamic spectrum sharing solutions. As shown in Fig. 7(a), we inquiry the TVWS geolocation database including the channel list and maximal transmission power constraint in the listed 15 locations using the database pilot hosted by Spectrum Bridge, which is uniformly distributed in the 2 km  $\times$  2 km region of Waterloo city, Ontario, Canada, from June 19, 2015 to June 26, 2015. According to the FCC rule and IEEE 802.11af standard for white space channel utilization, as shown in Fig. 7(b), there are 20 TVWS channels for the dynamic vehicular access, and the transmission power

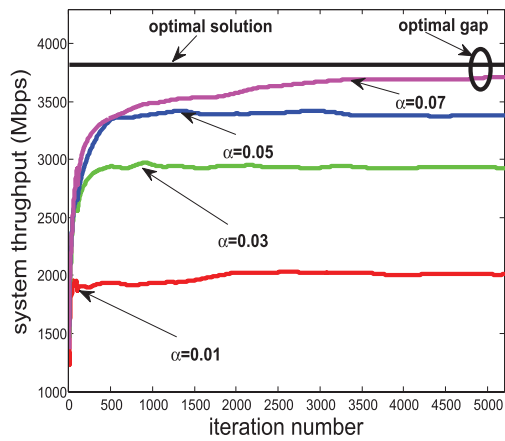


Fig. 8. The impact of approximation parameter  $\alpha$  on the LSE-WS algorithm performance.

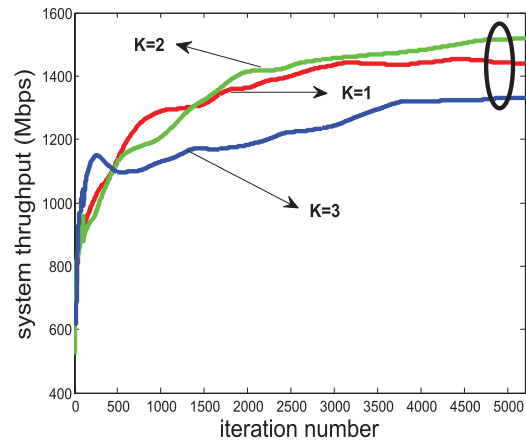


Fig. 10. The impact of channel aggregation number  $K$  on the LSE-WS algorithm performance.

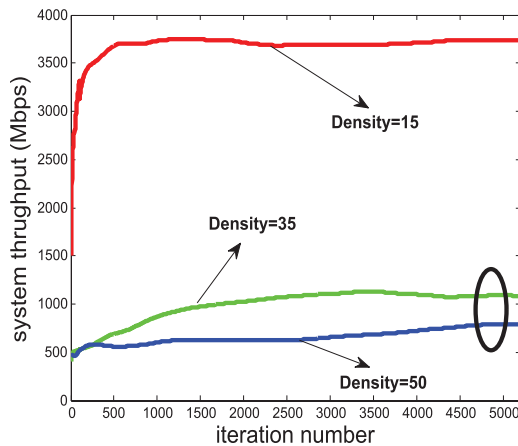


Fig. 9. The impact of traffic density on the LSE-WS algorithm performance.

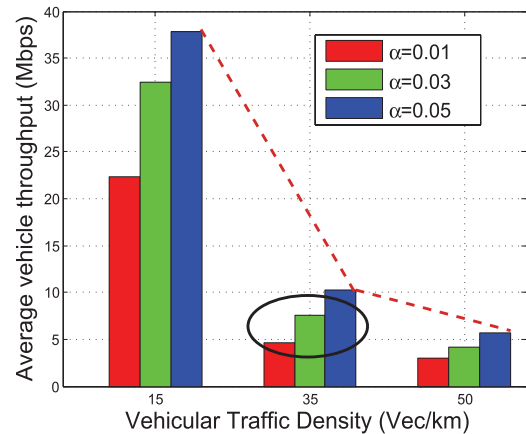


Fig. 11. The impact of vehicular traffic density on the TVWS data pipe performance with  $K = 1$  channel configuration.

limitation for Mode I and Mode II devices is 20 dBm and 16 dBm, respectively. In addition, we collect three sets of vehicular trace data by utilizing the VISSIM simulation software that can be shown in Fig. 7(c). We consider the high/intermediate/low flow density scenarios with parameter setting of 50 veh/km, 35 veh/km, and 15 veh/km, respectively.

*B. Simulation Results of TVWS Channel Assignment*

Fig. 8 shows the impact of approximation control parameter  $\alpha$  on the performance of LSE-WS algorithm. We can see from Fig. 8 that the LSE-WS optimal algorithm can be converged after running for around 600 iterations of iterations. In addition, we can also get that with the increase of approximation control parameter  $\alpha$ , the system throughput of vehicular networks employing the TVWS data pipe can be increased. However, but it will also take longer time to reach the convergence. To be more specific, when  $\alpha$  is increased from 0.01 to 0.05, the throughput of vehicular networks can improved by around 70% but the convergence time is enhanced by 4 times. In Fig. 8, the gap between the LSE-WS algorithm with  $\alpha = 0.07$  and the optimal traversal solution is only about 3.3%.

Fig. 9 investigates the impact of traffic density on the performance of LSE-WS algorithm. We can see from Fig. 9 that with the increase of vehicular traffic density value, the system throughput of vehicular networks employing the TVWS data pipe will be reduced. The main reason is that the increased vehicle users number will cause severe co-channel interference and decrease the vehicular networks capacity utilizing the white space channels accordingly. For specific, when traffic density value is increased from 15 vec/km to 50 vec/km, the throughput of vehicular networks is reduced by around 77%.

Fig. 10 presents the impact of TVWS channel aggregation number  $K$  on the LSE-WS algorithm performance. We can see from Fig. 10 that with the increase of TVWS channel aggregation number  $K$ , the system throughput of vehicular networks employing the TVWS data pipe will not always be improved. The optimal TVWS channel aggregation number  $K$  in our vehicular communication scenario is 2. The main reason is that the increased TVWS channel aggregation number also increases the co-channel interferences and decrease vehicular networks capacity utilizing white space channels accordingly.

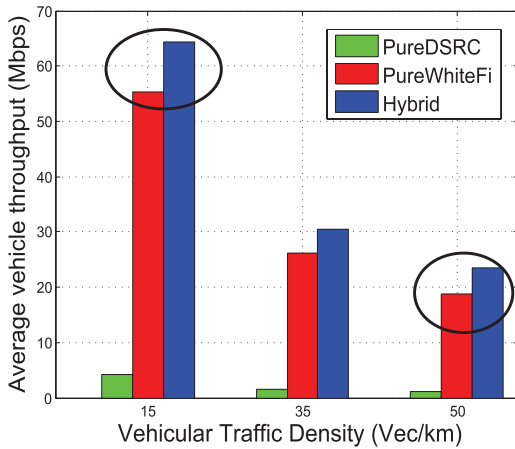


Fig. 12. The average vehicular throughput with  $K = 2$  channel configuration by leveraging different data pipes.

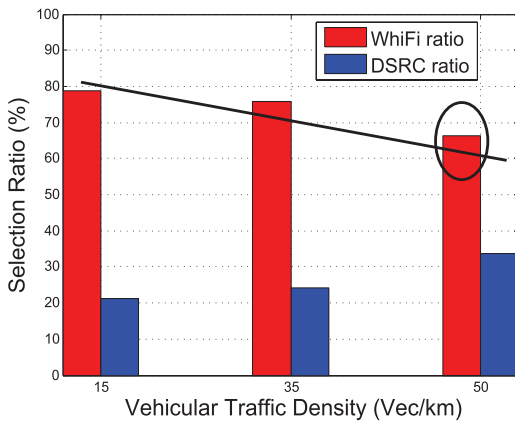


Fig. 13. The optimal vehicular data pipe selection ratio in terms of vehicular traffic density.

### C. Vehicular Communication Performance

Fig. 11 demonstrates the impact of vehicular traffic density on the average vehicular throughput by leveraging the TVWS data pipe. We can see from Fig. 10 that as more and more vehicle users on the road apply TVWS channels, the average vehicle throughput will be reduced obviously. For example, in high flow vehicular density scenarios (50 vec/km), the average vehicle throughput is only around 6Mbps, which indicates that it's crucial to optimize the number of vehicles on the road utilizing TVWS channels by considering the TVWS channel availabilities and traffic flow densities.

Figs. 12-13 present the average vehicular throughput by leveraging different data pipes and optimal vehicular data pipe selection ratio, respectively. Fig. 12 shows that TVWS spectrum resource can augment the capacity of vehicular networks, and the proposed adaptive data piping scheme can improve the average vehicular throughput by more than a dozen of times. Fig. 12 further suggests that the increase of vehicular traffic density limits the number of vehicles utilizing TVWS channels in order to reduce interferences. In addition, in high/intermediate/low flow density scenarios, Fig. 13 shows that the optimal vehicular data pipe selection ratio in our simulation scenario is 78%, 75%, and 66%, respectively.

## VII. CONCLUSIONS

In this paper, we have presented a geolocation database assisted vehicular data piping framework for dynamic DSRC/TVWS spectrum sharing, which can support the seamless data flow between the data pipe of DSRC and TVWS for high-throughput vehicular communications. The proposed framework provides guidance for augmenting the capacity of vehicular networks. We have formulated the adaptive vehicular data piping problem for dynamic DSRC/TVWS spectrum sharing as a coalitional formation game, and the proposed adaptive data pipe selection approach can reach the optimal and Nash-stable vehicular data pipe selection partition in a distributed way. In order to guarantee the best TVWS channel allocation, we have introduced a LSE approximation based TV white space database access algorithm, which has been explicitly taken into account both TVWS availability and vehicular mobility. In our future work, we will consider the real-world implementation and evaluation of the DSRC/TVWS interworking system for multi-radio adaptive vehicular data piping, including the coordination delay measurement in the control-plane link of cellular data pipe.

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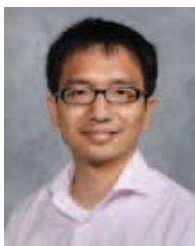
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