# Virtual Cells and Virtual Networks Enable Low-Latency Vehicle-to-Vehicle Communication

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***Abstract*—This paper presents a framework for pursuing low-latency communication among V2V networks underlaying V2I networks. To achieve low-latency communication, solely relying on the improvement of the air-interface may not be enough. To cope with the highly dynamic environment of vehicular networks, a time dynamic optimization approach is proposed that improves the latency performance through not only optimization of spectrum resources but also by constraining the network switching rate. To further decrease the complexity of the time dynamic optimization problem, we convert the original problem to a deterministic optimization problem through the Lyapunov Optimization Theory. The proposed algorithm becomes a more suitable scheme for the vehicular network. Analytical results show that the proposed scheme can approach the best tradeoff between the latency performance and the network switching rate. Simulation results are provided to verify the proposed algorithm.**

***Index Terms*—Fairness, LTE-V2X, Lyapunov Optimization, Underlay, Vehicular Network, V2V, Virtual Cell**

## I. Introduction

To achieve low-latency communication among vehicles, vehicle-to-vehicle (V2V) networks become a possible solution [1]. V2V communication allows groups of vehicles coordinating its driving maneuvers and solving traffic jams such as phantom traffic jam [2]. However, it is not possible to achieve low-latency communication by a pure ad hoc network architecture due to scalability issues [3]. To make the network scalable, it is necessary that some of the data are uploaded to the roadside infrastructure through edge communication by vehicle-to-infrastructure (V2I) networks. With V2I networks, vehicles can communicate with other ones not only through (multiple) wireless hops but also over V2I links. It not only helps improving the communication stability but also reduces the reaction time of the vehicles. Therefore, the efficiency and safety of the vehicular networks can be significant improved by cooperation in V2V and V2I networks.

To facilitate V2I networks, it is expected that the network capacity will be increased by deploying dense infrastructure networks with small coverage areas that take full advantage of the spatial spectrum reuse [4]. However, this approach introduces additional mobility-related issues such as frequent handover [5]. An advanced solution for the frequent handover problem is to form a virtual cell by sharing the dense infrastructures. The formation of a virtual cell follows a user-centric approach, that is, the vehicles are able to choose its serving infrastructure. The selected infrastructure operates in the original set of the spectrum to serve the vehicles. The approach not only increases the communication stability, it also enables that the coverage area moves with the vehicles and the frequent handover problem can be solved.

Though the efficiency of V2I networks can be improved by the virtualization technique, the integration of V2V networks into this architecture is still an open question. Due to the co-existence of V2V and V2I networks, interference between these two networks is inevitable. To establish virtual heterogeneous networks, two important rules should be considered

1) Complete isolation among different virtual networks and services,
2) Additional control-signaling overhead of the proposed scheme.

To keep the isolation between V2V and V2I networks, a possible solution is that V2V networks underlay V2I networks and share the spectrum resources with V2I networks. However, due to the fact that the interference effect to V2I networks depends on the location of the V2V networks, underlaying in the same virtual cell for a long time becomes impossible in the vehicular environment. We recall that the latency is determined by two main factors: the transmission of the air interface and the exchange of control-signaling overhead. For each network switching, the involved procedures at least includes searching for other possible available networks, notification of the next network to switch and channel reallocation among V2V networks, *etc*. After the network switching, the V2V network still needs to execute corresponding resource allocation to optimize not only the latency performance in the air interface but also the fairness among V2V members. Though we may optimize the latency performance in the air interface and ensure isolation by adopting a scheme such as always underlaying the

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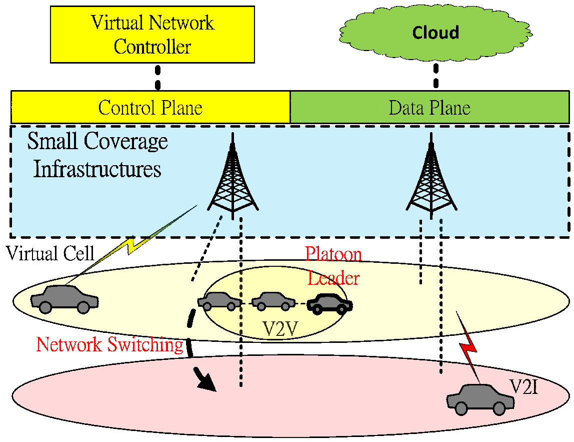


Fig. 1: A platoon creates a virtual V2V network. From the viewpoint of the physical resource management, the virtual V2V network underlays the virtual cell occupying a spectrum band.

best virtual cell, the frequent network switching may cause a large amount of additional control-signaling overhead and degrade the latency performance. Therefore, a new concept for the co-existence of V2V and V2I networks in the virtualized environment is needed.

In this paper, we consider heterogeneous networks composed of V2V and V2I networks under the coordination of a virtualization technique. In the V2I network, the cellular infrastructure with small coverage can form a virtual cell to provide seamless connectivity for the fast moving vehicles. The V2V network, underlaying the virtual cells, needs to avoid the interference to the V2I networks but simultaneously should avoid a frequent network switching rate that impairs its latency performance. To solve this problem, we formulate a time dynamic optimization problem and propose the corresponding algorithm to solve the problem. According to the simulation results, our proposed scheme can achieve low-latency communication in V2V networks. It avoids the unnecessary network switching and therefore reduces the additional latency-impairing control-signaling overhead.

## II. System Model

### *A. Network and Channel Model*

We consider a scenario with a platoon of vehicles driving on a freeway. We assume that each platoon has a leader (in general, it is the first vehicle of a platoon), which coordinates the maneuvers of the platoon and creates a V2V virtual network for the platoon members. In our network model, $M$ spectrum bands exist, each having $J$ orthogonal channels. Each channel is occupied by one vehicle in the V2I network (V2I-Veh) with a transmission power $P_{VI}$ and a probability being active $p$. The set of the $J$ channels in the $m$th spectrum band is denoted as $\mathbb{J}_m = \{1_m, \ldots, J_m\}$. An infrastructure has a service radius $L$ and the vehicles are randomly distributed with a uniform distribution in this region. The platoons are distributed in the straight line with a one-dimension Poisson point process (PPP) $\Phi$ with density $\lambda_p$ (platoons/m). The reason for adopting one-dimension PPP is that it is more suitable for the freeway scenario. Due to homogeneity of PPP, we can just analyze one platoon and represent the average performance of the whole network. A platoon consists of a set of $K$ vehicles, which is denoted as $\mathbb{K} = \{1, \ldots, K\}$. Each vehicle in the platoon has a transmit power $P_V$ and a corresponding receiver at a distance $d_V$. We note that all platoons do not necessarily have the same number of vehicles.

We denote $SIR_{kj}^m$ as the signal-to-interference-ratio (SIR) of the $k$th vehicle in the platoon underlaying the $j$th channel of the $m$th network. We assume that the effect of white noise is negligible due to the strong interference from other vehicles underlaying the same virtual cell. Furthermore, we ignore the interference from the V2I-Veh in the same channel because the interference degrades the performance of V2V communications only when the platoon moves into the close proximity of the vehicle. We can express $SIR_{kj}^m$ as

$$SIR_{kj}^m = \frac{P_V G_{mkj}^V d_V^{-\alpha}}{I_{kj}^m}, \tag{1}$$

where $G_{mkj}^V$ is the small scale channel fading with unitary mean in the $j$th channel of the $m$th network, and $I_{kj}^m$ is the aggregated interference from other vehicles at the $k$th vehicle of the platoon in the same channel. That is,

$$I_{kj}^m = \sum_{i\in\Phi} P_V G_{ij}^{V_m} d_{V_m ij}^{-\alpha}, \tag{2}$$

where $\alpha$ is the path-loss effect, $G_{ij}^{V_m}$ and $d_{V_m ij}$ represent the corresponding channel fading and distance between the vehicles in other platoon to the $k$th vehicle.

### *B. Non-Outage Probability*

To take the channel effects on the V2V communications into consideration, we adopt the non-outage probability to describe the quality of a communication link. We define a non-outage event as a successful packet transmission with a SIR larger than a threshold $\theta$. The probability of a non-outage event of the $k$th vehicle underlaying the $j$th channel of the $m$th network is

$$\begin{aligned}\mathbb{P}(SIR_{kj}^m \geq \theta) &= \mathbb{P}(G_{kj}^m \geq \frac{I_{kj}^m \theta}{P_V\ d_V^{-\alpha}}) \\ &= \mathbb{E}\left(\exp\left(\frac{-I_{kj}^m\theta}{P_V\ d_V^{-\alpha}}\right)\right).\end{aligned} \tag{3}$$

The last equality of (3) is actually the moment-generating function of $I_{kj}^m$. $\mathbb{E}(\exp(-sI_{kj}^m))$ can be derived by finding the *Laplace* functional $\mathbb{E}\left(\exp\left(\sum_{i\in\Phi} f(d_{V_m ij})\right)\right)$ [6], where $f(d_{V_m ij}) = P_V G_{ij}^{V_m} d_{V_m ij}^{-\alpha}$ and $s = \theta / P_V d_V^{-\alpha}$. In the one-dimension PPP case, $\mathbb{E}(\exp(-sI_{kj}^m))$ can be further expressed as

$$\mathbb{E}(\exp(-sI_{kj}^m)) = \exp\left(\frac{2\lambda\pi\,(sP_V)^{1/\alpha}}{\alpha\ \sin(\frac{\pi}{\alpha})}\right). \tag{4}$$

In (4), we can replace $s$ with $\frac{\theta}{P_V d_V^{-\alpha}}$. Then, the non-outage probability can be written as

$$\mathbb{P}(SIR_{kj}^m \geq \theta) = \exp\left(-\frac{2\lambda_p \ \pi \ d_V}{\alpha \ \sin\frac{\pi}{\alpha}}\theta^{1/\alpha}\right) \quad \triangleq \varphi. \tag{5}$$

We can find that the non-outage probability is the same for all vehicles in a platoon; therefore, we denote it as a constant $\varphi$.

### C. One-Way Access Control

To guarantee the performance of the V2I-Vehs, each V2V transmitter is allowed to access the channel only if the V2I-Vehs are not active or the non-outage probability of the V2I connections is larger than a threshold. Here, we assume that the infrastructure can broadcast the information about the received signal strength (RSS) from the V2I-Vehs to all the other vehicles. Then, the vehicle makes the decision whether to utilize the channel or not, according to the broadcasted information. This is called one-way access control because the vehicles access the resources according to the broadcasted information from the infrastructure and there is no need for feedback verification. The $j$th channel of the $m$th network is available for the $k$th vehicle at the time slot $t$ only if the following two conditions are satisfied:

$$\delta_{kj}^m(t) = 1, \textit{if} \begin{cases} \text{the V2I-Veh in } j\text{th channel is not active} \\ \mathbb{P}\left(\dfrac{P_{VI}G_{mj}^{VI}d_{VI_{mj}}^{-\alpha}}{P_V G_{kj}^{IN_m} d_{IN_m}^{-\alpha}} \geq \theta | P_{VI}G_{mj}^{VI}d_{VI_{mj}}^{-\alpha}\right) \\ \geq \eta, \text{when the V2I-Veh is active.} \end{cases} \tag{6}$$

$\delta_{kj}^m(t)$ denotes the indicator variable for the availability of the $j$th channel at time slot $t$, which is equal to 1 if the $j$th channel of the $m$th network is available for the $k$th vehicle, and 0 otherwise. To simplify the notation, we omit the notation of time index at the right hand side of (6). $G_{kj}^{IN_m}$ is the channel fading with unitary mean from the $k$th vehicle to the infrastructure in $j$th channel of the $m$th network. In (6), we approximate the distance from an individual vehicle to the infrastructure of the $m$th network by $d_{IN_m}$, which is the distance from the center of the platoon to the infrastructure of the $m$th network. The constant $0 \leq \eta \leq 1$ is the required minimal non-outage probability of V2I-Vehs. That is, all the V2V links need to guarantee the performance of V2I-Vehs before accessing the resources. The second part of (6) can be written as

$$\begin{aligned} &\mathbb{P}\left(G_{kj}^{IN_m} \leq \frac{P_{VI} \ G_{mj}^{VI} \ d_{VI_{mj}}^{-\alpha}}{\theta \ P_V \ d_{IN_{mk}}^{-\alpha}}\right) \\ &= 1 - \exp\left(\frac{P_{VI} \ G_{mj}^{VI} \ d_{VI_{mj}}^{-\alpha}}{\theta \ P_V \ d_{IN_m}^{-\alpha}}\right) \quad \geq \eta \end{aligned} \tag{7}$$

To arrange the equation above, the condition of the $j$th channel being available for the $k$th vehicle is

$$P_{VI} \ G_{mj}^{VI} \ d_{VI_{mj}}^{-\alpha} \geq P_V d_{IN_m}^{-\alpha} \ \theta \ \ln\frac{1}{1-\eta}. \tag{8}$$

This requirement states that the channels are available for the V2V communications only if the RSS from V2I-Veh to infrastructure is larger than a threshold (the right hand side of (8)).

Let $\rho_j^m$ indicate the probability that the $j$th channel of the $m$th network is available for the platoon vehicles. As shown in (6), a channel is available for a V2V vehicles in a platoon while the channel is not occupied by a V2I-Veh or the non-outage probability of the V2I-Veh is larger than a threshold $\eta$. Therefore, $\rho_j^m$ can be expressed as

$$\begin{aligned} \rho_j^m &\triangleq \mathbb{P}(\delta_{kj}^m(t) = 1) \\ &= p + (1-p)\exp\left(-\frac{P_V d_{IN_m}^{-\alpha} \theta \ln\frac{1}{1-\eta}}{P_{VI} d_{VI,j}^{-\alpha}}\right), \end{aligned} \tag{9}$$

where the exponential term is derived from calculating the probability of (8).

### D. Data Queue Model

To describe the dynamics of the queues in each vehicle in the V2V network, we define the data queue $U_k(t)$ to represent the backlogged data in the $k$th vehicle at time slot $t$. Then, the dynamics of each queue $U_k(t)$ can be expressed as

$$U_k(t+1) = (U_k(t) - u_k(t))^+ + a_k(t), \forall k \in \mathbb{K}, \tag{10}$$

where $u_k(t)$ and $a_k(t)$ are the number of serviced and arriving packets at time slot $t$, respectively, and the function $(.)^+ = max[., 0]$. From (9), we know that the probability of each channel being available ($\delta_{kj}^m = 1$) depends on the location of the vehicles. Due to high mobility, the platoon leader needs to make a decision in every time slot. There are three options in the decision space $\mathbb{D} = \{\mathbb{D}_0, \mathbb{D}_1, \mathbb{D}_2\}$.

1) $\mathbb{D}_0$: no resource re-allocation and no network switching,
2) $\mathbb{D}_1$: resource re-allocation (stay in the same network),
3) $\mathbb{D}_2$: execute the network switching.

Because the original channels cannot be utilized after switching to a new network, the platoon leader must re-allocate the newly acquired channels to its platoon members. Therefore, there is no decision of switching to a new network without re-allocating the channels.

The service rate of V2V communications highly depends on the channel allocation scheme, which is determined by the platoon leader. We define $\mathbf{1}_{kj}^{m_t}(t) = 1$ if the $j$th channel of the $m$th channel is allocated to the $k$th vehicle at time $t$ and $\mathbf{1}_{kj}^{m_t}(t) = 0$ otherwise. The subindex of $m_t$ denotes that the platoon underlays the $m$th network at time $t$. Then, the service rate of the $k$th vehicle with different decision can be expressed by (11).

## III. Network Switching & Re-Allocation Problem

As shown in (9), the transmission rate, which can be supported by each channel, depends on the location of the V2I-Vehs and the platoon. Therefore, the platoon needs to frequently switch to the best available network, *i.e.*, the network with the largest $\sum_{j\in\mathbb{J}_m} \rho_j^m$. Also, the platoon should change the resource allocation scheme to ensure fairness among the vehicles. However, switching among networks and the corresponding resource re-allocation imply additional control-signaling overheads and hence hurt the latency performance:

$$u_k(t) = \begin{cases} \sum_{j \in \mathbb{J}_m} \mathbf{1}_{kj}^{m_{t-1}}(t-1)\delta_{kj}^{m_{t-1}}(t)\mathbf{1}\left(SIR_{kj}^{m_{t-1}}(t) \geq \theta\right), \text{if } \mathbb{D}_t = \mathbb{D}_1 \\ \sum_{j \in \mathbb{J}_m} \mathbf{1}_{kj}^{m_{t-1}}(t)\delta_{kj}^{m_{t-1}}(t)\mathbf{1}\left(SIR_{kj}^{m_{t-1}}(t) \geq \theta\right), \text{if } \mathbb{D}_t = \mathbb{D}_2 \\ \sum_{j \in \mathbb{J}_m} \mathbf{1}_{kj}^{m_t}(t)\delta_{kj}^{m_t}(t)\mathbf{1}\left(SIR_{kj}^{m_t}(t) \geq \theta\right), \text{if } \mathbb{D}_t = \mathbb{D}_3. \end{cases} \tag{11}$$

For example, the V2V pairs need to terminate the current transmission once they receive the network switching or resource re-allocation notification. Second, if the platoon leader decides to switch to another virtual cell, further synchronization is necessary. To shorten the latency, we regard the execution of the network switching and the resource re-allocation as process cost. To take the fairness into considerations, we formulate a dynamic optimization problem to maximize the fairness and simultaneously to keep the resource re-allocation rate $\phi$ and the network switching $\psi$ under certain constraints.

### A. Dynamic Fairness Maximization Problem

At each time slot $t$, the platoon leader makes the decision whether to re-allocate the radio resources for the V2V pairs in a platoon or to switch to a better network. The platoon leader needs to maximize the fairness between vehicles and simultaneously keep the re-allocation rate and network switching rate satisfying the constraints. Since the environment is dynamic and all the quantities are time-varying, we focus on the time-average of the fairness, re-allocation rate and network switching rate. Then, the optimization of platoon operation can be formulated as shown in (12).

$$\max_{h(t),g(t),\mathbf{1}(t)_{kj},k\in\mathbb{K},j\in\mathbb{J}} \quad \overline{f(t)} \tag{12a}$$

$$\text{subject to} \quad \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} \mathbb{E}(U_k(t)) \leq \infty, \tag{12b}$$

$$\overline{g} = \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} g(t) \leq \phi, \tag{12c}$$

$$\overline{h} = \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} h(t) \leq \psi, \tag{12d}$$

$$\sum_{k\in\mathbb{K}} \mathbf{1}_{kj}(t) = 1, \tag{12e}$$

$$\sum_{j\in\mathbb{J}_m} \mathbf{1}_{kj}(t) \geq 1, \tag{12f}$$

$$\mathbf{1}_{kj}(t) = \mathbf{1}_{kj}(t-(1-g(t))), \tag{12g}$$

$$\forall k \in \mathbb{K}, \forall j \in \mathbb{J}_m. \tag{12h}$$

In (12), the fairness function $f(t)$ in (12a) is defined according to the $\alpha$-fairness function with $\alpha = 1$ [7].

$$f(t) = \sum_{k\in\mathbb{K}} \log u_k(t). \tag{13}$$

(12b) is the constraint that all the queues in the platoon should be stable. (12c) and (12d) are the re-allocation and network switching rate constraints. (12e) describes that each channel can be allocated to only one V2V pair. (12f) states that at least one channel is allocated to each vehicle. The constraint (12g) expresses that the allocation scheme remains the same if the platoon leader decides not to re-allocate the resource.

## IV. Dynamic Algorithm of Resource Re-Allocation and Network Switching Scheme

In this section, we propose a stochastic optimal control scheme to solve the network switching and resource re-allocation problem in (12). To achieve the best performance, the dynamic programming approach may can utilized [8]. However, without statistical knowledge, value iteration or policy iteration used in reinforcement learning can also approach the optimal performance [9]. However, this technique involves complex computation and may not be suitable for the highly dynamic environment found in vehicular networks. To design an online and computationally efficient algorithm, we propose the application of the *Lyapunov optimization* [10]. The advantage of *Lyapunov optimization* is that it can transform stochastic optimization problems into a series of deterministic optimization problems. Hence, it decreases the computational complexity and makes the algorithm more practical.

### A. Virtual Queue

To satisfy the re-allocation rate and network switching rate constraints in a dynamic way, a useful concept called *virtual queues* has been proposed [10]. The *virtual queues* for re-allocation rate and network switching rate are denoted as $G(t)$ and $H(t)$, respectively. The corresponding dynamic rules are

$$\begin{aligned} G(t+1) &= (G(t) - \phi + g(t))^+ \\ H(t+1) &= (H(t) - \psi + h(t))^+, \end{aligned} \tag{14}$$

where $g(t)$ and $h(t)$ are determined by the decision that the platoon makes. As stated in (11), three possible decisions exist. Their resulting $g(t)$ and $h(t)$ are illustrated as follows.

$$g(t) = \begin{cases} 0, \text{if } \mathbb{D}_t = \mathbb{D}_0 \\ 1, \text{if } \mathbb{D}_t = \mathbb{D}_1 \\ 1, \text{if } \mathbb{D}_t = \mathbb{D}_2, \end{cases} \quad h(t) = \begin{cases} 0, \text{if } \mathbb{D}_t = \mathbb{D}_0 \\ 0, \text{if } \mathbb{D}_t = \mathbb{D}_1 \\ 1, \text{if } \mathbb{D}_t = \mathbb{D}_2. \end{cases}$$

In the third decision, as mentioned before, the platoon leader also executes the channel re-allocation to guarantee the optimal allocation. Therefore, in this decision we have $g(t) = 1$ .

To guarantee that the proposed scheme can satisfy the constraints, the *virtual queues* should satisfy the *mean rate stability*, *i.e.*, $\lim_{T\to\infty} \frac{\mathbb{E}(G(T))}{T}$ [10]. The intuition is that if we stabilize the *virtual queues*, it means that the average "service rate" of the *virtual queues* is smaller than "arrival rate", *i.e.*, $\overline{g} \leq \phi$ and $\overline{h} \leq \psi$.

*Lemma 1:* If $G(0) = 0$ and the dynamic rule of $G(t)$ satisfies (14), then, for all integers $T > 0$,

$$\overline{g} - \phi \leq \frac{\mathbb{E}(G(T))}{T}, \tag{15}$$

where $\overline{g} = \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} \mathbb{E}(g(t))$.

*Proof:* According to (14), we have

$$G(t+1) \geq G(t) + g(t) - \phi.$$

Taking the sum from $t = 1$ to $T$, we get

$$G(T) - G(0) \geq \sum_{t=1}^{T} g(t) - \phi.$$

By dividing $T$ and taking the expectation, and finally using the fact that $G(0) = 0$, we can finish the proof. ■

Corresponding procedures can be applied to prove the stability of $H(t)$.

### *B. Lyapunov Optimization Based Approach*

We define the *Lyapunov function* as $L(t) \triangleq \sum_{k\in\mathbb{K}} \left(U^2(t) + G^2(t) + H^2(t)\right)$ and the *Lyapunov drift* function as $\triangle L(t) \triangleq L(t+1) - L(t)$, which describe the tendency of the increasing rate of each data queue $U_k(t)$ and two *virtual queues* $G(t)$ and $H(t)$. To keep all queues (including *virtual queues*) stable, it is necessary to keep the *Lyapunov drift* function as negative as possible because the *drift* can reduce the total size of the queues much faster. However, it also means that the platoon leader needs to increase the utilization rate of the network switching or resource re-allocation to achieve a faster service rate. Therefore, the *drift* function can become negative but this procedure may also violate the required constraints. To stabilize all the queues and simultaneously optimize the time-average objective function, we consider the *drift-plus-penalty* metric. The *drift-plus-penalty* metric is defined as $\triangle L(t) - Vf(t)$, where $\triangle L(t)$ is the *drift* part, $f(t)$ is the penalty part, and $V \geq 0$ is a constant determining the tradeoff between the *drift* and the penalty. We may consider that the *drift-plus-penalty* to describe the tradeoff between queue stability and the importance of fairness.

Based on the *Lyapunov optimization theory*, we propose the network switching and resource re-allocation scheme as follows.

> *Network Switching and Resource Re-Allocation Scheme*
> At each time slot $t$, the platoon leader tries to maximize the following objective function:
>
> $$\max_{\mathbf{1}_{kj}, g(t), h(t)} \sum_{k\in\mathbb{K}} \left(2U_k(t)u_k(t) + V\log u_k(t)\right) - 2G(t)g(t) - 2H(t)h(t) \tag{16}$$
>
> under the constraints (12e)∼(12g).

*Theorem 1:* With the proposed scheme, the time average of the expectation of the total aggregated queues $\mathbb{E}\left(\sum_{k\in\mathbb{K}} U_k(t)\right)$ can be upper bounded by

$$\begin{aligned}\lim_{t\to\infty} \frac{1}{T}\sum_{t=1}^{T}\sum_{k\in\mathbb{K}} \mathbb{E}(U_k(t)) &\leq \frac{\Omega + V\overline{\mathbb{E}(f^*(t) - f(t))}}{2\epsilon} \\ &\leq O(V)\end{aligned} \tag{17}$$

where $\Omega$ is the minimal constant satisfying

$$\Omega \geq \mathbb{E}\left(\sum_{k\in\mathbb{K}} B_k + C + D\right), \tag{18}$$

with $B_k = u_k^2(t) + a_k^2(t)$, $C = \phi^2 + g^2(t)$, $D = \psi^2 + h^2(t)$. $\mathbb{E}(f^*(t))$ is the resulting expectation of the fairness value from any other policy (including the optimal one). The lower bound of the fairness can be also guaranteed and satisfies

$$\overline{\mathbb{E}(f(t))} \geq \overline{\mathbb{E}(f^*(t))} - \frac{\Omega + 2\epsilon\sum_{k\in\mathbb{K}}\overline{\mathbb{E}(U_k(t))}}{V}. \tag{19}$$

From (17) and (19), we can find that $V$ determines the upper bound of latency performance and the lower bound of the fairness. By setting different $V$, the V2V virtual network can provide different service guarantees for other vehicle members.

*Proof:* Through optimizing (16), the following inequality holds (for the detailed procedure, we refer to [10]).

$$\begin{aligned}&\mathbb{E}\left(\triangle L(t) - Vf(t)\right) \leq \Omega - \mathbb{E}(Vf^*(t)) - \\ &\mathbb{E}\Bigg(\sum_{k\in\mathbb{K}} 2U_k(t)(u_k^*(t) - a_k(t)) - 2G(t)(\phi - g^*(t)) - \\ &2H(t)(\psi - h^*(t))\Bigg),\end{aligned} \tag{20}$$

where $u_k^*(t)$, $g^*(t)$, $h^*(t)$ and $f^*(t)$ are the results of any other possible policy (including the best one). $\Omega$ is the constant satisfying (18).

Rearranging the equation above and the take time average, we get

$$\begin{aligned}&\lim_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T}\sum_{k\in\mathbb{K}} \mathbb{E}\left(2\epsilon U_k(t) - Vf(t)\right) \leq \Omega + \\ &\lim_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T} \mathbb{E}\left(2G(t)(\phi - g^*(t)) + 2H(t)(\psi - h^*(t))\right) - \\ &\lim_{T\to\infty}\frac{1}{T}\mathbb{E}\left(L(T) - L(1)\right) - V\mathbb{E}\left(\overline{f^*}\right),\end{aligned} \tag{21}$$

where $\epsilon$ is the maximum constant such that summation of the expectation of data arrival rate $\boldsymbol{\lambda}$ and $\epsilon\mathbf{1}$ satisfying $\boldsymbol{\lambda} + \epsilon\mathbf{1} \prec \mathbb{E}(\boldsymbol{u})$. By observing the equation above, we can find: *(i)* The term $\lim_{T\to\infty}\frac{1}{T}(L(T) - L(1))$ disappears, while $T$ approaches infinity. *(ii)* If the solution-existing conditions are satisfied, the terms $\mathbb{E}(2G(t)(\phi - g^*(t)))$ and $\mathbb{E}(2H(t)(\psi - h^*(t)))$ are larger than or equal to 0. Therefore, we can further simplify (21) into

$$\overline{2\epsilon\sum_{k=1}^{K} \mathbb{E}\left(U_k(t) - Vf(t)\right)} \leq \Omega - V\overline{\mathbb{E}(f^*(t))} \tag{22}$$

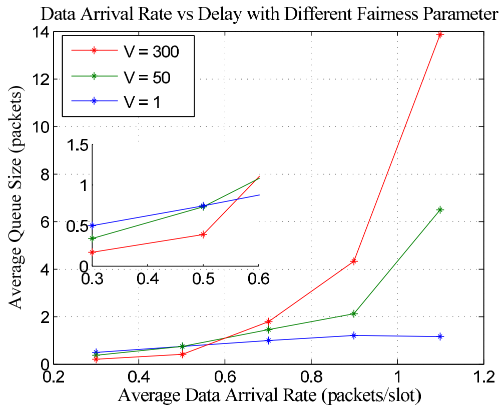


Fig. 2: Delay versus data arrival rate for different values of the fairness parameter $V$. The re-allocation rate constraint is $\phi = 0.2$.

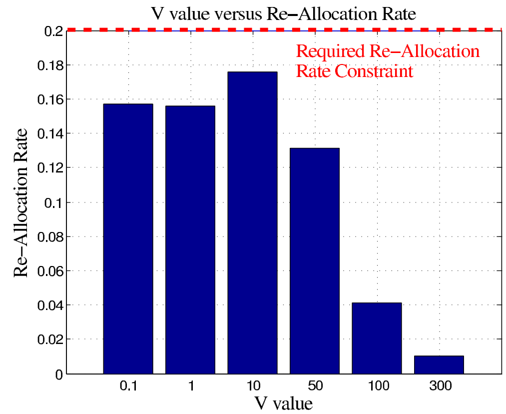


Fig. 3: Re-allocation rate vs. $V$. The network switching rate constraint is $\psi = 0.002$.

Rearranging the equation above, we get

$$\begin{aligned}\mathbb{E}\left(\sum_{k\in\mathbb{K}} U_k(t)\right) &\leq \frac{\Omega - V\overline{\mathbb{E}(f^*(t) - f(t))}}{2\epsilon} \\ &\leq O(V)\end{aligned} \tag{23}$$

To prove the upper bound of the expectation for the summation of the queues, we can rearrange (22) and get

$$V\overline{\mathbb{E}(f(t))} \geq V\overline{\mathbb{E}(f^*(t))} - \sum_{k\in\mathbb{K}} 2\epsilon\overline{\mathbb{E}(U_k(t))} - \Omega. \tag{24}$$

By dividing both sides with $V$, we get the lower bound of the expected fairness value as shown in (19). ∎

## V. SIMULATION

In this section, the tradeoffs between latency performance, network switching rate and resource re-allocation rate are evaluated by simulations. We model a vehicle platoon that moves in a straight line, i.e., on a freeway. The communication range of each infrastructure network covers a segment of this line with a length of 600 m. Considering the length of a vehicle, the distance between two proceeding vehicles in a platoon is 3 m. The platoon is composed of 5 vehicles. The data arrival process of each vehicle is modeled as a Poisson process with a mean of $0.3, 0.5, 0.7, 0.9$, and $1.1$ (packets/ time slot). The remaining parameters are set as follows: $P_{VI} = 10$, $P_V = 3$, $M = 6$, $J = 10$, $K = 5$, $\theta = 5$, $\eta = 0.8$, $p = 0.6$. Considering the duration of a frame in LTE, each time slot is $\Delta t = 10\,\text{ms}$. The platoon density is $\lambda_p = 5\times10^{-3}$ (platoons/m) and the path loss effect $\alpha = 4$. All channel fading effects are exponential with mean 1.

### A. Latency and Fairness

Fig. 2 shows how the fairness function affects the delay performance of the platoons for different data arrival rates. We can find that the more fairness we emphasize (the larger $V$ is), the delay becomes shorter with lower data arrival rates. If we ignore fairness (i.e., V = 1), we can find that the variation of the delay performance among the vehicles becomes much smaller. The reason is that we sacrifice the delay performance of the vehicles with smaller data arrival rate and allocate more channel resources to the vehicles with larger data arrival rate. The result also shows that a tradeoff between fairness and transmission performance exists [11]. That is, if we pursue fairness, it is hard to pursue extremely low latency for one of the vehicles in a platoon at the same time.

### B. Re-Allocation

Fig. 3 illustrates the resource re-allocation rate with the proposed scheme. We can find that the resource re-allocation rate can be successfully controlled under the considered constraints. The interesting aspect is the fact that the resource re-allocation rate decreases with growing $V$. This can be explained with the allocation scheme, *i.e.*, the solution space of $\mathbf{1}_{kj}$ becomes smaller while the $V$ increases. Therefore, it becomes less likely to find a solution that further maximizes the objective function (16) and thus the re-allocation rate decreases.

### C. Network Switching

Fig. 4 shows that the proposed scheme can also keep the network switching rate under the required constraints. Different from Fig. 3 we can see that the network switching rate approaches the required constraint with larger $V$. This observation can be explained by that solution space of the resource allocation schemes becomes smaller with stricter fairness requirements. With larger weighting ($V$) on the fairness, there is smaller solution space for channel allocation. Then, the network switching is executed more frequently to find the best network to keep the fairness and mitigate the congestion of the queues.

Fig. 5 illustrates one of the realizations of the simulation. It shows that the total queue size grows over time with $V = 1$ and $V = 300$ with the network switching rate constrained to $\psi = 0.002$. We can see that the size of the queues decreases abruptly after executing the network switching. In comparison, the resource re-allocation provides only a small scale improvement for the delay performance. Considering

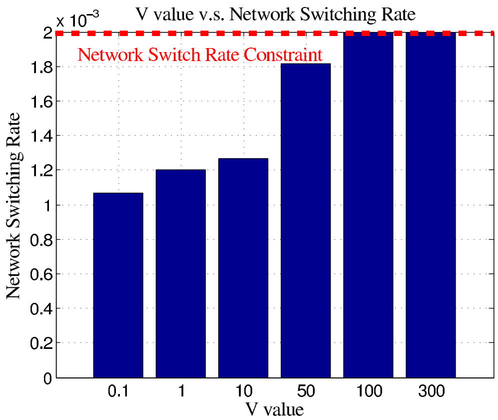


Fig. 4: Network switching rate versus fairness $V$. The network switching rate is constrained to $\psi = 0.002$.

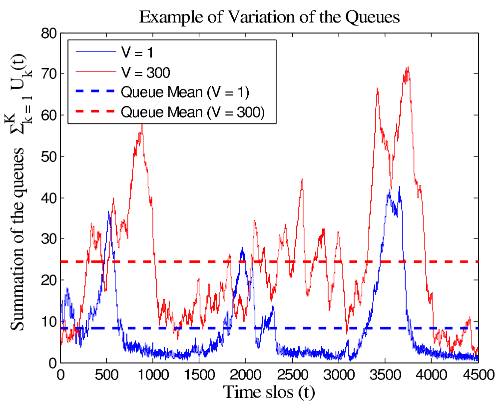


Fig. 5: Queueing performance after executing network switching. The velocity of the platoon is $\upsilon = 45\,\mathrm{m/s}$.

different values of $V$, we observe that the variation of the queue size with $V = 300$ is larger than with $V = 1$. The reason is the larger weighting of the fairness (larger $V$), which implies a smaller space of the problem (16). To satisfy the fairness, the platoon leader needs to pursue a network with more spectrum resource in order to satisfy the fairness requirements among the vehicles. However, with less weighting of the fairness, the platoon leader can only rely on resource re-allocation to satisfy the fairness requirement. In other words, we can decrease the constraint of the network switching rate by increasing the constraint of the resource re-allocation rate.

Fig. 6 illustrates the latency of each vehicle in the same platoons under different network switching rate constraints. Here, we can see that the latency improves while we increase the network switching rate constraints. This is a tradeoff between the network switching rate and the communication latency. We note that the latency shown here is similar to the waiting time in queues. The latency caused by the network switching is not considered.

## VI. Conclusion

In this work, a framework for low-latency communication of V2V networks underlaying V2I network is proposed. Solely

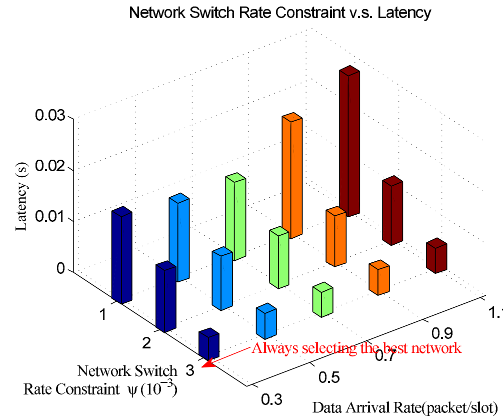


Fig. 6: Impact of network switching rate constraints on latency performance ($V = 1$, $\upsilon = 45\,\mathrm{m/s}$)

relying on improvements of the air interface to achieve low-latency communication may not be enough. To overcome the latency issues in the highly dynamic environment of vehicular networks, a time dynamic optimization approach is proposed. This approach improves the latency performance not only through the optimization of spectrum resources but also by constraining the network switching rate. To further decrease the complexity of the time-dynamic optimization problem, the original problem is converted into a deterministic optimization problem through *Lyapunov Optimization Theory*. Analytical results show that the proposed scheme approaches the best tradeoff between latency performance and network switching rate. Simulation results also verify it.

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