An Efficient Radio Resource Re-Allocation Scheme for Delay Guaranteed Vehicle-to-Vehicle Network

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***Abstract*—To achieve *low delay* for vehicular communication in cellular networks, the use of direct device-to-device (D2D) communication among vehicles is regarded as a key functional requirement. When D2D users share the spectrum with regular cellular users (D2D underlay), resource allocation schemes assure the coexistence between D2D and cellular users. Due to the high mobility of the vehicles, the resources need to be re-allocated, but frequent updates cause high signaling overhead and degrade the delay performance. In this paper, we present a radio resource re-allocation scheme for vehicular D2D users in a platoon scenario. The scheme reduces the re-allocation rate and gives delay guarantees for each vehicle. With the help of *Lyapunov optimization*, a closed form of the upper delay bound and resource re-allocation rate is also derived. The simulation results show that the proposed scheme can provide an delay upper bound and simultaneously minimizes the resource re-allocation rate.**

I. Introduction

By 2020, it is expected that the number of connected vehicles will surpass 25 billion [1] enabling new in-vehicle services and automated driving capabilities and the corresponding standards are frequently discussed recently [2]. Among those, use cases related to safety and traffic efficiency require a low delay exchange of information among vehicles in their vicinity. In cellular networks, device-to-device communication (D2D) enables direct communication between devices and is therefore considered as a solution for low delay vehicle-to-vehicle (V2V) communication [3]. However, due to limited availability of spectrum for wireless communication, V2V users need to share the frequency band with regular cellular users in the licensed or unlicensed bands.

Compared to regular cellular communication, D2D has several advantages: First, the transmission of messages over a short distance benefits from less path-loss effect and thus increases the communication reliability and reduces message retransmissions. Second, most of the vehicular applications, such as hazard warnings, vision sharing or platooning, happen locally among the neighbor vehicles. Routing the data through a roadside base station (BS) not only occupies resources of the communication system but results also in a long delay. Last but not the least, V2V communication does not have the classical handover problem that occurs at the edges of the wireless cell. Because the receiver is a nearby vehicle, the vehicles do not require executing classical handover procedures with the BS. However, it is important to note that for D2D communication the BS is still in charge of resource allocation and optimization.

Several studies about the radio resource optimization in D2D underlay scenarios exist, but cannot be directly applied to V2V scenarios. Due to the requirements of safety and traffic efficiency applications, the delay of the vehicular users and the quality-of-service (QoS) for regular cellular users (user equipment, UE) should be simultaneously guaranteed. In conventional D2D scenarios, the most common approach is – given the constraints of QoS of UEs – to design the best resource allocation scheme and maximize the transmission rate of D2D pairs [4]–[8]. It has been shown that these schemes work in static environments, disregarding the effects of mobility. However, in the high mobility environment with vehicles, the optimal resource allocation can quickly become outdated. For example, the vehicles may move close to a UE and thus one of the channels suffers from serious interference and the transmission quality degrades quickly. Therefore, a dynamic resource allocation scheme for V2V communication is necessary that guarantees the delay.

To maintain optimal resource utilization in a highly-dynamic environment, frequent executions of resource re-allocation procedures become necessary. Without the latest information about the environment, the resource allocation scheme would rely on out-of-date information, and thus, the optimal performance may not be achieved. Nevertheless, these procedures also imply the exchange of control information and may further jeopardize the delay performance. To achieve *low delay*, one solution is to reduce the signaling exchange [9]. How to balance between the cost of information exchange and the communication performance is the major point in the design of V2V communication.

In this work, we consider the scenario that the platoons move straightly like on the freeway environment and every vehicular user in a platoon shares the spectrum with the cellular UEs, *i.e.* the V2V communication underlays the cellular UE-BS communication. Considering the fact that the signaling exchange introduces the delay in the data communication, we try to minimize the rate of resource re-allocation to decrease the burden of the signaling to the network. That is, we regard the execution of resource re-allocation as the process cost, which should be minimized. To tackle the intrinsic dynamics in the vehicular network, we develop a dynamic resource allocation scheme that strikes the balance between *low delay*

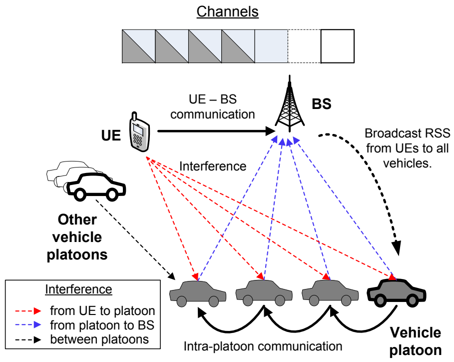

Fig. 1. Scenario: Vehicles drive in a platoon and communicate with each other underlaying the UE-BS communication.

and resource re-allocation rate, and guarantees the queuing delay.

II. System Model

A. Network and Channel Model

We consider a scenario in which a group of vehicles with the same mobility pattern on a freeway create a platoon. For the communication within the platoon, the vehicular users share the spectrum with the regular cellular users and the V2V network underlays the cellular network (Fig. 1). To avoid interference among platoon vehicles, the platoon leader allocates orthogonal channels to each vehicle.

In the cellular network, there are total J channels and J cellular user equipments (UEs). Each UE occupies a single dedicated channel with a transmit power P_{UE}. The set of the J channels (UEs) is denoted as $\mathbb{J} = \{1, \dots, J\}$. UEs are randomly distributed along a line of length L following uniform distribution and the BS is located at the center $L/2$. The platoons are distributed in the straight line with one-dimension Poisson point process (PPP) Φ with density λ_p (platoons/m). The reason for adopting one-dimension PPP is that it is more suitable for the freeway scenario. The homogeneity of PPP allows us to analyze a single platoon and represent the average performance of the whole network. The platoon consists of a set of K vehicles, which is denoted as $\mathbb{K} = \{1, \dots, K\}$. Each vehicle in the platoon has a corresponding receiver, *i.e.* the following vehicle, with distance d_V and transmit power P_V. It is noted that not necessarily all platoons have K vehicles; other platoons can have a different number of vehicles.

We denote SIR^V_{kj} as the signal-to-interference-ratio (SIR) of the kth vehicle in a platoon in the jth channel. Here, we assume that the effect of white noise is negligible due to the strong interference from other vehicles in the underlay network. Furthermore, the interference from other UEs degrades the performance of V2V communication only when the platoon moves into the close proximity (about 5 meters)of UEs. Therefore, this effect can be ignored at most of time. Now we can express SIR^V_{kj} as

$$SIR^V_{kj} = \frac{P_V G^V_{kj} d_V^{-\alpha}}{I^V_{kj}}, \tag{1}$$

where G^V_{kj} is the channel fading between the kth vehicle in the platoon and its corresponding receiver in channel j. In (1), I^V_{kj} is the aggregated interference from the vehicles in the other platoons at the kth vehicle in the jth channel.

$$I^V_{kj} = \sum_{i\in\Phi} P_V G^{VV}_{ij} d^{-\alpha}_{VV,ij}, \tag{2}$$

where G^{VV}_{ij}, $d_{VV,ij}$ represent the corresponding channel fading and distance between the vehicles (in other platoons) to the kth vehicle.

B. Non-outage Probability

To take the channel effect on the transmission into consideration, we adopt the non-outage probability to describe the transmission rate. We define a non-outage event as a successful packet transmission where the SIR is larger than a threshold θ. The non-outage probability of the kth vehicle in the jth channel is

$$\mathbb{P}(SIR^V_{kj} \geq \theta) = \mathbb{P}(G^V_{kj} \geq \frac{I^V_{kj}\theta}{P_V d_V^{-\alpha}}) = \mathbb{E}\left(\exp\left(\frac{-I^V_{kj}\theta}{P_V d_V^{-\alpha}}\right)\right). \tag{3}$$

The last equality of (3) is actually the moment-generating function of I^V_{kj}. $\mathbb{E}(\exp(-sI^V_{kj}))$ can be derived by finding the *Laplace* functional $\mathbb{E}\left(\exp\left(\sum_{i\in\Phi} f(d_{VV,ij})\right)\right)$ [10], where $f(d_{VV,ij}) = P_V G^{VV}_{ij} d^{-\alpha}_{VV,ij}$. Then the non-outage probability can be expressed as

$$\mathbb{P}(SIR^V_{kj} \geq \theta) = \exp\left(-\frac{2\lambda_p \pi d_V}{\alpha \sin\frac{\pi}{\alpha}}\theta^{1/\alpha}\right) \triangleq \varphi. \tag{4}$$

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

C. On-Off Power Control

To guarantee the transmission quality of UE in the underlay scenario, it is necessary to execute transmit power control. In a D2D scenario, we may assume that the information about the interference from D2D transmitters to the BS is available. Then, the BS can allocate these channels to the D2D communication with the maximum transmit power constraints, which can be modified adaptively according to the D2D users' location. In vehicular networks, however, this strategy works only if the channel fading information from vehicles to the BS is known a priori. This information may not be available, especially when the number of the vehicles is large and the vehicles are highly mobile. One possible solution is that the BS broadcasts the information about the received signal strength (RSS) from the UE to all the vehicles. Then the vehicle makes the decision whether to utilize the channel or not according to this information. To guarantee the performance of the UEs, each vehicle transmitter is allowed to access the channel only if the non-outage probability of UEs is larger than a threshold. That is, the jth channel is available for the kth vehicle only if the following equation is satisfied:

$$\mathbb{P}\left(\frac{P_{UE} G^{UE}_j d^{-\alpha}_{UE,j}}{P_V G^{VBS}_{kj} d^{-\alpha}_{VBS,k}} \geq \theta | P_{UE} G^{UE}_j d^{-\alpha}_{UE,j}\right) \geq \eta, \tag{5}$$

where G_{kj}^{VBS} and $d_{VBS,k}$ is the small scale channel fading and distance from the kth vehicle to BS, respectively, and $0 \leq \eta \leq 1$ is the required minimal non-outage probability of UEs.

To arrange the equation above, the condition of the jth channel being available for the kth vehicle is

$$P_{UE} G_j^{UE} d_{UE,j}^{-\alpha} \geq P_V d_{VBS,k}^{-\alpha} \theta \ln \frac{1}{1-\eta}. \quad (6)$$

Let δ_{kj} denote the indicator variable, which is equal to 1 if the jth channel is available to the kth vehicle, and 0 otherwise. Then ρ_{kj} indicates the probability that the jth channel allocated to the kth vehicle is available. It can be expressed as

$$\begin{aligned} \rho_{kj} &\triangleq \mathbb{P}(\delta_{kj} = 1) \\ &= \mathbb{P}\left(P_{UE} G_j^{UE} d_{UE,j}^{-\alpha} \geq P_V d_{VBS,k}^{-\alpha} \theta \ln \frac{1}{1-\eta}\right) \\ &= \exp\left(-\frac{P_V d_{VBS,k}^{-\alpha} \theta \ln \frac{1}{1-\eta}}{P_{UE} d_{UE,j}^{-\alpha}}\right) \end{aligned} \quad (7)$$

III. Data Queues Model

To describe the dynamics of the queues in each vehicle, we define the data queue $U_k(t)$ as the untransmitted data in the kth vehicle at time slot t. Then the dynamics of each queue $U_k(t)$ can be expressed as

$$U_k(t+1) = (U_k(t) - u_k(t))^+ + a_k(t), \forall k \in \mathbb{K}, \quad (8)$$

where $u_k(t)$ and $a_k(t)$ are the number of serviced packet and arriving packet at time slot t, respectively, and the function $(.)^+ = max[., 0]$. From (7), we know that the probability of each channel being available ($\delta_{kj} = 1$) depends on the location of the vehicles. Due to dynamic environment, the platoon leader needs to make a decision at each time slot whether to execute a resource re-allocation or not. We denote $u_k^0(t)$ as the service rate of the kth vehicle before re-allocating the channels in the time slot t and $u_k^1(t)$ as the rate after re-allocation. Then the service rate at time slot t can be expressed as

$$u_k(t) = (1 - g(t)) u_k^0(t) + g(t) u_k^1(t), \quad (9)$$

where $g(t) = 1$ if the re-allocation is adopted, and $g(t) = 0$ otherwise.

The service rate highly depends on the channel allocation of the vehicles. We define $\mathbf{1}_{kj}(t) = 1$ if the jth channel is allocated to the kth vehicle at the tth time slot and $\mathbf{1}_{kj}(t) = 0$ otherwise. Then the service rate of the kth vehicle can be expressed as

$$\begin{aligned} u_k^0(t) &= \sum_{j=1}^{J} \mathbf{1}_{kj}(t-1) \delta_{kj} \mathbf{1}(SIR_{kj}^V \geq \theta) \\ u_k^1(t) &= \sum_{j=1}^{J} \mathbf{1}_{kj}(t) \delta_{kj} \mathbf{1}(SIR_{kj}^V \geq \theta) \end{aligned} \quad (10)$$

It is worth noting that the expectation of δ_{kj} and $\mathbf{1}(SIR_{kj}^V \geq \theta)$ is determined by the location of each vehicle as shown in (7). Therefore, the resulting channel allocation can be different at each time slot.

IV. Problem Formulation

As shown in (7), the transmission rate that each channel can support depends on the location of the UEs and the platoon. Therefore, vehicles need to be able to switch frequently to the channels with larger ρ_{kj}. However, switching between channels causes the exchange of control messages and hence introduces delay to the communication. The first reason for the delay is that the vehicles must terminate the current transmission once they receive the resource re-allocation notification. Second, if the allocated channel is different from the previous one, further synchronization between transmitter and receiver is needed. To decrease the delay, we regard the execution of resource re-allocation as process cost and formulate a dynamic optimization problem to minimize the time average of it.

A. Radio Resource Re-Allocation Problem

At each time slot t, the platoon leader needs to make the decision whether to re-allocate the resources for the vehicles in the same platoon. To minimize the rate of resource re-allocations and simultaneously keep the queues in each vehicle stable, the problem that the platoon leader faces can be formulated as follows.

$$\begin{aligned} \min_{g(t), \mathbf{1}(t)_{kj}, k \in \mathbb{K}, j \in \mathbb{J}} \quad & \lim_{T \to \infty} \frac{1}{T} \sum_{t=1}^{T} g(t) \\ \text{subject to} \quad & \lim_{T \to \infty} \frac{1}{T} \sum_{t=1}^{T} \mathbb{E}(U_k(t)) \leq \infty, \forall k \in \mathbb{K} \\ & \sum_{k=1}^{K} \mathbf{1}_{kj}(t) = 1, \forall j \in \mathbb{J} \\ & \sum_{j=1}^{J} \mathbf{1}_{kj}(t) \geq 1, \forall k \in \mathbb{K} \\ & \mathbf{1}_{kj}(t) = \mathbf{1}_{kj}(t - (1 - g(t))). \end{aligned} \quad (11)$$

Since $g(t)$ is the resource re-allocation indicator, the aim is to minimize the time average of the resource re-allocation function. The first constraint in (11) indicates that all queues in every vehicle should be stable over time. The second constraint states that each channel j can be allocated to only one vehicle in the same platoon. The third one is that at least one channel should be allocated for every vehicle. The last constraint is that if the platoon leader decides not to re-allocate the radio resource, the resource allocation remains the same.

B. Condition of Solution Existence

Before designing the re-allocation scheme to solve the dynamic optimization problem in (11), we first need to prove that the solution exists.

Theorem 1: We denote the probability of jth channel allocated to the kth vehicle being available as $\rho_{kj} = \mathbb{P}(\delta_{kj} = 1)$ and $\rho_j^m = min\{\rho_{1j}, \ldots, \rho_{Kj}\}$. Given a realization of UE locations, the following equation should hold to guarantee the stability of the vehicles' queues:

$$\sum_{k=1}^{K} \lambda_k \leq \varphi \sum_{j=1}^{J} \rho_j^m, \quad (12)$$

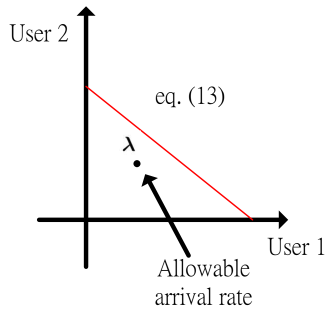

Fig. 2. Illustration of the region Γ. The arrival rate vector $\boldsymbol{\lambda}$ should be strictly in this region to guarantee the stability of the queues.

where $\lambda_k = \mathbb{E}(a_k(t))$ is the average number of arriving packet in the kth vehicle.

Proof: To simplify the notation, we denote the $\boldsymbol{\lambda} = (\lambda_1, \ldots, \lambda_K)$, $\mathbf{u} = (\mathbb{E}(u_1(t)), \ldots, \mathbb{E}(u_K(t)))$ and Γ to be the set of all possible service rates $\mathbf{u}$, that is, $\mathbf{u} \in \Gamma$. According to fundamental queuing theory, it is necessary to keep the average service rate larger than average arriving rate, that is, the vector λ should be strictly interior in the set Γ. For this reason, we first need to know the region Γ.

To find the region Γ, we denote $p_{kj} = \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} \mathbf{1}_{kj}(t)$ as the average time ratio of jth channel allocated to kth vehicle. Then u_{kj}, the service rate of kth vehicle utilizing jth channel, can be expressed as $u_{kj} = p_{kj}\rho_{kj}\mathbb{P}(SIR_{kj}^{V} \geq \theta)$ and the total service rate of kth vehicle is $u_k = \sum_{j=1}^{J} u_{kj}$. To sum up from $k = 1$ to K, we can get

$$\begin{aligned}\sum_{k=1}^{K} u_k &= \varphi \sum_{k=1}^{K}\sum_{j=1}^{J} p_{kj}\rho_{kj} \\ &\geq \varphi \sum_{j=1}^{J} \rho_j^m \sum_{k=1}^{K} p_{kj} = \varphi \sum_{j=1}^{J} \rho_j^m\end{aligned} \tag{13}$$

As illustrated in Fig. 2, (13) provides the lower bound of Γ. According to fundamental linear programming, for $\boldsymbol{\lambda}$ being strictly interior in Γ, $\sum_{k=1}^{K} \lambda_k \leq \varphi \sum_{j=1}^{J} \rho_j^m$ has to be satisfied. ■

V. Dynamic Algorithm of Radio Resource Re-Allocation Scheme

In this section, we propose a scheme to reduce the dynamic resource re-allocation rate that solves the problem in (11). We first describe the concept of *Lyapunov optimization* and then discuss the proposed scheme.

A. Lyapunov Optimization

The following *Lemma* [11] is useful when we derive the proposed scheme based on *Lyapunov optimization*.

Lemma 1: For positive real numbers X, Y, μ, υ satisfying

$$Y = \max[X - \mu, 0] + \upsilon,$$

then the following inequality holds

$$Y^2 \leq X^2 + \mu^2 + \upsilon^2 - 2X(\mu - \upsilon). \tag{14}$$

We define the *Lyapunov function* as $L(t) \triangleq \sum_{k=1}^{K} U_k^2(t)$ and *Lyapunov drift* function as

$$\triangle L(t) \triangleq L(t+1) - L(t), \tag{15}$$

which describes the tendency of increasing rate of each data queue $U_k(t)$. To keep the queues stable, it is expected that the scheme should make the *Lyapunov drift* function as negative as possible because the *drift* can reduce the total queue lengths much faster. However, it also means that we should increase the utilization rate of the re-allocation scheme to increase the service rate and thereby the *drift* function becomes negative. To keep the balance between *drift* and the cost of re-allocation, the *drift-plus-penalty* function is introduced, which is defined as

$$\triangle L(t) + Vg(t). \tag{16}$$

$\triangle L(t)$ is the *drift* part, $g(t)$ is the cost (penalty) part, and $V \geq 0$ is a constant determining the tradeoff between the *drift* and cost. Intuitively, the *drift-plus-penalty* function describes the tradeoff between queue stability and re-allocation rate.

According to *Lemma* 1, the following equation holds

$$\begin{aligned}\mathbb{E}\left(\triangle L(t) + Vg(t)\right) &= \mathbb{E}\left(\sum_{k=1}^{K} U_k^2(t+1) - U_k^2(t) + Vg(t)\right) \\ &\leq \sum_{k=1}^{K} B_k - 2\mathbb{E}\left(U_k(t)(u_k(t) - a_k(t)) + Vg(t)\right) \\ &= \sum_{k=1}^{K} B_k + 2U_k(t)\lambda_k - \mathbb{E}\left(\sum_{k=1}^{K} 2U_k(t)u_k(t) - Vg(t)\right),\end{aligned} \tag{17}$$

where $B_k \triangleq \mathbb{E}(u_{max}^2) + \mathbb{E}(a_k(t)^2)$, and u_{max} is the maximal service rate that the vehicles can achieve.

To keep the balance between *drift*, cost, and queues stable, we try to minimize the *drift-plus-penalty* function. Since it is hard to derive the *drift-plus-penalty* function, especially without the assumption of packet arrival rate, we minimize the upper bound of it. That is, given the queues state $U_k(t) \forall k \in \mathbb{K}$ at each time slot t, we solve

$$\min_{g(t), \mathbf{1}_{k,j}(t), k\in\mathbb{K}, j\in\mathbb{J}} \sum_{k=1}^{K} 2U_k(t)u_k(t) - Vg(t), \tag{18}$$

with the last three constraints in (11).

From (18), we can find that the information about the queue status in each vehicle is necessary for the channel allocator, *i.e.* the platoon leader. However, the frequent exchange of control information among vehicles and platoon leader is not be acceptable to achieve low delay. To reduce it, the vehicles do not always need to update the status of the queue and we propose a concept called "floored queue" and the corresponding scheme as follows.

B. Floored Queue and Proposed Scheme

The "floored queue" $Q_k(t)$ is defined as

$$Q_k^M(t) = \left\lfloor \frac{U_k(t)}{M} \right\rfloor. \tag{19}$$

That is, the kth vehicle only reports its queue status to the platoon leader if the original queue $U_k(t)$ is a multiple of M. In this way, the exchange of control information between vehicles and platoon leader is reduced, however, the leader also cannot use the latest information to assign the best resource allocation. This may result in performance degradation.

With the approach of "floored queues" $Q_k^M(t)M \leq U_k(t)$, the *drift-plus-penalty* function in (17) becomes

$$\triangle L(t) + Vg(t) \leq \sum_{k=1}^{K} (B_k + 2Q_k(t)Ma_k(t)) - \mathbb{E}\left(\sum_{k=1}^{M} 2Q_k(t)Mu_k(t) - Vg(t)\right). \tag{20}$$

To minimize the upper bound of *drift-plus-penalty* function as in (18), the problem can be converted to minimize the right side of (20). That is,

$$\max_{g(t),\mathbf{1}_{kj}(t),k\in\mathbb{K},j\in\mathbb{J}} \sum_{k=1}^{K} 2MQ_k^M(t)u_k(t) - Vg(t) \tag{21}$$

with the last three constraints in (11).

C. Performance Analysis

Theorem 2: With the proposed scheme in (21), the upper bound for the average queue size satisfies

$$\lim_{T\to\infty} \frac{1}{TK} \sum_{t=1}^{T}\sum_{k=1}^{K} \mathbb{E}(U_k(t)) \leq \frac{\sum_{k=1}^{K} B_k + V}{2\epsilon K} + M, \tag{22}$$

where ϵ is the maximal constant satisfying $\epsilon\mathbf{1} + \boldsymbol{\lambda} \in \Gamma$. The rate of resource re-allocation can be upper bounded by

$$\overline{g} = \lim_{T\to\infty} \frac{1}{T} \sum_{t=1}^{T} g(t) \leq g^* + \frac{\sum_{k=1}^{K} B_k}{V}. \tag{23}$$

Proof: Taking the time-average of (20), we can get

$$\begin{aligned}
&\lim_{T\to\infty}\left(\frac{1}{T}\sum_{t=1}^{T}\triangle L(t) + \frac{V}{T}\sum_{t=1}^{T} g(t)\right)\\
&\leq \lim_{T\to\infty}\left(\frac{1}{T}\sum_{t=1}^{T}\sum_{k=1}^{K} B_k - \frac{2\epsilon M}{T}\sum_{t=1}^{T}\sum_{k=1}^{K} Q_k^M(t) + \frac{V}{T}\sum_{t=1}^{T} g(t)\right)\\
&\leq \sum_{k=1}^{K} B_k - 2\epsilon M \sum_{k=1}^{K} \overline{Q_k^M} + Vg^*,
\end{aligned} \tag{24}$$

where $\overline{Q_k^M} = \lim_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T} Q_k^M(t)$ and g^* is the resulting time-average of $g(t)$ from any other arbitrary resource re-allocation scheme (including the best one) minimizing $\overline{g}$. The last inequality comes from the fact that the proposed scheme minimizes the right side of (20). By further rearrangement of (24), we can get

$$\begin{aligned}
&2\epsilon M \sum_{k=1}^{K}\left(\frac{\overline{U_k}}{M} - 1\right) \leq 2\epsilon M \sum_{k=1}^{K} \overline{Q_k^M}\\
&\leq \sum_{k=1}^{K} B_k + Vg^* + \lim_{T\to\infty}\frac{1}{T}(L(T) - L(1)) \leq \sum_{k=1}^{K} B_k + V.
\end{aligned} \tag{25}$$

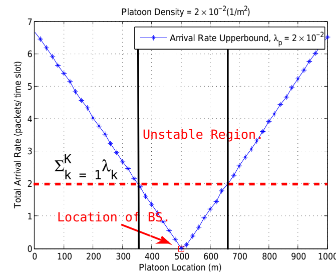

Fig. 3. There is no algorithm that can guarantee the delay of V2V communication underlaying BS while the location of platoons is too close to the BS.

The first inequality considers that $Q_k^M(t) \geq U_k(t)/M - 1$, the last inequality $g^* \leq 1$. Because $2\epsilon M \sum_{k=1}^{K}\left(\overline{U_k}/M - 1\right) = 2\epsilon M\left(\sum_{k=1}^{M}\overline{U_k}/M - K\right)$, both side of (25) are divided by $2\epsilon M$. After moving MK to the right side, (22) is proved.

To prove (23), we can first move the $\lim_{T\to\infty}\frac{1}{T}\sum_{t=1}^{T}\triangle L(t)$ in (24) to the right side and get

$$V\overline{g} \leq \sum_{k=1}^{K} B_k - 2\epsilon M \sum_{k=1}^{K}\overline{Q_k^M} + Vg^* \leq \sum_{k=1}^{K} B_k + Vg^*. \tag{26}$$

The last inequality in (26) considers that ϵ, M and $\overline{Q_k^M}$ are larger than 0. Then dividing both sides of (26) by V, completes the prove of (23). ■

VI. Simulation

The following parameters are set for the simulation: platoon density $\lambda_p = 2{\times}10^{-2}$, the number of channels and UEs $J = 10$, the number of vehicles in a platoon $K = 5$, data arrival rate $\boldsymbol{\lambda} = \{2/5, 2/5, 2/5, 2/5, 2/5\}$, $\eta = 0.8$, $P_{UE} = 10$, $P_V = 3$, $d_V = 2$, $\theta = 5$, and each time slot is $5ms$. The simulation time is 3,000 time slots with 300 iterations. The analytical upper bounds of queue sizes are transformed into time scale by *Little's Theorem*.

To calculate the $\mathbb{E}(u_{max})$ in B_k, the maximal service rate of vehicles can be achieved by assigning the best $J - K + 1$ channels to the vehicles. Because the maximal service rate of each channel is 1, the maximal value of $\mathbb{E}(u_{max}^2)$ is equivalent to $\mathbb{E}(u_{max}^2) = (J - K + 1)^2$.

Fig. 3 illustrates the upper bound of the summation of the arrival rate of a platoon. We find that the proximity of BS is the unstable region in which the delay performance of the platoons cannot be guaranteed. The reason is that the interference from the vehicles affects the performance of the UEs while they are close to the BS. Therefore, the probability of accessing the channel decreases and thereby the service rate. Fig. 4 demonstrates that the delay increases abruptly when the platoon approaches the boundary of the stable region and thus verifies the accuracy of *Theorem* 1.

Fig. 5 shows that the delay can be successfully upper bounded by (22). By adjusting V, we can design the network such that the delay requirement is satisfied. Fig. 6 illustrates the tradeoff between the probability of resource re-allocation and the average delays of queues. Fig. 7 highlights the benefit of utilizing the floored queues to update the queue status to

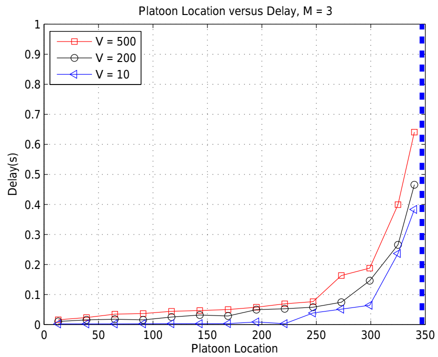

Fig. 4. Average delay versus minimal distance d_V^m. We observe that the delay increases to infinity when the vehicle approaches the unstable region as shown in Fig. 3. The dashed line is based on (13).

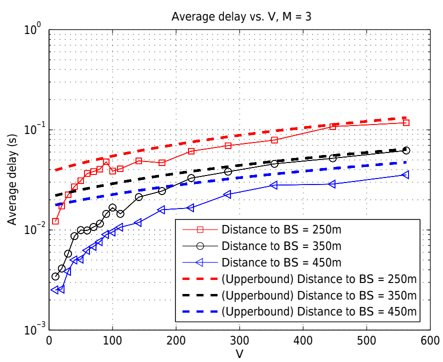

Fig. 5. Average delay performance of vehicles versus V.

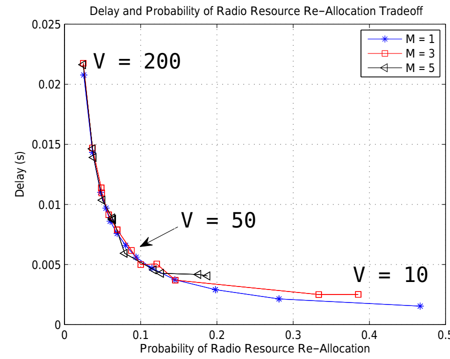

Fig. 6. Tradeoff between delay and probability of resource re-allocation with different M.

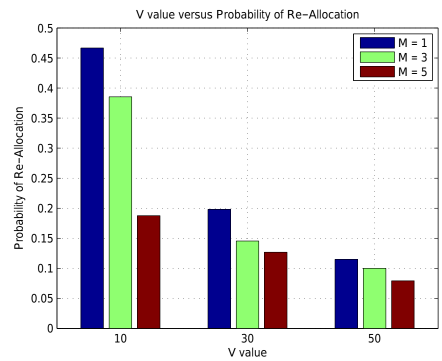

Fig. 7. With larger M, the reduction in the utilization of resource re-allocations is larger, especially when V is small.

the platoon leader. We observe that the resource re-allocation rate is further reduced when V gets smaller. From Fig. 6 we see that the delay is mainly determined by V if it is large. However, the probability of resource re-allocation can still be reduced by the floored queue. Here, we only take the queuing delay into account, not the delay caused by the exchange of control information. If the cost of information exchanges is large, the floored queue becomes more necessary, e.g. the platoons contain a large number of vehicles.

VII. Conclusion

To achieve *low delay* in V2V communication in underlay D2D networks, the frequent exchange of signaling messages for resource re-allocation may burden the cellular network and affect the delay performance of the V2V communication. We first prove that there exists a geographical region close to the BS in which no algorithm can guarantee the delay performance. Then, in the solution-existence region, we propose an algorithm that reduces the rate of dynamic radio resource re-allocation. The proposed algorithm achieves the best rate-delay tradeoff asymptotically. Simulation results are provided to validate the proposed algorithm.

Acknowledgements

This work is supported by the Ministry of Science and Technology, Taiwan, R.O.C. and MediaTek Inc. under the contract MOST 104-2622-8-002-002.

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