On Optimal Device-to-Device Resource Allocation for Minimizing End-to-End Delay in VANETs

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***Abstract*—In vehicular ad hoc networks (VANETs), the IEEE 802.11p is a popular and standardized protocol for communications among vehicles and infrastructure (e.g., roadside units). However, because of a limited communication range and the randomly access nature of the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism, the end-to-end delay could be high due to both store-and-catch-up (SAC) delay when the network is temporally disconnected and the channel access contention delay. In this paper, we propose a new method based on fifth-generation device-to-device (D2D) technology to improve the delay performance of VANETs. The basic idea is that direct D2D-based communications among vehicles remove the contention delay and can support longer distance. Specifically, we design a hybrid system with both D2D- and IEEE 802.11p-based communications, where the D2D links are controlled by the cellular base stations (BSs) in the overlay scheme. Each vehicle periodically checks its packet lifetime and requests the BSs to establish D2D links, if needed. The optimal resource allocation problem at the BSs is to select optimal receiver vehicles to establish D2D links and assign proper channels for them so that the total delay is minimized. The problem is equivalent to a maximum weighted independent set problem with dependent weights (MWIS-DW), which is NP-hard. To calculate the weights, an analytical approach is developed to model the expected end-to-end delay. Furthermore, we propose a greedy-based algorithm to solve this problem and develop a theoretical performance lower bound for the algorithm. The effectiveness of the algorithm under various scenarios is evaluated through simulations.**

***Index Terms*—Device-to-device (D2D) communications, end-to-end delay, IEEE 802.11p, link selection, vehicular *ad hoc* network.**

I. INTRODUCTION

As a KEY component of intelligent transportation systems (ITSs), vehicular ad hoc networks (VANETs) can connect the vehicles in both highway and urban areas and provide wireless communications among vehicles and between the vehicles and roadside infrastructure. VANETs can support a wide range of applications such as information dissemination, Internet access and data downloading, accident alarming, congestion warning and detouring guidance, mobility enhancement, and mobile advertising [1]–[3].

As a most popular and standardized protocol specified for VANETs, IEEE 802.11p uses the spectrum in the licensed 5.9-GHz ITS band to provide physical-layer and medium access control (MAC) layer protocols for data exchange in VANETs [4]. The MAC layer features in the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism, by which all vehicles contend to access the channel and transmit packets. Basically, a vehicle has to sense the channel before transmitting a packet. If the channel is sensed busy, it applies random backoff and attempts to transmit after the backoff counter decrements to zero. The backoff counter will be suspended if there are ongoing transmissions sensed by the vehicle.

The IEEE 802.11p protocol may introduce two types of delay to the communications among vehicles. First, due to the contention nature of the CSMA/CA mechanism, a vehicle has to spend time in conducting backoff. The length of this time could be long if the target vehicle's neighbor size is large and the transmission time of others' packets is long (due to backoff counter suspension). Moreover, if retransmissions are allowed to increase data transmission reliability, the total contention delay will be much longer. The second type of delay relates the limited transmission range of the IEEE 802.11p. The range is typically 100–200 m, which is relatively short compared with the intervehicle distances, particularly in highway VANET scenarios. Thus, the network connectivity is difficult to ensure during motion. If a vehicle finds no relay within its communication range, it has to store and carry the current packet and forward to another only when it is able to find a new relay. Such store-and-catch-up (SAC) delay could be large since vehicles moving speed is relatively much lower than wireless communication speed. In time-sensitive application, e.g., critical and emergence message dissemination, a packet may be assigned a strict deadline for reaching its destination, and a large delay may cause packet drop and performance degradation of the whole application.

To address the delay issue, we propose to explore the device-to-device (D2D) communication technique over the cellular band. As a promising fifth-generation technology, D2D communications allow physically approximal devices to directly communicate with each other over licensed cellular band, bypassing the base station (BS) [5]. Compared with IEEE 802.11p-based communications, D2D communications can achieve a higher data rate and a longer transmission range [6]. Therefore,

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it is potentially able to reduce the SAC delay by bridging the vehicles that were previously disconnected with IEEE 802.11p. Moreover, since D2D communications are contention free, the first type of delay mentioned earlier is also removed.

However, since D2D communications have to share the spectrum resources with cellular users, the performance improved introduced by D2D communications in VANETs is highly affected and limited by the resource allocated by the BS to the vehicles. There are two types of spectrum sharing schemes between D2D users and original cellular users: underlay and overlay schemes [7], [8]. In the underlay scheme, D2D users and legacy cellular users use the same cellular band simultaneously, and D2D users have to seek for transmission opportunities only when cellular users are well protected, i.e., either they do not present or the intended D2D transmissions do not disturb ongoing cellular communications. With the underlay scheme, the spectrum utilization is improved but with high signaling overhead [9]. Moreover, since the cellular user activities are highly dynamic, the availability of D2D opportunities is difficult to guarantee. However, in the overlay scheme, a fraction of the cellular spectrum is allocated for D2D transmissions such that the D2D and legacy cellular transmissions take place in separated bands. Therefore, with the overlay scheme, cellular users are well protected, but the spectral efficiency may be relatively low in some cases since the spectrum is not reused. However, as analogous to that, a portion of the spectrum in the 5.9-GHz band is allocated to ITS communications, a certain portion of the licensed band can be allocated to support such D2D links based on the overlay scheme. In addition, as specific to the VANET applications particularly in the highway scenarios, since there always can be demands for D2D communications among the vehicles and the D2D communication could only happen geographically within the highways, the utilization of the allocated spectrum can be guaranteed at a certain level.

In this paper, we focus on the overlay scheme where a set of orthogonal channels are allocated for D2D communications. We propose a hybrid system to incorporate D2D communications in the IEEE 802.11p-based VANETs. In our scheme, each vehicle periodically checks its packet lifetime and decides whether to send a request to the BS asking for D2D link establishment. The scheme is different from some existing D2D resource allocation schemes where potential D2D links are already discovered before allocating the D2D resources. In our scheme, upon receiving the requests, the BSs will choose appropriate receiver vehicles for some of the requesting vehicles to establish D2D links, in the sense that the selected D2D links can work simultaneously with guaranteed signal-to-interference-plus-noise ratios (SINRs) for all links, and the total network delay is expected to be reduced the most. When a vehicle switches to D2D mode for transmitting its current packet, the contention intensity of its neighbors will reduce, and their packet delay is expected to decrease. Therefore, in our optimization problem, for the selected D2D links, we take the delay reduction for both the transmitters of the links and other vehicles into consideration. Our major contributions can be summarized as follows.

1) We consider the resource allocation problem for the delay minimization to select a set of D2D links and assign appropriate channels to them to maximize the total network weighted delay reduction under the SINR constraints for the selected links, where the weights depend on both packet lifetime and the expected end-to-end delay.
2) We propose an analytical method to model the expected end-to-end delay in multihop IEEE 802.11p-based VANETs. With this mode, we show that the original optimization problem is equivalent to a maximum weighted independent set problem, but with dependent weights (MWIS-DW).
3) To solve this NP-hard problem, we propose a greedy-based algorithm and derive a theoretical performance lower bound for the algorithm. Simulation results validate the effectiveness of the proposed method.

The remainder of this paper is organized as follows. Section II reviews more related work. Sections III and IV present the problem setup and the delay prediction framework, respectively. The greedy algorithm for solving the optimization problem is presented in Section V. Section VI presents simulation results, and Section VII gives concluding remarks.

II. RELATED WORK

With the popularization of D2D communications, the standardization of D2D is being carried out in an early stage. The ad-hoc mode defined in IEEE 802.11 is potential to support D2D communications where user devices are able to directly communicate with each other [10]. Similarly, it might be possible to enable D2D in IEEE 802.15.8 as it is optimized for infrastructureless communications [11]. Moreover, D2D communications over licensed band is also being standardized by IEEE 802.15.4g, Qualcomm, and Long-Term Evolution Advanced (LTE-A) [10]. The support of D2D in the LTE-A architecture has been defined in the Third Generation Partnership Project standard Release 12 [12] in which the support is enabled by the proximity-based service (ProSe) function, ProSe application server, and ProSe application at the user side.

The key issue in D2D resource allocation lies in how to properly allocate spectrum resources and transmission opportunities to D2D users such that the network performance could be improved without causing too much interference to cellular users [13]. The framework in [14] allows mobile users to decide the operation mode under which to establish a cellular link or a D2D link for transmission. Stochastic geometry tool is utilized to optimize network parameters with the target of improving network coverage. Spectrum sharing between cellular users and D2D users is investigated in [15], where bidirectional D2D communications are exploited to assisting cellular transmissions. Spectrum resources are limited and hence valuable, which motivated auction or game-based approaches to address the resource allocation problem. A reverse iterative combinatorial auction mechanism is proposed in [16], where spectrum resources act as bidders to compete for packages of D2D transmission pairs, and system sum rate will be optimized with the auction-based scheme. In [17], a Stackelberg game model is developed, in which a cellular user is the leader and a D2D user is the follower buying spectrum resources. Based on the game framework, a joint scheduling and resource allocation

TABLE I
MAIN NOTATION DEFINITIONS

Notation	Definition
$\mathcal{C}$	set of channels
T_{th}	threshold that determines whether or not to send a request to the base station (BS)
Ω	set of vehicles within the coverage of the BS
Ω_s	set of vehicles that send requests to the BS
$\mathcal{L}$	set of D2D links to be established as determined by the BS
t_v	the remaining lifetime of vehicle v's packet
D_v^w	the time delay that a packet experiences from v to its destination without using any D2D links in $\mathcal{L}$
D_v^d	the time delay that a packet experiences from v to its destination with D2D links $\mathcal{L}$
$\Delta D_v(\mathcal{L})$	expected delay reduction due to $\mathcal{L}$
$tx(l)$, $rx(l)$	transmitter and receiver of D2D link l, respectively
$\mathcal{D}$	set of potential D2D links from vehicles in Ω_s to vehicles in Ω

algorithm is proposed to manage the interference and improve network throughput. A similar resource allocation game with D2D users as players in an auction system is proposed in [18], where the objective focuses on network lifetime.

Resource allocation for D2D users have also been studied in many other scenarios. For example, in [19], social connection between D2D users and its relationship with link quality are investigated, based on which, a sociality aware resource allocation optimization is proposed. A column-generation-based method is introduced in [20] for resource allocation to optimize spectrum utilization, in which the quality of service (QoS) of D2D links can be guaranteed without affecting cellular users with harmful interference. In the literature, many existing studies on D2D resource allocation focus on the network throughput performance, whereas in VANETs, transmission delay is an important performance metric that has not been well examined. In this paper, we address this issue by considering delay reduction as the objective and construct a D2D resource allocation framework to maximize the reduction.

There have been only a few research efforts toward applying D2D communications in VANETs. D2D-assisted transmissions can be used to maintain connection and recover deadends in VANET as proposed in [21] and [22]. For a vehicle, if all other vehicles are temporally outside of its transmission range based on 802.11p, a D2D link can be established at this time to recover such a one-hop failure. In [23], the resource allocation problem for D2D assisted VANETs is investigated, and an algorithm to determine whether a D2D link can be established to minimize cellular resource consumption (due to D2D communications) while maintaining connectivity of the vehicles is proposed. Nevertheless, how to improve the VANET delay performance is not considered.

III. PROBLEM SETUP

Here, we first present the hybrid system where both IEEE 802.11p- and D2D-based communications coexist. Then, we present the system model and formulate our optimization problem.

A. Hybrid System

We assume that each vehicle has two radio interfaces: one for IEEE 802.11p and the other one for cellular communications. For simplicity, we assume that, at a time, each vehicle has one packet (either self-generated or forwarded) to transmit, such that it will either use the 802.11p or the cellular interface. Alternatively, a vehicle can use both 802.11p and cellular radios to transmit its packet. However, this may not get better performance. Detailed explanations are given in Remark 2 later.

Normally, a vehicle will use its 802.11p interface and apply the IEEE 802.11p protocol (which basically runs the CSMA/CA protocol) to contend for accessing the free-band channel and transmitting their data packets. We assume that each packet has a deadline of arriving at the specific destination vehicle or geographical location. For example, a multimedia packet may have a playout deadline, and a packet related to emergency event information dissemination will also have a deadline due to its time sensitivity. If a vehicle finds that the deadline of its packet is quite stringent, it can request to use the cellular band by sending a D2D request message to the cellular BS that covers this vehicle. Specifically, if the remaining lifetime of a packet (the time remained before the deadline) is less than a threshold T_{th}, a corresponding request message will be sent to the BS that contains the following information: the vehicle ID (or address), the direction of transmission, and the remaining lifetime, where the direction of transmission points at the destination node or location. If the remaining lifetime of a packet is less than another much lower threshold value, e.g., T'_{th}, the corresponding vehicle will be treated as a regular cellular user, and the packet will be forwarded by the BS itself. Further, if the remaining lifetime is too short such that even the BS cannot handle the packet before its deadline, the packet will be directly dropped. In the following, we shall focus on the nontrivial cases that the remaining lifetime of each packet is larger than T'_{th}.

With the overlay scheme, the cellular system allocates a certain set of orthogonal channels, which is denoted set $\mathcal{C}$, for D2D communications among the vehicles. The amount of dedicated cellular channels for use in the VANET can be determined based on both other cellular users' activities and the demands of D2D links in the VANET. In this paper, we consider a generic $\mathcal{C}$ and assume that it is fixed. The main notations used throughout this paper are summarized in Table I.

B. Problem Formulation

In this paper, we target allocating the cellular resource to a VANET by selecting the vehicles to establish D2D links and allocating the operating channels for those established D2D links. Aside from the conventional IEEE 802.11p-based communications, the D2D communications in the cellular band can provide another pool of spectrum resource for use and, hence, can improve the performance of the VANET. However, the use of the cellular resource should be properly coordinated to cause not much interference. We focus on D2D link selection and channel assignment, during which the set of all potential D2D links are determined based on the maximum transmission power of the transmitter vehicles. Since we focus on the scenario that each vehicle only request to transmit a single packet over a D2D link at a time, the transmission time of each D2D request is fixed. In this sense, along with channel allocation, the system can be implemented such that the cellular BS actually selects D2D links and allocates resource blocks with a fixed number of slots for each link.

Consider an arbitrary cell and all vehicles within its coverage (denoted set Ω). The vehicles check their packet remaining lifetimes periodically such that each time period is sufficiently long for sending a request message and transmitting a data packet over some D2D link. Moreover, all vehicles update their locations with the BS at the same pace as they check the packet lifetimes. Consider an arbitrary period. Let Ω_s be the set of vehicles that send requests to the BS for establishing D2D links; however, it is possible that only a subset of the requests will be approved by the BS. Note that, at this moment, the requested D2D links have yet to be specified.

Upon receiving the requests, the BS will determine which D2D links, denoted set $\mathcal{L}$, to establish to improve the data transmission delay performance as compared with that without using these D2D links. For a packet carried by vehicle v, if no D2D links are established, i.e., v has to use the Wi-Fi interface and apply the CSMA/CA protocol to transmit this packet, let D_v^w be the time delay that the packet will experience from v to its destination. Otherwise, if $\mathcal{L}$ are established, denote the time delay as D_v^d. The detailed steps for estimating D_v^w and D_v^d will be discussed later. Then, the expected delay reduction due to the D2D links $\mathcal{L}$ for the packet of vehicle v is

$$\Delta D_v(\mathcal{L}) = \mathbb{E}\left[D_v^w\right] - \mathbb{E}\left[D_v^d\right]. \tag{1}$$

The objective of the BS is to maximize the weighted sum of the delay reductions, i.e.,

$$\max \sum_{v \in \Omega} w_v(\mathcal{L}) \tag{2}$$

where $w_v(\mathcal{L}) \triangleq (1/t_v)\Delta D_v(\mathcal{L})$ is called the weighted delay reduction, where t_v denotes the remaining lifetime of vehicle v's packet. Notice that we have assumed $t_v > T'_{\text{th}} > 0$. In the above, the coefficient is set inversely proportional to the remaining lifetime in the sense that the D2D links should be established for those packets that have stringent deadlines.

The D2D links $\mathcal{L}$ to be established should satisfy the SINR requirements, i.e., for every $l \in \mathcal{L}$

$$\frac{P_{\text{tx}(l)}\alpha^{-1}_{\text{tx}(l),\text{rx}(l)}}{\sum_{l' \in \mathcal{L}} P_{\text{rx}(l')}\alpha^{-1}_{\text{tx}(l'),\text{rx}(l)} + n_r} \geq \bar{\gamma} \tag{3}$$

where $\text{tx}(l)$ and $\text{rx}(l)$ denote the transmitter and receiver of link l, respectively. In the above, P_u denotes the transmit power of vehicle u, $\alpha_{u,v}$ is the path loss from vehicles u to v, n_r is the receiver noise level, and $\bar{\gamma}$ is the required SINR threshold for the receiver of l to correctly decode the packet from the transmitter of l.

Therefore, our optimization problem can be written as follows.

Problem 1: The BS decides the set of D2D links $\mathcal{L}$ based on the set of requested vehicles Ω_s to

$$\max_{\mathcal{L}} \quad \sum_{v \in \Omega} w_v(\mathcal{L}) \tag{4}$$

$$\text{s.t.} \quad (3) \text{ holds for all } l \in \mathcal{L} \tag{5}$$

$$\text{tx}(l) \in \Omega_s \qquad \forall\, l \in \mathcal{L}. \tag{6}$$

IV. DELAY PREDICTION

For a D2D link $l \in \mathcal{L}$, it will introduce the delay reduction for both the transmitter vehicle $\text{tx}(l)$ itself and the other vehicles other than $\text{tx}(\mathcal{L})$, whose paths traverse the interference area of the above transmitter vehicle, where $\text{tx}(\mathcal{L})$ stands for the set $\{\text{tx}(l)|l \in \mathcal{L}\}$. The first delay reduction, i.e., $\Delta D_{\text{tx}(l)}(\mathcal{L})$, is mainly due to that the established D2D link has higher data rate and is without random contention delay, whereas the major reason for the second type of delay reduction, i.e., $\Delta D_v(\mathcal{L})$ $\forall\, v \in \Omega \backslash \{\text{tx}(l)\}$, is the reduced channel contention intensity.

For each packet, the time of arriving from its current carrier vehicle to its destination can be approximated statistically by the BSs. For instance, they can analyze all historical data of the transmission time from the location of the current vehicle to the destination location.[1] However, since each BS knows the locations and velocities of all vehicles within its coverage, they can, together, more accurately predict the time of arrival of each packet. In the following, we develop an analytical model to predict the arriving delay and delay reduction benefit from using D2D links for each packet. We shall focus on the vehicles within one BS's coverage and assuming that the BS also knows the locations and velocities of other vehicles outside of its coverage due to information sharing among the BSs.

For those vehicles without establishing D2D links, they apply the IEEE 802.11p protocol for data transmission. At the network layer, some unicast routing protocol is implemented to provide source–destination multihop routings. The detailed design of such a routing protocol is out the scope of this paper; interested readers can find many existing designs in the literature, e.g., in [24]. Here, for analysis simplicity, we focus on the greedy position-based routing (e.g., the GPSR protocol [24]) to develop analytical models of the per-packet delay performance. In this protocol, a packet will be transmitted to the next-hop vehicle that is geographically the closest to the destination. To ensure packet delivery, retransmissions are implemented. For other protocols, different models may be established; however, our algorithm designed in Section V still works effectively.

A. Single-Hop Contention Delay

We start with the single-hop transmission scenario. Since the transmissions over the D2D links are free of contention, their

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[1] The mobility of the destination should be taken into account.

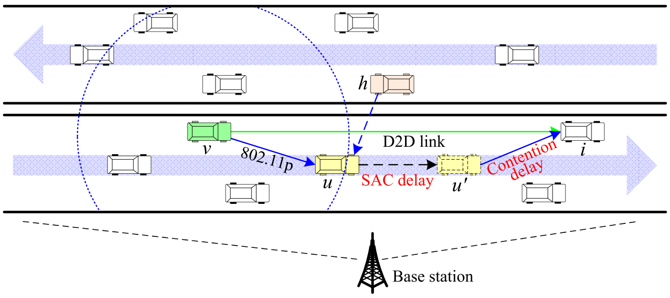

Fig. 1. Hybrid system model with both IEEE 802.11p and D2D in VANETs.

delay is simply determined by the data rate and the distances (to account for propagation delay). Thus, we focus on the delay induced by the application of IEEE 802.11p protocol in the following.

As shown in Fig. 1, suppose the destination of the packet of vehicle v is to the right side of the road on which v runs. According to the routing protocol, v will choose u as the next-hop vehicle and try to transmit the packet to u. With the CSMA/CA mechanism of the IEEE 802.11p protocol, vehicle v first senses the channel (in the ITS band) before transmitting the packet, and a backoff procedure is launched if the channel is busy. Basically, the length of the backoff procedure is controlled by a backoff counter that is initialized at a value randomly chosen between 0 and W_0. Here, W_0 is called the initial contention window size. The backoff counter decreases by 1 in one time slot if the channel is idle and freezes when the channel is busy. When the counter reduces to zero, v will transmit the packet. If that transmission was unsuccessful, v will retransmit the packet and run the CSMA/CA mechanism again but with the contention window size doubled (unless the maximum contention window size is reached).

For each vehicle i, define τ_i and p_i as the channel access and packet successful transmission probabilities of vehicle i. Since the traffic loads of the vehicles are not saturated, we define $1 - \rho_i$ as the probability that vehicle i has no packet to send out. Given the locations of the vehicles at a specific time, we can define for each i the sets of communication vehicles $\mathcal{N}_i$ and interference vehicles $\mathcal{T}_i$ (i.e., vehicles within i's communication range and carrier sensing range), respectively. Considering the vehicles' mobility, we can carry out our analysis step by step, with the step length short enough so that both $\mathcal{N}_i$ and $\mathcal{T}_i$ do not change within each step. Suppose that the velocities of the vehicles do not change during the analysis period, the information of $\mathcal{N}_i$ and $\mathcal{T}_i$ in all steps can be predicted. In the literature, there are several available mathematical models with good accuracy for calculating τ_i and p_i in multihop ad hoc networks, given the information of ρ_i, $\mathcal{N}_i$, and $\mathcal{T}_i$, e.g., the models in [25]–[28], which are basically extensions of the Bianchi's model in [29] for single-hop networks. In particular, the model can be dramatically simplified if we assume that the contention window size is fixed at W_0. In this case, the expression of transmit probability reduces to

$$\tau_v = \frac{2\rho_v}{W_0 + 1}. \tag{7}$$

Due to the use of request-to-send/clear-to-send mechanism, when v transmits, other vehicles in $\mathcal{N}_v$ will stay in channel listening. However, the transmission of v will still get collided if any of the vehicles in $\mathcal{N}_u$ but hidden to v simultaneously transmits. Therefore, the successful transmission probability is

$$p_v = \left(\prod_{i \in \mathcal{N}_v} (1 - \tau_i)\right) \left(\prod_{i \in \mathcal{N}_u \cap \overline{\mathcal{N}}_v} (1 - \tau_i)\right)^{L_v} \tag{8}$$

where $L_v = L + T_{\text{SIFS}} + \sigma + \delta$ is the vulnerability period during which a collision due to transmissions from hidden vehicles may occur. L is the packet length, T_{SIFS} is duration of the SIFS, σ is the slot time, and δ is the propagation delay.

Let T_s^{tx} and T_c^{tx} be the average time that the channel is busy due to a successful transmission and a collided transmission, respectively. Detailed expressions for T_s^{tx} and T_c^{tx} can be found in [29], from which we have $T_s^{\text{tx}} > T_c^{\text{tx}}$. With τ_v and p_v obtained for each vehicle, we can then calculate the expected delay for a successful transmission from v to u as follows. Based on [29], the average length of a slot time consists of three portions.

1) The idle channel period as observed by v, which happens with probability $p_{\text{idle},v} = \prod_{i \in \mathcal{T}_v} (1 - \tau_i)$, i.e., the probability that none of the vehicles within v's carrier sensing range transmits packets.
2) The successful transmission time that is of length T_s^{tx}. For any vehicle i, it successfully transmits a packet with probability $\tau_i p_i$, where p_i is given in (8).[2] Therefore, vehicle v observes a successful transmission with probability $p_{\text{tx},v} = \sum_{i \in \mathcal{T}_v} \tau_i p_i$.
3) The collided transmission time that is of length T_c^{tx}. Vehicle v observes a collided transmission with probability $p_{c,v} = 1 - p_{\text{idle},v} - p_{\text{tx},v}$, where $1 - p_{\text{idle},v}$ can be viewed as that vehicle v observes a busy channel (i.e., there are transmissions on the channel).

Then, the expected length of a slot time can be given as

$$\mathbb{E}[T_{\text{slot},v}] = p_{\text{idle},v}\sigma + p_{\text{tx},v} T_s^{\text{tx}} + p_{c,v} T_c^{\text{tx}}. \tag{9}$$

Given the successful transmission probability p_v, $1/\tau_v p_v$ can be viewed as the number of slot time that vehicle v should wait before successfully transmits its own packet. Thus, the average channel contention delay from v to its receiver vehicle, which is denoted $\mathbb{E}[D_v]$, can be approximated as follows:

$$\mathbb{E}[D_{\text{contention},v}] = \frac{\mathbb{E}[T_{\text{slot},v}]}{\tau_v p_v}. \tag{10}$$

B. Delay Reduction Over a Multihop Route

The multihop delay should take both contention delay and SAC delay into consideration. Consider the normal scenario that the D2D links $\mathcal{L}$ are not used. Since the BS knows the locations and average velocities of the vehicles, it can simulate the

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[2] Notice that when using (8) to calculate p_i, the BS needs to know the receiver of vehicle i. Since the BS can predict the positions of the vehicles, it can, hence, predict the receiver of i based on the routing protocol.

routing process and, thus, predict a route based on the greedy routing protocol for each packet from its current carrier vehicle to its destination. During this process, it runs the given model to estimate the contention delay of each single-hop transmission until the target packet reaches its destination when the expected total delay can be obtained. Note that, during this process, it is possible that the network is disconnected at the packet carrier vehicle at some time, i.e., other vehicles closer to the destination are outside of the carrier vehicle's communication range. In this case, the carrier vehicle should store the packet until it can transmit it to another vehicle that surpasses it. In this way, the packet will always be carried by the front vehicle that can be reached toward the destination and then passed down toward the destination when the front vehicle catches up with others. Therefore, the BS can predict both the SAC delay and contention delay of each single-hop transmission and hence can obtain an estimate of the total delay (i.e., $\mathbb{E}[D_v^w]$) from the current carrier vehicle to the packet's destination. Similarly, the BS can simulate the scenario with the D2D links $\mathcal{L}$ and obtain an estimate of another delay (i.e., $\mathbb{E}[D_v^d]$). Then, based on (1), it can estimate the delay reduction $\Delta D_v(\mathcal{L})$ by comparing the delay between the scenarios with and without the D2D links $\mathcal{L}$.

Since the transmissions of the D2D links $\mathcal{L}$ are carried out independently, $\Delta D_{\mathrm{tx}(l)}(\mathcal{L}) = \Delta D_{\mathrm{tx}(l)}(l)$. The delay reductions for those vehicles other than the transmitters of $\mathcal{L}$ are mainly determined by the single-hop delay in the ranges where the transmitters of $\mathcal{L}$ quit the IEEE 802.11p contention procedure. As shown in [25], the delay scales almost linearly as the number of nodes increases. This motivates us to approximate the delay $w_v(\mathcal{L})$ by $\sum_{l\in\mathcal{L}} w_v(l)$. Therefore, $\forall\, v \in \mathrm{tx}(\mathcal{L})$

$$\begin{aligned}\sum_{v\in\Omega} w_v(\mathcal{L}) &= \sum_{l\in\mathcal{L}} w_{\mathrm{tx}(l)}(l) + \sum_{v\in\Omega\setminus\mathrm{tx}(\mathcal{L})} w_v(\mathcal{L})\\ &\approx \sum_{l\in\mathcal{L}} w_{\mathrm{tx}(l)}(l) + \sum_{v\in\Omega\setminus\mathrm{tx}(\mathcal{L})}\sum_{l\in\mathcal{L}} w_v(l)\\ &= \sum_{l\in\mathcal{L}}\sum_{v\in\Omega} w_v(l) - \sum_{l\in\mathcal{L}}\sum_{l'\in\mathcal{L}\setminus\{l\}} w_{\mathrm{tx}(l')}(l)\\ &= \sum_{l\in\mathcal{L}}\left(w(l) - \sum_{l'\in\mathcal{L}\setminus\{l\}} w_{\mathrm{tx}(l')}(l)\right) \qquad (11)\end{aligned}$$

where $w(l) \triangleq \sum_{v\in\Omega} w_v(l)$. Let $J(\mathcal{L})$ be the right-hand side of (11). Then, $\forall\, l^* \notin \mathcal{L}$

$$J(\mathcal{L}\cup\{l^*\}) - J(\mathcal{L}) = w(l^*) - \sum_{l\in\mathcal{L}}\left(w_{\mathrm{tx}(l^*)}(l) + w_{\mathrm{tx}(l)}(l^*)\right). \qquad (12)$$

Note that, with (11), the original problem is approximately equivalent to a MWIS problem, but the weights for the links are no longer independent. As shown in (11), the weight for each link depends on $\mathcal{L}$, i.e., the set of D2D links to be selected. Therefore, the resulted problem is a MWIS-DW, for which many existing algorithm designed for MWIS may not work. In the following, we propose a greedy-based algorithm that is proven to have guaranteed performance lower bound.

V. PROPOSED ALGORITHM

Problem 1 is to find a link set $\mathcal{L}$ such that the weighted sum of the delay reductions is maximized. It can be seen that this problem is NP-hard. Instead of searching all possible $\mathcal{L}$ to find the optimal solution, in what follows, we shall develop an algorithm to find suboptimal solutions with low computation complexity. The complete algorithm in multichannel cases is shown in Algorithm 1. However, for ease of exposition, we shall focus on the single-channel case to discuss the algorithm in the following.

For an arbitrary target vehicle, its transmit power constraint can be translated into its maximum transmission range. All other vehicles within this range are potentially able to establish D2D links with the target vehicle. Let $\mathcal{D}$ be the set of all potential D2D links between Ω_s (i.e., vehicles who requested D2D links) and all vehicles within the BS's coverage. For each potential D2D link $l \in \mathcal{D}$, we can calculate the corresponding weight $w(l)$ as if only l was selected by the BS. For each l, denote $\mathcal{I}_l$ as its interfering links, which are the set of potential D2D links that cannot work simultaneously with l, i.e., the SINR constraint (3) does not simultaneously hold for any pair of (l', l) with $l' \in \mathcal{I}_l$. For convenience, define $\mathcal{I}_l^+ = \mathcal{I}_l \cup \{l\}$. Moreover, define the weighted interference degree for link l as

$$d(l) = \frac{\sum_{l'\in\mathcal{I}_l} w(l')}{w(l)}. \qquad (13)$$

Then, the BS chooses the first D2D link l_0 to be the one with the minimum degree d_l.

With l_0 selected to work, all the potential links in $\mathcal{I}_{l_0}$ cannot be selected to work. Therefore, we consider the remaining potential D2D links $\mathcal{D}_1 = \mathcal{D}\setminus\mathcal{I}_{l_0}$. For each of $l \in \mathcal{D}_1$, its new weight can be calculated based on (12), i.e.,

$$w'(l) = w(l) - \left(w_{\mathrm{tx}(l_0)}(l) + w_{\mathrm{tx}(l)}(l_0)\right). \qquad (14)$$

Thus, $J(\{l_0, l\}) = J(l_0) + w'(l)$. Based on the weight function $w'(\cdot)$, we can define the new weighted interference degree based on set $\mathcal{D}_1$ similarly, as in (13), i.e.,

$$d'(l) = \frac{\sum_{l'\in\mathcal{I}_l\cap\mathcal{D}_1} w'(l')}{w'(l)}. \qquad (15)$$

Then, the BS chooses the second D2D link as the one in $\mathcal{D}_1$ that has minimum d_l'.

Following this way, the BS can finally choose a set of D2D links, e.g., $\mathcal{L}$, that satisfy the constraints in Problem 1. The detailed algorithm is presented formally in Algorithm 1, where $\mathcal{I}_{\mathcal{L}}$ stands for the interference set of $\mathcal{L}$, i.e., the set of potential D2D links that cannot work simultaneously with $\mathcal{L}$.

In practice, the vehicles' requests may arrive asynchronously. In this case, the BS can run Algorithm 1 periodically such that it accepts requests during a period and make decisions based on Algorithm 1 at the end of the period. For the extra delay caused by the BS between the time of receiving request and sending out the decisions, before sending out a request to the BS, each vehicle should subtract this delay from the corresponding packet's remaining lifetime and check whether the threshold T_{th} is surpassed or not. Alternatively, a vehicle can request the BS to reserve a future period of time to transmit its packet over some D2D link; a similar scheme is presented in [30]. The advantage of this scheme is the support of asynchronous decision-making. However, it is difficult to control the extra delay between the time of requesting and the reserved transmission time.

```
Algorithm 1: Greedy D2D link selection algorithm
input     : The set of all potential D2D links $\mathcal{D}$ and the
            set of orthogonal channels $\mathcal{C}$
output    : Set of selected D2D links and their working
            channels $\mathcal{S} = \{(l,c)|l \in \mathcal{D}, c \in \mathcal{C}\}$
initialize: Selected D2D links $\mathcal{L} = \emptyset$; decision set $\mathcal{S} = \emptyset$
for $i = 1, 2, \ldots, |\mathcal{C}|$ do
    $\mathcal{D}_i \leftarrow \mathcal{D}\backslash\mathcal{L}$, $t \leftarrow 0$, $\mathcal{D}_{i,0} \leftarrow \mathcal{D}_i$, $\mathcal{L}_{i,0} \leftarrow \mathcal{L}$;
    calculate the link weights $\{w_{i,0}(l)|l \in \mathcal{D}_{i,0}\}$;
    while $\mathcal{D}_{i,t} \neq \emptyset$ do
        for $l \in \mathcal{D}_{i,t}$ do
            if $t > 0$, calculate the new weight $w_{i,t}(l)$
            based on (12), i.e.,
                $$w_{i,t}(l) = w_{i,t-1}(l) - \sum_{l' \in \mathcal{L}_{i,t}} \left(w_{tx(l)}(l') + w_{tx(l')}(l)\right); \quad (16)$$
            calculate the weighted interference degree
            based on (13), i.e.,
                $$d_{i,t}(l) \triangleq \frac{\sum_{l' \in \mathcal{I}_l \cap \mathcal{D}_{i,t}} w_{i,t}(l')}{w_{i,t}(l)};$$
        end
        choose link $l_{i,t}$ as follows:
            $$l_{i,t} = \operatorname*{argmin}_{l \in \mathcal{D}_{i,t}} d_{i,t}(l);$$
        update selected link set: $\mathcal{L}_{i,t+1} \leftarrow \mathcal{L}_{i,t} \cup \{l_{i,t}\}$;
        update potential link set: $\mathcal{D}_{i,t+1} \leftarrow \mathcal{D}_t \backslash \mathcal{I}_{\mathcal{L}_{i,t+1}}$;
        update decision set: $\mathcal{S} \leftarrow \mathcal{S} \cup \{(l_{i,t}, c_i)\}$;
        $t \leftarrow t + 1$;
    end
    $\mathcal{L} \leftarrow \mathcal{L}_{i,t}$;
end
```

Remark 1: In this paper, we focus on a single cell and only consider the scenario with one BS. For those scenarios that the transmitter and receiver of a D2D link belong to two adjacent cells, we assume that the two corresponding BSs can share information and coordinate with other to make unified decisions. This is reasonable since the BSs can communicate with each other through cables, and hence their coordination does not introduce much delay. In other cases in which the cellular BS is temporally unavailable or with poor connections for some vehicles, their D2D requests will not be acknowledged by the BS, and hence, they have to use their Wi-Fi interfaces to transmit their packets. However, in this case, the performance of the proposed method will degrade.

Remark 2: As mentioned in Section III, an alternative design is that the vehicles can use both 802.11p and cellular radios for transmitting the same packet. Intuitively, this can improve the packet transmission reliability. However, with Algorithm 1, a D2D transmission is scheduled without colliding with other transmissions; hence, if a packet can be transmitted over a highly reliable D2D link, it is unnecessary to transmit it through the 802.11p radio again. Moreover, transmission over the 802.11p radio will intensify the channel access contention of other nearby vehicles and, thus, incur longer contention delay to others. Therefore, if a D2D request is approved by the BS, the corresponding vehicle should transmit its packet only using the cellular radio and over the established D2D link; otherwise, it has to use the 802.11p radio.

A. Performance Analysis

In the following, we analyze the performance of the given iterative algorithm, focusing on the single-channel case. Our analysis can be easily extended to multichannel cases. For the initial potential D2D link set $\mathcal{D}_0$ and the weight function $w_0(\cdot)$, define the weighted average interference degree as

$$\bar{d}_0 = \frac{\sum_{l \in \mathcal{D}_0} w_0(l) d_0(l)}{\sum_{l \in \mathcal{D}_0} w_0(l)}. \tag{17}$$

We have the following properties of the algorithm.

Theorem 1: In the single-channel case, the solution of Algorithm 1, e.g., $\mathcal{L}^*$, ensures that

$$J(\mathcal{L}^*) \geq \frac{(W - \Delta)^2}{(\bar{d}_0 + 1)W} \tag{18}$$

where

$$\begin{cases} W = \sum_{l \in \mathcal{D}_0} w_0(l) \\ \Delta = \frac{1}{2} L(L+1)|\mathcal{D}_0| w_{\max} \\ w_{\max} = \max\left\{w_{\mathrm{tx}(l')}(l) + w_{\mathrm{tx}(l)}(l') | \forall\, l, l' \in \mathcal{D}_0, l \neq l'\right\} \end{cases}$$

and L is the maximum number of links in $\mathcal{D}_0$ that are mutually outside of each other's interference set, i.e., they can work simultaneously.

Proof: First, we have the following inequality:

$$\begin{aligned} (\bar{d}_0 + 1)W &= \sum_{l \in \mathcal{D}_0} w_0(l)\left(d_0(l) + 1\right) \\ &= \sum_t \sum_{l \in \mathcal{I}^+_{l_t} \cap \mathcal{D}_t} w_0(l)\left(d_0(l) + 1\right) \\ &\geq \sum_t \sum_{l \in \mathcal{I}^+_{l_t} \cap \mathcal{D}_t} w_t(l)\left(d_t(l) + 1\right) \\ &\geq \sum_t \sum_{l \in \mathcal{I}^+_{l_t} \cap \mathcal{D}_t} w_t(l)\left(d_t(l_t) + 1\right) \\ &= \sum_t \frac{\left(\sum_{l \in \mathcal{I}^+_{l_t} \cap \mathcal{D}_t} w_t(l)\right)^2}{w_t(l_t)} \\ &\geq \frac{\left(\sum_t \sum_{l \in \mathcal{I}^+_{l_t} \cap \mathcal{D}_t} w_t(l)\right)^2}{\sum_t w_t(l_t)} \end{aligned} \tag{19}$$

where the second inequality comes from the fact that l_t has the minimum weighted interference degree among all its interfering links in $\mathcal{D}_t$, whereas the last inequality stems from the Cauchy-Schwarz inequality. Based on (16), we have

$$\begin{aligned} w_t(l) &\geq w_{t-1}(l) - w_{\max}|\mathcal{L}_t| \\ &\geq w_0(l) - \frac{1}{2} w_{\max}|\mathcal{L}_t|\left(|\mathcal{L}_t| + 1\right). \end{aligned}$$

Thus

$$\sum_{t}\sum_{l\in\mathcal{I}^{+}_{l_t}\cap\mathcal{D}_t} w_t(l) \geq \sum_{l\in\mathcal{D}_0}\left(w_0(l) - \frac{1}{2}w_{\max}|\mathcal{L}^*|\left(|\mathcal{L}^*|+1\right)\right)$$
$$= W - \Delta.$$

Based on (16), we can also obtain that $J(\mathcal{L}_t) = J(\mathcal{L}_{t-1}) + w_t(l_t)$. Since $J(l_0) = w_0(l_0)$

$$J(\mathcal{L}^*) = \sum_{t} w_t(l_t). \tag{20}$$

Therefore, it can be easily seen from (19) that

$$J(\mathcal{L}^*) \geq \frac{(W-\Delta)^2}{(\bar{d}_0+1)W} \tag{21}$$

which completes the proof of this theorem. ■

VI. SIMULATION RESULTS

Here, we present simulation results to evaluate the performance of the proposed method. We developed C++ program within the OMNeT++ environment (an open-source network simulator). In the simulations, we consider a highway VANET of 20 km long with 300 vehicles by default. The vehicles are initially randomly positioned on the road. The initial speed of the vehicles is randomly generated within the range [15, 30] m/s. During the simulation, we allow each vehicle to dynamically change its speed within that range every 10 s. We assume that 20 randomly selected vehicles act as the sources that generate packets with probability 25% each time; the sources' packets are to be sent (possibly through multihop routes) to destination vehicles that are also randomly chosen. The other vehicles serve as relays. The payload sizes of the packets are assume the same as 112 B. The transmission and interference range for communications over IEEE 802.11p are set as 250 m and 500 m, respectively. These ranges are used for making routing decisions and estimating the contention delay. Parameters for simulating the CSMA/CA protocol are set as follows: CWmin = 7, CWmax = 1023, and the maximum number of retransmissions is 7. Upon generation, each packet is assigned with a lifetime of 60 s. A vehicle will send a request message to the cellular BS if the lifetime of its current packet is less than a threshold T_{th}, which is 50 s by default.

In our simulations, for the D2D communications, we assume the transmission power of the vehicles is fixed at 28 dBm and the receiver sensitivity is −90 dBm. The cellular BS controls the D2D link establishment such that it makes sure that, for each D2D link to be established, the received signal power at the receiver is higher than a certain threshold (which is set −80 dBm in our simulations). This is similar to the scenario that the vehicles use a truncated channel inversion power control to compensate path loss and keep the received signal power higher than the threshold [31]. We adopt a power-law path-loss model where the signal power decays at a rate $\text{dist}^{-\alpha}$, where dist is the transmission distance, and α is the path-loss exponent that is set as 4. With the above matrix transmission power of the vehicles and based on the path-loss model, the maximum distance of a D2D link is around 500 m. The cellular BS offers, by default, one channel to the VANET. The simulation runs for 500 s for each simulation parameter settings.

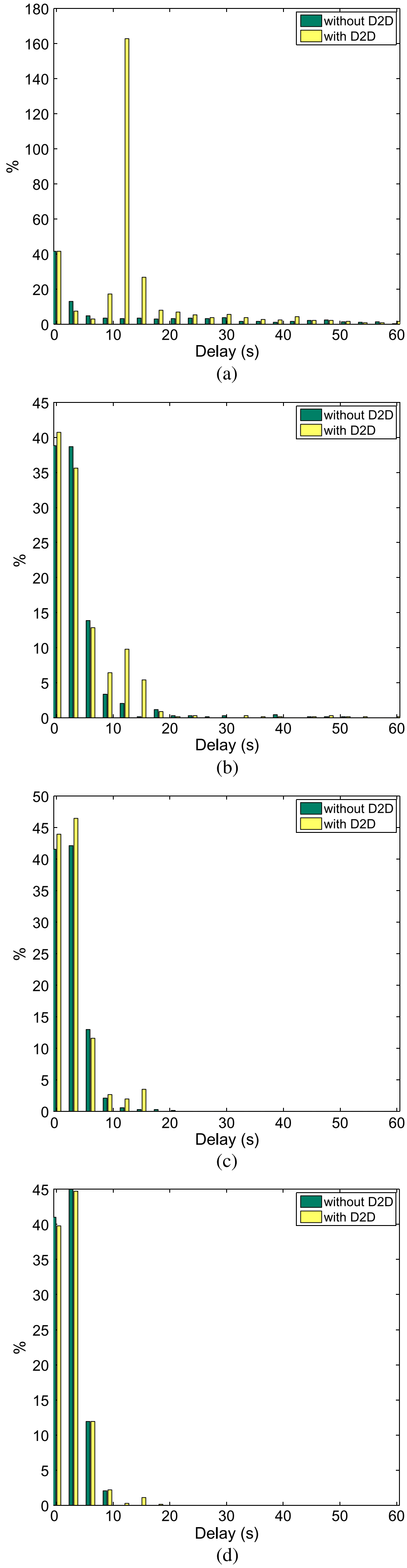
We first compare the performance between the scenarios with and without using our method under different numbers vehicles. As shown in Fig. 2, the performance is compared in terms of the (multihop) delay distributions of vehicle packets. The vertical axes mean the percentage of the successfully delivered packets (which successfully arrive their corresponding destinations before their expiration time) with delay falling within the range indicated by the horizontal axes, where, for each figure, the number of totally successfully delivered packets in the scenario without using D2D communications is set as 100%. The delay of each packet mainly consists of the channel access contention and data transmission time over IEEE 802.11p, the SAC time during which the packet is stored in a vehicle since it temporally cannot find a relay for the packet within the transmission range, and the transmission time over D2D links if applied. Thus, at any time, the delay of a packet reflects how much time it has experienced before reaching its destination.

As shown in Fig. 2(a), by introducing D2D communications and applying our method at the BS for D2D link selection, the number of successfully delivered packets increases. As discussed above in Section IV, establishing D2D links has two major benefits. First, it will reduce the CSMA/CA-induced contention delay. This type of delay is, however, low when the traffic load is light and the network density is low. By switching some vehicles from IEEE 802.11p mode to D2D mode, they will reduce the contention intensity (and further the contention time) of both their neighbors and those vehicles to which the transmitters of the D2D links are hidden. Second, it will reduce the SAC time. In sparse VANETs where the SAC time is large due to short communication range over IEEE 802.11p, D2D links with longer ranges can significantly improve the network connectivity and reduce the SAC time. As demonstrated in Fig. 2(a), the number of successfully delivered packets with delay around 10 s is increased significantly by D2D communications. In contrast, for those packets with long SAC delay, they may not be delivered before the expiration time if only 802.11p is used. Note that even with D2D links, the SAC delay may not be completely eliminated. This is because the D2D range is also limited; hence, the packets still have to traverse multihop routes to reach their destinations.

The other figures in Fig. 2 for scenarios with more vehicles show similar comparison results to those in Fig. 2(a). Basically, with more vehicles, the network connectivity is improved; hence, the SAC delay is reduced (which can be seen in the figures that the delay becomes decreasingly shorter). As a result, we can observe that the amount of delay reduction becomes less significant when the number of vehicles increases.

A. *Impact of Vehicles' Speeds*

The speeds of the vehicles have an impact on the network connectivity and hence on the SAC delay performance. To evaluate this impact, we conduct simulations by varying the range of the vehicles speed. We fix the minimum speed of each vehicle as 10 m/s while changing their maximum speed from 10 to 35 m/s. In the special case with the maximum speed at 10 m/s,



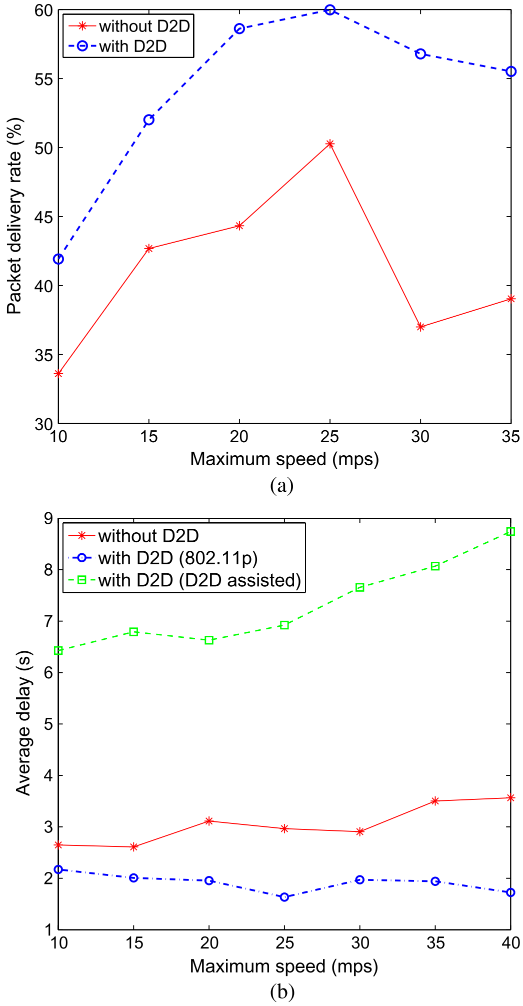
(a)

(b)

(c)

(d)

Fig. 2. Delay performance with different numbers of vehicles. (a) 100 vehicles. (b) 300 vehicles. (c) 500 vehicles. (d) 700 vehicles.



(a)

(b)

Fig. 3. Impact of vehicles' speeds. (a) Multihop packet delivery rate. (b) Average delay.

the mutual distances among the vehicles are not changing, which means that the network can be viewed as a static one. As shown in Fig. 3, as the maximum speed limit increases from 10 to 25 m/s, the network changes from static to dynamic, such that previously unreachable vehicles may become reachable but at the cost of SAC delay. In this sense, the connectivity is improved, and the successful delivery rate is increased, as shown in Fig. 3(a) for both scenarios. However, due to the SAC delay, the average delay of the packets increases in the scenario without using D2D communications, as shown in Fig. 3(b). In Fig. 3(b), for the scenario with D2D, the packet delay is divided into two cases: one (marked as (802.11p) in the figure) accounts for the delay of packets that are delivered to their destinations without the help of D2D links, and the other (marked as (D2D assisted) in the figure) accounts for the delay of packets for which the routes contains some D2D links. As shown, when the maximum speed limit increases, more packets with longer SAC delay can be successfully delivered, which, in turn, increases the delay of the D2D assisted case. Moreover, since more packets are transmitted through D2D links, the contention intensity is reduced for 802.11p transmission; thus, the delay of the 802.11p case slightly reduced.

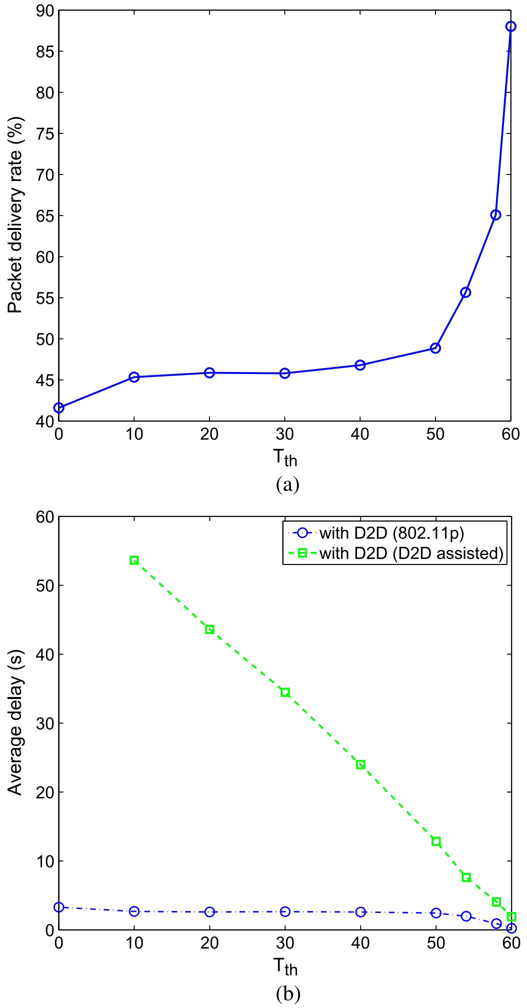


Fig. 4. Impact of the threshold T_{th}. (a) Multihop packet delivery rate. (b) Average delay.

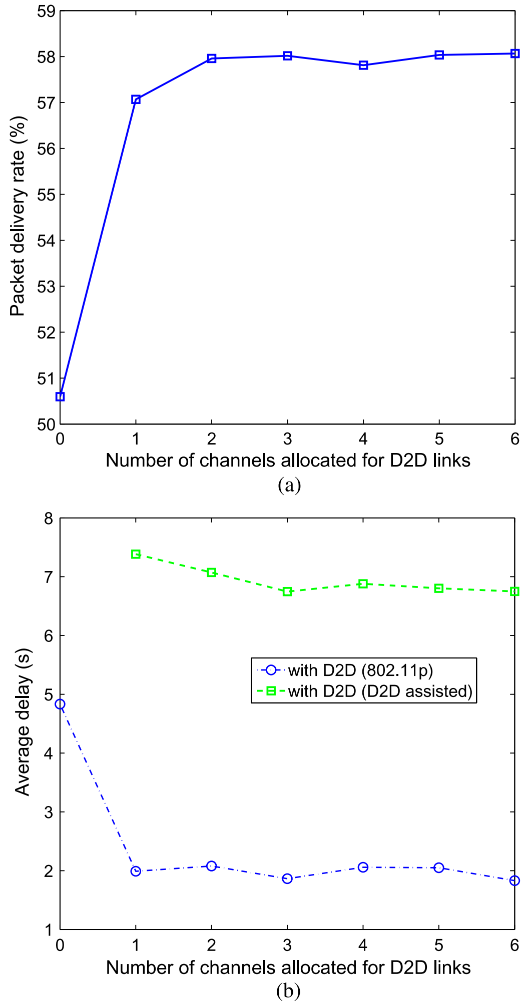


Fig. 5. Impact of the number of channels. (a) Multihop packet delivery rate. (b) Average delay.

When the maximum speed limit increases further, a vehicle with low speed may be not able to catch its packets' destination if the latter has high speed. In this case, the network connectivity becomes worse, and the successful delivery rate drops, as shown in Fig. 3(b). As a result, the delay in both 802.11p- and D2D-assisted cases increases to some extent.

B. Impact of the Threshold T_{th}

For fair comparison of the performance, we run our algorithm with different threshold T_{th} over the same VANET scenario, i.e., for any vehicle, its location is fixed at any particular time. The simulation results in Fig. 4 show that both the successful delivery rate and the delay (in both 802.11p- and D2D-assisted cases) are improved as the threshold increases. This is in consistent with the intuition that the number of vehicles that send requests to the cellular BS for establishing D2D links is likely to become lager as the threshold becomes higher. In particular, when $T_{\mathrm{th}} = 60$, all vehicles can request the BS for using D2D communications. Otherwise, $T_{\mathrm{th}} = 0$ means that no requests will be sent; thus, the network will behave the same as the scenario without D2D.

C. Impact of the Number of Channels

We also conducted simulations to evaluate the impact of the number of cellular channels allocated for D2D links on the performance. As shown in Fig. 5(a), there is noticeable improvement of the number of successfully delivered packets by our method when one cellular channel is used compared that only IEEE 802.11p is used. With more channels, the amount of successfully delivered packets slightly increases. This matches our intuition because more D2D links can be established, which will result in more delay reduction; however, the improvement becomes less significant since the number of vehicles that send D2D requests is limited. Similarly, as shown in Fig. 5(b), both delay of the 802.11p case and the delay of the D2D-assisted case are reduced as the number of cellular channels increases.

VII. CONCLUSION

In this paper, we have proposed a hybrid system where D2D communications are introduced to IEEE 802.11p-based VANETs to improve the network delay performance. We developed a new algorithm for the cellular BSs to select the optimal set of D2D links overlaying cellular communications to minimize the total delay and derived a theoretical performance lower bound for the algorithm. Simulation results demonstrate that the proposed algorithm can improve the delay performance as the number of packets that successfully arrive their destinations through multihop routes before their expiration time is increased. Moreover, the performance improvement increases as more dedicated channels are allocated by the BSs or larger threshold $T_{\rm th}$ is applied. In addition, it is demonstrated that a moderate increase in the vehicles' speed can improve the network connectivity and, hence, improve delay performance, but a large speed increase may cause long SAC delay and, thus, increase the delay.

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