VANET aided D2D Discovery: Delay Analysis and Performance

Hussein Chour*, Youssef Nasser*, Hassan Artail*, Alaa Kachouh*, Ahmed Al-Dubai†
(*) American University of Beirut, Faculty of Engineering and Architecture, ECE Department, Lebanon
(†) School of Computing, Edinburgh Napier University, UK

***Abstract*— The proposed solutions in the literature for integrating Device-to-Device (D2D) communication in cellular networks require added functionalities and consume valuable network resources, mainly in the discovery process. Unlike existing solutions, this paper mitigates the requirement of additional resources in the LTE-A network. This is achieved by proposing to offload a portion of the discovery traffic and processing of D2D communications that involve vehicular users (drivers and passengers) into Vehicular Ad-hoc Networks (VANETs) by using the inherent knowledge of the Road Side Units (RSUs) about users in their coverage areas. In addition, the paper develops an analytical model to analyze the duration of peer discovery in highway scenarios. The results are validated through simulation experiments using both the Network Simulator NS3 and Matlab. The analytical and numerical results demonstrate the effectiveness of the proposed scheme, and show that a low discovery latency is obtained**

Index Terms*—VANET, device-to-device, D2D discovery, offloading, RSU, OBU

I. INTRODUCTION

The transportation and communication sectors have become an essential part of our lives, and according to [1], the number of automobiles in the world surpassed already one billion in 2011 and the number of mobile subscriptions has exceeded the world's population [2]. With the pervasiveness of these technologies, several related problems have risen. This includes traffic collision, transportation problems and huge mobile data traffic on the cellular networks. Moreover, certain drivers' habits, such as reckless driving and drunk driving, and the emerging users' demands, such as online gaming and videos streaming, make the aforementioned problems more severe. Thus, the flag has been raised to find solutions to increase the cellular network capacity, and make transportation safer. Recently, two innovative ideas and promising concepts have been introduced to accommodate the traffic collision problem and the network capacity shortage, namely Vehicular Ad hoc Networks (VANETs) and Device-to-Device (D2D) communication. Both VANETs and D2D provide cost effective solutions that can promote road safety and reduce the economic loss due to vehicular crashes and the cost per bit in the cellular link. A VANET enables vehicles to communicate with each other and with other infrastructure, thus providing road safety services. Besides the safety applications of VANETs, non-safety applications were also proposed. On the other hand, D2D communication enables the cellular network to offload traffic to devices in proximity by allowing two nearby devices to communicate without or with limited base station participation. Cellular network operators do not allow signaling between the users, and hence, a discovery phase that involves the core network is needed before two UEs can set up a D2D link and start direct communication. Accordingly, D2D communication is divided into two phases: D2D discovery, and D2D communication. The former is an introduction to the communication phase in which a user discovers the proximity of other Proximity-Based Services (ProSe) users. In general, there are two approaches for D2D discovery, known as direct discovery and network assisted discovery. The direct discovery method has been investigated in different out-of-band wireless technologies e.g. Wi-Fi direct, Bluetooth, and ZigBee. However, the unlicensed band systems do not guarantee good Quality of Service (QoS) due to the stochastic behavior of these bands. Moreover, the transmission power is quite low in such systems, and so, the coverage of the devices and the number of neighbors they can discover are limited [3]. The unlicensed band problems motivated researchers to design direct discovery methods based on the cellular licensed band [4]. A new communication system that creates awareness in smart devices is introduced in [5], and is named "FlashLinQ". It operates basically in the licensed band to bypass the stochastic characteristics of the ISM bands, allowing devices to sense each other and discover each other's range. The proposed design in [5] keeps the involvement of the network at a minimum, mainly to provide synchronization signals to devices. This system was the base for a new technology, named LTE-Direct [6], and was integrated in the 3GPP standard studying the architecture enhancements to support Prose services [7].

The direct discovery scheme is implemented through general beaconing signals and sophisticated scanning, which makes it time- and energy-consuming [3]. Moreover, the security procedures often involve higher layers and/or interactions with the end user [3]. Therefore, with a little network participation, the aforementioned problems can be tackled. Hence, network-assisted discovery attracted both the researchers and the standardization bodies [8]-[11]. In network-assisted discovery [34], users rely on the network to detect and identify each other. The User Equipment (UE) informs the Base Station (BS) about its desire to initiate a D2D link by sending a request signal, prompting the BS to order some message exchanges with the devices to acquire identity and information about the link. This approach though requires the network to mediate in the

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*H. Chour, Y. Nasser, H. Artail and A. Kachouh are with the Department of Electrical and Computer Engineering at the American University of Beirut, Bliss Street, Beirut, Lebanon. E-mails: hic03@mail.aub.edu; {yn10, hartail}@aub.edu.lb; atk07@mail.aub.edu

†A. Al-Dubai is with the School of Computing at the Edinburgh Napier University, 10 Colinton road, Edinburgh. E-mail: A.Al-Dubai@napier.ac.uk

discovery process to recognize D2D candidates, coordinate time and frequency allocations by sending/scanning beacon signals, and provide identity information [3][11]. The proposed implementations thus cost valuable network resources, and could overload the cellular infrastructure when trying to discover D2D candidates.

This paper mitigates the network load issue discussed above by offloading part of the discovery traffic and processing to the VANETs for D2D sessions that involve VANET users, i.e., drivers and passengers who are currently riding in cars. Hence, our system only applies to VANET users, but given the significant number of cellular users who are in cars throughout the day, and are increasingly using their mobile devices while on the road, a major portion of the D2D discovery signaling traffic and in-network processing can be shifted outside the network, and hence, improve its scalability. Obviously, this portion varies from time to time and from one place to another, depending on users driving habits, type of work (e.g., taxi drivers), average driving distances (e.g., from home to work), and so on.

A preliminary version of our work, which we called FREDDY (FRamework for vanEt aided D2D discoverY) was published in [12], and is being significantly extended in this work, as we shall explain. Specifically, our work in [12] presented the basic design of the proposed system and described a delay analysis of the discovery protocol for a general highway scenario with full RSU deployment. On the other hand, in this work, the mathematical framework of the D2D discovery in [12] is developed to provide advanced analysis and performance results. The proposed framework is applicable to any VANET application that relies on the Road Side Units (RSUs) network to perform its tasks, like content downloading. As part of our work, we propose a new routing approach based on the well-known carry and forward routing protocol [35] which helps in avoiding the broadcast storm problem. The analytical and experimental results, which we present later, demonstrate the effectiveness of the proposed protocol, and illustrate that low discovery latency can be attained.

The key contributions of this study are summarized as follows:

- A novel D2D discovery technique, based on the VANET network. To the best of our knowledge, there is no existing work that implements D2D discovery using VANET networks for offloading purposes.
- A new analytical model that characterizes the end to end delay for any VANET application in a highway scenario. This model could be used for evaluating car distribution and traffic delays in multi-lane networks.
- A new routing and clustering algorithms for cars driving on multi-lane highways. It is shown via simulations how the broadcast storm is avoided through the routing mechanism that we adopt.
- Validating the results in real environments using simulations.

The remainder of this paper is organized as follows. In Section II, we discuss the related work. Section III shows the proposed framework, while in Section IV and V, we develop a comprehensive mathematical framework to study the delay of discovery over VANETs in a highway scenario. Simulation results and a discussion are presented in Section VI. Finally, we conclude in Section VII.

II. RELATED WORK

This study relates to cellular data offloading through VANETs, as well as to connectivity analysis in VANET. Below, we review the studies that are most relevant to our contribution, thus highlighting the novelty of our approach.

For cellular data offloading through VANET, the majority of works have focused on content downloading and dissemination in mobile network [13] [14] [15]. The authors in [13] analysed the performance of offloading the cellular traffic to vehicle ad hoc network, and aimed to maximize the amount of data that can be offloaded by taking into account the ability of RSUs to predict the mobility of users, prefetching data from the Internet, and scheduling data for transmission [37]. In their study, the authors proposed a cost function by considering constraints related to channel access and flow conservation. Similar to [13], the authors of [14] studied the ability of offloading the data content via VANETs, based on an optimization function, taking into account several constraints like the connectivity between the nodes, channel load, and the RSU features. As compared to [13], the work in [14] considers the effect of the data volume and duration of channel occupation on the channel contention, whereas the work in [15] focuses on making the access of the Web in mobile networks efficient by using prefetching as a technique. On the other hand, our work considers a specific application and analyses it thoroughly, namely the leveraging of the inherent knowledge of the VANET (specifically the RSU network) about the locations of cars (and therefore the mobile users inside them) and using this knowledge to effectively perform D2D discovery for users in transportation vehicles.

The second part of our review concerns connectivity analysis in VANETs. Many works investigated this subject through simulation and/or analytical evaluation [16] [17] [18]. The authors in [16] developed an analytical model which describes the behavior of a VANET in low density scenarios without the existence of fixed nodes. The work in [17] investigated a hybrid vehicular communication protocol relying on both vehicles and RSUs. A more comprehensive study about the benefits of RSUs was given in [18], in which a mathematical model was developed for the VANET connectivity in a highway scenario, considering both connected and disconnected RSUs. The results showed that the interconnected RSUs can reduce the end to end delay by several orders of magnitude, which in turn shows the significant role of RSUs in VANETs, as also illustrated in [36][38][39].

The physical distribution of RSUs in urban areas is also an important design consideration for communication optimization for VANET users in real-life scenarios. The reader may refer to [19] [20] for more information on the placement of RSUs for Internet access, on RSU deployment at popular junctions [21], and on the determination of critical network points [22] [23] [24]. Network connectivity for Vehicular to Infrastructure (V2I) communication has also been an important research area [25] [26], where the tradeoffs between RSU density/placement and overall VANET connectivity can be determined. In [38]and [39] RSU based routing have been proposed.

Of more relevance to our work are the studies in [16] and [18], which also investigated the delay performance of VANETs in highway scenarios. However, in both works, the authors assumed a single-lane road where all vehicles travel at a fixed speed (the average speed of the road). Thus, the derived models do not comprehensively model the latency in the more realistic multiple Lane highway scenarios, especially when the traffic volume increases. To that end, this paper adopts a more realistic highway mobility model in which the vehicles on each lane move with the maximum allowed speed of that lane. We mention another aspect having to do with the fact that the above discussed works do not address the broadcast storm problem associated with the carry and forward routing protocol, whereas our work does.

III. PROPOSED FRAMEWORK

A. System environment

As depicted in Fig. 1, we consider a wireless access in vehicular environments (WAVE) system composed of mobile nodes (Vehicles carrying UEs) and RSUs nodes, deployed over a topology of roads, assuming to be within the eNodeB transmission coverage. Vehicles may communicate with other vehicles and with the RSUs through the On-Board unit (OBU) implemented within each vehicle. The driver and passengers inside the vehicles possess smartphones which can communicate with the vehicles' OBUs through a proper interface. Consequently, all the users inside the cars can execute a set of VANET applications that run in the application unit (AU) of each node (vehicle). We assume that each RSU has two WAVE interfaces, while the vehicle has only one such interface. According to the Dedicated Short Range Communication (DSRC) protocol, which is part of the WAVE set of protocol, a vehicle has to always alternate between the control channel (CCH) and one of the six service channels (SCHs) so they can use both safety and non-safety application, respectively. Moreover, the D2D discovery service can only be performed during the SCH interval, as detailed in the next subsection. We refer the reader to the previous work in [12] for more information about the architecture of our proposed framework, and more specifically details on the necessary software and hardware for communications with the UE inside the vehicle.

B. Proposed discovery protocol

The proposed algorithm consists of two phases: *initialization phase* and *transaction phase*. The initialization phase (Fig.2) makes all the surrounding nodes aware of all the users in their vicinities while, the transaction phase (Fig.3) answers the users' discovery requests.

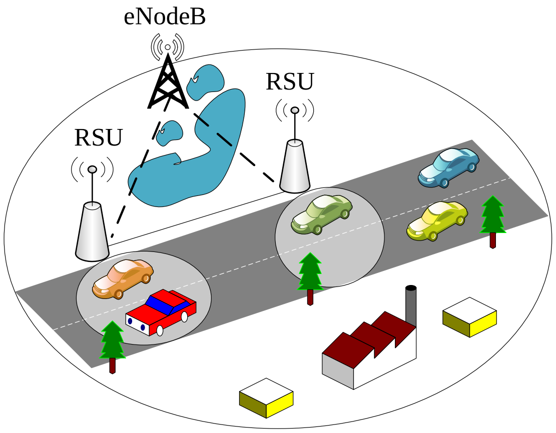

Fig. 1. Proposed system model

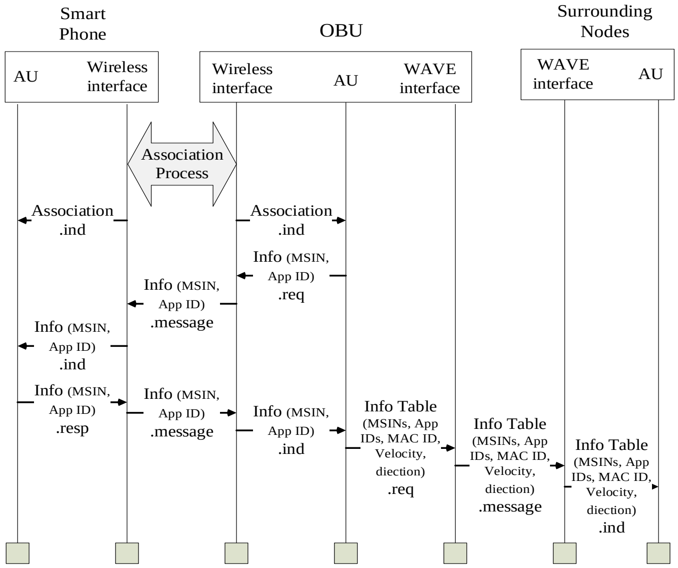

Fig. 2. Discovery algorithm- Initialization phase

As can be seen in Fig. 2, the first step in our algorithm is to attach to the OBU through the association process, one of the MAC layer functionalities as proposed in [29]. In case of successful attachment, the AU of each node will receive an association notification. In order to efficiently use the VANET capabilities, the AUs in the OBU request some info from their counterparts in the user's smart phone (described in details in [12]). Specifically, this concerns the Mobile Subscriber Identification Numbers (MSIN) or the ProSe ID (3GPP terminology) and the app id of the attached user. The collected MSINs will be appended to the OBU MAC address and vehicle's mobility information (position, velocity, acceleration and direction), thus forming an info table. This table will be sent periodically on the CCH to the surrounding nodes by means of the wave interface. When a node receives an info table, it saves it in its own database. With this mechanism, all nodes will be aware of all the users in their vicinities. Here, it is worth noting that the majority of the applications in VANET (e.g., SAE J2735 [30]) require periodic update of the basic safety information including position, velocity, acceleration, and direction. Hence, the initialization step of our protocol does not add a new load to the VANET. Instead, it uses the VANET architecture in a proper way to monitor the surrounding nodes.

A peer discovery process starts whenever an OBU receives discovery requests from a UE's smartphone (Fig. 3). The OBU in this case searches in its database for the discoveree ID. If no match occurs, it forwards the message to the RSU in its range, which in turn looks for the requested ID in its database. If no match happens it seeks help from the neighboring RSUs. Whenever a match occurs, either at the OBU or on the RSU side, the related node has to calculate the expected time, using learning techniques [31], during which the callee will remain in proximity of the caller, and informs the eNodeB about this information by means of the LTE-A interface.

When proximity is guaranteed, the eNodeB allocates some resources and informs the discoveree and the discoverer about it via the system information block (SIB) to enable the related application to proceed and initiate a direct communication link. When no proximity is guaranteed or no match occurs, the concerned communication application prompts the UE to switch to a regular cellular call after a given timeout. Proximity Guaranteed means that both discoverer and discoveree will stay in proximity of each other for a certain amount of time (i.e. the expected time). This is to ensure that both users can benefit from D2D services and to avoid allocating resources to users that will not be able to use them.

C. *Routing*

In our model, the RSUs are uniformly distributed on the road. Thus, depending on the vehicle's current location, it may not be able to directly send the discovery request to the RSUs backbone. In such situations, the carry and forward routing protocol can prove helpful to deliver the message [16] [17] [18] to the desired destination. In this protocol, the message is sent to an intermediate node where it is kept and sent at a later time to the final destination, or to another intermediate node. In the literature most of the works adopt the broadcast approach to send the message to the intermediate nodes [16] [17] [18], but as is well known in this field of mobile ad hoc networking, this could lead in the high traffic volume situations to a serious problem, known as the data storm problem, since the message is sent to all nodes in vicinity which in turn will carry the sent message and forward it to their neighboring nodes until the message reaches the destination.

To avoid this problem and mitigate the load on the VANET we adopt a simple but yet effective strategy. The vehicle unicasts the packet to the vehicles having the lowest travel time to the front and back RSUs. The travel times are the times needed to reach those RSUs. Note that, each node knows all the info about its neighbors and the RSUs locations can be easily retrieved from the digital map available in the vehicle's OBU.

Accordingly, the intermittent RSU coverage nature on the road adds delay to the discovery process by forcing the vehicles to queue the discovery message until they are within an RSU's range. Moreover, when a number of vehicles enter the RSU range at the same time, a contention process will take place, which in turn adds another delay to the discovery mechanism. Finally, the node that gets access to the channel will wait for the RSU to send it back the discovery answer. Therefore, the end-to-end delay can be modeled as the summation of queuing, contention, and answer delay. The next section derives analytical expressions for the aforementioned delay components.

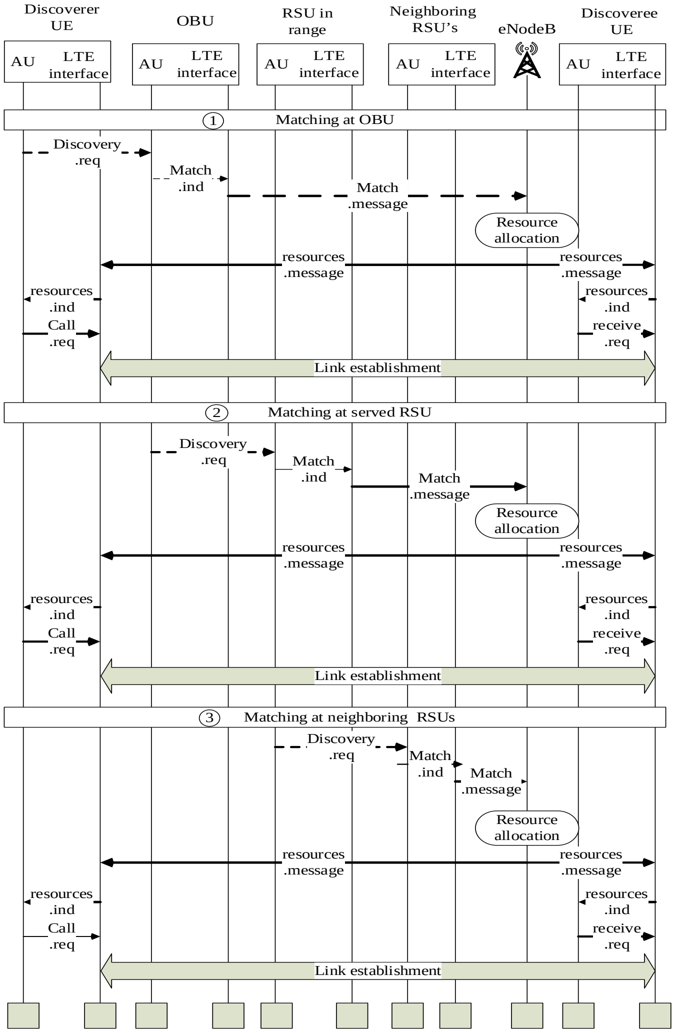

Fig. 3. Peer discovery process

IV. QUEUING DELAY

The queuing delay is the time needed for a disconnected vehicle (i.e., outside the RSUs range) to enter the range of an RSU. We consider a highway, which consists of multiple lanes, where each lane has a different speed limit. The inter arrival time on a lane j is assumed to be exponentially distributed with traffic density λ_j [16][17][18]. We also consider a low to medium traffic flow, T_{f_j} on each lane *j*, without loss of generality, as given in [16][18]. Thus, the inter vehicle spacing *S* on lane *j* will be exponentially distributed with parameter $\lambda_{s_j} = \lambda_j / v_j$, where v_j is the speed level on this lane. Hence, clusters will be formed on each lane when two or more vehicles are in the same range. Here, we aim first to extend the work in [16] to support multiple lanes traffic by mathematically describing the key characteristics of clusters formed on each lane in VANETs, including the probability of being the leading vehicle in a cluster, probability of being the last vehicle in a cluster, the probability density function (PDF) of intra-cluster spacing and inter-cluster spacing, average cluster size, and average cluster length. Then we derive the average queuing time to enter an RSU's range on a multiple lanes highway. It is worth indicating that in this work, one directional highway scenario is considered to shed the light on the importance of neighboring lanes with different speeds in reducing the routing delay. Moreover, this work can be easily generalized for bidirectional highway.

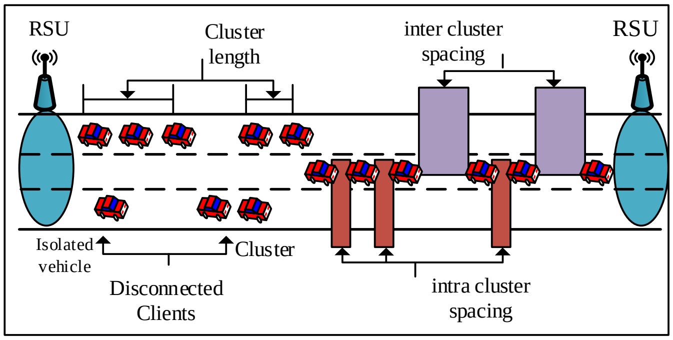

Fig. 4. A multiple lanes highway scenario depicting several characteristics of VANET

A. PDF of intra-cluster and inter-cluster spacing

Cluster is formed when at least two vehicles are in the communication range (R) of each other. Therefore, the distance between any two vehicles belonging to the same cluster should be less than R. Moreover, the inter-vehicle spacing (S) is exponentially distributed. Thus, the PDF of intra cluster spacing can be written as follows:

$$f_{S_{j,intra}}\left(s_{j,intra}\right) = Pr\left[S_j | S_j \leq R\right] = \frac{\lambda_{s_j} e^{-\lambda_{s_j} s_{j,intra}}}{1 - e^{-\lambda_{s_j} R}} \tag{1}$$

Similarly, the distance between the last vehicle in the leading cluster and the first vehicle in the following cluster, i.e. the inter cluster spacing, should be greater than R. Given that (S) is exponentially distributed, the PDF of the inter-cluster spacing $S_{j,inter}$ can be expressed as follows:

$$\begin{aligned} f_{S_{j,inter}}\left(s_{j,inter}\right) &= Pr\left[S_j | S_j > R\right] \\ &= \lambda_{s_j} e^{-\lambda_{s_j}\left(s_{j,inter} - R\right)} \end{aligned} \tag{2}$$

B. Probability of being the leading and the last vehicle in a cluster on lane j $\left(P_{L_j}\right)$

A vehicle seeking a service from the RSU can generate the related message and distribute it within the cluster to minimize the delay time to reach the RSU. However, the generated message cannot be spread across the cluster border, i.e., the leading and the last vehicles in the cluster, until passing-by-vehicles become within the range of the boundary vehicles. Thus, it is important to analyze the probability of being the leading and the last vehicle in a cluster. We define P_L as the probability that there are no frontal vehicles and no following vehicles within the transmission range (R) of the leading and the last vehicle, respectively. Hence, the probability of being the leading vehicle or the last vehicle in a cluster on lane j (P_{L_j}) is simply given by:

$$\begin{aligned} P_{L_j} &= \Pr\left\{S_j > R\right\} \\ &= 1 - \mathrm{F}_{\mathrm{S_j}}\left(\mathrm{s_j}\right) = e^{-\lambda_{s_j} R} \end{aligned} \tag{3}$$

where $F_{S_j}\left(s_j\right)$ is the cumulative distribution function (CDF) of the inter vehicle spacing on lane j. The term P_{L_j} is the metric used to calculate many other important metrics, such as cluster length and average end to end delay.

C. Cluster length on a lane

The cluster length is the length between the first vehicle and the last vehicle in a cluster (Fig. 4), denoted C_{L_j}. It is a function of the number of cluster members (N) and $S_{j,intra}$. It is given by:

$$C_{L_j} = \sum_{k=1}^{n-1} \left(S_{j,intra}\right)_k \tag{4}$$

where n is the number of cluster members. Similar to [16], its probability mass function (PMF) is given by:

$$f_N\left(n\right) = P_{L_j}\left(1 - P_{L_j}\right)^{n-1} \tag{5}$$

Using the law of total probability (LTP), the PDF of C_{L_j} is:

$$f_{C_{L_j}}\left(C_{L_j}\right) = \begin{cases} P_{L_j} & n = \\ \displaystyle\sum_{i \in range\ of\ n} P(n = i)\ f_{C_{L_j}}\left(C_{L_j} | n = i\right) & n > \end{cases} \tag{6}$$

The cluster length by definition (4) is the summation of the intra cluster distances. Accordingly, the PDF of the cluster length on each lane $\left(\mathrm{i.e}\ \mathrm{f}_{C_{L_j}}\left(C_{L_j} | n = i\right) \doteq f_{S_{j,intra_1} + S_{j,intra_2} + S_{j,intra_3} + \cdots + S_{j,intra_{i-1}}}\left(\sum_{k=1}^{i-1}\left(S_{j,intra}\right)_k\right)\right)$ Is the PDF of the summation of independent exponential distribution with the same density. The PDF of such summation is given in [41]. Therefore, (6) can be written as:

$$f_{C_{L_j}}\left(C_{L_j}\right) = \begin{cases} P_{L_j} & n = 1 \\ \displaystyle\sum_{i \in range\ of\ n} \left[\begin{matrix} P(n = i) \times \left(1 - e^{-\lambda_s R}\right)^{-(i-1)} \\ \times \left(\dfrac{\lambda_{s_j}^{i-1}\ s_{i,intra}^{i-2}\ e^{-\lambda_{s_j} s_{j,intra}}}{(i - 2)!}\right) \end{matrix}\right] & n > 1 \end{cases} \tag{7}$$

Through numerical interpolation and Monte Carlo fitting, $f_{C_{L_j}}\left(C_{L_j}\right)$ could be approximated by:

$$\mathrm{f}_{C_{L_j}}\left(C_{L_j}\right) = \begin{cases} P_{L_j} & C_{L_j} = 0 \\ a\ e^{-b C_{L_j}} & C_{L_j} > 0 \end{cases} \tag{8}$$

where $a = \left(1 - P_{L_j}\right)^2 \times \frac{P_{L_j} \lambda_{s_j}}{1 - P_{L_j}(1 + R\lambda_s)}$ and $b = \frac{a}{1 - P_{L_j}}$

Note that the coefficient of this approximation fits with a confidence ratio equal to 0.9967. A comparison between (7) and (8) was given in Appendix B. Moreover, this approximation is very simple to be implemented in the analysis of the delay results.

The average cluster length on lane j can easily be calculated from (8). It is given by:

$$\mathrm{E}\left[C_{L_j}\right] = \left(\frac{1}{P_{L_j}} - 1\right)\left(\frac{1}{\lambda_{\mathrm{s_i}}} - \frac{\mathrm{R} e^{-\lambda_{\mathrm{s_i}} \mathrm{R}}}{1 - e^{-\lambda_{\mathrm{s_i}} \mathrm{R}}}\right) \tag{9}$$

The PDF of the cluster length will be used to derive the average queuing delay on a road with interconnected RSUs and disconnected coverage.

D. Delay model to meet a RSU on lane j

In a highway where RSUs are uniformly distributed with separation distance d_{RSU}, and where each RSU has a radio range R_I, a client vehicle cannot benefit from the RSU services until it becomes within its range, i.e., connected to the RSU network. Intuitively, to minimize the time needed to reach the RSU, the client vehicle will try to contact the RSU through other vehicles (multi-hop communication). On the other hand, the vehicle that is travelling on lane *j* cannot relay its message to a neighboring lane's vehicle until it enters into its range. Thus, we are interested in characterizing the queuing delay time on lane *j*. Here, we observe that a client vehicle on lane *j* can be either part of a cluster (clustered client) or not (isolated client). This will lead to different queuing delay values. The following cases are based on this observation:

Definition 1: A client is considered connected if it is in range of an RSU or it is part of a cluster with at least one member in range of an RSU. In such case, the average time to meet a RSU is equal to zero (assuming an ideal routing protocol).

Definition 2: A client is considered disconnected if it is located in the uncovered area of the road, i.e. it must be located in the area with a length of $d_{RSU} - 2R_I$.

Moreover, it is logical to assume that on average the vehicle will be located in the center of this region, *i.e. at the midpoint between two RSUs. This assumption is verified for any symmetric distribution of the cars with respect to the inter-RSU distance. This is surely not the practical case however it is widely accepted by the research community* [16] [18]. Given that the isolated client is disconnected, it follows that the average time to meet a RSU on lane *j* is given by the time to traverse half the distance with no RSU coverage:

$$\mathrm{E}\left[T_{I,j}|v_d\right] = \frac{d_{RSU} - 2R_I}{2v_j} \tag{10}$$

where v_j is the traveling speed on lane *j*. On the other hand, the probability that an isolated vehicle is disconnected from the RSU backbone ($Pr\ [v_d]$), at any given point in time, is equal to the proportion of the highway that is not covered by the RSUs. Accordingly, Pr $[v_d]$ can be written as:

$$\mathrm{Pr}\ [v_d] = \frac{d_{RSU} - 2R_I}{d_{RSU}} \tag{11}$$

As a result, the average time to meet a RSU for an isolated vehicle that is traveling on lane *j* is:

$$\mathrm{E}\left[T_{I,\mathrm{j}}\right] = \mathrm{E}\left[T_{V,j}|\mathrm{v_d}\right] \times \ \mathrm{Pr}\ [v_\mathrm{d}] = \frac{(d_{RSU} - 2R_I)^2}{2\ d_{RSU}\ v_j} \tag{12}$$

Definition 3: a cluster of vehicles is considered disconnected when none of its members is in range of an RSU. Accordingly, the edge vehicles of a disconnected cluster must be in the uncovered region $[R_I; d_{RSU} - R_I]$ (considering the zero point being the center of the RSU's coverage area), and the length of a disconnected cluster has to be less than the distance of the uncovered part of the road (i.e. $C_{L_j} < d_{\mathrm{RSU}} - 2R_\mathrm{I}$). Therefore, by taking the center of the cluster as reference, it follows that the cluster's center must be in a region of length $\left((d_{RSU} - 2R_I) - E\left[C_{L_j}|C_{L_j} < d_{RSU} - 2R_I\right]\right)$. Here, $E\left[C_{L_j}|C_{L_j} < d_{RSU} - 2R_I\right]$ is the expected length of a disconnected cluster and is given by Lemma 2 in the Appendix. Hence, the probability of having the edge vehicles of a cluster on lane *j* in the uncovered region, $P\left[C_{d_j}\right]$, is given by:

$$P\left[C_{d_j}\right] = \frac{(d_{RSU} - 2R_I) - E\left[C_{L_j}|C_{L_j} < d_{RSU} - 2R_I\right]}{d_{RSU}} \tag{13}$$

Statistically speaking, it is correct to assume that the center of the cluster is in the middle of the uncovered region. Thus, the mean delay time to reach an RSU for a disconnected clustered client travelling on lane *j* can be expressed as follows:

$$\begin{aligned} &E\left[T_{C,j}|C_{d_j} \cap \left(C_{L_j} < d_{RSU} - 2R_I\right)\right] \\ &= \frac{(d_{RSU} - 2R_I) - E\left[C_{L_j}|C_{L_j} < d_{RSU} - 2R_I\right]}{2\ v_j} \end{aligned} \tag{14}$$

Hence, the average delay for a disconnected cluster on lane *j* is:

$$\begin{aligned} &E\left[T_{C,j}\right] \\ &= E\left[T_{C,j}|C_{d_j} \cap \left(C_{L_j} < d_{RSU} - 2R_I\right)\right] \times \ P\left[C_{d\_}\right] \\ &\qquad \times P\left[C_{L_j} < d_{RSU} - 2R_I\right] \\ &= \frac{\left((d_{RSU} - 2R_I) - E\left[C_{L_j}|C_{L_j} < d_{RSU} - 2R_I\right]\right)^2}{2\ v_j\ d_{RSU}} \\ &\qquad \times \left(1 - \frac{1 - P_{L_j}}{e^{b(d_{RSU} - 2R_I)}}\right) \end{aligned} \tag{15}$$

Finally, the average delay for each lane will be as follows:

$$\begin{aligned} \mathrm{E}\left[T_j\right] &= \mathrm{E}\left[T_{V,j}\right].\mathrm{P}[n = 1]\ \ +\ \mathrm{E}\left[T_{C,j}\right].\mathrm{P}[n > 1] \\ &= \frac{1}{2v_j\ \mathrm{d_{RSU}}}\left(P_{L_j}.A + \left(1 - P_{L_j}\right)B.C\right) \\ \text{with } A &= (\mathrm{d}_{\mathrm{RSU}_I} - 2R_I)^2 \\ B &= \left((\mathrm{d_{RSU}} - 2\mathrm{R_I}) - \mathrm{E}[C_L|C_L < \mathrm{d_{RSU}} - 2\mathrm{R_I}]\right)^2 \\ C &= \left(1 - \frac{1 - P_{L_j}}{e^{b(\mathrm{d_{RSU}} - 2R_I)}}\right) \end{aligned} \tag{16}$$

where $\mathrm{P}[n = 1]$ and $\mathrm{P}[n > 1]$ are the probability of having an isolated vehicle and clustered vehicle, respectively.

E. Delay model for reaching the RSU

This section provides the average delay of using the services provided by the RSU network while driving on a multiple lanes highway. For a message transmission requiring one or more gaps to be traversed, the need for relaying through cars on neighboring lanes occurs when the edge cars in a cluster on lane *j* have received a message and are unable to deliver the message to an RSU. As shown in Fig. 5, using the front-most or rear-most vehicle as a point of reference, two main scenarios can be identified:

- **Worst case scenario (WCS):** it occurs when there is no neighboring vehicle in range of the client vehicle. Thus the client node must wait for one relaying vehicle.

- **Best case scenario (BCS)**: this is when the client vehicle is in range of vehicles capable of receiving and relaying the message.

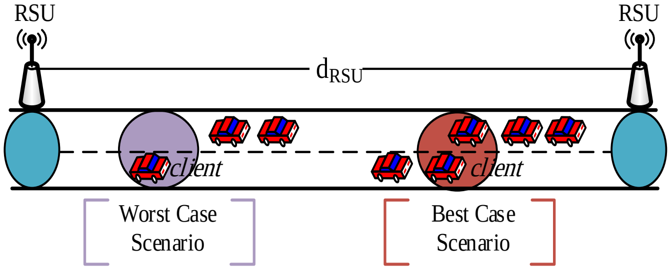

Fig. 5. Examples of the best case scenario and the worst case scenario

Since the average delay for a connected client is zero, we can derive the analytical models that describe the road level delay time in each of these cases assuming the client, i.e. a vehicle seeking a service from the RSU network, is to be disconnected from the RSU backbone.

Case 1: Worst case scenario (WCS)

WCS occurs when *a client* cannot immediately relay the message to a cluster with a higher speed. The time needed to contact an RSU for this case is simply the summation of the following two delay components:

- **Temporal delay:** The time until the client comes in range with a relay vehicle travelling on a neighboring lane.
- **Spatial delay:** The time needed for a relay vehicle to meet the *RSU* network. Here, to have non-zero value the relay vehicle must be disconnected from the RSU network.

Here we observe that WCS could involve two different subcases: i) the client is an isolated vehicle, and ii) the client belongs to a disconnected cluster.

Isolated client: In this case, the client has no relay within its range. The probability of this scenario, $P_{i,r_{11}}$, is given in the Appendix by Lemma 3. To calculate the expected time to meet a relay cluster on a neighboring lane we assume the client on lane *j* is in the middle of an inter cluster gap on lane *i* $\left(S_{i,inter}\right)$. Statistically speaking this is a correct assumption and it is well used in the literature [16] [17] [18]. Hence, $\left(S_{i,inter}\right)$ should at least be greater than *2R*, and the expected temporal delay for this case is given by:

$$E\left[T_{i,temp_{11}}\right] = \frac{0.5\,E\left[S_{i,inter}|S_{i,inter} > 2R\right] - R}{(v_j + v_i)} = \frac{1}{\lambda_{i,s}\,(v_j + v_i)} \qquad (17)$$

The spatial delay is simply equal to the average delay to meet an RSU while driving on lane *i*, i.e. $\mathrm{E}[T_i]$. Hence, the average delay to deliver the message to the RSU using a car on a neighboring lane *i* is given by:

$$E\left[T_{i,r_{11}}\right] = \left(E[T_i] + E\left[T_{i,temp_{11}}\right]\right) \times P_{i,r_{11}} \times P_{C_{d_i}} \qquad (18)$$

Clustered client: In this case, the client is a member of disconnected cluster on lane *j* and has no relay within its range. The probability of this scenario, $P_{i,r_{12}}$, is given in the Appendix by Lemma 4. The temporal delay to meet a relay cluster can be approximated by assuming the source is the center of cluster and it is located in the middle of the $S_{i,inter}$ gap. Hence, $S_{i,inter}$ should at least be greater than $E\left[C_{L_j}|C_{L_j} < C_I - 2R_I\right]$ and the expected temporal delay for this case is:

$$\begin{aligned} E\left[T_{i,temp_{21}}\right] &= \frac{0.5E\left[S_{i,inter}|S_{i,inter} > E\left[C_{L_j}|C_{L_j} < C_I - 2R_I\right]\right] - R}{(v_j + v_i)} \\ &= \frac{0.5\left(E\left[C_{L_j}|C_{L_j} < C_I - 2R_I\right] + \frac{1}{\lambda_{i,s}}\right) - R}{(v_j + v_i)} \end{aligned} \qquad (19)$$

The spatial delay is simply equal to the average delay of the relay to meet the RSU, i.e., $E[T_i]$. As a result, the average delay to deliver the message to the RSU using a car on lane *i* with a different speed is given by:

$$E\left[T_{i,r_{21}}\right] = \left(E[T_i] + E\left[T_{i,temp_{21}}\right]\right) \times P_{i,r_{21}} \times P_{C_{d_i}} \qquad (20)$$

Case 2: Best case scenario (BCS)

Here, the requested message will be directly relayed to the neighboring lane. Hence, the temporal delay for this case is zero. As in WCS, we observe that in BCS the client can be isolated or be part of a cluster.

Isolated client: In this subcase, the client is an isolated vehicle on lane *j*, disconnected from the RSUs backbone, and has a relay cluster on lane *i* within its range. The probability of this scenario, $\mathrm{P}_{j,r_{21}}$, is given in the Appendix by Lemma 5. The relay vehicle could be either disconnected or connected to the RSUs. In case of a disconnected relay, the delay to deliver the message to the RSU is simply equal to $\mathrm{E}[T_i]$. In addition, the probability of a relay on lane *i* to be disconnected $\left(P_{C_d}\right)$ is given in (20). On the other hand, in case of having a connected relay cluster, the delay to deliver the message to the RSU is equal to zero. The probability of this event is simply the complement of the probability given in (20). The average delay to deliver the message to the RSU using lane *i* while the client is on lane *j* is given by:

$$\mathrm{E}\left[T_{j,r_{21}}\right] = \mathrm{E}[T_i] \times \mathrm{P}_{j,r_{21}} \times P_{C_{i,d}} \qquad (21)$$

Clustered client: In this case the client belongs to a disconnected cluster on lane *j* and has a relay vehicle on lane *i* within its range. The probability of this scenario, $\mathrm{P}_{i,r_{22}}$, is given in the Appendix by Lemma 6. Similar to WCS, to have a non-zero spatial delay the relay vehicle must be disconnected from the RSUs. In such a situation, the delay to deliver the message to the RSU is simply equal to $\mathrm{E}[T_i]$, and similar to the earlier subcase, the probability of this event is given in (20). The average delay to deliver the message to the RSU using a vehicle on lane *i* while the client is on lane *j* is given by:

$$\mathrm{E}\left[T_{j,r_{22}}\right] = \mathrm{E}[T_i] \times \mathrm{P}_{i,r_{22}} \times P_{C_{d_i}} \qquad (22)$$

Finally, the average queuing time needed to deliver the message to the RSU is given by:

$$\begin{aligned} E[Q] = \sum_{j\in L} \sum_{i\,\in L/j} \Big\{ \Big(\big(P[n=1]\ \left(E\left[T_{i,r_{11}}\right] + E\left[T_{i,r_{21}}\right]\right) \\ + P[n>1]\ \left(E\left[T_{i,r_{12}}\right] + E\left[T_{i,r_{22}}\right]\right) \big) \Big) \\ \times P\left[v_j\right] \Big\} \end{aligned} \qquad (23)$$

where *L* is the set of the lanes on the road.

V. CONTENTION AND ANSWER DELAY

The contention delay is caused by the competition between the vehicles in order to access the wireless channel. This type of delay was the subject of our previous work [12], where we modeled and verified the contention delay analytically and experimentally. The derived average contention delay is [12]:

$$E[c] = \begin{cases} E[cw].T_{slot} & if\ E[cw].T_{slot} < T_{SCH} \\ E[Macq] + E[cw].T_{slot} & if\ E[cw].T_{slot} > T_{SCH} \end{cases} \quad (24)$$

where $E[cw]$ is the average contention window, T_{slot} is the average duration of a logical slot, $E[Macq]$ is the average buffering time needed until the next SCH starts. These are equal to:

$$E[cw] = \frac{cw_{max} - 1}{2} \quad (25)$$

$$T_{slot} = P_{idle}\sigma + T_{success}P_{success} + T_{coll}P_{coll} \quad (26)$$

$$E[Macq] = T_{guard} + \frac{T_{CCH}}{2} \quad (27)$$

where P_{idle} is the probability that a channel is idle in a given slot, $P_{success}$ is the probability that a slot is occupied by a successful transmission, P_{coll} is the probability that a collision occurs during a slot, σ is the duration of an empty slot, $T_{success}$ is the required time for a successful transmission, T_{coll} is the average time of a collision event, T_{guard} is the duration of the guard time, and T_{CCH} is the duration of the CCH interval. For more details about the above parameters, the reader may refer to [12].

On the other hand, the answer delay is the time needed to deliver the discovery result to the discoverer. Considering a scenario where no matching occurs at the serving RSU's lookup table, the discovery request will be forwarded to the neighboring RSU. The latter will process the request and a matching message will be sent to the eNodeB to allocate the necessary resources to the UEs. Consequently, the delay to initiate a call will be as follows

$$E[T_{ans}] = T_{process} + \frac{L}{R} + \frac{S}{R'} + \frac{m}{R''} \quad (28)$$

where $T_{process}$ is the process delay at the RSUs, and the eNodeB, L is the packet size of the discovery message, S is the packet size of the forwarded discovery message, and m is the packet size of the allocated resources message. Finally, R, $R'$and $R''$are the data rate between the RSU_RSU, the RSU-eNodeB, and eNodeB-UE respectively.

As a result, the average end-to-end delay is equal to the sum of queuing (T_q), contention (C), and the answer delays given in (23), (24) and (28) and:

$$E[d] = E\left[T_q\right] + E[c] + E[T_{ans}] \quad (29)$$

The queuing delay depends only on the road structure and the RSU distribution. The contention delay depends on the number of nodes that are trying to access the channel at the same time, while the answer delay depends on the RSU capability and the communication link between the nodes. In the next section we observe the effect of all these factors on the average delay, and provide both analytical and simulation results.

VI. SIMULATION RESULTS

Here, we present experimental results to gain insights into the performance aspects of our proposed discovery protocol.

A. *Queuing delay*

This section presents the results obtained from the analytical model proposed in Section 3, and from the Monte Carlo simulation using NS3 [33]. First we outline the network topology, the nodes' communication unit, and the network communication model assumed in our simulation. Then we validate the lane characteristics and extract the average queuing time needed to connect to the RSU network.

Network topology: we simulate a 10km of an uninterrupted multiple-lane highway, where each lane has a specific speed limit. In addition, we deploy an RSU network where the RSUs are placed at fixed intervals ($d_{RSU} = 1000m$) as recommended in [18], and generate vehicles on each lane independently in accordance with a Poisson process. The vehicles' speeds are allocated according to the lane speed level, and hence, our mobility model, in contrary to [16] [17] [18], covers better the real scenarios that are encountered on highways. Furthermore, we also implement an open system model, i.e., when a vehicle leaves the road, a new vehicle is generated and gets inserted on the road, also according to the Poisson process. Here it is important to mention that our synthetic mobility traces used in our simulation are based on empirical traces i.e. real measurements. Two sets of empirical data are selected to verify the mobility behaviors of cars in real scenario. The sets of data were collected from the I-80 highway in Berkeley 2007 and from the Gardiner Expressway ([42].

Nodes' communication unit: Vehicles have one 802.11p physical device with alternating access. The time interval of CCH and SCH is set to 50ms and the guard interval of both channels is set to 4ms (the default 802.11p parameters). RSUs have two 802.11p devices with continuous access to CCH and SCH channel, and the radio range of both the vehicles and the RSUs is set to 250m, which follows the federal Communication Commission (FCC) regulations.

Communication model: The communication procedure is as follows: first the vehicles are located on each d_{RSU} distance, then one source that aims to communicate with the RSU backbone is randomly selected on each d_{RSU}. The routing algorithm is assumed to be the store-carry-forward scheme with two different approaches. The first broadcasts the stored packet to every node in its vicinity as in [16] and [18], while the second one unicasts the packet to the vehicles with lowest travel time to the front and back RSUs on segment d_{RSU}. Here, we assume that each vehicle knows about the RSUs from its digital map, and periodically broadcasts its travel info (speed and location).

1) *Validation of Lane characteristics*

Fig. 6 shows the probability of being a leading vehicle on a lane j (P_{L_j}). As expected, the lower the traffic volume, the higher the probability of being the leading vehicle on any lane. However, as the velocity increases the probability of being the leading vehicle increases, as well. This is due to the fact that at high speed, vehicles tend to move isolated more, i.e., each one will be an isolated one-member cluster.

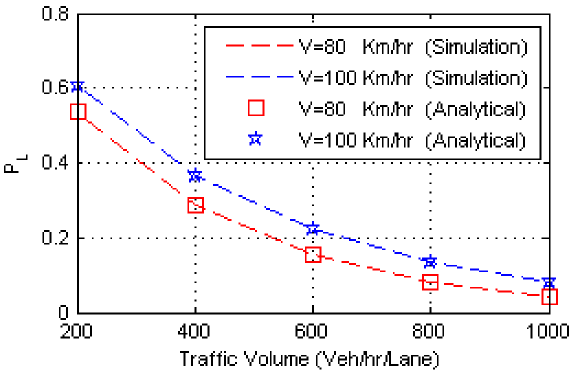

Fig. 6. Probability of being the last or the leading vehicle in a cluster

Fig. 7 and Fig. 8 show the intra and inter cluster spacing on each lane. Unlike the case of being a leading vehicle, as traffic volume increases both inter and intra cluster spacing decreases, while as velocity increases, cluster spacing increases. In addition, we observe a very close match between the simulation and the analytical derivation of the lane characteristics. Indeed, in our mobility model the traffic inter arrival time is constant per lane. In other words, even though our mobility model allows bypassing, however the bypassing does not take place on the same lane, so the condition of [16] (i.e. bypassing is not allowed on the road) does not change things on a per lane level.

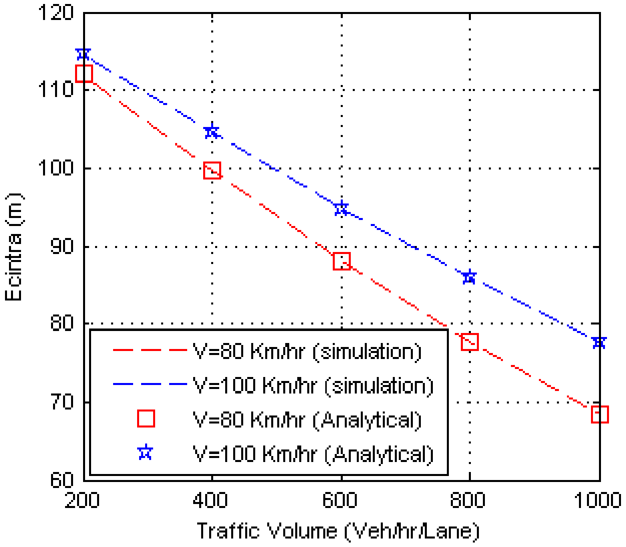

Fig. 7. Average intra cluster spacing

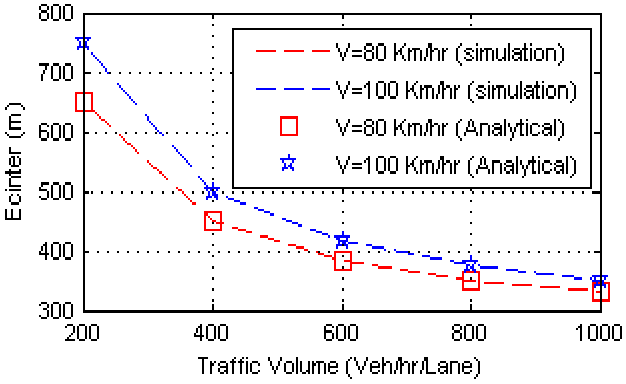

Fig. 8. Average inter cluster spacing

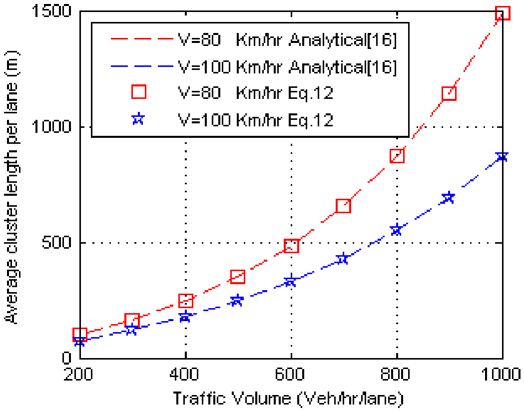

Fig. 9. Average cluster length

The average cluster length derived in (9) is shown in Fig. 9. As can be seen, the average of cluster size increases with the traffic volume, but decreases with increased velocity because in this case the number of cluster members decreases. In addition the excellent match between our average values and those derived in [16] makes the derived cluster length probability (8) reliable. Thus we can totally rely on it to get the average queuing time.

2) Validation of the analytical model

Fig. 10 compares the average delay computed using our analytical model provided in (23), the analytical model provided in [18], and the simulation results. The strength of our model is clearly shown from the excellent matching with the simulation results even for high traffic volumes. Here we assumed a 3-lanes highway with an average speed equal to 30 m/s and delta speed between the lanes equal to 5.55 m/s. As expected, when the traffic volume increases the average delay decreases. This is because when the traffic increases the probability to find vehicles in the vicinity increases. In other words, when traffic intensifies, the cluster length increases. On the other hand, the shortfall of the model in [18] is clearly shown in Fig. 10. For instance, we can conclude that this model is bounded by a low traffic volume ($TV \leq 1000$ vehicles/hr) and cannot be used for high traffic cases. Indeed, the model disagrees with the NS3 real measurements from one side and it gives negative delay for high traffic volume from the other side. So, it is expected to be highly unreliable when the number of lanes increases because in this case traffic will largely increase. This is shown in Fig. 11 in which we have studied the effect of the number of lanes in [18] focusing on the sparse VANET situation, i.e., low traffic volumes (300 vehicles/hr/Lane [16][18]). As expected, as the number of lanes increases the performance worsens increasingly. Note that, the shortage percentage in Fig. 11 indicates the error percentage between the NS3 results and the analytical model used in [18].

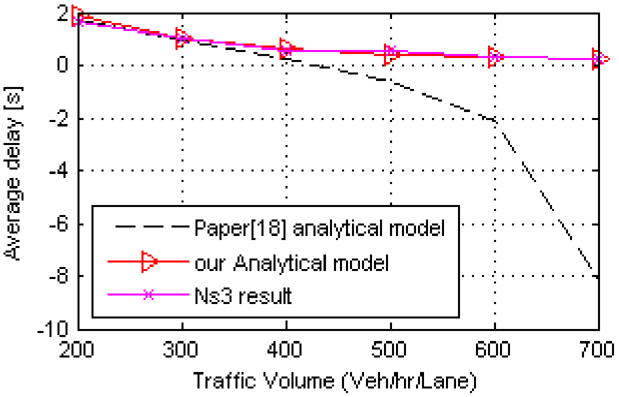

Fig. 10. Average queueing delay time

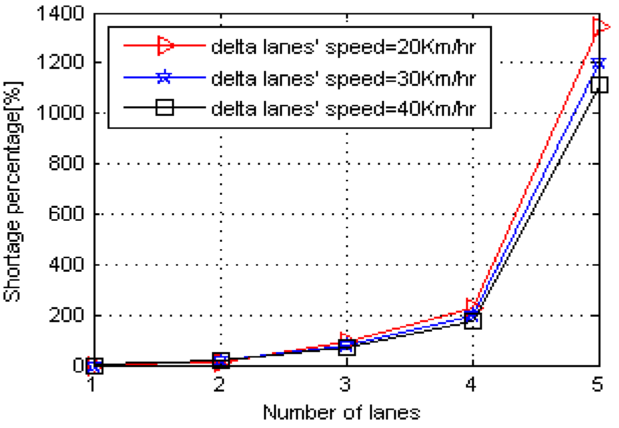

Fig. 11. Shortage percentage of analytical model in [18]

Fig. 12 shows the efficiency of our routing approach (i.e., unicasting packets to vehicles with lowest travel time). As shown, the average number of packets needed to reach the RSU network in the unicast approach is almost stable (2 packets) while in the conventional broadcasting approach it increases with traffic increase. Here it is worth to mention that the average number of packets in Fig 12 are the average number of transmitted packets that are correctly received by the intermediate receivers until a first copy of the message is received by the final destination i.e. the RSU network. Thus the proposed Unicast approach effectively mitigates congestion of the broadcast storm problem. We should mention that both services, i.e. Unicast and Broadcast, offer the same average delay. Indeed, in the proposed Unicast approach, the protocol is designed so that packet is served through the fastest path. In broadcasting approach, the packet is received by the shortest path. This has been also verified by simulation results.

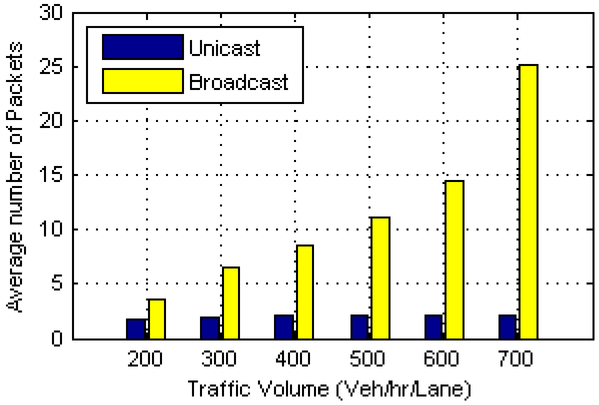

Fig. 12. Comparison between the unicast and the broadcast routing approaches

B. *Contention delay*

The validation of our contention delay model has been verified in our previous work [12]. For completeness, we confirm this by providing a comparison between the analytical and experimental results based on NS3. In our simulations we consider the same network topology and mobility model as in the previous subsection, i.e., 10Km of a straight highway, RSUs are uniformly distributed, vehicles are generated on each lane according to a Poisson process and are moving at the Lane's speed limit. In order to simulate the contention mechanism in real conditions, we periodically identify the vehicles that are in the RSUs range, we then consider these cars as sources aiming to access a Service Channel (SCH) provided by the RSUs. Fig. 13 shows that the analytical contention model closely agrees with the simulation results.

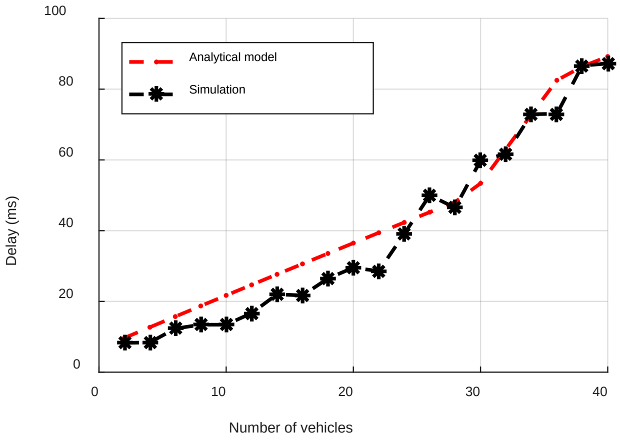

Fig. 13. Comparison of Analytical contention delay model with simulation (Number of Lanes=3)

C. *End to End delay*

After validating the analytical model of the contention and the queuing delay, we discuss now the average end to end D2D discovery delay on a multiple lane road. The average total delay is the summation of the queuing, contention, and answer delay. In order to model the answer delay we add a conservative 30ms processing delay at the RSU and the eNodeB, similar to [18]. Fig. 14 shows the average total delay of the discovery protocol. As illustrated, the delay of the discovery process ranges from 0.3 to 2s which is a manageable value, and shows the significance and efficiency of our system in discovering D2D peers using the Vehicle Ad hoc Network. Compared with the conventional LTE-based D2D discovery process [40], the proposed VANET aided D2D discovery offers the same range of delay. Indeed, LTE-based D2D scheme offers two types of service discovery: Type 1 and Type 2-A, each presents different characteristics in terms of power consumption and delay varying from few msec up to 1.4 sec. [40]. It is clear that this range of delay is comparable with our proposed scheme as long as there is traffic volume larger than 300veh/hr/lane.

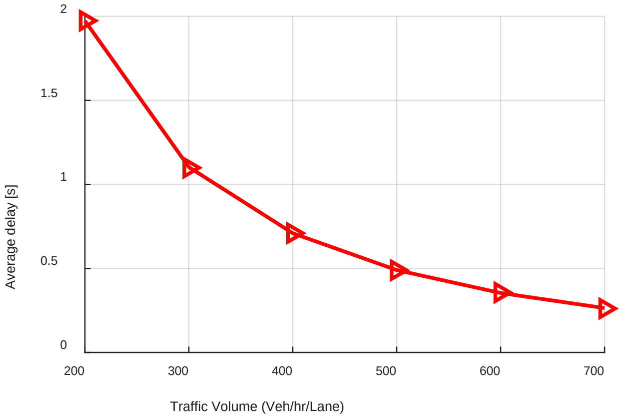

Fig. 14. Average delay for the VANET aided discovery protocol

We should mention that the average delay for VANET aided discovery highly depends on the inter-RSUs distance and on the RSU coverage. An increase in the inter-RSUs distance will surely increase the delay however the results obtained in Fig. 14 with dRSU=1000 m and RSU range equal to 250 m are comparable with those obtained by LTE-based discovery.

VII. CONCLUSION

In this paper we have proposed a new D2D discovery scheme for vehicular users by exploiting the capabilities of the Vehicle Ad hoc Network (VANET). We suggested to use the RSUs' capabilities for the discovery process, and proposed new schemes related to the OBU architecture, and its association with the drivers' and passengers' mobile devices. We also proposed a new routing approach based on the carry and forward protocol which hugely decreases the amount of traffic generated by the routing of discovery messages. Overall, our proposed protocol mitigates the requirement for additional cellular resources and offloads a part of the D2D discovery load from the cellular network. In addition, our protocol adds minimum load on the VANET, as it uses the VANET architecture in an efficient way to perform the discovery process.

Furthermore, we developed a mathematical model to analyze the discovery latency, and validated it through simulations using NS3. Our analytical model was shown to closely match the simulation results, even in the presence of high traffic scenarios, in contrast to models proposed in literature. The analytical and numerical results demonstrated the effectiveness of the proposed protocol and showed that a low latency could be reached without using additional cellular resources. An obvious future work that would build on the work presented in this paper is to consider non-highways road scenarios, like urban areas with intersections and relatively short road stretches. Such scenarios tend to be different in that RSUs could be installed at road intersections, and so, most locations on such roads will likely fall within the transmission range of one or more RSUs.

APPENDIX

Lemma 1. The probability that the length of a cluster on lane *j* is less than $d_{RSU} - 2R_I$ is given by:

$$\mathrm{P}\left[C_{L_j} < d_{\mathrm{RSU}} - 2R_{\mathrm{I}}\right] = 1 - \frac{1 - P_{L_j}}{e^{b(\mathrm{d_{RSU}} - 2R_I)}} \tag{30}$$

Proof: Using the PDF of the cluster length given in (8), Lemma 1 can be easily calculated as follows:

$$\begin{aligned}\mathrm{P}\left[C_{L_j} < d_{\mathrm{RSU}} - 2R_{\mathrm{I}}\right] & \\ &= \int_0^{\mathrm{d_{RSU}-2R_I}} a\, e^{-bc_L}\, dc_l \\ &= \left(1 - e^{-b(\mathrm{d_{RSU}}-2R_I)}\right) \times \left(1 - P_{L_j}\right) \\ &+ \ P_{L_j} = 1 - \frac{1 - P_{L_j}}{e^{b(\mathrm{d_{RSU}}-2R_I)}}\end{aligned} \tag{31}$$

Lemma 2. The expected length of a cluster on lane j, conditioned by $0 < C_{L_j} < C_I - 2R_I$, is given by*:*

$$\begin{aligned}&\mathrm{E}\left[C_{L_j} | 0 < C_{L_j} < \mathrm{d_{RSU} - 2R_I}\right] \\ &= \frac{a}{b^2} \times \frac{1 - e^{-b(d_{RSU}-2R_I)}(1 + b(d_{RSU} - 2R_I))}{(1 - e^{-b(\mathrm{d_{RSU}-2R_I})})\left(1 - P_{L_j}\right)}\end{aligned} \tag{32}$$

Proof: Using (8) and Lemma 1, Lemma 2 can be derived as follows:

$$\begin{aligned}&\mathrm{E}\left[C_{L_j} | 0 < C_{L_j} < \mathrm{d_{RSU} - 2R_I}\right] \\ &= \int_0^{\mathrm{d_{RSU}-2R_I}} c_{L_j} \frac{a\, e^{-bc_{L_j}}\, dc_{L_j}}{\mathrm{P}\left[0 < C_{L_j} < \mathrm{d_{RSU} - 2R_I}\right]} \\ &= \frac{a}{b^2} \times \frac{1 - e^{-b(d_{RSU}-2R_I)}(1 + b(d_{RSU} - 2R_I))}{(1 - e^{-b(\mathrm{d_{RSU}-2R_I})})\left(1 - P_{L_j}\right)}\end{aligned} \tag{33}$$

Lemma 3. The probability to have no vehicles in range of an isolated and disconnected vehicle is given by:

$$\mathrm{P}_{i,r_{11}} = \frac{d_{RSU} - 2R_I}{d_{RSU}} \times e^{-2R\lambda_i} \tag{34}$$

Proof: Using the memoryless property of the exponential function, the probability of a vehicle located on lane *j* having no relay vehicle within its range on lane *i* ($\mathrm{p^0_{i,0relay}}$) is:

$$\begin{aligned}\mathrm{p^0_{i,0relay}} = P_r(no\ vehicles\ exist) = \frac{(2R\lambda_i)^0}{0!} e^{-2R\lambda_i} \\ = e^{-2R\lambda_i}\end{aligned} \tag{35}$$

On the other hand, the probability of a car on lane *j* to be disconnected from the RSU is given in (11). Hence Lemma 3 can be obtained by multiplying (11) and (35)■

Lemma 4. The probability to have no cars within the range of a disconnected cluster is given by:

$$\begin{aligned}\mathrm{P}_{i,r_{12}} = \frac{d_{RSU} - 2R_{I}{-}\mathrm{E}\left[C_{L_j} | C_{L_j} < d_{RSU} - \mathrm{2R_I}\right]}{d_{RSU}} \\ \times\ (e^{-\mathrm{E}\left[C_{L_j} | C_{L_j} < d_{RSU} - \mathrm{2R_I}\right]\lambda_i})\end{aligned} \tag{36}$$

Proof: Using the memoryless property of the exponential function, the probability of a cluster located on lane *j* having no relay vehicle within its range on lane *i* ($\mathrm{p}^{0}_{\mathrm{j,0relay}}$) is:

$$\mathrm{p}^{1}_{\mathrm{j,0relay}}$$

$$= P_r\,(no\ vehicles\ exist\ within\ the\ range\ of\ a\ disconnected\ cluster)$$

$$= \frac{\left(\mathrm{E}\left[C_{L_j}|C_{L_j} < d_{RSU} - 2\mathrm{R_I}\right]\lambda_i\right)^0}{0!} e^{-\mathrm{E}\left[C_{L_j}|C_{L_j}<d_{RSU}-2\mathrm{R_I}\right]\lambda_i} \quad (37)$$

$$= e^{-\mathrm{E}\left[C_{L_j}|C_{L_j}<d_{RSU}-2\mathrm{R_I}\right]\lambda_i}$$

On the other hand, the probability of a cluster on lane *j* to be disconnected from the RSU is given in (13). Hence Lemma 4 can be obtained by multiplying (13) and (37)■

Lemma 5. The probability to have a relay in range of an isolated and disconnected vehicle is given by:

$$\mathrm{P}_{j,r_{21}} = \frac{d_{RSU} - 2R_I}{d_{RSU}} \times (1 - e^{-2R\lambda_i}) \quad (38)$$

Proof: The probability of having a relay vehicle on lane *i* within the range of the isolated vehicle on lane *j* is the complement of (35). Moreover, the probability of an isolated vehicle to be disconnected from the RSU on lane *j* is given in (13). Hence Lemma 5 can be obtained by multiplying (13) and the complement of (35)■

Lemma 6. The probability to have a relay within the range of a disconnected cluster is given by:

$$\mathrm{P}_{j,r_{22}} = \frac{d_{RSU} - 2R_{I-}\mathrm{E}\left[C_{L_i}|C_{L_i} < d_{RSU} - 2\mathrm{R_I}\right]}{d_{RSU}} \times (1 - e^{-\mathrm{E}\left[C_{L_i}|C_{L_i}<\mathrm{C_I}-2\mathrm{R_I}\right]\lambda_i}) \quad (39)$$

Proof: The probability of a cluster of cars located on lane *j* having at least one relay vehicle on neighboring lane *i* is the complement of (37). Moreover, the probability of a cluster on lane *j* to be disconnected from the RSU is given in (13). Hence Lemma 6 can be obtained by multiplying (13) and the complement of (37)■

Appendix B

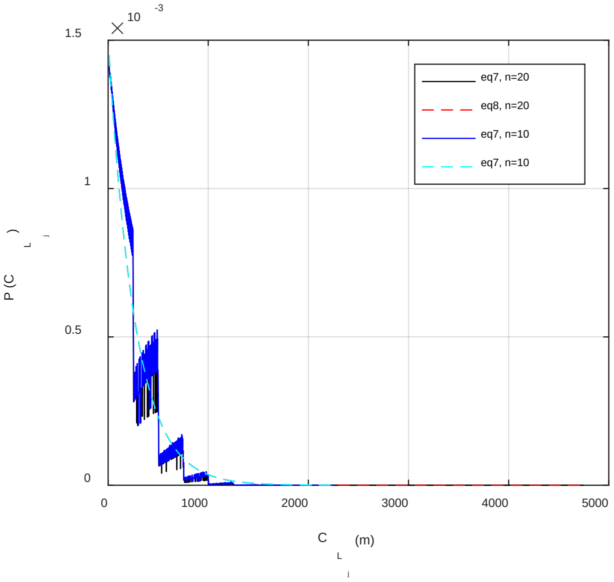

Fig. 15 Comparison between equations (7) and (8). R=250m

As can be seen in Fig. 15 increasing the number of n extend the range of C_{L_j}. However, the occurrence probability of large C_{L_j} is very small. This is normal because the vehicles are in the free flow regime. For n=10 the mean square error equal to $5.6 * 10^{-8}$ while when increasing n the MSE decreases to $2.9 * 10^{-8}$.

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