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VANET INHERENT CAPABILITY FOR D2D DISCOVERY

by
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AN ABSTRACT OF THE THESIS OF

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Device-to-Device (D2D) communication has gained a lot of interest in the last years. Recently, it has been accepted as a promising concept as part of the third generation partnership project (3GPP) standard in the LTE-A release 12 and release 13 under the name of Proximity-Based Services (ProSe). However, the proposed solutions to integrate the D2D in the cellular network require added functionalities on the network resources, mainly in the discovery process. In this thesis, we mitigate the requirement of additional resources in the LTE-A network by proposing a novel D2D discovery protocol. Specifically, we propose to offload the D2D discovery onto the Vehicular Ad-hoc Networks (VANETs) by using the inherent knowledge of the Road Side Unit (RSU) about the users in its coverage area. In addition, we propose a framework to model and analyze the duration of our discovery protocol in sparse highway network through mathematical derivations. Then, all the results are validated through extensive simulations on both Network Simulator 3 (NS3) and Matlab. The analytical and numerical results demonstrate the effectiveness of the proposed protocol and show that low discovery latency can be reached without using additional cellular resources.

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ABBREVIATIONS

3GPP	Third-Generation Partnership Project
LTE	Long Term Evolution
D2D	Device to Device
VANET	Vehicular Ad-hoc Network
MANET	Mobile Ad-hoc Network
DSRC	Dedicated Short Range Communications
OBU	On Board Unit
RSU	Road Side Unit
ITS	Intelligent Transportation Systems
WAVE	Wireless Access in Vehicular Environment
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
IEEE	The Institute of Electrical and Electronics Engineers
FCC	The U.S. Federal Communications Commission
WSMP	WAVE Short Message Protocol
WSM	WAVE Short Message
CCH	Control Channel
SCH	Service Channel
ProSe	Proximity-Based Services
eNodeB	Evolved Node B
BS	Base Station
QoS	Quality of Service
UE	User Equipment
PDF	Probability Density Functions
IVv6	Internet Protocol Version 6

CHAPTER I

INTRODUCTION

In the last centuries, the human life faced two technological paradigm shifts. The first one is the introduction of the first commercially steam-engine automobile in 1712 by Thomas Newcomen. While the second is the launching of the first commercially automated cellular network (1G) in 1979 by Nippon Telegraph and Telephone Corporation (NTT). Since that time, the transportation and the communication sectors have gain a lot of popularity due to their direct influence on the society. According to [1] the number of automobiles in the world has surpassed 1 billion in 2011 and the number of mobile subscriptions will exceed the world's population by 2016 [2]. As a result, many new problems have risen. This includes traffic collision, transportation problems and huge mobile data traffic on the cellular network. Thus, the flag has been raised to find solutions in order to increase the cellular network capacity, and make the transportation safer.

Recently, two innovative ideas and promising concepts have introduced to accommodate the traffic collision problem and the network capacity shortage called Vehicular ad hoc network (VANET) and device to device communication (D2D). In addition to that both VANET and D2D provide a cost effective solutions that can reduce the economic loss due to the vehicular crashes and the cost per bit in the cellular link.

A. VANET Background

VANET is composed of mobile nodes and fixed nodes as shown in Figure 1.1. The mobile nodes are the vehicles moving on the road while the fixed nodes are roadside infrastructure known as Roadside units (RSUs) located in some critical sections on the road, such as the intersections, the traffic lights, and the light poles. The aim of VANET is to allow the vehicles to communicate with each other as well as with RSUs in order to improve the driving experience and make it safer. Vehicles are equipped with communication devices called On-Board Units (OBUs) that permit the drivers to communicate with each other as with RSUs.

Beside the safety applications, VANET can provide many network applications including internet access by connecting the RSUs to a backbone network. In general VANET is a subclass of mobile ad-hoc network (MANET) that connects the vehicles and RSUs to each other and to the internet in order to provide safety and comfort applications.

Recently, the U.S. Federal Communications Commission (FCC) has allocated 75 MHz of Dedicated Short Range Communications (DSRC) spectrum at 5.9 GHz to be used exclusively for vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communications [4]. Although the primary purpose of FCC is to enable public safety applications that decrease fatalities accidents and improve traffic flow, the FCC allows private services in this spectrum in order to lower the cost and to encourage DSRC development and adoption.

The DSRC spectrum is also known as the Intelligent Transportation Systems (ITS) Radio, and it is composed of seven 10 MHz channels as shown in Figure 1.2. The central channel is called the control channel (CCH) and it is restricted to safety communications only. The edge channels are reserved for future advanced accident avoidance applications and high-powered public safety usages, and the rest are service channels available for both safety and non-safety applications.

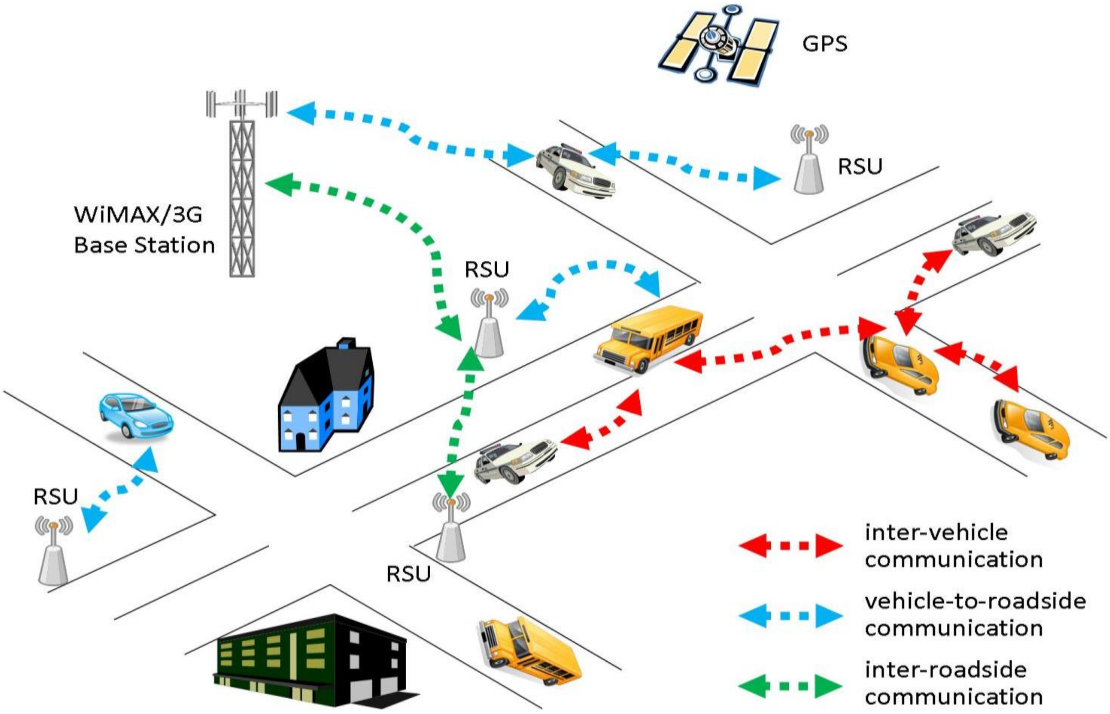

Figure 1.1 Block diagram of VANET [3]

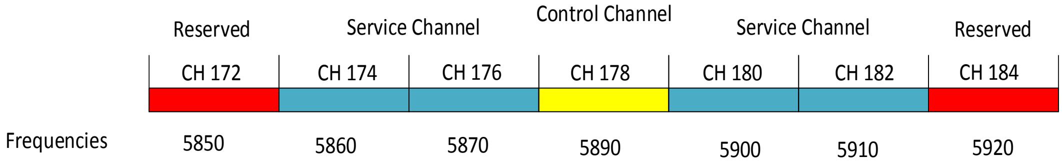

Figure 1.2 ITS radio channel assignment in North America

Currently, the Institute of Electrical and Electronics Engineers (IEEE) 1609 series of standards for Wireless Access in Vehicular Environment (WAVE) is considered as the most promising technology for vehicular networks [5]. This family of standards defines the architecture and the set of services and interfaces that enable secure wireless communication and physical access for high speed (up to 27 MB/s), short range (up to

1000 m), and low latency wireless communication in the vehicular environment [5, 6].

Table 1.1 summarizes the usage and the description of WAVE standards.

Table1.1 IEEE WAVE Family Standards Description [5]

WAVE	Standard Usage	Description
IEEE P1609.0	Architecture	Describes the architecture and service necessary for multi-channel WAVE devices
IEEE P1609.2	Security Services for Applications and Management Message	Covers methods for securing WAVE management messages and application messages, It also describes administrative functions necessary to support the core security functions
IEEE P1609.3	Networking Service	Describes standard messages that support higher layer communication stacks, including TCP/IP
IEEE P1609.4	Multi-Channel Operation	Describes various standard message formats for DSRC applications at 5.9 GHz
IEEE P1609.5	Communication Manager	Defines communication management services in support of wireless connectivity among vehicles, and between vehicles and roadside units.
IEEE P1609.11	Over-the-Air Electronic Payment Data Exchange Protocol	Defines a basic level of technical interoperability for electronic payment equipment, i.e. On board unit (OBU) and roadside equipment (RSE) using DSRC
IEEE P1609.12	Identifier Allocations	Specifies allocations of WAVE identifiers defined in the IEEE 1609 series of standards

The WAVE Physical Layer is based on the IEEE 802.11, however, because of the operating environment of vehicular networks an amendment of the standard, known as IEEE 802.11p and now it is incorporated in IEEE 802.11-2012, has been made [7, 8]. IEEE 802.11p standard defined a small number of extensions to IEEE 802.11-2012 for operating outside the context of a basic service set that is supporting the types of vehicular scenarios required for WAVE system operation [9]. It uses carrier sense multiple access with collision avoidance (CSMA/CA) as the basic medium access scheme for link sharing, the 5.9 GHz OFDM PHY Layer (5.850–5.925 GHz in the U. S., 5.855–5.925 GHz in Europe), and defines channel bandwidths, operating classes, transmit power classification, transmission masks, the alternate channel and alternate adjacent channel rejection requirements.

WAVE also introduces two protocol stacks, sharing a common lower stack at the data link and physical layers called WAVE Short Message Protocol (WSMP) and IPv6. WAVE Short Messages (WSM) may be sent on any channel while IP traffic is only allowed on service channels (SCHs), so as to offload high-volume IP traffic from the control channel (CCH).

Nodes in WAVE standards could have multi physical layer device or single physical layer device. Multi physical layer device will typically work in CCH and at least one SCH, while single Physical layer device may switch between CCH and SCH. Nodes with single physical layer device should monitor the control channel at CCH interval as important safety information may be transmitted or advertisement messages about services that will be available during the next SCH interval. While during the SCH interval, WAVE device can be tuned to any of the six service channels and transmit data of non-safety related applications.

B. D2D Background

Recently, the D2D concept has gained a lot of interest in the research community. The momentum behind this interest lies is the inherent features of D2D in terms of cost and cellular characteristics. In fact, D2D seems to play pivotal role in the future cellular networks due to its several advantages which can be summarized by the following points [10, 11]:

- Cost per bit reduction
- High Throughput
- Low Delay
- Power saving
- Spectral Efficiency
- Introduction of new Proximity Based Services

The D2D communication allows two nearby devices to communicate without base station participation or with a limited participation. Figure 1.3 illustrates the concept of D2D. UE1 and UE2 are remote from cellular infrastructure and in proximity to each other. Therefore, they have the chance to initiate a D2D link instead of the traditional cellular link. Thus, a reliable communication with high data rate, lower power consumption and lower delay will occur between UE1 and UE2. Hence, by enabling this type of links the network operators can increase their coverage, earn more profits and fulfill the users' demands.

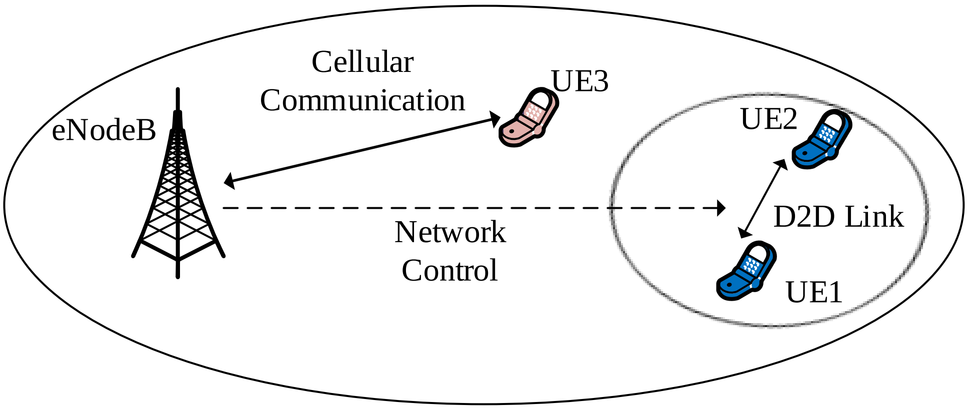

Figure1.3 D2D concept

The D2D communications can be divided into two types called in-band and out-band. The former type operates in the licensed band (i.e. cellular spectrum), where D2D UEs share the cellular resources with cellular UEs, while the latter operates in the unlicensed band (i.e. ISM band such as Wi-Fi Direct, Bluetooth and ZigBee) [12].

Furthermore, the in-band communication can be classified into underlay and overlay categories. The in-band underlay communication refers to the case where both cellular and D2D links share the same resources, while in the in-band overlay communications dedicated cellular resources are reserved to the D2D links[12].

On the other hand, the out-band communications can also be categorized into controlled and autonomous. In the controlled out-band D2D, the responsibility of coordination between the radio interfaces (cellular and Wi-Fi or Bluetooth) is taken by the eNodeB. While, in the autonomous out-band communications, the users themselves take the responsibility to coordinate between different radio technologies [12].

The reason behind introducing the out-band D2D communication is to eliminate the interference caused by using the same resources in the in-band communication. However, due to the uncontrollable and unpredictable interference in the ISM band the researchers have focused more on the in-band D2D communication [13]. Therefore, in order to manage the interference in the in-band, several interference management schemes have been proposed and they can be classified into three categories [14]:

1. Interference avoidance: it is based on the allocation of orthogonal resources to D2D and cellular links.
2. Interference coordination: it is based on the implementation of smart power control and resource allocation.
3. Interference cancellation: it proposes advanced coding and decoding techniques at the cellular and D2D links to remove the interference from the intended signals.

Table 1.2 summarizes the difference between these technologies.

Table 1.2 Comparison of Different D2D Technologies [12]

	D2D	WI-FI Direct	Bluetooth	ZigBee
Licensed spectrum	✓	✗	✗	✗
Interference Management	✓	✗	✗	✗
Security	✓	✗	✗	✗
Income for operators	✓	✗	✗	✗

Within the standardization body, the D2D concept was introduced in the 3GPP release 12 under the Proximity services (ProSe) framework. The standardization work has started by a feasibility study on ProSe (Fs ProSe) [15] in which different use cases of proximity services for both general and public safety use cases have been investigated. In addition potential requirements related to UE operations, network operations, charging and security for ProSe have been identified in this study.

The Prose study has led to some changes in other specifications such as TR 22.115 and 22.287 by adding new normative specifications for Prose. Where TR 22.287 describes the service requirements for the Evolved Packet System (EPC) to maintain its features i.e. low latency, high user data rates, capacity improvement and low operational costs and TR 22.115 primarily described the Service Aspects of charging and billing of the 3GPP System.

Based on the new requirements that were defined in TR 22.115 and 22.287, a new TR 23.703 was written to describe the needed architecture enhancements to support the ProSe functionality. Thus, different solutions are proposed in this TR as well as the key issues that should be considered to study the impact of the proposed solutions on the existing network. The security and the radio access network (RAN) aspects of the ProSe features have also been studied in different groups and led to two technical reports[16,17]. Table 1.3 summarizes the standards related to D2D

Table 1.3 3GPP ProSe Standards [22]

Technical Specs Group	Description	Stage	Specs Number	Goal
Group Services and System Aspects	Service Aspects	Stage1 (Study Item)	TR 22.803 [15]	To study use cases and service requirements
		Stage 1 (Work Item)	TS 22.278 [18]	To specify service requirements for the Evolved Packet System
			TS 22.115 [19]	To specify service requirements (charging and billing)
	Technical Realization	Stage 2	TR 23.703 [20]	To define the architectural enhancements
			TS 23.303 [21]	
	Security Aspects	Stage 3	TR 33.833 [16]	To study the threats and the security requirements
Group RAN		RAN	TR 36.843 [17]	To define the evaluation models (channel, traffic, mobility)

In general, the cellular network operators do not allow signaling between the users. Therefore, a discovery phase is needed before two UEs can set up a D2D link and start direct communication. So two users are D2D candidates if they find each other during the discovery process. Accordingly, the D2D communication can be divided into two phases:

- D2D discovery phase: The discovery step is an introduction to the communication feature in which a user observes the proximity of other ProSe users.
- D2D communication phase: After completing the discovery phase, the D2D candidates can use the cellular resources to initiate a direct communication. Hence, the communication phase includes channel estimation, mode selection, resource allocation, power control, and the actual transmission of information.

C. Objectives

Although, the D2D concept has a lot of advantages, the proposed implementations in literature use some of the LTE resources and the network capabilities which lead to waste in network resources and add more load on the cellular infrastructure mainly in the discovery process In this thesis, we address this problem by proposing a novel D2D discovery protocol which mitigates the requirement of additional cellular resources and reveals part of the load from the cellular network. Specifically, we propose to offload the D2D discovery onto the Vehicular Ad-hoc Networks by using the inherent knowledge of the RSU about the users in its coverage area.

In addition, we propose a framework to model and analyze the duration of our discovery protocol in highway network through mathematical derivations. Then, all the results are validated through extensive simulations on both Network Simulator 3 (NS3) and Matlab. The analytical and numerical results demonstrate the effectiveness of the proposed protocol and show that low discovery latency can be reached without using additional cellular resources.

In the rest of this report, Chapter II discusses some D2D discovery protocols proposed in the literature and the standard along with their shortcomings that we address in our model. Also, it describes the system model including the new discovery protocol. Chapter III states the analytical study for the discovery latency. Chapter IV shows the simulation validation for the discovery time of our new protocol. And finally, Chapter V concludes the report and presents directions for future work.

CHAPTER II

D2D DISCOVERY SYSTEM MODEL

As we have mentioned in chapter I the D2D communication has two phases, discovery phase and communication phase. The D2D discovery is the preliminary process to the D2D communication. In other words, the D2D bearer cannot be established until the two D2D candidates find each other in the discovery phase. In general there are two approaches for the D2D discovery phase known as direct discovery and network assisted discovery.

- Direct discovery: in which the devices communicate with each other directly without the assisting from network via some randomized procedure [12].
- Network assisted discovery: in which the devices find and characterize each other with the assistance of network.

A. Direct discovery

The direct discovery method has been investigated in different out-band wireless technologies e.g. Wi-Fi direct, Bluetooth, ZigBee. However, the unlicensed band systems do not guarantee a good QoS due to the stochastic behaviour of these bands, and without synchronization, the energy efficiency for these technologies is very low. Moreover, the transmission power is quite low in such systems, so the coverage of the devices and the number of neighbors they can discover are limited. The aforementioned problems of the unlicensed band induce the researchers to design new direct discovery methods based on the cellular licensed band. In [23], the authors have proposed a D2D discovery protocol that runs in the licensed band, in which the discovery process is based on the transmission of beacons between the devices using Orthogonal Frequency Division Multiple Access (OFDMA) and building on the existing beacon design of the 3GPP Long Term Evolution (LTE). To resolve the problem of synchronization when multiplexed together in the same OFDMA symbols, the devices are divided into groups that use different patterns to transmit in different beaconing opportunities.

A new communication system that creates awareness in smart devices is introduced in [24]. This system called "FlashLinQ" 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 over 1 Km. The proposed design in [24] keeps the involvement of the network at a minimum, mainly to provide synchronization signals to devices. Notice that this system was the base for a new technology named LTE direct (invented by Qualcomm [25]) and it was integrated in the 3GPP standard studying the architecture enhancements to support Proximity-based Services (ProSe) [20].

The 3GPP standard also studied the direct discovery method under the name of ProSe Direct Discovery. In their work they identify two two types of ProSe Direct Discovery: open and restricted. Open is the case where there is no explicit permission that is needed from the UE being discovered, whereas restricted discovery only takes place with explicit permission from the UE that is being discovered [21]. To that end, the work group proposed two models for direct discovery in the ProSe services, Model A and Model B.

Model A known as "I am here" assumes that there is an announcer and a monitoring users. While the announcer UE broadcasts the discovery messages at pre-defined discovery intervals, the UEs interested in these messages can read and process them [21]. Figure 2.1 illustrates the overall procedure for ProSe direct discovery (Model A) where the ProSe function is the logical function that is used for network related actions required for ProSe. Model B called "who is there/are you there" assumes a discoverer UE and a discovered UE. The discoverer transmits a request containing certain information about what it is interested to discover (e.g. Application Identity), while the discoveree is the user that receives the request message and respond with some information related to the discoverer's request [21]. The main difference between these two models is that Model A supports both open and restricted discovery, while only restricted discovery type is supported by Model B [21].

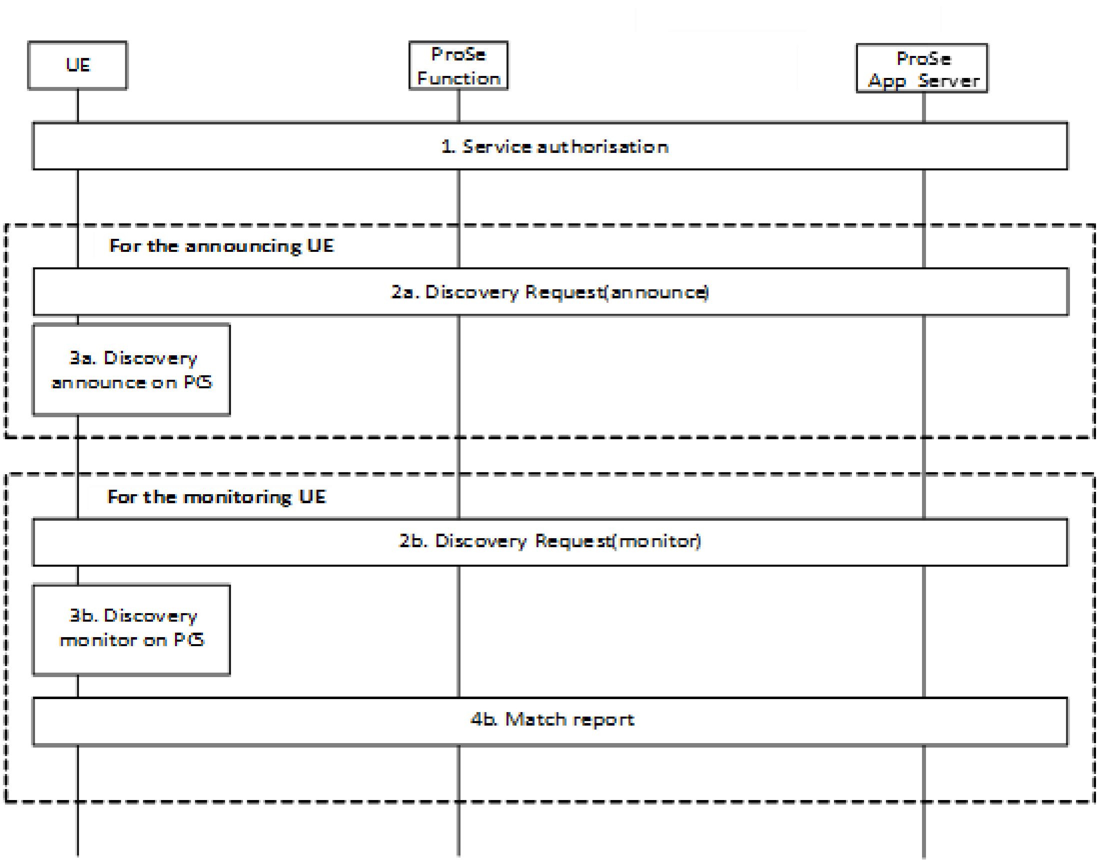

Figure 2.1 Overall procedure for ProSe Direct Discovery (Model A) [21].

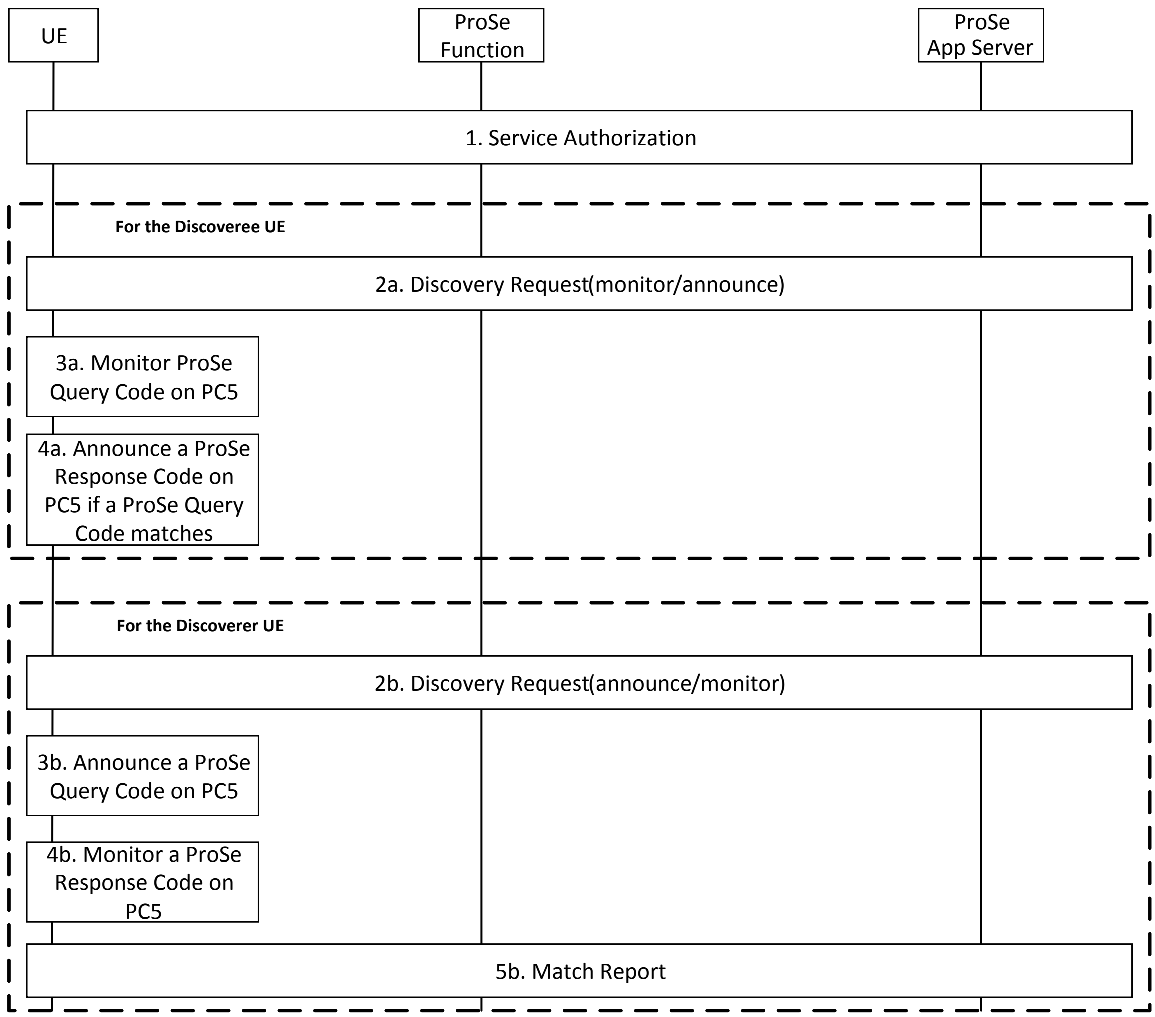

Figure 2.2 Overall procedure for ProSe Direct Discovery (Model B) [21].

B. Network assisted discovery

The direct discovery scheme employs beacon signals and sophisticated scanning which make it time- and energy-consuming [12]. In a high load system and without the help of network the UEs can hardly discover expected number of their neighbors [12]. Moreover, the security procedures often involve higher layers and/or interactions with the end user [12]. Therefore, with a little network participation, the aforementioned problems can be tackled. As a result, this kind of discovery attracts both the researchers and the standardization bodies [21, 26, 27 and 28]. In the network assisted discovery, the users rely on the network to detect and identify each other. The UE informs the BS about its desire to initiate a D2D link with another UE by sending a request signal. Then the BS orders some message exchanges between the devices, in order to acquire identity and information about the link between them. This approach is centralized or semi centralized as the network can mediate in the discovery process by recognizing D2D candidates, coordinating the time and frequency allocations for sending/ scanning beacon signals, and providing identity information [12, 28].

The authors in [28] proposed two methods for detecting D2D users in a network assisted scheme, the a-priori scheme and the a-posteriori scheme. In the a-posteriori scheme the network recognizes the D2D candidate during an ongoing communication session either by a token agreed on by the two devices, or by analyzing the source and destination IP addresses. In the a-priori scheme, the eNodeB detects the D2D candidate before the start of D2D session. In this case, the network can loosely control the discovery procedure by advertising the peer discovery resources so that the D2D candidates can find each other by sending beacons or it can fully control the discovery phase by specific beacon configurations and trigger beacon signaling. The priori loosely controlled procedure and the priori fully controlled procedure is illustrated in the below figure where a-UE denotes the announcing user and r-UE is the receiver.

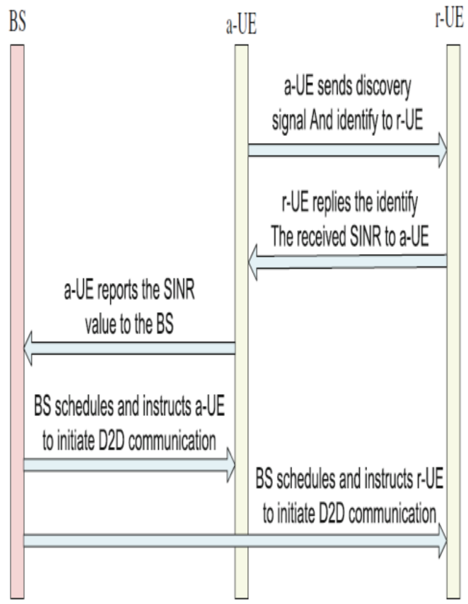

Figure 2.3 loosely controlled procedure [12]

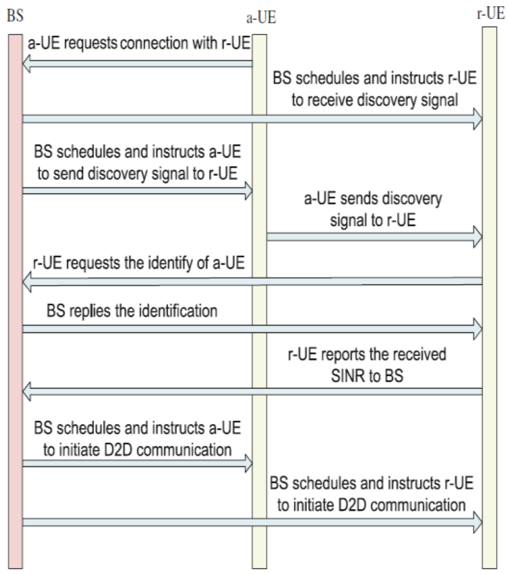

Figure 2.4 Fully Controlled Procedure [12]

As a result, the network assisted discovery mechanism resolves the direct discovery problems. However, it adds a major load on the network. In order to benefit from the advantages of the network assisted discovery approach, we propose a new discovery protocol based on the VANET network which resolves the problem caused by the aforementioned works. Specifically, in our protocol the users have no power consumption problem because they rely on the VANET network to discover each other. Moreover, the proposed D2D discovery protocol offloads the discovery process to the VANET network.

Thus, the new protocol will help increase the cellular network throughput and decrease the load of the network.

The system model including the new discovery protocol will be described throughout the rest of this chapter.

C. System Environment

In this section, we develop the system model in the Dedicated Short Range DSRC based vehicular network. As depicted in Figure 2.5, the proposed system is composed of mobile nodes (Vehicles carrying UEs) and fixed road side units (RSUs) nodes which are within the eNodeB coverage. The communication between the RSU and the vehicles (UEs) occurs via the On-Board unit (OBU) implemented within each vehicle.

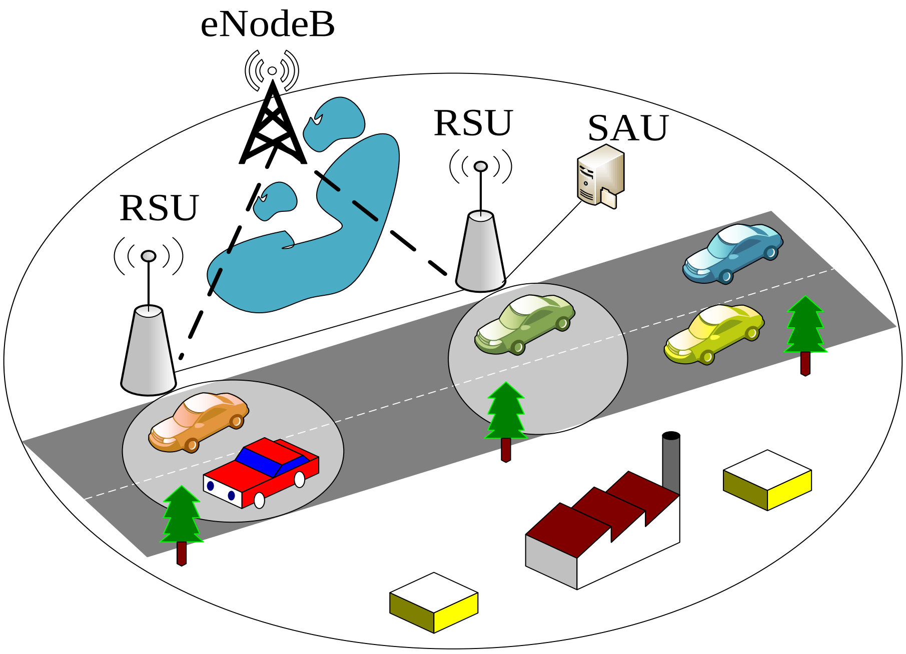

Figure 2.5 Proposed system model

The OBU architecture is not specifically defined in literature but most of the works assume that the OBU contains a list of specific hardware like CPU, Transceiver (TX), Global Positioning System (GPS), Sensors, Human interface (HI) and application unit (AU). The AU is an embedded or portable device that executes a set of OBU applications via wired or wireless channel (e.g., Bluetooth, WUSB, or UWB) [29,30]. In our model we adopt an 802.11 wireless interface, and we assume the AU to be an application uploaded to the passenger's smartphone as illustrated in Figure 2.6.

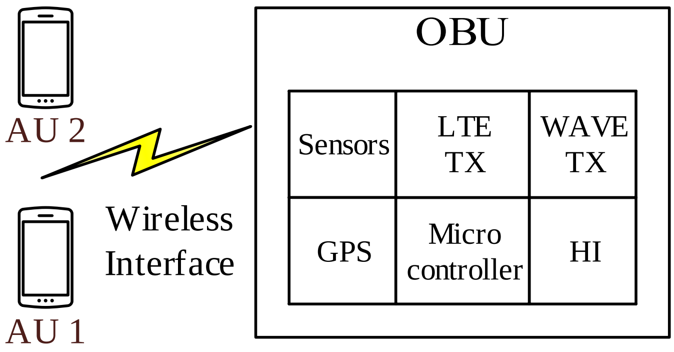

Figure 2.6 OBU architecture

The RSUs are deployed in a planned manner over a road and they communicate with each other via special links like virtual private link (VPN) or wired links. In addition, they are connected to the LTE-A network and to a service advertisement unit (SAU). The SAU is a back end server that stores advertisements used for marketing purposes, and may be managed by a third party. Each RSU has an AU, two WAVE devices and one LTE-A interface as showed in Figure 2.7. The AU in the RSU is an embedded application that resides above the WAVE and cellular protocols. Hence it is equivalent to the AU on the OBU and may make use of WAVE and LTE communication services. A first RSU WAVE radio is tuned to the control channel (CCH). Its role is to transmit a series of wave service advertisement (WSAs) that announce the presence of the discovery service and deliver the specifications of the service, including the service channel (SCH) to be used. The second WAVE radio is tuned to the SCH and executes the exchange of messages that accomplish the discovery transaction. Contrariwise, the mobile nodes have only one radio device for both safety and non-safety application by always alternating between the CCH and SCH interval and one LTE-A interface.

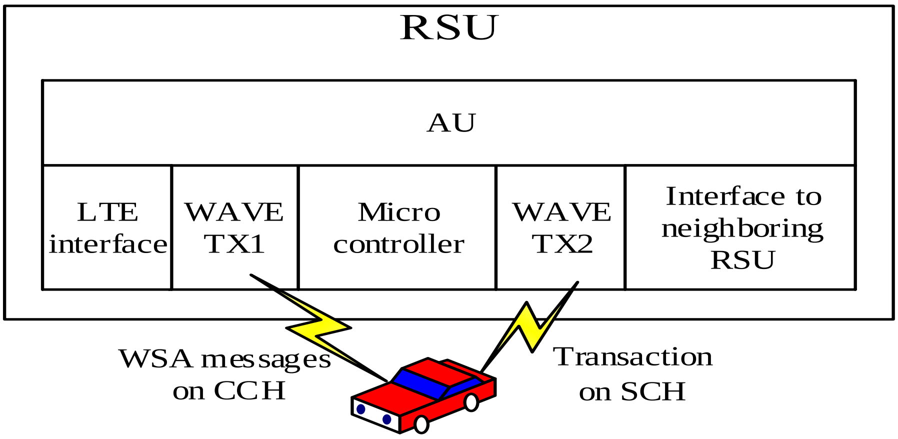

Figure 2.7 RSU architecture

In our model, we recognize two types of D2D discovery, and equivalently two AU types: “direct communication app” (AU1) and “Services discovery app” (AU2). The former aims to initiate a direct link between two users but requires a direct discovery phase. The latter app is a standalone service enabler i.e. it uses the discovery information to enable its features (e.g. "find me a Hotel", "find me a restaurant")

As a result, each vehicle within the RSU range that monitors the CCH channel for received WSAs or other safety information could play on the role of potential discoverer unit. Hence, to support the D2D discovery, we propose in our work to use the VANET network capability as specified in the discovery model detailed in the next section.

D. Proposed discovery model

The initializing phase of our protocol is shown in Figure 2.8 while the discovery transaction phase is illustrated in Figure 2.9 and Figure 2.10. As can be seen in Figure 2.8 the first step in our algorithm is to attach to the OBU through the association process, one of the MAC layer functionalities. It involves several types of packets exchange (i.e. scanning, authentication and association packets) between the OBU and the users (AUs) as proposed in [31].

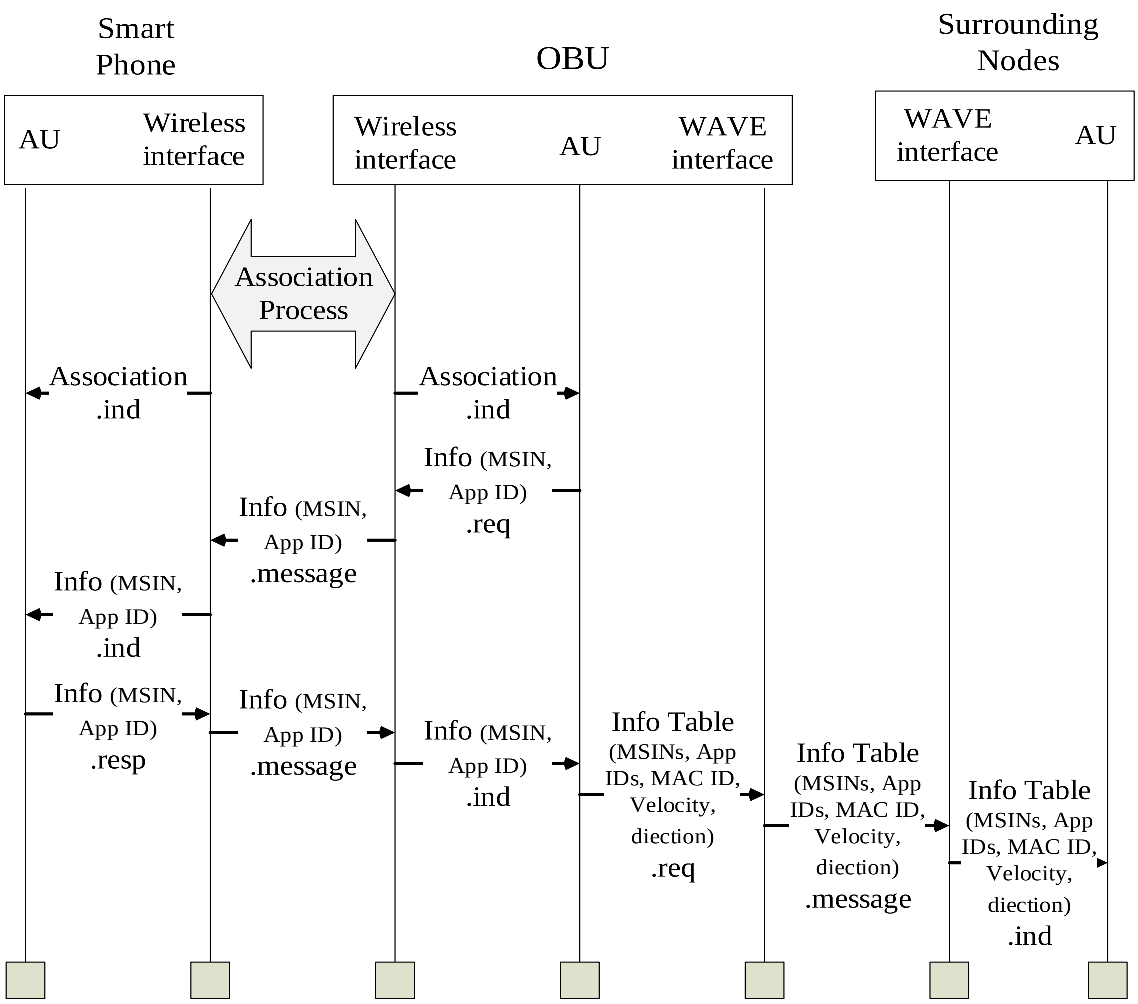

Figure 2.8 Discovery algorithm- Initialization phase

Once the passengers successfully finish the association process, the wireless interface of each node (i.e. OBU and the user's smart phone) will send a notification to the AU in each node. 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. As illustrated in Figure 2.8 the information request and response is sent and received by mean of the wireless interface in both sides. Specifically, the OBU's direct communication app requires 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 some vehicle information gathered from the vehicle's sensors and GPS like, position, velocity, acceleration, direction forming an info table. This info table will be sent periodically on CCH to the surrounding nodes by means of the wave interface. When a node receives an info table, it will save it in its own database. Thus, all the surrounding 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 [35]) requires periodically sending basic safety info including position, velocity, acceleration, direction. So the initialization step of our protocol does not add new load to the VANET. Instead, it uses the VANET architecture in a proper way to monitor the surrounding nodes.

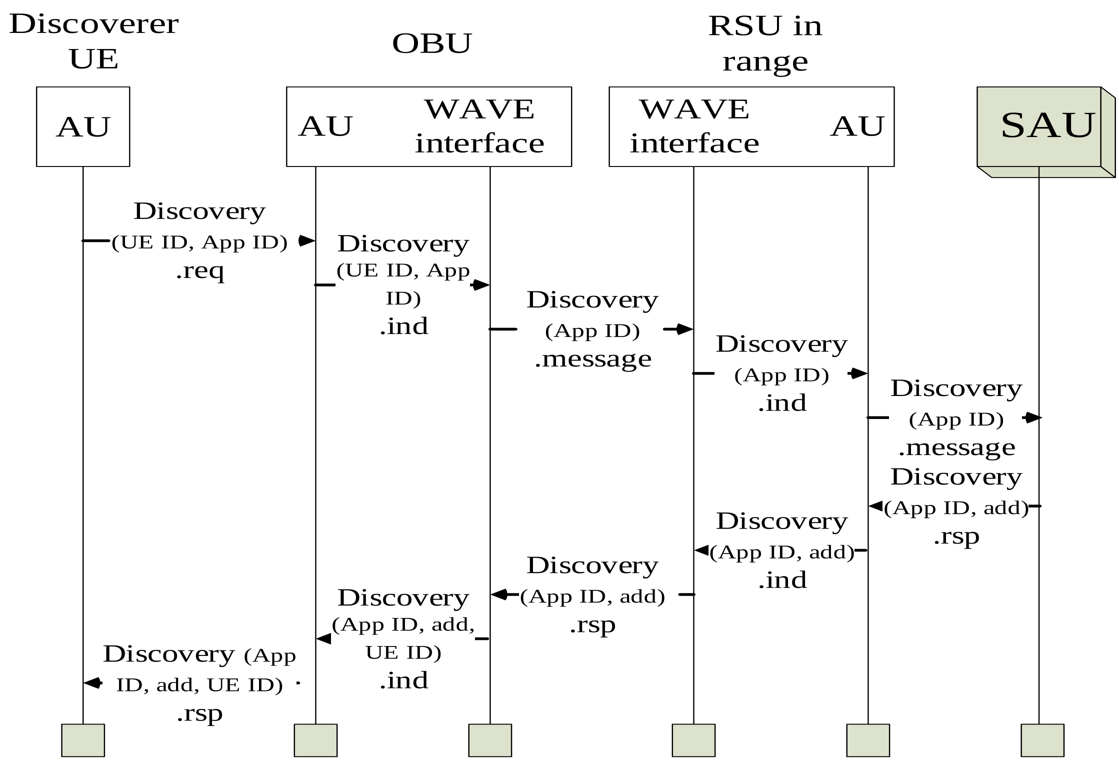

Figure 2.9 Services Discovery Process

Figure 2.9 illustrates the services discovery process. A discovery process starts whenever an OBU receives queries, i.e. discovery requests, from an AU .The services discovery request will be forwarded directly to the RSU in range via the WAVE interface. When the related AU in the RSU is notified about this request it will retrieve the required advertisement from the SAU and send it back to the OBU. Finally the OBU will deliver the discovery response to the discoverer AU which will pop up the discovery result on the UE's smartphone. Here the OBU can use a function similar to the network address translation (NAT) to deliver the response to the correct user.

When a user sends a peer discovery request (Figure 2.10), the OBU searches in its table for the discoveree ID and if no matching occurs it will send the message to the RSU in its range. Again, the RSU will search in its table for this ID. If no matching happens it will forward this request to its neighboring RSUs which will do the same work. Whenever a matching occurs, either at the OBU side or the RSU side, the related node has to calculate the expected time, using learning techniques like Kalman filter [39], the callee will remain in proximity of the caller and informs the eNodeB about this information by means of LTE-A interface. When proximity is guaranteed the eNodeB will allocate some resources and inform 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 matching occurs the direct communication application will not receive the necessary information to proceed. Hence after a given timeout it prompts the UE to switch to a regular cell call.

In our model the RSU are uniformly distributed on the road. So the vehicle will not be able to directly send the discovery request to the RSUs backbone. In such situation the carry and forward routing protocol is widely used to deliver the message [33, 34] to the desired destination. In the carry and forward routing 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 literature they adopt the broadcast approach to send the message to the intermediate nodes [33, 34]. However, this approach will lead to a broadcast storm problem especially in the high traffic volume situation because it requires to send the message to all the nodes in vicinity which in turn will carry the sent message and forward it to all their neighboring nodes until the message reaches the destination.

To avoid this problem and mitigate the load in VANET we moderate the sending approach in the carry and forward routing protocol. More precisely, in our approach the vehicle unicasts the packet to the vehicles with lowest travel time to the front and the back RSUs. The travel time is the time needed to reach the RSU and it can be easily calculated by dividing the distance to the RSU to the node's velocity. Note that, each node knows all its info about its neighbors and the RSU location can be easily retrieved from the digital map located in the vehicle. The performance of this approach will be analyzed in the next section.

The main problem however in this approach is that the intermittent RSU coverage nature on the road and the multiple level messages exchange between the different units will add delay on the discovery process, which will be modeled and thoroughly analyzed in the next chapter.

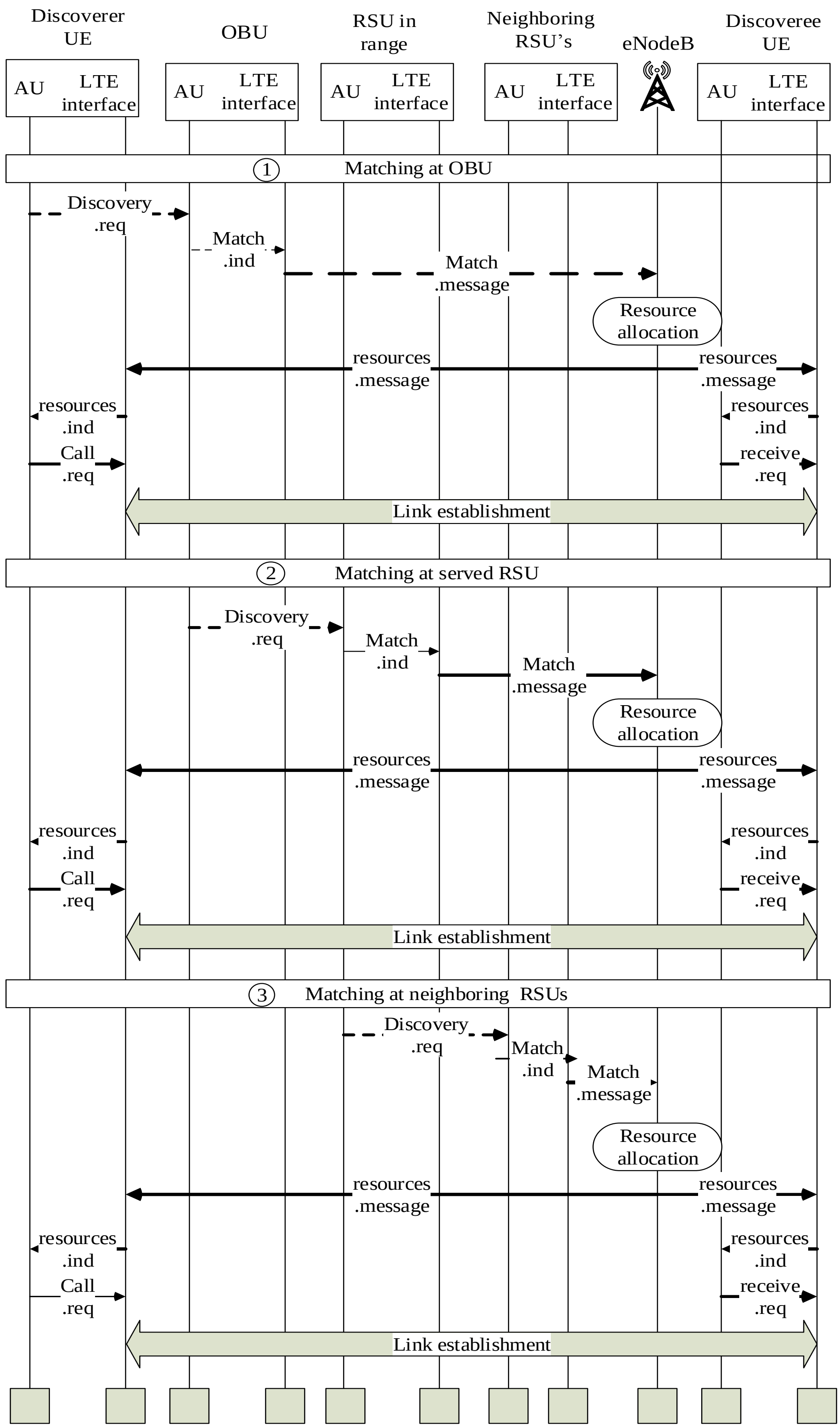

Figure 2.10 Peer Discovery Process

CHAPTER III

ANALYTICAL DELAY MODEL

In this chapter, we will develop the delay model of the proposed discovery protocol in chapter II. Let's assume a general case scenario in which *M* vehicles on a road (Figure 2.5) decide to use the VANET capability for discovery purposes. We consider a scenario where none of these *M* vehicles has found the discoveree in its info databases. Hence they must send a discovery message to the RSU. To generalize our delay model we assume that the road has discontinuity in the RSU coverage which obligates the vehicles to queue the D2D discovery message until they become within a RSU range. Hence, once vehicles enter the RSU range a contention between nodes will take place in order to access the channel. Finally, the node who get access to the channel will send the discovery request to the RSU which in turn will process the request as mentioned in Chapter II-D and deliver back the answer to the discoverer either itself (in case of services discovery) or via the eNodeB (in case of peer discovery with matching and proximity guaranteed) . As a result, the average end to end delay can be modeled as the summation of queuing, contention and answer delay.

The remainder of this chapter will tackle each one of the aforementioned delay components.

A. Queueing delay

Considering a Highway which consists of multiple lane each lane has maximum speed limit. Accordingly, vehicles that have same speed must be on the same lane. Hence, clusters will be formed on each lane when two or more vehicles are in the same range. In this section we aim to derive the average time needed to meet a RSU on a multiple lane highway. To that end, we first derive several key characteristics of VANET in such kind of environment.

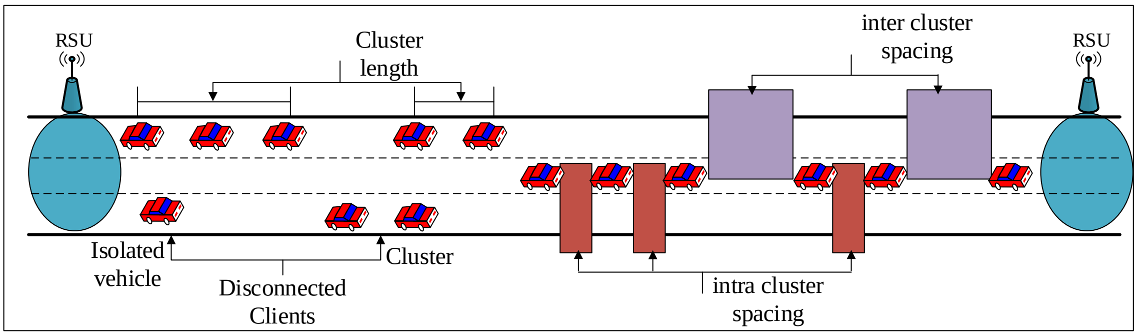

Figure 3.1 A multiple lanes highway scenario depicting several characteristics of VANET

1. ***Network Traffic Model In a Multiple Lane Highway***

Here, we aim to derive the key characteristics of disconnected VANET, including probability of being the leading vehicle in a cluster, probability of being the last vehicle in a cluster, average intra-cluster spacing, average inter cluster spacing, average cluster size, and average cluster length. These parameters will form the raw materials that enable us to derive the average queueing delay in next sections.

a. Probability of being the leading and the last vehicle in a cluster on lane j $(P_{L,j})$

The safety and the delay sensitive infotainment applications aim to deliver their messages as fast as possible. Here, the source vehicle seeking a service from the RSU or requesting to announce a warning message can generate the related message and distribute it to the cluster boundaries i.e. the leading and the last vehicles in the cluster in order to decrease the delay and the congestion on the RSU. This message cannot be spread across the cluster border until passing through vehicles become within the range of the leading or last vehicles in the cluster. In this case, the boundary vehicles will relay the message to the surrounding clusters which in turn will deliver the message to the RSU network. Thus, it is very important to analyze the probability of being the leading and the last vehicle in a cluster. We define P_L is the probability that there are no frontal vehicles and no following vehicles within the transmission range (R) of the leading and the last vehicle. To calculate P_L we must first find the inter vehicle space distribution. The study in [33] has shown that the inter vehicle space (S) in low traffic volume ($T_V < 1000\ veh/hr$) follows an exponential distribution with density (λ_s). This result was based on the well-known assumption that the inter arrival time on the road follows an exponential distribution with parameter $\lambda = \frac{T_V}{3600}$ [33, 34]. Hence, in case of multi lanes road, where the inter arrival time on each lane is exponentially distributed with parameter λ_j and the summation of their densities equal to the road density (i.e. $\sum_j \lambda_j = \lambda$), the probability density function (PDF) of the inter vehicle space on each lane is simply given by:

$$f_{S_j}\left(s_j\right) = \lambda_{s_j} e^{-\lambda_{s_j} S} \qquad (1)$$

where λ_{s_j} is the vehicles density on lane j . It is given by:

$$\lambda_{S_j} = \frac{T_{V_j}}{3600\ v_j} = \frac{\lambda_j}{v_j} \qquad (2)$$

where T_{V_j} and v_j are respectively the average traffic volume, and the average speed on lane j. The probability mass function (PMF) of the velocity can be simply derived as follows:

$$f_{\mathrm{V}_j}\left(\mathrm{v_j}\right) = \frac{\lambda_{S_j}}{\sum_j \lambda_{S_j}} \quad (3)$$

The PDF of the intra cluster space and inter cluster space on lane *j* (Figure 3.1) will be similar to those derived in [33] and they are given by:

$$\mathrm{f}_{\mathrm{S_{j,intra}}}\left(\mathrm{s_{j,intra}}\right) = \Pr\left[S_j | S_j \leq R\right] = \frac{\lambda_{\mathrm{s_j}} \mathrm{e}^{-\lambda_{\mathrm{s_j}} \mathrm{s_{j,intra}}}}{1 - \mathrm{e}^{-\lambda_{\mathrm{s_j}} \mathrm{R}}} \quad (4)$$

$$\mathrm{f}_{\mathrm{S_{j,inter}}}\left(\mathrm{s_{j,inter}}\right) = \Pr\left[S_j | S_j > R\right] = \lambda_{\mathrm{s_j}} \mathrm{e}^{-\lambda_{\mathrm{s_j}}\left(\mathrm{s_{j,inter}} - R\right)} \quad (5)$$

As a result, the probability of being the leading vehicle or the last vehicle in a cluster on lane *j* (P_{L_j}) is simply given by:

$$\begin{aligned} P_{L_j} &= \Pr\left\{S_j > R\right\} \\ &= 1 - \mathrm{F}_{\mathrm{S_j}}\left(\mathrm{s_j}\right) = e^{-\lambda_{s_j} R} \end{aligned} \quad (6)$$

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

b. Cluster length on lane j (C_{L_j})

The cluster length is the length between the first vehicle and the last vehicle in a cluster (Figure 3.1). Hence C_{L_j} is a function of the number of cluster's members (N) and $S_{j,intra}$. In particular C_{L_j} is given by:

$$C_{L_j} = \sum_{k=1}^{n-1} \left(S_{j,intra}\right)_k \tag{7}$$

where n is the number of cluster's members. Similar to [33], its PMF is given by:

$$f_N\,(n) = P_{L_j}\left(1 - P_{L_j}\right)^{n-1} \tag{8}$$

Using the low of total probability (LTP):

$$f_{C_{L_j}}\left(C_{L_j}\right) = \begin{cases} P_{L_j} & n = 1 \\ \sum_{i \in range\ of\ n} P(n = i)\ f_{C_{L_j}}\left(C_{L_j} | n = j\right) & n > 1 \end{cases} \tag{9}$$

Using the fact that the summation of independent exponential distribution with the same density leads to an Erlang distribution eq.9 can be written as:

$$f_{C_{L_j}}\left(C_{L_j}\right) = \begin{cases} P_{L_j} \\ \sum_{i \in range\ of\ n} P(n = i) \times \left(1 - e^{-\lambda_s R}\right)^{-(i-1)} \left(\frac{\lambda_{s_j}^{i-1}\, s_{i,intra}^{i-2}\, e^{-\lambda_{s_j} s_{j,intra}}}{(i-2)!}\right) \end{cases} \tag{10}$$

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

$$\mathrm{f}_{C_{L_j}}\left(C_{L\,j}\right) = \begin{cases} P_{L_j} & C_{L_j} = 0 \\ a\, e^{-bC_{L\,j}} & C_{L_j} > 0 \end{cases} \tag{11}$$

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. 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 eq.11. It is given by:

$$\mathrm{E}\left[C_{L\,j}\right] = \left(\frac{1}{P_{L_j}} - 1\right)\left(\frac{1}{\lambda_{s_i}} - \frac{\mathrm{Re}^{-\lambda_{s_i}\mathrm{R}}}{1-\ \mathrm{e}^{-\lambda_{s_i}\mathrm{R}}}\right) \tag{12}$$

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

2. ***Delay Analysis for VANET on a highway with interconnected RSUs network***

We address here the scenario where vehicles flow on a multiple lanes in a highway equipped RSUs backbone. The RSUs are uniformly distributed on the road and they are connected to each other’s and to WAN nodes. Considering the low traffic condition which leads to the VANET disconnected problem the mobile nodes between the RSUs will not be able to deliver their request messages until they encounter a RSU. Thus it is important to study the delay until a mobile node can reach RSU coverage.

In a multiple lane highway the vehicles are distributed on the lanes according to their instantaneous speed. Hence, the cluster's structure will continuously change on the road while it will be stable on each lane if and only if the inter arrival time on each lane remains constant. Therefore, it is important to study the average delay for an isolated lane as it is a necessary step to derive the average queueing time. The delay model for an isolated lane and the delay to meet the RSU will be tackled in the next subsections.

a. Delay model to reach the RSU on an isolated lane

In a highway with RSU backbone providing various types of services, a client vehicle cannot benefit from these services until it becomes into the RSU range. In this section we derive the average delay to benefit from these services considering the case where vehicles on different lanes are disconnected. Accordingly, the message only propagates on the same lane.

Definition 1. A client on an isolated lane is considered disconnected if it is not in range of an RSU. With interconnected RSUs, delay time is the average time a disconnected vehicle waits until it can contact an RSU, either by itself (single-hop) or through other vehicles in its cluster (multi-hop).

Here two main cases are identifiable:

- **Isolated client:** If the vehicle is isolated on its lane, its delay time is the time for the vehicle to contact an RSU.

- **Clustered client:** if the client is part of a cluster on a lane, its delay time is the shortest time for any member in the cluster to reach an RSU.

We now derive analytical models that characterize the delay time in each of these main cases.

1) *Isolated vehicle:* we identify the following three metrics:
    a. $\Pr[v_d]$: probability that an isolated vehicle is disconnected from an RSU,
    b. $E[T_{V,i}|v_d]$: average delay for a disconnected vehicle on lane j to reach an RSU's radio range,
    c. $\Pr[n = 1]$: probability that a vehicle is isolated, (i.e., the vehicle is not part of a cluster).

The probability $\Pr[v_d]$ that an isolated vehicle is disconnected from an RSU at the time of transmission or reception of a message is obtained in a straightforward manner from the density of RSUs and their radio range. For an RSU separation distance equal to d_{RSU}, and an RSU radio range equal to R_I, the proportion of road not covered by the RSUs' radio ranges equals the probability that, at any given point in time, a vehicle is disconnected from its nearby RSUs. It is given by

$$\Pr[v_d] = \frac{d_{RSU} - 2R_I}{d_{RSU}} \quad (13)$$

Taking into account that the RSU range is much larger than the road width, the above relation is correct for all lanes. If the vehicle is disconnected, then it must be located within the span of the road between two consecutive RSUs' radio ranges, i.e., it must be located in the area with a length of $d_{RSU}-2R_I$. Statistically, it is safe to assume that, on average, the vehicle will be located in the center of this region; therefore, the average time to reach the RSU is given by the time to traverse half the length of the lane with no RSU coverage. Hence, we can write:

$$\mathrm{E}\left[T_{V,j}|\mathrm{v_d}\right] = \frac{d_{RSU} - 2R_I}{2v_j} \tag{14}$$

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

$$\mathrm{E}\left[T_{V,i}\right] = \mathrm{E}\left[T_{V,j}|\mathrm{v_d}\right] \times \ \mathrm{Pr}\left[v_\mathrm{d}\right] = \frac{(d_{RSU} - 2R_I)^2}{2\ d_{RSU}\ v_j} \tag{15}$$

2) *Clustered clients:* as in [2] in a cluster of vehicles, it is sufficient to have a single vehicle in the cluster in range of an RSU for all vehicles in the cluster to be able to communicate with the RSU. This requires vehicle-to-vehicle multi-hop communications in the cluster. The following definition is based on this observation.

- **Definition 2.** In a highway where RSUs are deployed uniformly with separation distance of d_{RSU}, and where each RSU has a radio range R_I, if the length of a cluster of vehicles is equal to or larger than d_{RSU}-$2R_I$, then at least one vehicle in that cluster will always be directly connected to an RSU, and therefore all vehicles in the cluster are considered ‘connected’.

For clustered vehicles, we observe that the following must occur so that the delay time is not zero:

- The length of the cluster the vehicle belongs to must be less than d_{RSU}-$2R_I$. This event's probability is $P[C_L < dRSU - 2R_I]$.
- If the cluster's length satisfies the above condition, it may happen that one or more of the vehicles in the cluster are in range of an RSU in the time period where the communication is requested. We denote the probability that this event does not occur by $Pr[Cd]$.

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

$$\mathrm{P}[C_L < \mathrm{d_{RSU}} - 2\mathrm{R_I}] = 1 - \frac{1 - P_{L_j}}{e^{b(\mathrm{d_{RSU}} - 2R_I)}} \tag{16}$$

Proof of Lemma 1: Using the PDF of the cluster length i.e. eq.11 the above Lemma can be easily calculated as follows:

$$\begin{aligned} &\mathrm{P}[C_L < \mathrm{d_{RSU}} - 2\mathrm{R_I}] \\ &\qquad = \int_0^{\mathrm{d_{RSU}} - 2\mathrm{R_I}} a\, e^{-bc_L}\, dc_l = \left(1 - e^{-b(\mathrm{d_{RSU}} - 2R_I)}\right) \times \left(1 - P_{L_j}\right) \\ &\qquad + P_{L_j} = 1 - \frac{1 - P_{L_j}}{e^{b(\mathrm{d_{RSU}} - 2R_I)}} \end{aligned} \tag{17}$$

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

$$\mathrm{E}[C_L|0 < C_L < \mathrm{d_{RSU}} - 2\mathrm{R_I}] = \frac{a}{b^2} \times \frac{1 - e^{-b(d_{RSU}-2R_I)}(1 + b(d_{RSU} - 2R_I))}{(1 - e^{-b(\mathrm{d_{RSU}}-2\mathrm{R_I})})\left(1 - P_{L_j}\right)} \quad (18)$$

Proof of Lemma 2: Using eq.11 and eq.17 the above Lemma can be derived as follows:

$$\begin{aligned}
&\mathrm{E}[C_L|0 < C_L < \mathrm{d_{RSU}} - 2\mathrm{R_I}] \\
&\qquad = \int_0^{\mathrm{d_{RSU}}-2\mathrm{R_I}} c_L \frac{a\, e^{-bc_L}\, dc_L}{\mathrm{P}[0 < C_L < \mathrm{d_{RSU}} - 2\mathrm{R_I}]} \\
&\qquad = \frac{a}{b^2} \times \frac{1 - e^{-b(d_{RSU}-2R_I)}(1 + b(d_{RSU} - 2R_I))}{(1 - e^{-b(\mathrm{d_{RSU}}-2\mathrm{R_I})})\left(1 - P_{L_j}\right)}
\end{aligned} \quad (19)$$

For the cluster to be disconnected, the edge vehicles of the cluster must be in the region $[R_I; d_{RSU} - R_I]$. Therefore, by taking the center of the cluster as reference, it follows that the cluster's center must be in a region of length $(d_{RSU} - 2R_I) - E[C_L\,|C_L < d_{RSU} - 2R_I]$, otherwise one of the edge vehicles will be in range of an RSU. The cluster's center can be located anywhere in $[0; d_{RSU}]$. Therefore, the probability of a cluster being disconnected from the RSU network, $P\,[C_d]$ is given by:

$$\mathrm{P}[\mathrm{C_d}] = \frac{(\mathrm{d_{RSU}} - 2\mathrm{R_I}) - \mathrm{E}[\mathrm{C_L}|\mathrm{C_L} < \mathrm{d_{RSU}} - 2\mathrm{R_I}]}{\mathrm{d_{RSU}}} \quad (20)$$

Statistically speaking, it is correct to assume that the center of the cluster is in the middle of region [0; CI]. Thus, the shortest re-healing time is the time for the front-most vehicle in the cluster to reach the next RSU's radio range, which corresponds to a travel distance of $((d_{RSU} - 2R_I) - E\,[C_L\,|C_L < d_{RSU} - 2R_I])/2$.

The mean delay time for any vehicle in a cluster on lane *j* which is both disconnected and smaller than $d_{RSU} - 2R_I$ is given by:

$$\mathrm{E}\left[T_{C,j} | C_d \cap (C_L < \mathrm{d_{RSU}} - 2\mathrm{R_I})\right] = \frac{(\mathrm{d_{RSU}} - 2\mathrm{R_I}) - \mathrm{E}[C_L | C_L < \mathrm{d_{RSU}} - 2\mathrm{R_I}]}{2} \cdot \frac{1}{v_j} \quad (21)$$

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

$$\mathrm{E}\left[T_{C,j}\right] = \mathrm{E}\left[T_{C,j} | C_d \cap (C_L < \mathrm{d_{RSU}} - 2\mathrm{R_I})\right] \times \mathrm{P}[C_d] \times \mathrm{P}[C_L < \mathrm{d_{RSU}} - 2\mathrm{R_I}]$$
$$= \frac{\left((\mathrm{d_{RSU}} - 2\mathrm{R_I}) - \mathrm{E}[C_L | C_L < \mathrm{d_{RSU}} - 2\mathrm{R_I}]\right)^2}{2\, v_j\, \mathrm{d_{RSU}}} \left(1 - \frac{1 - P_{L_j}}{e^{b(\mathrm{d_{RSU}} - 2R_I)}}\right) \quad (22)$$

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

$$\mathrm{E}\left[T_j\right] = \mathrm{E}\left[T_{V,j}\right] . \mathrm{P}[n = 1] + \mathrm{E}\left[T_{C,j}\right] . \mathrm{P}[n > 1]$$
$$= \frac{1}{2 v_j\, \mathrm{d_{RSU}}} \left\{ P_{L_j} (\mathrm{d_{RSU}}_I - 2R_I)^2 + \left(1 - P_{L_j}\right)\left((\mathrm{d_{RSU}} - 2\mathrm{R_I}) - \mathrm{E}[C_L | C_L < \mathrm{d_{RSU}} - 2\mathrm{R_I}]\right)^2 \left(1 - \frac{1 - P_{L_j}}{e^{b(\mathrm{d_{RSU}} - 2R_I)}}\right)\right\} \quad (23)$$

b. <u>Delay model to reach the RSU on a multiple lane highway</u>

This section provides the average delay time to use the services provided by the RSU network while driving on a multiple lane's highway. Here, clusters can relay their messages by passing through lanes. For a message transmission requiring one or more gaps to be traversed, the need for re-healing happens when the leading car in a cluster has received a message and is unable to deliver the message to requested destination i.e. RSU. Using the front-most or the last vehicle as a point of reference, two main scenarios can be identified:

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

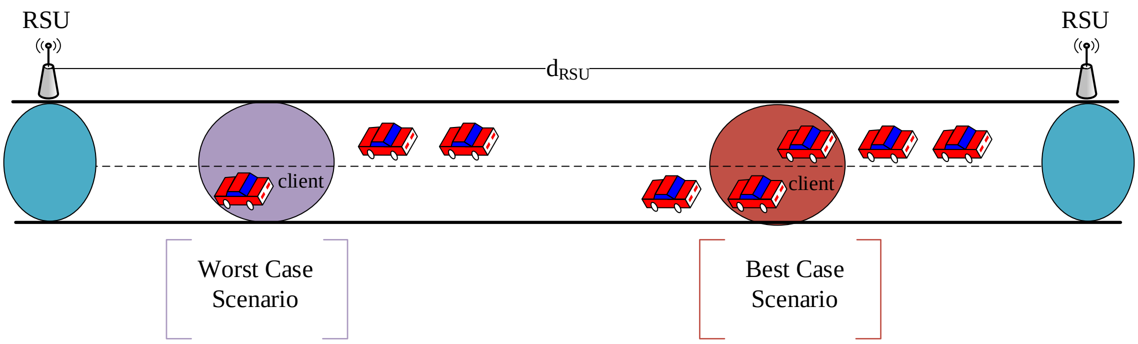

Figure 3.2 Examples of the best case scenario and the worst case scenario

We now derive the analytical models that describe the road level delay time in each of these main cases:

1) *Best case scenario*: In this case the client vehicle is disconnected and is in range to neighboring vehicles with different speed. Therefore the request message will be directly relayed to the neighboring lane. At this point, we observe that BCS could involve two different subcases: i) the source is an isolated vehicle; ii) the source belongs to a disconnected cluster i.e. (C_L<d_{RSU}-$2R_I$).

- BCS-i) In this scenario, the source is an isolated vehicle on lane *j*, disconnected from the RSUs backbone and it has a relay cluster on lane *i* within its range. The probability of this scenario is given by Lemma 3.

Lemma 3. The probability of this scenario BSC-i) is given by:

$$\mathrm{P}_{j,r_{10}} = \frac{d_{RSU} - 2R_I}{d_{RSU}} \times (1 - e^{-2R\lambda_i}) \qquad (24)$$

Proof of Lemma 3: First we derive the probability to have a relay vehicle on lane *i* within the range of the isolated vehicle on lane *j* ($\mathrm{p}^0_{\mathrm{j,relay}}$). Using the fact that the inter arrival time of the vehicle is exponentially distributed, $\mathrm{p}^0_{\mathrm{j,relay}}$ can be easily calculated using the memory less property of the exponential function.

$$\mathrm{p}^0_{\mathrm{j,relay}} = 1 - P_r(no\ vehicles\ exist\ on\ lane\ i) = 1 - \frac{(2R\lambda_i)^0}{0!} e^{-2R\lambda_i} = 1 - e^{-2R\lambda_i} \qquad (25)$$

On the other hand, the probability of an isolated vehicle to be disconnected from the RSU on lane *j* is given in eq.13. Hence Lemma 3 can be obtained by multiplying eq.13 and eq.25■

Going back to the scenario in i), the relay vehicle could be either disconnected or connected to the RSUs. In case of 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 ($P_{C_{i,d}}$) is given in eq.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 (Assume an ideal routing protocol). The probability of this event is simply the complement of the probability given in eq.20. As a result the average delay to deliver the message to the RSU using lane *i* while the client is on lane *j* is given by:

$$\mathrm{E}\left[T_{j,r_{10}}\right] = \mathrm{E}[T_i] \times \mathrm{P}_{j,r_{10}} \times P_{C_{i,d}} \quad (26)$$

- BCS- ii) In this case the client belongs to a disconnected cluster on lane *j* and it has a relay vehicle on lane *i* within its range. The probability of this scenario is given by the following Lemma.

Lemma 4. The probability of this scenario BSC-ii) is:

$$\mathrm{P}_{j,r_{11}} == \frac{d_{RSU} - 2R_I - \mathrm{E}\left[C_{I,L} | C_{I,L} < d_{RSU} - 2\mathrm{R_I}\right]}{d_{RSU}} \times (1 - e^{-\mathrm{E}\left[C_{I,L}|C_{I,L}<\mathrm{C_I}-2\mathrm{R_I}\right]\lambda_i}) \quad (27)$$

Proof of Lemma 4: Using the memory less property of the exponential function, the probability of a cluster of cars located on lane *j* having at least one relay vehicle on neighboring lane *i* ($\mathrm{p^1_{j,relay}}$).

$$\mathrm{p^1_{j,relay}} = 1 - P_r(no\ vehicles\ exist\ on\ lane\ i)$$

$$= 1 - \frac{\left(\mathrm{E}\left[C_{I,L}|C_{I,L} < \mathrm{C_I} - 2\mathrm{R_I}\right]\lambda_i\right)^0}{0!} e^{-\mathrm{E}\left[C_{I,L}|C_{I,L}<\mathrm{C_I}-2\mathrm{R_I}\right]\lambda_i} \quad (28)$$

$$= 1 - e^{-\mathrm{E}\left[C_{I,L}|C_{I,L}<\mathrm{C_I}-2\mathrm{R_I}\right]\lambda_i}$$

On the other hand, the probability of a cluster on lane *j* to be disconnected from the RSU is given in eq.20. Hence Lemma 3 can be obtained by multiplying eq.20 and eq.28■

Similar to BSC-i) the relay vehicle could be either disconnected or connected to the RSUs. In case of 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 vehicle on lane *i* to be disconnected ($P_{C_{i,d}}$) is given in eq.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 (Assume an ideal routing protocol). The probability of this event is simply the complement of the probability given in eq.20. As a result the average delay to deliver the message to the RSU using lane *i* while the client is on lane *j* is given by:

$$\mathrm{E}\left[T_{j,r_{11}}\right] = \mathrm{E}[T_i] \times \mathrm{P}_{i,r_{11}} \times P_{C_{i,d}} \quad (29)$$

2) *Worst case scenario:* WCS occurs when *a client* cannot immediately relay the message to a cluster with a higher speed. The re-healing time for this case is simply the summation of the following two delay components:

- **Temporal delay:** The time until the client comes into contact with a relay vehicle with a higher speed.
- **Spatial delay:** The time that the relay vehicle has to carry the message until it comes into *RSU* range.

Similarly to BCS, we observe that WCS could involve two different subcases: i) the client is an isolated vehicle; ii) the client belongs to a disconnected cluster i.e. ($C_L < d_{RSU} - 2R_I$).

- WSC-i) In this case, the client is an isolated disconnected vehicle and it has no relay within its range. The probability of this scenario is given in Lemma 5.

Lemma 5. The probability to have no vehicles within the range of an isolated and disconnected vehicle is given by:

$$\mathrm{P}_{i,r_{20}} = \frac{d_{RSU} - 2R_I}{d_{RSU}} \times e^{-2R\lambda_i} \tag{30}$$

Proof of Lemma 5: Using the memory less property of the exponential function, the probability of a vehicle located on lane j having no relay vehicle within its range on lane i ($\mathrm{p}^0_{\mathrm{i,0relay}}$).

$$\mathrm{p}^0_{\mathrm{i,0relay}} = P_r(no\ vehicles\ exist) = \frac{(2R\lambda_i)^0}{0!}e^{-2R\lambda_i} = e^{-2R\lambda_i} \tag{31}$$

On the other hand, the probability of a car on lane j to be disconnected from the RSU is given in eq.13. Hence Lemma 5 can be obtained by multiplying eq.13 and eq.31■

To calculate the expected time to meet a relay cluster on neighboring lane we assume the client on lane *j* to be in the middle of inter cluster gap on lane *i* ($S_{i,inter}$), Statistically speaking this is a correct assumption and it is well used in literature [1],[2]. Hence, $S_{i,inter}$ should at least be greater than 2R and the expected temporal delay for this case is given by:

$$\mathrm{E}\left[\mathrm{T}_{\mathrm{i},temp_{20}}\right] = \frac{0.5\,E\left[S_{i,inter}|S_{i,inter} > 2R\right] - R}{(v_j + v_i)} \tag{32}$$

$$= \frac{1}{\lambda_{i,s}\,(v_j + v_i)}$$

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

$$\mathrm{E}\left[T_{i,r_{20}}\right] = \left(\mathrm{E}[T_i] + \mathrm{E}\left[\mathrm{T}_{\mathrm{i},temp_{20}}\right]\right) \times \mathrm{P}_{i,r_{20}} \times P_{C_{i,d}} \tag{33}$$

- WSC-ii) In this case, the client is a member of disconnected cluster on lane *j* and it has no relay within its range. The probability of this scenario is given in Lemma 6.

Lemma 6. The probability to have no cars within the range of a disconnected cluster is given by:

$$\mathrm{P}_{i,r_{21}} = \frac{d_{RSU} - 2R_{I} - \mathrm{E}\left[C_{j,L} | C_{j,L} < d_{RSU} - 2\mathrm{R}_{\mathrm{I}}\right]}{d_{RSU}} \times \left(e^{-\mathrm{E}\left[C_{j,L} | C_{j,L} < d_{RSU} - 2\mathrm{R}_{\mathrm{I}}\right]\lambda_i}\right) \tag{34}$$

Proof of Lemma 6: Using the memory less 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 given by:

$$
\begin{aligned}
&\mathrm{p}^{1}_{\mathrm{j,0relay}}\\
&= P_r(\textit{no vehicles exist within the range of a disconnected cluster})\\
&= \frac{\left(\mathrm{E}\left[C_{j,L}|C_{j,L} < d_{RSU} - 2\mathrm{R_I}\right]\lambda_i\right)^0}{0!} e^{-\mathrm{E}\left[C_{j,L}|C_{j,L}<d_{RSU}-2\mathrm{R_I}\right]\lambda_i}\\
&= e^{-\mathrm{E}\left[C_{j,L}|C_{j,L}<d_{RSU}-2\mathrm{R_I}\right]\lambda_i}
\end{aligned}
\qquad (35)
$$

On the other hand, the probability of a car on lane j to be disconnected from the RSU is given in eq.20. Hence Lemma 6 can be obtained by multiplying eq.20 and eq.35■

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 $S_{i,inter}$ gap. Hence, $S_{i,inter}$ should at least be greater than $\mathrm{E}\left[C_{j,L}|C_{j,L} < \mathrm{C_I} - 2\mathrm{R_I}\right]$ and the expected temporal delay for this case is given by:

$$
\begin{aligned}
\mathrm{E}\left[\mathrm{T}_{\mathrm{i},temp_{21}}\right] &= \frac{0.5E\ \left[S_{i,inter}|S_{i,inter} > \mathrm{E}\left[C_{j,L}|C_{j,L} < \mathrm{C_I} - 2\mathrm{R_I}\right]\right] - \mathrm{R}}{(v_j + v_i)}\\
&= \frac{0.5\ \left(\mathrm{E}\left[C_{j,L}|C_{j,L} < \mathrm{C_I} - 2\mathrm{R_I}\right] + \frac{1}{\lambda_{i,s}}\right) - R}{(v_j + v_i)}
\end{aligned}
\qquad (36)
$$

The spatial delay is simply equal to the average delay of the relay to meet the RSU i.e. $\mathrm{E}[T_i]$. As a result the average delay to deliver the message to the RSU using a lane i with higher speed is given by:

$$
\mathrm{E}\left[T_{i,r_{21}}\right] = \left(\mathrm{E}[T_i] + \mathrm{E}\left[\mathrm{T}_{\mathrm{i},temp_{21}}\right]\right) \times \mathrm{P}_{i,r_{21}} \times P_{C_{i,d}} \qquad (37)
$$

Finally the average delay to deliver the message to the RSU will be:

$$\mathrm{E}[T] = \sum_{j\in L} \sum_{i\in L/j} \Big\{ \big\{ \big(P_{j,d} \big(E\big[T_{i,r_{10}}\big] + E\big[T_{i,r_{20}}\big] \big) + \big(1 - P_{j,d}\big) \big(E\big[T_{i,r_{11}}\big] + E\big[T_{i,r_{21}}\big] \big) \big) \big\} \times P\big[v_j\big] \Big\} \tag{38}$$

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

B. Contention delay

As we have said earlier, the contention delay caused by the competition between the vehicles in order to access the channel. The average contention delay is given by [32]:

$$E[C] = E[cw].T_{slot} \tag{39}$$

where $E[cw]$ is the average contention window, T_{slot} is the average duration of a logical slot and are equal to:

$$E[cw] = \frac{cw_{max} - 1}{2} \tag{40}$$

$$T_{slot} = P_{idle}\sigma + T_{success}P_{success} + T_{coll}P_{coll} \tag{41}$$

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 and T_{coll} is the average time of a collision event. The above parameters are provided as follows [17] :

$$P_{idle} = (1-\tau)^M \tag{42}$$

$$P_{success} = M.\tau.(1-\tau)^{M-1} \tag{43}$$

$$P_{coll} = 1 - P_{idle} - P_{success} \tag{44}$$

$$\tau = \frac{1}{E[cw] + 2} \quad (45)$$

$$T_{success} = AIFS + \sigma + \frac{L}{R} + T_{preamble} \quad (46)$$

$$T_{coll} = EIFS + \sigma + \frac{L}{R} + T_{preamble} \quad (47)$$

where τ is the probability of transmission in a given slot, *M* is the number of vehicles trying to access the channel, *AIFS* is Arbitrary Inter-Frame Space, *EIFS* is Extended Inter-Frame Space. *L* is the message size and R is the data rate.

Whenever a vehicle could not access the channel (i.e. could not transmit or receive successfully the messages) during the SCH interval, it needs to queue the message until the next SCH channel. To model this channel switching effect we introduce another parameter called MAC queuing time (Mac_q) which is the buffering time needed until the next SCH starts. The average MAC queuing time can be written as

$$E[Macq] = T_{guard} + \frac{T_{CCH}}{2} \quad (48)$$

where T_{guard} and T_{CCH} are the duration of the guard time and CCH interval respectively. Considering that all the vehicles are within the coverage of RSU the switching effect can be easily detected when $E[c]$ exceeds the typical duration of channel interval, i.e. 50ms. Hence, the switching effect can be added to $E[c]$ as follows:

$$E[c]_{new} = \begin{cases} E[c] & if\ E[c] < T_{CCH} \\ E[Macq] + E[c] & if\ E[c] > T_{CCH} \end{cases} \quad (49)$$

C. Answer delay

Considering the services discovery scenario, the RSU will extract the necessary information from the SAU and send it back to the OBU. Thus, the delay to answer back is:

$$E[T_{services\,ans}] = AIFS + T_{process} + \frac{S}{R'} + \frac{L}{R} \quad (50)$$

where $T_{process}$ is the process delay at the RSU, S is the packet size of the info request message, R and R' are the data rate between the OBU-RSU and the RSU-SAU respectively.

Now, let's consider the peer discovery scenario where no matching occurs at the OBU and the served 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

$$E\left[T_{peer\,ans}\right] = AIFS + T_{process} + \frac{L}{R} + \frac{S}{R'} + \frac{m}{R''} \quad (51)$$

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

As a result, the average end-to-end delay of peer and services discovery is equal to the sum of queuing (T_q), contention (C) and the related answer delays given in (13) and (14):

$$E\left[d_{peer}\right] = E\left[T_q\right] + E[C]_{new} + E\left[T_{peer\,ans}\right] \quad (52)$$

$$E[d_{services}] = E\left[T_q\right] + E[C]_{new} + E[T_{services\ ans}] \qquad (53)$$

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 and the answer delay depends on the RSU capability and the communication link between the nodes. Therefore in section IV we observe the effect all these aspects on the average delay and we provide both analytical and simulation results.

CHAPTER IV

SIMULATION RESULTS

In this chapter, we present our simulation results to gain insights into the performance aspects of our proposed discovery protocol. Specifically, we investigate the delay time of our protocol. To that end, we calculate the delay time of the VANET assisted discovery model presented in chapter III through simulation and analytical model (chapter IV).

A. Queueing delay

This section presents the results obtained from the analytical model proposed in chapter IV-A and the Monte Carlo simulation using NS3 [36]. 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 we extract the average queueing time needed to meet the RSUs network.

- **Network topology:** we simulate 10 km of an uninterrupted multiple lanes' highway where each lane has a specific speed level. In addition, we deploy a RSU network where the RSUs are placed at fixed intervals $d_{RSU} = 1000m$ as recommended in [34]. Vehicles on each lane are generated independently from a Poisson process. Vehicles speed is allocated according to the lane speed level.

Accordingly, our mobility model on contrary to [33] and [34] covers the overtaking aspect on highway. Furthermore, we also implement an open system model i.e. when vehicles exists the road a new vehicle is generated and get inserted on the road according to the assumed Poisson process.

- **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. The radio range of both vehicles and RSUs is set to 250m which follows the federal Communication Commission (FCC) regulation.
- **Communication model:** The communication procedure is as follows: first we locate the vehicles on each d_{RSU} then we randomly select one source on each d_{RSU} . The sources aim to communicate with the RSUs backbone. The routing algorithm is assumed to be the store-carry-forward algorithm with two different approaches. The first broadcasts the stored packet to every node in its vicinity as in [33] and [34], and the second one unicasts the packet to the vehicles with lowest travel time to the front and the back RSUs on segment d_{RSU} . Here, we assume that each vehicle knows the RSUs location from its digital map, and it periodically broadcasts its travel info (speed and location).

1. ***Validation of Lane characteristics***

Figure 4.1 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 is. However, as velocity increases the probability of being the leading vehicle increases. This is due to the fact that at high speed vehicles tend to move isolated i.e. not member of a cluster hence each one will be an isolated one-member cluster.

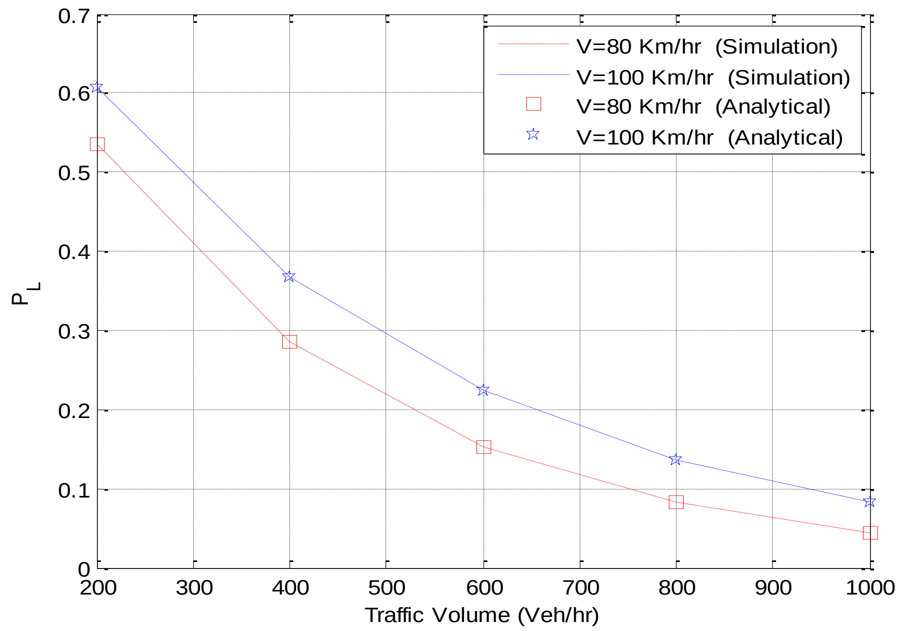

Figure 4.1 Probability of being the last or the leading vehicle in a cluster

Figure 4.2 and Figure 4.3 show the intra and inter cluster space on each lane. As the traffic volume increases both inter and intra cluster spaces decreases. However, as velocity increases, inter and intra cluster spaces increase. In addition, we observe a perfect 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 lane level, so the condition of [33] (i.e. bypassing in not allowed on the road) does not change on lane level.

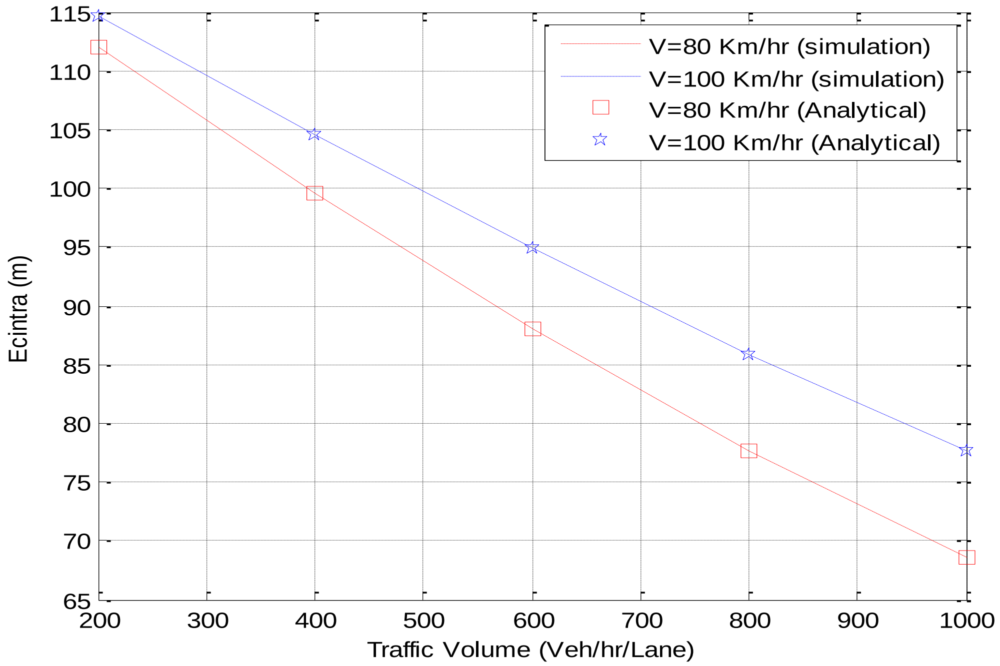

Figure 4.2 Average Intra cluster spacing

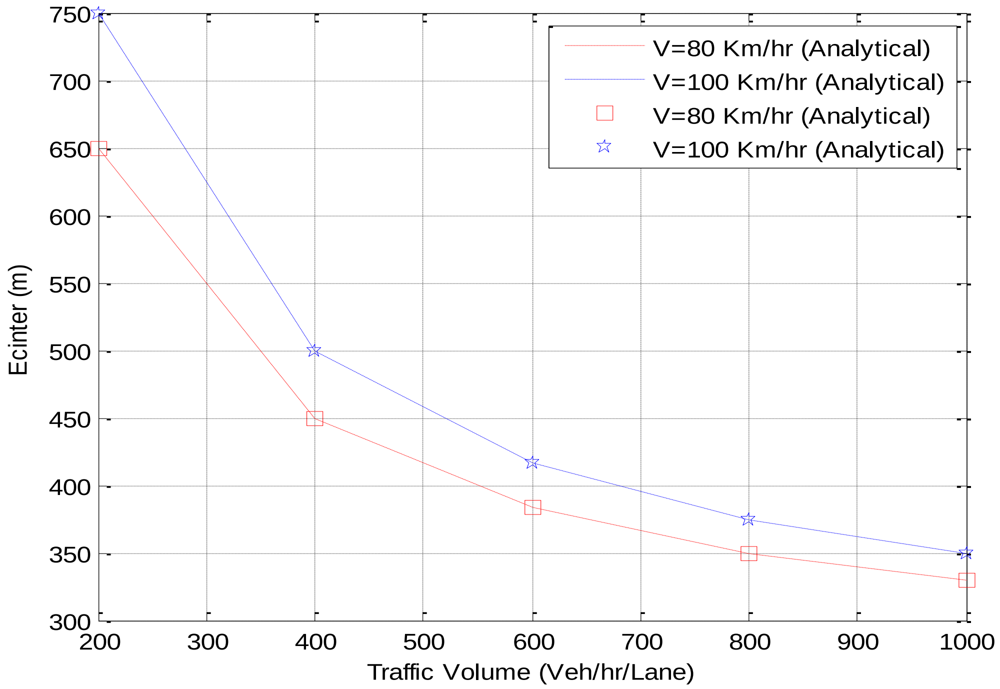

Figure 4.3 Average inter cluster spacing

The average cluster length derived in IV is shown in Figure .5.4. As can be seen, the average of cluster size increases with the traffic volume. However, as the velocity increases, the average cluster length decreases as in this case the number of cluster members decreases. In addition the excellent match between our average and the average derived in [33] makes the derived cluster length probability (Eq.11) reliable. Thus we can totally rely on it to derive the average queueing time.

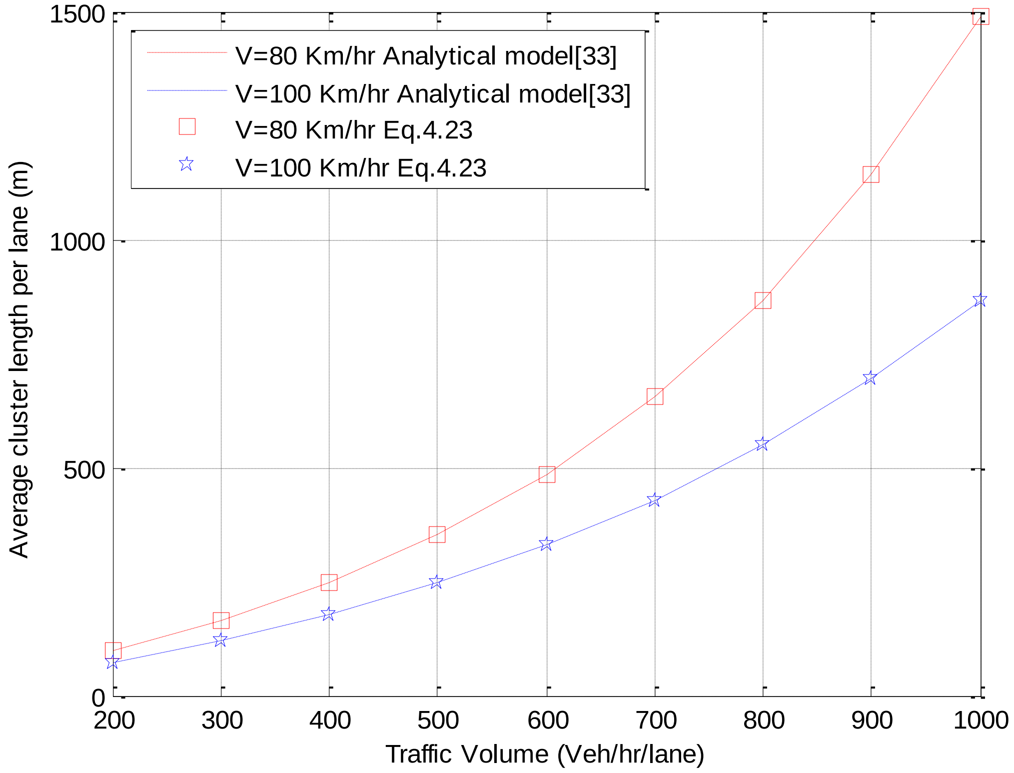

Figure 4.4 Average cluster length

2. ***Validation of the analytical model***

Figure 4.5 compares the average delay computed using the analytical model provided in IV, the analytical model provided in [34] and the simulation results. The strength of our model is clearly shown from the excellent matching with the simulation results even for high traffic volume. 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 volume increases the probability to find vehicles in the vicinity increases. In other words, when the traffic volume increases the cluster length increases. On the other hand, the shortage of the analytical model provided in [34] is clearly shown in Figure 4.5. For instance, we can conclude that this model is bounded by the low traffic volume (*TV<= 1000 veh/hr*) and cannot be used for the high traffic case. So it is expected to be highly unreliable when the number of lanes increases. This is shown on Figure 4.6 in which we have studied the effect of the number of lanes in [34] focusing on the sparse VANET situation i.e. low traffic volume (300 Veh/hr [33, 34]). As expected, as the number of lanes increases the shortage percentage increases.

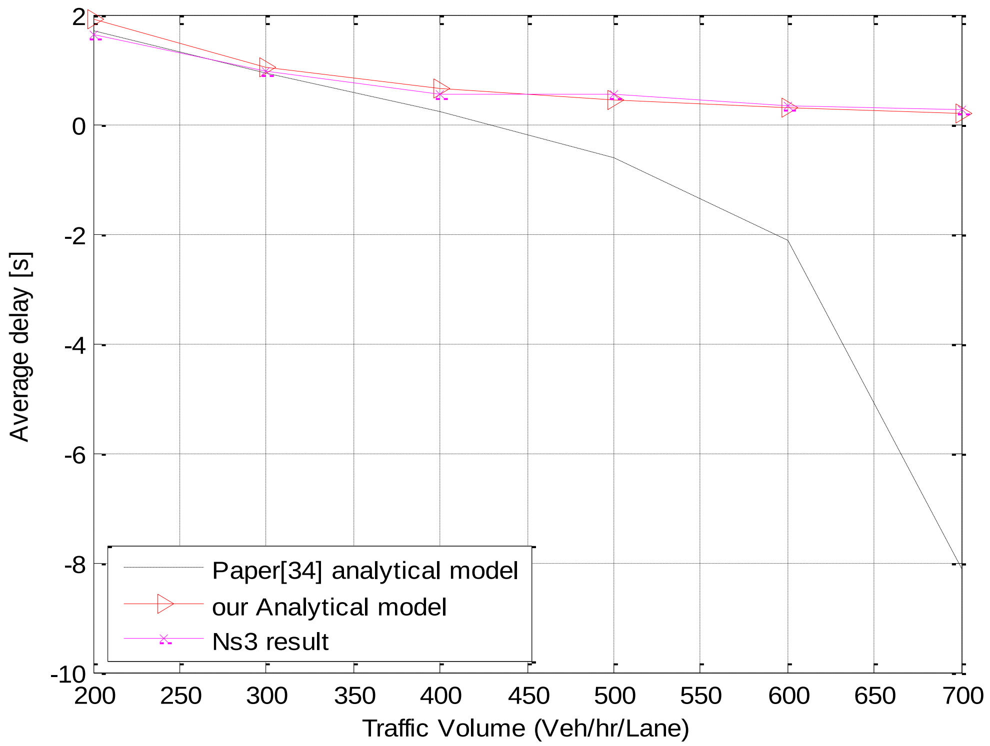

Figure 4.5 Average queueing analysis

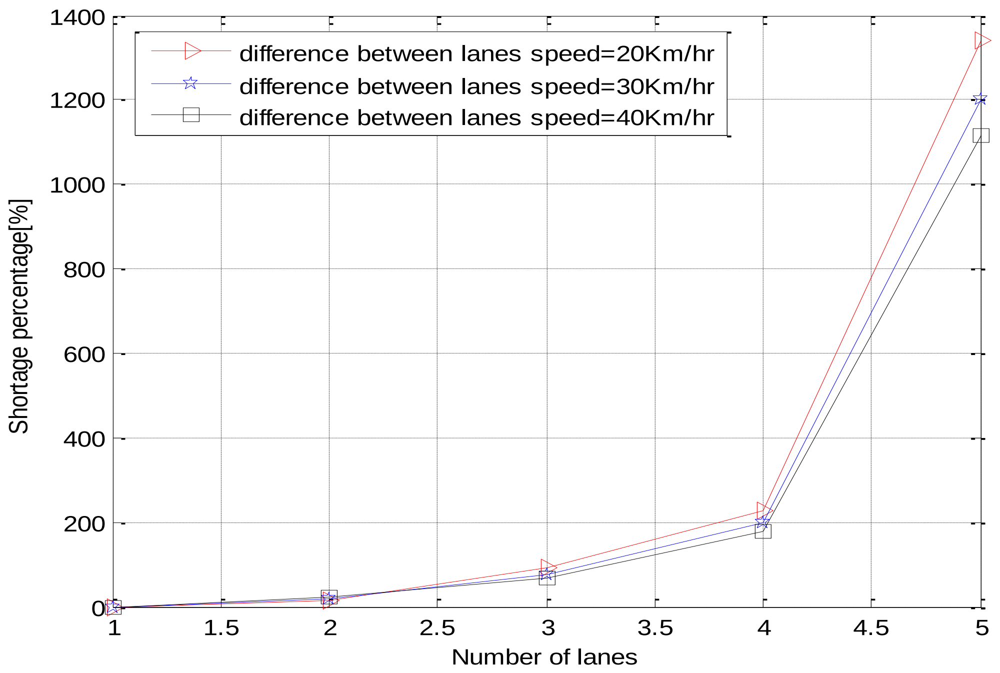

Figure 4.6 Shortage percentage of analytical model in [34]

Figure 4.7 shows the power of our simple routing approach (i.e. unicasting packets to the vehicles with lowest travel time). As can be seen the average number of packets needed to reach the RSUs network in the unicast approach is almost stable (2 packets) while in the broadcasting approach it increases with the increasing of the traffic volume. In other words, the unicast approach reduces the number of packets in the network. Thus it can be used to avoid the congestion and the broadcast storm problems.

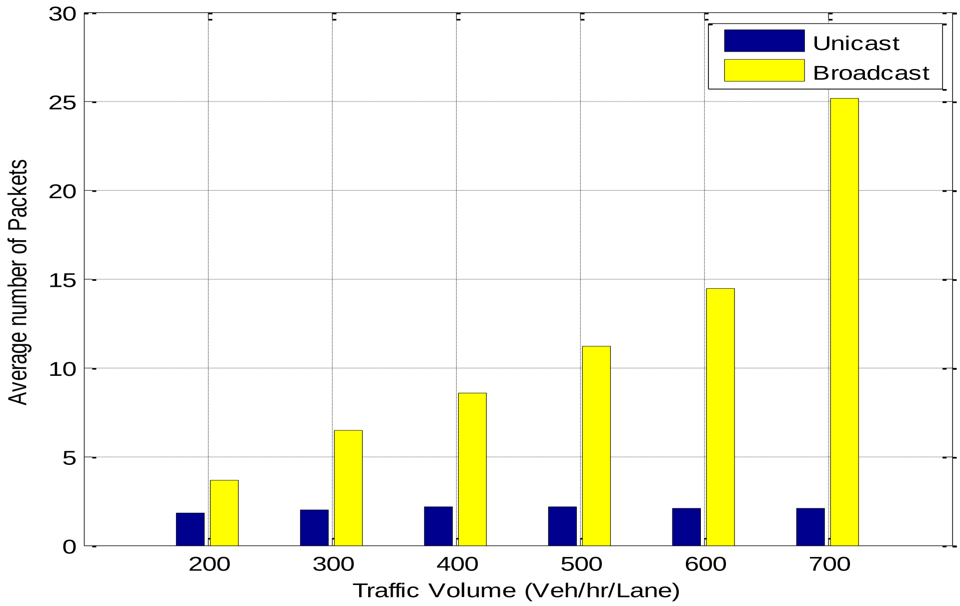

Figure 4.7 Comparison between the unicast and the broadcast routing approaches

B. Contention delay

1. *Analytical model*

In this section, we firstly evaluate the delay expression given in the previous section. Table 4.1 gives a summary of the parameters considered in our work and the four access categories (AC): Voice (VO), Video (VI), Best effort (BE), and Background (BK) as defined in the IEEE standard [31].

Table 4.1 Simulation Parameters

Access category [AC]	CWmax	AIFSN [AC]	AIFS[AC]	$SIFS + AIFSN[AC_i].\sigma$
VO	7	2	SIFS	32 μs
VI	15	3	EIFS	188 μs
BE	1023	6	$P_{reamble}$	40 μs
BK	1023	9	R	6 Mbps

Figure 4.8 shows the effect of the traffic type and packet size (L) on the average delay. As we can see in Figure 4.8a) the average delay time for the BK and BE access categories increases linearly with the number of vehicles. However, for the other two priorities, the average delay remains below 50ms in all cases. Notice that, the 802.11p standard [35] gives the WSA message the higher priority (VO). Hence, the delivery of D2D services will be guaranteed for all the vehicles. On the other hand, the infotainment messages like discovery messages have the lower priority (BK). Figure 4.8b) shows the effect of message size on the overage delay of discovery messages. As can be seen, when L increases the average delay also increases. In case of L=1000 bytes the SCH interval was not sufficient for answering back all the requests. Hence an addition buffering time Mac_q is needed until all the vehicles get their ACK.

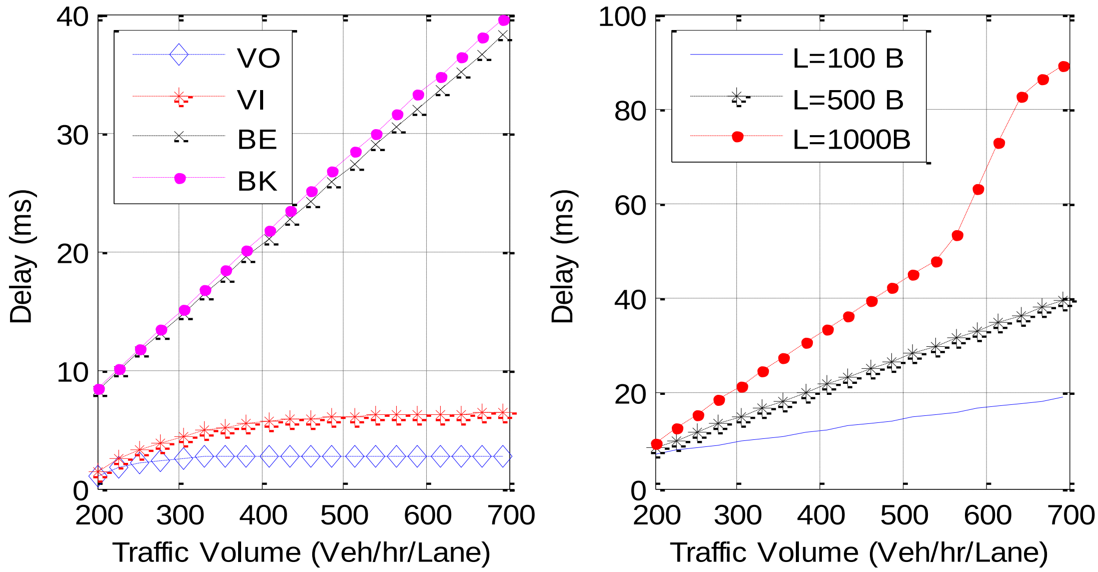

Figure 4.8 Effect of the traffic type and packet size on the average delay (Lanes=5)

Here it is worth mentioning that the number of vehicles that are within the RSU transmission range at the same time ranges from 1 to 40. Figure 4.8 depicts the relation between the number of vehicles in the RSU range, the traffic volume and the number of lanes.

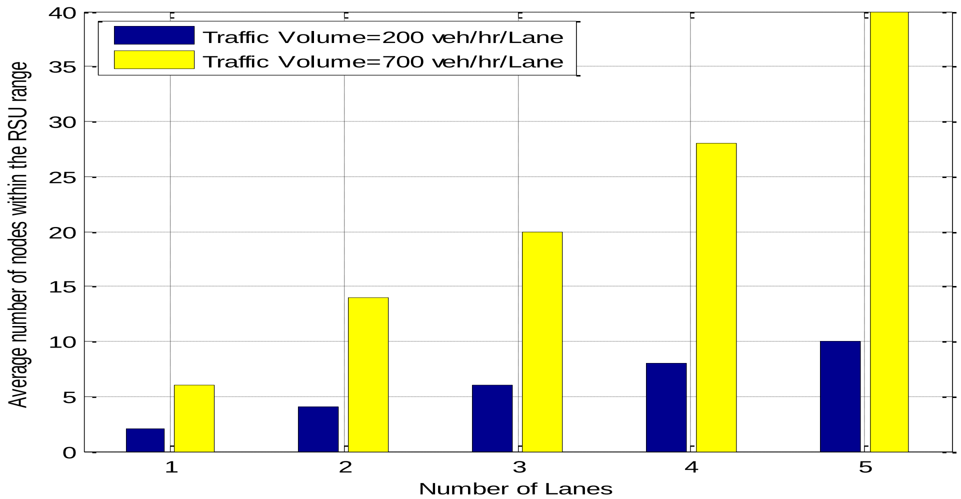

Figure 4.9. The average number of vehicles that are in the RSU range

2. ***Simulation model***

To validate our model, we provide in this section experimental results using the network simulator 3 (NS3)**.** We consider two types of mobility models. The first one is a realistic model generated using the Simulation of Urban Mobility traffic simulator (SUMO) [37]. The underlying roads map, which was used in SUMO to generate the movement file for the vehicles, consists of a 1Km highway, and is illustrated in Figure 4.10. The second one is the synthetic Random Way Point (RWP) model, which is a well-known mobility model. It is typically used to model pedestrian mobility, but nonetheless, it was used previously to generate experimental mobility results in VANET scenarios, such as the one in [38]. Table 4.2 summarizes the parameters considered in our simulations.

Table 4.2 NS3 simulation parameters

Simulation time	10 s
RSU coverage	disconnected
Number of vehicles	1 to 40
IEEE standard	802.11p and 1609.4
Mobility model	RWP and SUMO
Delay type	MAC and Physical delay

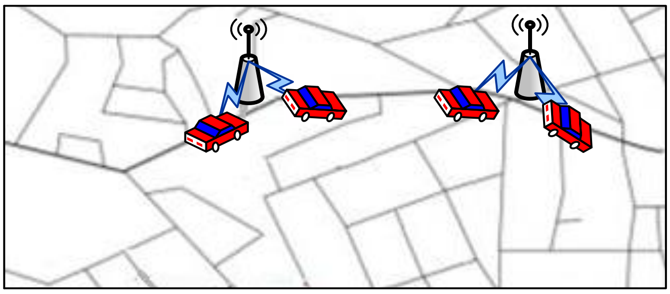

Figure 4.10 Road map used in the simulation

Figure 4.11 a) shows that the average delay of discovery messages increases linearly as the number of vehicles that attempt to access the channel increases. Same conclusion could be driven on the effect of the packet size. In addition, we can see that both RWP and realistic mobility have almost the same effect. The packet delivery ratio (PDR) of the above scenarios are given in Figure 4.11 b). As expected when the number of vehicles increases the contention also increases. Hence each node will retransmit its packet until it receives an ACK from the receiver. Therefore the PDR will decrease as the number of nodes increases. Figure 4.11 b) clearly shows this fact. In addition this figure shows that the SUMO mobility traces and the RWP mobility model have almost the same performance.

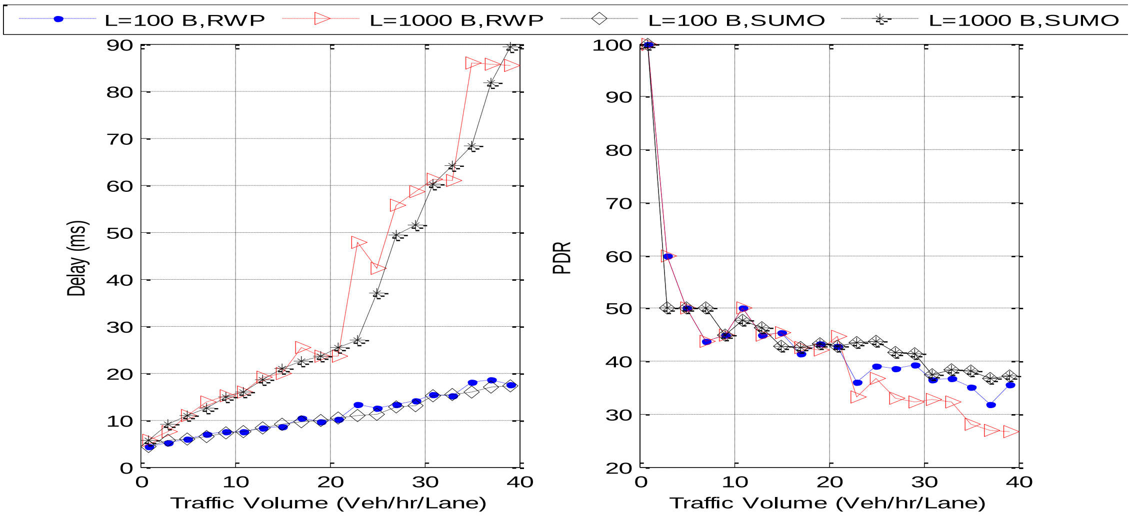

Figure 4.11 Average delay and PDR versus the number of cars

Figure 4.11 assumes that all the vehicles transmit their packets at the beginning of SCH channel i.e. at 50ms. To see the effect of the alternation between channels on the average delay, we create another scenario, shown in Figure 4.12. In this scenario, a fixed number M of vehicles try to access the channel at all possible times between 0 and 100ms. In this figure, it is worth mentioning that the time from 0 to 50ms corresponds to CCH interval while the rest is for SCH. From II, the vehicles are not allowed to perform any D2D transaction during the CCH interval. Hence if a discovery request reached the MAC entity during CCH interval, it will be buffered until beginning of SCH interval. As a result the average delay will decrease as we move toward the SCH channel. This aspect is clearly shown in Figure 4.12 during the CCH interval i.e. between 0 and 50ms. Figure 4.12 also clarifies the effect of channel hopping and the number of nodes on the average delay.

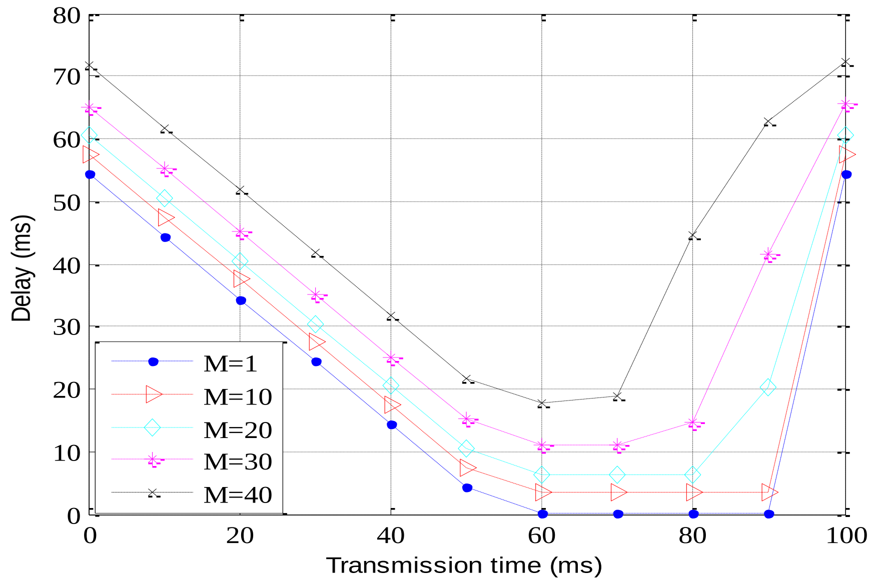

Figure 4.12 Effect of transmission time on the average delay.

Indeed, when the number of vehicles is small the switching effect only appears at 100ms and that is because at this point all the vehicles must switch to CCH channel. As *M* increases the switching effect appears in more points as the contention delay becomes higher and, the SCH interval will not be sufficient for all vehicles. A number of vehicles that fail to access the channel during the SCH interval will have to buffer their packets until the beginning of next SCH.

Finally, to validate our analytical delay model we compare with simulation results obtained through NS3. Assuming that the transmission is at the beginning of SCH, Figure 4.13 shows that the analytical model matches the simulations results and proves the proposed algorithm.

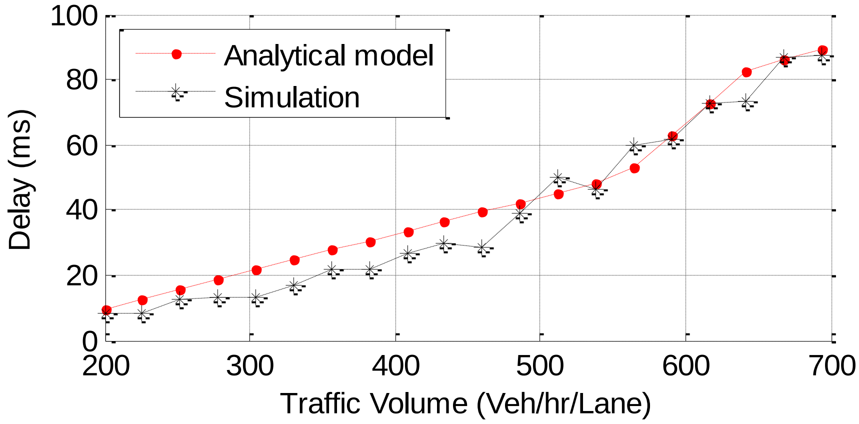

Figure 4.13 Comparison of Analytical delay model with simulation (L=1000B, SUMO, Lanes=3)

3. ***End to End delay***

After validating the analytical model of the contention and the queueing delay, we discuss now the average end to end delay on a multiple lane road. The average total delay is the summation of the queueing, contention and answer delay. In order to model the answer delay we add a conservative 30ms [34] processing delay at the RSU and the eNodeB. Figure 4.14 shows the average total delay for the discovery protocol. As can be seen the delay of the discovery process ranges from 0.3 to 2s which in turn shows the significance of our protocol.

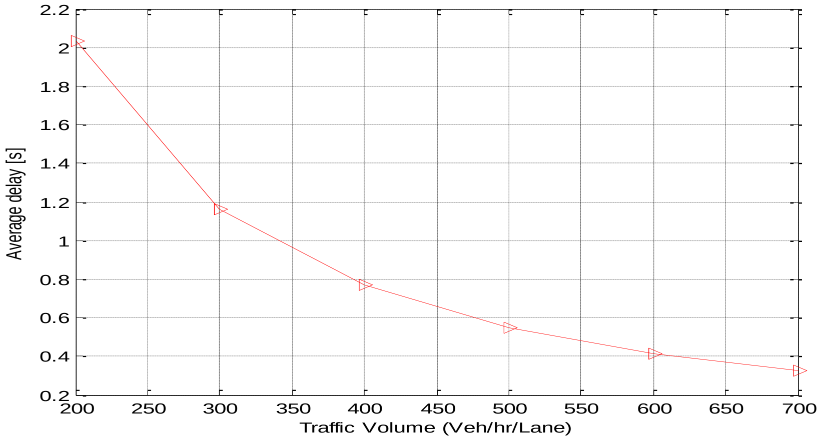

Figure 4.14 Average delay for the VANET aided discovery protocol

CHAPTER V

CONCLUSION

In this thesis we have proposed a new D2D discovery scheme based on the VANET network. In our work we suggested to use the RSUs' capabilities for discovery process. To that end, we proposed new schemes related to the OBU architecture, and its association with the passengers. In addition, we proposed a new routing approach based on the carry and forward protocol which hugely decreases the amount of traffic generated by our protocol and helps avoiding the broadcast storm problem. The proposed protocol mitigates the requirement of additional cellular resources and reveals part of the load from the cellular network. In addition, our protocol does not add new load to the VANET. Instead, it uses the VANET architecture in a proper way to perform the discovery process.

Furthermore, we have developed a mathematical model to analyze the latency of our discovery protocol which is validated through extensive simulations using NS3. Our analytical model has perfect match with the simulation result even at a high traffic volume scenario on contrary to the models proposed in literature. The analytical and numerical results demonstrate the effectiveness of the proposed protocol and show that a low latency could be reached without using additional cellular resources or increasing the load on the cellular network.

For future work, we will study our delay model in a realistic highway by allowing lane changing. In addition, a study on how we can integrate our protocol within the 3GPP network must be performed i.e. we will propose a framework that includes all the necessary messages and protocols to integrate our discovery approach in the 3GPP ProSe standards. Furthermore, the security aspect of our protocol will be under investigation in our future work.

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