Relay Selection for Heterogeneous Transmission Powers in Connected Vehicles

by

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Thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the requirements
For the Ph.D. degree in
Electrical and Computer Engineering

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Abstract

It is widely believed that the advances of Vehicle-to-Vehicle (V2V) communications will help to remodel the prospect of road transportation systems. By virtue of V2V communications, information generated by the vehicle control system, on-board sensors or passengers can be effectively disseminated among vehicles in proximity, or to vehicles in multiple hops away in a vehicular ad-hoc network (VANET). Without assistance from any built infrastructure, a variety of active road safety applications (e.g., Vehicle-Based Road Condition Warning, Cooperative Collision Warning, Approaching Emergency Vehicle Warning) and traffic efficiency management applications (e.g., Wrong Way Driver Warning) are enabled by inter-vehicle wireless links. The purpose of connecting vehicle technologies is to improve road safety, awareness, and transportation systems efficiency.

The Wireless Access for Vehicular Environments (WAVE) technology/Dedicated Short-Range Communications (DSRC) is the main enabling wireless technology for both V2V and vehicle-to-Infrastructure (V2I) communications. From USDOT and stakeholders detailed analysis, it is resolved that WAVE is the only viable option for critical safety and other low latency mobility and environmental applications. WAVE technology has reached to a mature stage and a basic V2V system is expected to be deployed in the next few years. In the late part of 2015, USDOT announce that WAVE is sufficiently robust to proceed with the preparation for deployment of connected vehicle environments. The USDOT has created a roadmap with preliminary plans to guide industries and public agencies implementation efforts. However, there are persisting major concerns regarding the V2V initiative needing more analysis and testing. One of the concerns is the channel congestion. Channel congestion may impact WAVE effectiveness, which may in turn impact the effectiveness of supported safety applications. Suggested solutions to mitigate congestion are focused on supporting adaptive control of the message transmission power. The Institute of Electrical and Electronics Engineers (IEEE), and European Telecommunications Standards Institute (ETSI) have included transmit power component per packet to be used for channel congestion control mechanism. The adjustment of transmission powers has created an environment of vehicles with different transmission powers. Such environment will affect the performance of the proposed protocols to disseminate warning messages. It may also affect the performance of periodic beaconing that is required by most of the safety applications. Thus far, several protocols have been proposed to help identify appropriate relay vehicles. However, such approaches neglect the fact that vehicle transmission ranges are typically heterogeneous due to different transmission power values or dynamic adjustment of power to alleviate congestion. The proper selection of relay nodes governs high delivery ratio, acceptable overall end-to-end delay and efficient bandwidth usage. In this work, area-based relay selection protocols that work in heterogeneous transmission powers are introduced. Mathematical functions are developed for a timer and decision probability to be used by each vehicle receiving the message. The values of the two functions allow the vehicle to determine if it is the next to act as relay node or not. Geometric taxonomy for all possible overlap patterns in wireless environment is constructed with the related math calculations. Moreover, an adaptive expiry time for neighbours-table entries that harmonizes with dynamic beacon scheduling is proposed.

Table of Contents

List of Figures

List of Tables

Nomenclature

List of Abbreviations

ADT	Area Defer Transmission
$ADTr$	Area Defer Transmission with Retransmission of Redundant Received message
APT	Area-based Probabilistic Transmission
APT_t	Area-based Probabilistic and Timer-based Transmission
$APTr$	Area based probabilistic approaches with Relaying Redundant Received message
AIFS	Arbitration Inter-Frame Space
BSM	Basic Safety Message
C-ITS	Cooperative Intelligent Transport Systems
CBP	Channel Busy Percentage
CCH	Control Channel
CV	Connected Vehicle
CW	Contention Window
DCC	Decentralized Congestion Control
DGPS	Differential Global Positioning System
DIFS	Distributed coordination function Inter-Frame Space
DSRC	Dedicated Short-range Communications
EDCA	Enhanced Distributed Channel Access
ETSI	European Telecommunications Standards Institute
EU	European Union
FCC	Federal Communications Commission
FMCSA	Federal Motor Carrier Safety Administration
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile communications
IEEE	Institute of Electrical and Electronics Engineers
ITS	Intelligent Transportation Systems

IVN	In-Vehicle-Networking
LTE	Long-Term Evolution
MAC	Media Access Control
MIB	Management Information Base
NHTSA	National Highway Traffic Safety Administration
OBU	On Board Unit
PSID	Provider Service Identifier
RSU	Roadside Side Unit
SAE	Society of Automotive Engineers
SCH	Service Channel
SUMO	Simulation of Urban MObility
TPID	Transport Protocol Identifier
USA	United States of America
USDOT	United States Department of Transportation
VANETs	Vehicle Ad-hoc Networks
VSCC	Vehicle Safety Communications Consortium
WAVE	Wireless Access for Vehicular Environments
WHO	According to the World Health Organization
WiMAX	Worldwide Interoperability for Microwave Access
WSMP	WAVE Short-Message Protocol
XML	Extensible Markup Language

List of Symbols

$(\bar{x}_i, \bar{y}_i)$	actual position coordinate for vehicle i
$(\breve{x}_i, \breve{y}_i)$	virtual position for vehicle i
(x_i, y_i)	position coordinate for vehicle i with error
(x_{ij1}, y_{ij1})	coordinates of intersections between the two transmission area of vehicle v_i, and vehicle v_j
β	the maximum allowed transmission range
δ	uniform random variable within DIFS
γ	the allowed minimum transmission range
$\hat{A}_k$	potential new coverage area for vehicle i
μ	Gaussian distribution mean for the error in vehicle position
σ	Gaussian distribution standard deviation for the error in vehicle position
τ	deferred time
θ_i	the angle of the circle sector of vehicle v_i transmission range inside neighbour vehicle
ϑ_k	the orientation of vehicle k
A_i	transmission area for vehicle i $(\pi * R_i^2)$

A_{ijk}	common overlapped area between vehicle i, vehicle j and vehicle k
A_{ijk}	common overlapped area between vehicle i, vehicle j, and vehicle k
A_{ij}	common overlapped area between vehicle i and vehicle j
$ADR(f)$	the additional delivery ratio achieved by relaying the $f-1$ copy of the message
d_{ij}	distance between vehicle i and vehicle j
$d_{ik[1,2]-j}$	the distance between the two intersection points of R_i with R_k and the center of R_j
P	retransmission probability
R_i	transmission range for vehicle i
S_i	the area of circle sector of vehicle v_i transmission range that overlapped with other vehicle
s_k	the speed of vehicle k
T_{max}	maximum defer time

Chapter 1

Introduction

1.1 Overview

Governmental organizations all over the world have recognized the need to reduce fatalities and serious injuries that result from vehicle crashes, as well as the need to reduce traffic congestion. According to the World Health Organization (WHO), about 1.25 million people die each year as a result of road traffic crashes. Between 20 and 50 million more people are injured or disabled every year [2]. This cost most countries approximately 3% of their gross national product. This rises to 5% in some low and middle-income countries. The demand to improve road safety, awareness, and efficiency of the transportation systems was the motivated reason of creating wireless communication technology to enable vehicles to exchange data between each other and road infrastructure. This wireless communication technology is required to operate in a highly dynamic environment with high relative speeds between transmitters and receivers. It is also required to support extremely low latency in the safety-related applications to provide accurate status about surrounding environments and exact positions for neighbouring vehicles. Also, it should ensure high reliability under challenging vehicular environment characteristics.

United States of America (USA) is one of the leading countries in this field. On July 6, 2012, President Obama signed into law a two-year transportation reauthorization bill, the Moving Ahead for Progress in the 21st Century Act (MAP-21) (Public Law 112-141). This new law includes lots of important provisions intended to assist the Federal Motor Carrier Safety Administration (FMCSA) in its important mission to reduce crashes, injuries and fatalities involving large trucks and buses [3]. Part of this law (Section 53001-53006) is dedicated to Intelligent Transportation Systems (ITS) activities. The objective of this part is to facilitate, in cooperation with the motor vehicle industry, the introduction of vehicle-based safety enhancing systems, and to support the application of intelligent transportation systems that increases the safety and efficiency of commercial motor vehicle operations. In addition, this law ensures a system approach that includes cooperation among vehicles, infrastructure, and the users. The possibility to reduce crashes in USA brought about the focus on a set of critical crash V2V safety applications.

Other regions of the world such as the European Union (EU), Japan, South Korea, Australia, and Canada also participate in the ITS solutions. However, their priorities are reflected by the market needs. For example, the priorities of the EU include sixteen applications for driver safety advisories (such as, Road work warning), traffic efficiency management (such as, Regulatory/contextual speed limits), and commercial applications (such as, Insurance and financial services). These applications are defined according to responses received from a questionnaire distributed to stakeholders active in ETSI and ISO ITS standards development and in EU ITS projects [4]. In Japan the initial focus of the government is on adopting the electronic toll collection system.

Thus, vehicular wireless communication technology should also enable a wide variety of applications from safety applications to entertainment. To facilitate the provision of wireless access in vehicular environments, new wireless technology with dedicated spectrum is allocated for use by the Intelligent Transportation Systems (ITS). This technology is called WAVE (Wireless Access for Vehicular Environments) or dedicated short range communications (DSRC) technology or some times V2X, which is dedicated to vehicular applications. WAVE consists of multiple cooperating standards from the Institute of Electrical and Electronics Engineers (IEEE), and the Society of Automotive Engineers (SAE). The WAVE standards consist of IEEE 802.11p, IEEE 1609/1/2/3/4,SAE J2735, and SAE J2945 standards. The IEEE and SAE standards related to WAVE architecture have international scope. However, it has been developed in close coordination with U.S. automotive and governmental strategic plans [5].

In July 2015, the United States Department of Transportation (USDOT) announced that no other wireless technology has proven the ability to provide all of the critical attributes that is needed to support V2V and V2I safety applications like WAVE. The USDOT revealed that DSCR/WAVE is adequate to proceed with the preparation for deployment of connected vehicle environments. The National Highway Traffic Safety Administration (NHTSA) estimates that V2V, which is based on WAVE technology, has the potential to address approximately 80% of multi-vehicle crashes. This is in turn will save thousands of lives and billion of dollars. The analysis conducted shows that for just two applications, intersection movement assist and left turn assist, there could be a 50% reduction, on average, regarding crashes, injuries, and fatalities [6, 7].

However, there are some major concerns for the V2V initiative that need more analysis and testing. One of the concerns is the channel congestion. Channel congestion may impact WAVEs effectiveness, which may in turn impact the effectiveness of supported safety applications and services. Two algorithms for congestion mitigation are under consideration by NHTSA. One of the algorithm supports the adaptive control of the message transmission rate and transmission power [7]. This is beside the fact that transmit power element is defined in WAVE Short Message Protocol (WSMP) packet to directly control radio parameters [8,9]. European Telecommunications Standards Institute (ETSI) also has include transmit power control (TPC) per packet as a component of the decentralized congestion control (DCC) mechanisms for the channels of ITS station [10]. The dynamic adjustment of transmission power will create heterogeneous transmission powers environments.

1.2 Challenges

In light of the aforementioned discussions, the adaptive control of the transmission power to mitigate congestion will create heterogeneous transmission powers and accordingly heterogeneous transmission ranges. The difference in the transmission powers/transmission ranges could affect the selection of the proper relay vehicles to retransmit the messages, which consequently impact the effectiveness of disseminating the messages to the targeted vehicles. The Vehicle-to-Vehicle (V2V) multi-hop data dissemination has been considered a promising technology to support safety-related applications that have strict quality-of-services requirements such as low latency, high-reliability, and scalability. It is based on a wireless medium that is an error-prone with scarce resources. Especially in dense environment that have many vehicles compete for the wireless medium. This performs a challenge to efficient relay selection approach. Relay selection process is required to eliminate message redundancy. This is achieved by suppressing useless transmission, but at the same time ensure high reception of a message by all vehicles within the required distance.

The high speed and mobility of vehicles is another challenge to relay selection protocol. This means the communication period between these vehicles can be lasting only a short time. Therefore, relay selection process should be fast enough to allow the relay nodes to retransmit the message within a strict time in order for it to be of benefit to the ITS applications. Improper timing may cause information to be outdated or delayed. Delay constraint is crucial to most connected vehicle applications. Many of the vehicle safety application scenarios require having latency of the range of 100 milliseconds. Maximum delay is critical for such application to avoid accidents in order to safe life.

Another interesting challenge is the non-uniformity in vehicle density, where the density is highly variable regarding time and space. It varies throughout time of the day, for example, the density reaches high level during the rush hours, while it is sparse at other time of the day especially highway scenarios. The places also has impact on density value, for instance, vehicles are densely packed at the middle of intersection, a road gradient, on/off-ramp in urban areas etc. As a consequence, network will suffer from low packet reception rate due to either intermittent connectivity in sparse environments or due to congestion/overhead during high density. In other words, if warning message is disseminated to avoid critical accident or hazardous situation it may not get to all vicinity vehicles. Hence, relay selection should be scalable to traffic density and ensure all vehicles in the dedicated distance receive the message.

1.3 Motivations

Relay selection protocols reported in the literature generally assume an equal maximum transmission range for all vehicles in the network. Whereas, vehicle transmission ranges are typically heterogeneous owing to the different transmission power values. Difference in transmission power values may occur also due to the dynamic adjustment of transmission power for vehicles to prevent congestion in high density networks such as [11–15]. ETSI

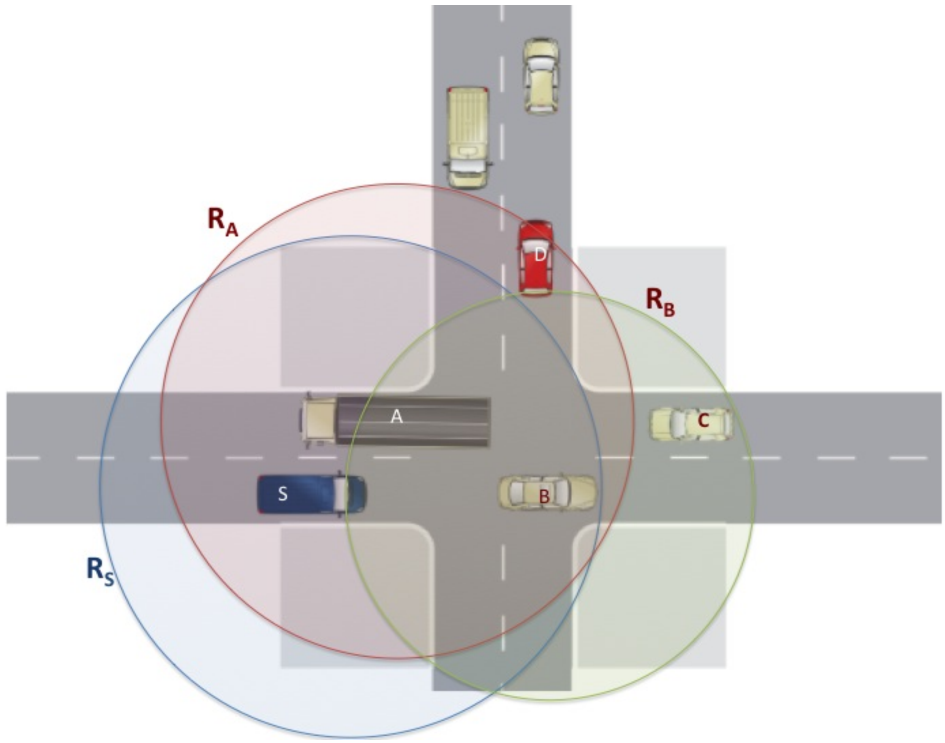


Figure 1.1: Example of selecting relay node as the farthest

has include transmit power control (TPC) per packet as a component of the decentralized congestion control (DCC) mechanisms for the channels of ITS station [10]. Also, IEEE defines a transmit power element in WSMP packet to directly control radio parameters [8, 9]. The difference in transmission powers/transmission ranges could affect the selection of the proper relay node to retransmit the message beyond the transmission range. It may also require some applications to switch from one-hop dissemination to multi-hop data transmission.

For most protocols, the receiving vehicles make the decision to forward the message based on how far it is from the preceding forwarder. This is to ensure that the farthest vehicle gets the highest opportunity to relay the message and suppress transmissions scheduled by close vehicles. Even though the choice of farthest neighbouring only as the relay node helps to accelerate the message propagation, it may jump over many vehicles in the vicinity. As consequence, some vehicles in the surrounding area may not be aware of the message. This could happened in urban areas, where there are lots of intersections or ramp on/off. For Example, in Figure 1.1 after the transmission by vehicle S, vehicle B is the farthest in vehicle A transmission range. Accordingly, vehicle B is the next relay node. However, if vehicle A does not retransmit, vehicle D will not receive the message. Therefore, depending on the farthest conditions only may prevent other vehicles in the vicinity from getting the message.

The farthest receiver may also have a transmission range that is relatively small or enclosed by the sender. This means all neighbourhood vehicles will already be aware

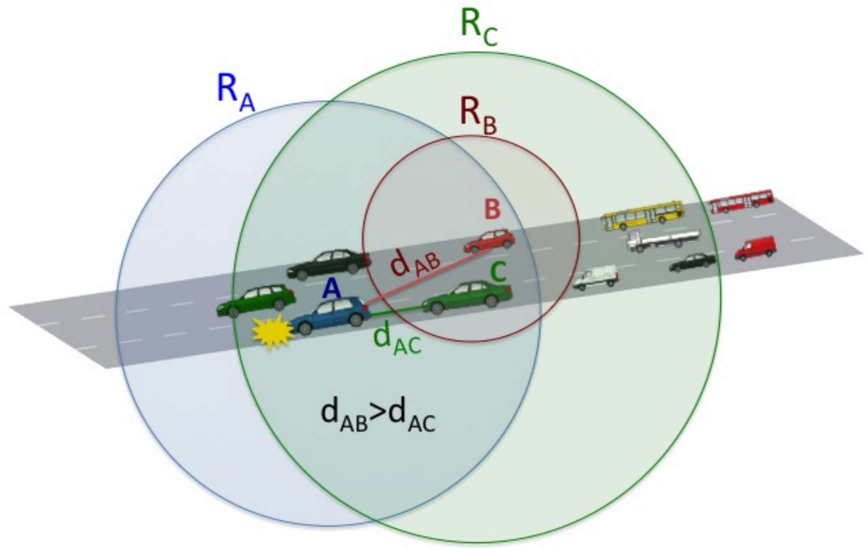


Figure 1.2: Illustrative example of heterogeneous transmission ranges

of the message. On the other hand, vehicles in between may have larger transmission ranges than the farthest vehicles and if it does not relay the message, many vehicles in the neighbourhood will not be aware of the message or more vehicles will relay the message. This leads to more redundancy in the network and/or less delivery ratio. An illustrative example is shown in Figure 1.2. The figure shows that after transmission by vehicle A, vehicle B will be the next relay node according to the distance criteria. Vehicle B has a smaller transmission range than vehicle C and all its neighbourhood vehicles are already aware of the message. In spite of that, it will retransmit before vehicle C. This transmission is considered useless since it will increase the redundancy of the network without reaching new area. Also, if vehicle C cancels the transmission after receiving a redundant copy of the message from vehicle B, many vehicles in the transmission range of vehicle C will not be aware of the message.

Another interesting problem is the selection of relay node based on network topology from neighbours table. Neighbours table is constructed by frequent broadcast of beacon messages to notify its presence to its one-hop neighbours. Vehicle stores the neighbour information such as position and speed upon receiving a beacon message from neighbours. The vehicle should be able to determine the time to remove an entry from a neighbours-table. As far as one can tell, all adopted approaches in literature depend on the beaconing rate of vehicles [16–25]. In such approaches, the entry is removed from the neighbours-table if the vehicle does not receive any new beacon messages from neighbouring vehicles within two or more consecutive beacon intervals. However, with the efforts to control the overload in the network caused by beaconing process, beaconing interval may dynamically be adjusted according to road conditions, number of vehicles and channel load [10, 15, 26–33]. Accordingly, neighbours-table may contain outdated data if the consecutive beacon period is chosen too long or a valid entry may be removed from the table if the next beacon is lost or blocked, due to short scheduling interval or temporal non-line-of-sight areas. Thus, a good estimate of the beacon information lifetime is required without affecting the vehicle awareness level of neighbouring vehicles and the surrounding road conditions.

1.4 Objectives

The efficiency of multi-hop dissemination is related to the selection criteria of relay nodes. Inadequate selection of the relay vehicles to retransmit important information could seriously degrade the ITS applications performance in terms of latency, overhead, and/or reception rate. The Low reception rate, overhead, and high latency might have devastating consequences on the performance of the ITS applications and consequently on the safety of road users.

Thus, the main objective is to design protocols that work in heterogeneous transmission powers and deliver the data in a high speed with low overhead. It should be able to support extremely low latency in the safety-related applications (e.g. 50 ms for the pre-crash sensing). The protocols should be able to eliminate useless transmission and retransmission that could be contained by other relays transmissions. The transmissions between relay vehicles should be also ordered in way that ensure that the node with high potential new coverage area transmits first. Each vehicle should decide independently to transmit or suppress transmission considering the amount of area that would be covered by potential new transmissions. They should use local measurements with no need for control messages exchange that induce overhead.

Another objective is to develop an estimation of the periodic beacon information lifetime without affecting the vehicle awareness level of neighbouring vehicles and the surrounding road conditions. This estimate should work in dynamically adjusted periodic beacon rate. It should works in situations where beacons could be lost or blocked due temporal non-line-of-sight areas or overhead.

1.5 Thesis contributions

In light of the above discussion, the design of relay selection protocol should be made to harmonize with vehicles networks characteristics and meets applications requirements. This research indicates relay vehicles should be selected in a way that useless transmission that may overwhelm the network with redundancy can be avoided. At the same time it should ensure reliability and avoid degradation of the applications performance. Accordingly, the following contributions are provided:

1. Efficient relay selection protocols are created to work in heterogeneous transmission powers environments. The protocols are instant-based that do not depend on

network topology information. Instead, each node decides independently based on information inside the message (e.g. position and sender transmission range) and local information at the receiving vehicle. This eliminates the need for periodic control messages exchange that may overwhelm the network with overheads. The protocols are timer-based, probabilistic-based and an integration of both. These protocols ensure elimination of useless retransmission or retransmission with small coverage areas that would be covered by other transmissions. The protocols are based on developed timer and decision making probability functions. These functions are used by each vehicle receiving an event message. The value of the functions allow the vehicle to determine if it is the next to act as relay node or not. The functions used to order vehicles transmission according to the amount of new area that would be covered by the potential retransmissions, considering the heterogeneity in vehicle transmission ranges. The formula is based on all possible scenarios of the overlapping between transmitter and receiver transmission ranges in a wireless environment. Each scenario is uniquely identified by mathematical conditions that must be satisfied.

2. A reliable area-based dissemination protocols that work in heterogeneous transmission ranges are introduced. These protocols allow retransmission for a duplicate received message only if it is predicated to cover new area. The non covered area are computed as function of overlap area between relay nodes. Thus, geometric taxonomies for all possible overlap patterns are developed. The common area includes diverse variety of patterns in wireless environment, which is an apparently an unsolved geometrical problem. The mathematical criteria used to define each pattern and relevant algebraic function to compute the potential additional coverage area is introduced. Moreover, probability formula in probabilistic approaches is enhanced to order transmission according to potential coverage areas in the network. This is to ensure that useless retransmission, or retransmission with small coverage areas that would be covered by other transmissions, will be eliminated.

3. Adaptive expiry time for neighbours-table entries that harmonizes with dynamic beacon scheduling is proposed. This is done by computing the life time for beacon data independent of the beaconing frequencies and based on the movement information of the neighbour, for example, position, speed and orientation, collected from the beacon.

1.6 Thesis organization

The rest of the thesis is organized as follows. Chapter 2 presents a background to VANETs. It provides a brief description of the core WAVE standards, IEEE and SAE standards, developed in close coordination with U.S. automotive and governmental strategic plans. Most of these standards were recently published and reviewed in 2016. After that, the status of WAVE technology is presented. Then, the chapter lists other wireless communications technologies and some of their features to support vehicles wireless communications. At the end of the chapter, we introduce an overview of related works in the field, which is classified into instant-based protocols and network topology-based protocols. The instant-based protocols are more classified as linear-based protocols and area-based protocols. Chapter 3 describes the proposed formula for computing the common overlap area between the transmitter and the receiver coverage area in heterogeneous transmission powers. This formula considers all possible cases in wireless radio environment. It will helps each vehicle to decide independently to transmit or suppress transmission considering the amount of area that would be covered by potential new transmissions. The formula is utilized to introduce relay section protocols based on the potential non-covered area. The proposed protocols are instant-based protocols that use local measurements with no need for periodic messages exchange and therefore does not induce an overhead. Chapter 4 presents Area Defer Transmission with relaying redundant received message (ADTr). In this chapter, we also introduce geometric taxonomy for all possible patterns of three overlapped transmission ranges and identify the relevant algebraic expression for each pattern to get the potential additional coverage area. Chapter 5 presents the mathematical formula used to determine the expiry time for a new entry when long term knowledge is used instead of instantaneous solution. Chapter 6 comprises conclusion and future works.

List of Publication

1. M. Alotaibi, A. Boukerche, and H. Mouftah, "Distributed relative cooperative positioning in vehicular ad-hoc networks," in IEEE Global Information Infrastructure and Networking Symposium (GIIS), Montreal, Quebec, Canada, September 2014.

2. M. AlOtaibi, H. Mouftah, and A. Boukerche, "Joint Unicast and Broadcast Protocols for Efficient Data Dissemination in VANets", Wisense workshop, August 2014.

3. M. M. AlOtaibi and H. T. Mouftah, "Adaptive Expiration Time for Dynamic Beacon Scheduling in Vehicular Ad-hoc Networks," in IEEE 82nd Vehicular Technology Conference (VTC2015-Fall), Boston 6th September 2015.

4. M. M. AlOtaibi and H. T. Mouftah, "High Speed Multi-hop Data Dissemination for Heterogeneous Transmission Ranges in VANETs," IEEE ICUWB 2015, Montreal, Quebec, Canada, 4th October 2015.

5. M. M. AlOtaibi and H. T. Mouftah, "Probabilistic Area-based Dissemination for Heterogeneous Transmission Ranges in Vehicular Ad-hoc Networks," in IEEE IUCC 2015, October 2015 in Liverpool, UK.

6. M. M. AlOtaibi and H. T. Mouftah, "Data Dissemination for Heterogeneous Transmission Ranges in VANets," IEEE LCN15th Annual IEEE Workshop on Wireless Local Networks 2015, Clearwater Beach, Florida, USA October 2015.

7. M. M. AlOtaibi and H. T. Mouftah, "Relay Selection for Heterogeneous Transmission Powers in VANETs," IEEE Access journal, February 2017.

Chapter 2

Relay Selection Protocols Overview

2.1 Background

Intelligent Transportation Systems (ITS) has a crucial role to improve road safety, awareness, efficiency of the transportation systems, and comfort to both drivers and passengers. It enables a wide variety of applications from safety applications to entertainment. Vehicle Safety Communications Consortium (VSCC) comprising BMW of North America, LLC, DaimlerChrysler Research and Technology North America, Inc., Ford Motor Company, General Motors Corporation, Nissan Technical Center North America, Inc., Toyota Technical Center USA, Inc., and Volkswagen of America, Inc., in partnership with U.S Department of Transportation (USDOT), provided a comprehensive list of communications-based vehicle safety and non-safety application scenarios in [34]. They have compiled a list of 34 safety and 11 non-safety applications scenario descriptions with the preliminary communication requirements, as summarized in Table 2.1. In addition, detailed communication requirements were developed for eight high potential benefit safety application that is marked with $*$ sign in Table 2.1.

Safety applications are based on their ability to reduce traffic accidents and to improve general public safety. They have been categorized to Intersection Collision Avoidance, Public Safety, Sign Extension, Vehicle Diagnostics and Maintenance, and Information from other Vehicles. On the other hand, the purpose of non-safety applications is to improve passenger's comfort and traffic efficiency. Applications of this category are classified into Traffic Management, Tolling, and Information from Other Vehicles. Table 2.1 demonstrates the compiled list of the vehicular safety and non-safety applications and their classification. In the table, The Frequency column represents the rate at which a transmission should be repeated (e.g. 1 Hz). While the Range column shows the maximum required range of communication or the distance between two nodes that is needed to effectively support a particular application. The Transmission Mode column describes whether the transmission is triggered by an event (i.e. event-driven), or whether it is sent automatically at regular intervals (i.e. periodic). The table also illustrates the different communication patterns of the applications such as point-to-point, point-to-multipoint, and if the communication is one-way or it should establish a dialogue with another unit or with multiple

Table 2.1: Vehicular applications compiled by VSCC

Application	Freq.	latency	Range	Transmission Mode	Src2Dest	Communications Types
Safety Applications						
Intersection Collision Avoidance						
*Traffic Signal Violation	10Hz	100ms	250m	Periodic	I2V	Point-to-multipoint, one-way
Stop Sign Violation Warning	10Hz	100ms	250m	Periodic	I2V	Point-to-multipoint, one-way
*Left Turn Assistant (LTA)	10Hz	100ms	300m	Periodic	I2V, V2I	Point-to-multipoint, one-way
*Stop Sign Movement Assistance	10Hz	100ms	300m	Periodic	I2V, V2I	Point-to-multipoint, one-way
Intersection Collision Warning	10Hz	100ms	300m	Periodic	V2I	Point-to-multipoint, one-way
Blind Merge Warning	10Hz	100ms	200m	Periodic	V2I	Point-to-multipoint, one-way
Pedestrian Crossing Information at Designated Intersections	10Hz	100ms	200m	Periodic	V2I	Point-to-multipoint, one-way
Public Safety						
Approaching Emergency Vehicle Warning	1Hz	1s	1000m	Event-driven	V2V	Point-to-multipoint, one-way
Emergency Vehicle Signal Preemption	N/A	1s	1000m	Event-driven	V2I	Point-to-point, two-way
SOS Services	1Hz	1s	400m	Event-driven	V2I, V2V	Point-to-multipoint, one-way
Post-Crash Warning	1Hz	0.5s	300m	Event-driven	V2I, V2V	Point-to-multipoint, one-way
Sign Extension						
In-Vehicle Signage	1Hz	1s	200m	Periodic	I2V	Point-to-multipoint, one-way
*Curve Speed Warning	1Hz	1s	200m	Periodic	I2V	Point-to-multipoint, one-way
Low Parking Structure Warning	1Hz	1s	100m	Periodic	I2V	Point-to-multipoint, one-way
Wrong Way Driver Warning	10Hz	100ms	500m	Periodic	V2V	Point-to-multipoint, one-way
Low Bridge Warning	1Hz	1s	300m	Periodic	I2V	Point-to-multipoint, one-way
Work Zone Warning	1Hz	1s	300m	Periodic	I2V	Point-to-multipoint, one-way
In-Vehicle Amber Alert	1Hz	1s	250m	Event-driven	I2V	Point-to-multipoint, one-way
Vehicle Diagnostics and Maintenance						
Safety Recall Notice	N/A	5s	400m	Event-driven	I2V	Point-to-point, one-way
Just-In-Time Repair Notification	N/A	N/A	400m	Event-driven	I2V, V2I	Point-to-point, two-way
Information from Other Vehicles						
*Cooperative Forward Collision Warning	10 Hz	100 ms	150m	Periodic	V2V	Point-to-multipoint, one-way
Vehicle-Based Road Condition Warning	2 Hz	0.5s	400m	Event-driven	V2V	Point-to-multipoint, one-way
*Emergency Electronic Brake Lights	10 Hz	100ms	300m	Event-driven	V2V	Point-to-multipoint, one-way
*Lane Change Warning	10 Hz	100ms	150m	Periodic	V2V	Point-to-multipoint, one-way
Blind Spot Warning	10 Hz	100ms	150m	Periodic	V2V	Point-to-multipoint, one-way
Highway Merge Assistant	10 Hz	100ms	250m	Periodic	V2V	Point-to-multipoint, one-way
Visibility Enhancer	2 Hz	100ms	300m	Periodic	V2V	Point-to-multipoint, one-way
Cooperative Collision Warning	10 Hz	100ms	150m	Periodic	V2V	Point-to-multipoint, one-way
Cooperative Vehicle-Highway Automation System(Platoon)	50 Hz	20 ms	100m	Periodic	V2V, V2I	Point-to-point/multipoint, one/two-way
Cooperative Adaptive Cruise Control	10 Hz	100ms	150m	Periodic	V2V, V2I	Point-to-multipoint, one-way
Road Condition Warning	1 Hz	1s	200m	Event-driven	I2V	Point-to-multipoint, one-way
*Pre-Crash Sensing	50 Hz	20ms	50m	Event-driven	V2V	Point-to-point, two-way
Highway/Rail Collision Warning	1Hz	1sec	300m	event-driven/Periodic	I2V, V2V	Point-to-multipoint, one-way
Vehicle-To-Vehicle Road Feature Notification	2 Hz	0.5s	400m	Event-driven	V2V	Point-to-multipoint, one-way
non-safety applications						
Traffic Management	1 Hz	1s	100m	Event-driven	V2I	Point-to-point, one-way
Intelligent Traffic Flow Control	1Hz	1s	250m	Event-driven	V2I	Point-to-point, one-way
Tolling	N/A	50ms	50m	Event-driven	I2V, V2V	Point-to-point, one-way
Information from Other Vehicles						
Cooperative Glare Reduction	1 Hz	1s	400m	Periodic	V2V	Point-to-multipoint, one-way
Instant Messaging	N/A	1s	50m	Event-driven	V2V	Point-to-point, two/one-way
Adaptive Headlamp Aiming	1 Hz	1s	200m	Periodic		Point-to-multipoint, one-way
Adaptive Drive train Management	1 Hz	1s	200m	Periodic	I2V	Point-to-multipoint, one-way
Enhanced Route Guidance and Navigation	N/A	1s	200m	Event-driven	I2V	Point-to-point, two-way
Point of Interest Notification	1 Hz	1s	400m	periodic	I2V	Point-to-multipoint, one-way
Map Downloads and Updates	1Hz	1s	400m	Periodic/Event-driven	I2V, V2I	Point-to-point/multipoint, one/two-way
GPS Correction	1 Hz	1s	400m	Periodic	I2V	Point-to-multipoint, one-way
Other potential applications: 30 applications identified without providing their requirements						

$*$:Eight high potential benefit safety applications.

Table 2.2: European union basic set of applications

Application	Freq.	latency	Transmission Mode	Src2Dest	Communications Types
Road safety:					
Road work warning	2 Hz	100 ms	Event-driven	I2V	Point-to-multipoint, one-way
Signal violation warning	10 Hz	100 ms	Event-driven	V2X	Point-to-multipoint, one-way
Traffic condition warning	1 Hz	–	Event-driven, Periodic	V2X	Point-to-multipoint, one-way
Stationary vehicle warning	10 Hz	100 ms	Event-driven, Periodic	V2X	Point-to-multipoint, one-way
Slow vehicle warning	2 Hz	100 ms	Periodic	V2V	Point-to-multipoint, one-way
Emergency vehicle warning	10 Hz	100 ms	Periodic	V2X	Point-to-multipoint, one-way
Traffic efficiency management:					
In-vehicle signage	1 Hz	500 ms	Periodic	I2V	Point-to-point, one-way
Regulatory/contextual speed limits	1 Hz-10 Hz	–	Periodic	I2V	Point-to-multipoint, one-way
Traffic information and recommended itinerary	1 Hz-10 Hz	500 ms	Periodic	I2V	Point-to-multipoint, Point-to-point
Limited access warning, detour notification	1 Hz-10 Hz	500 ms	Periodic	I2V	Point-to-multipoint, one-way
Decentralized floating car data	1 Hz-10 Hz	–	Event-driven	V2X	Point-to-multipoint, one-way
Traffic light optimal speed advisory	2 Hz	100 ms	Periodic	I2V	Point-to-multipoint, one-way
Local services and global internet services:					
Vehicle software/data provisioning and update	1 Hz	500 ms	Periodic	I2V	Point-to-multipoint one-way, Point-to-point
Fleet management	1 Hz	500 ms	Periodic	I2V	Point-to-multipoint one-way, Point-to-point
Local electronic commerce	1 Hz	500 ms	Periodic	I2V	Point-to-multipoint one-way, Point-to-point
Insurance and financial services	1 Hz	500 ms	Periodic	I2V	Point-to-multipoint one-way, Point-to-point

units (i.e. two-way communication). Moreover, it shows the source and destination of the transmission (i.e. infrastructure-to-vehicle, vehicle-to-infrastructure, or vehicle-to-vehicle communications).

The EU has defined border set of applications more or less similar to the applications defined by USDOT. But they differ on the priority order list of the applications. The EU has selected sixteen cases that reflect the decisions taken by vehicles manufacturers, equipment suppliers, road network operators, public authorities, and service provider. These decisions consider business value, technological maturity, customer value, time to value, and societal value that represents the contribution of these applications to road safety, traffic efficiency and environmental protection. The basic set of applications and the priority list are specified by European Telecommunications Standards Institute ITS (ETSI ITS) in standard [4]. The list has been summarized in Table 2.2. It has been categorized into three classes: road safety, traffic efficiency, and local services and global internet services. The road safety class includes applications that improve road safety. The primary objective of the applications in the traffic management class is the improvement of traffic fluidity. On the other hand, the applications in the local services and global internet services class advertises and provides on-demand information to passing vehicles on either a commercial or non-commercial basis. These services may include infotainment, comfort and vehicle or service life cycle management.

In order for such applications to work in vehicular environment, communication technologies must satisfy applications requirements including fast and reliable information delivery. Also, it should comply with the environment characteristics. The vehicular environment has its own distinctive characteristics that makes it different from other mobile environments. The major characteristics can be summarized as follow:

1. It is very dynamic environment due to high mobility. This results to quick changing topology. Thus, surrounding vehicles as mean of communication requires the periodic transmission. The purpose is to provide accurate status about surrounding environments and the exact positions for neighbouring vehicles.

2. The non-uniformity of vehicle density where the density is highly variable in time and space. Vehicle density vary throughout the day, for example, the density during rush hours is very high, while it is very sparse at other time of the day especially highway scenarios. The places also has impact on density value, for instant, vehicles are very densely packed at the middle of intersection, a road gradient, on/off-ramp in urban areas etc. As consequence, network will suffer from low packet reception rate due to either intermittent connectivity in sparse environments or due to congestion/overhead during high density. In other words, if warning message is disseminated to avoid critical accident or hazardous situation it may not reach all vicinity vehicles.

3. Delay constraint is crucial by most ITS's safety applications, such as intersection collision avoidance applications as shown in Table 2.1. The maximum delay is critical for such application to avoid accident and safe life.

4. Vehicles can identify their geographic location, where it can be equipped with electronic maps, and Global Positioning System (GPS) receiver or Differential Global Positioning (DGPS).

5. Vehicles move only on a predefined road/streets and known directions. This will help to identify the area of interest. It also helps to predict vehicle route and the duration of the route.

6. No power constraint, where each vehicle has an infinite power supply for all communications and computation tasks.

According to the aforementioned vehicular environments and application requirements, new wireless technology with dedicated spectrum is allocated for use by ITS. It allows wireless networks to be formed among vehicles, and between vehicles and road infrastructure, which is known as Vehicle Ad-hoc Networks (VANETs). Vehicles must be equipped with a network device called On Board Unit (OBU) that enables wireless connection to be performed with other vehicles, road infrastructure, and In-Vehicle-Networking (IVN). The connection to road infrastructure is established through Roadside Units (RSUs). RSUs are stationary network devices usually installed in light poles, traffic lights, road signs, etc. RSUs connect vehicles to access networks, which in turn is connected to a core network, for example, Department of Transportation. IVN is a specialized internal communication network that interconnects components inside a vehicle [35, 36]. IVN provide important information as input to vehicle-based applications [34]. Each vehicle in VANETs can take the role of a sender, receiver, and router to broadcast required information.

This technology is required to operate in a very dynamic environment with high relative speeds between transmitters and receivers. They need to support extremely low latency in the safety-related applications (50 ms for the pre-crash sensing, see Table 2.1) and to

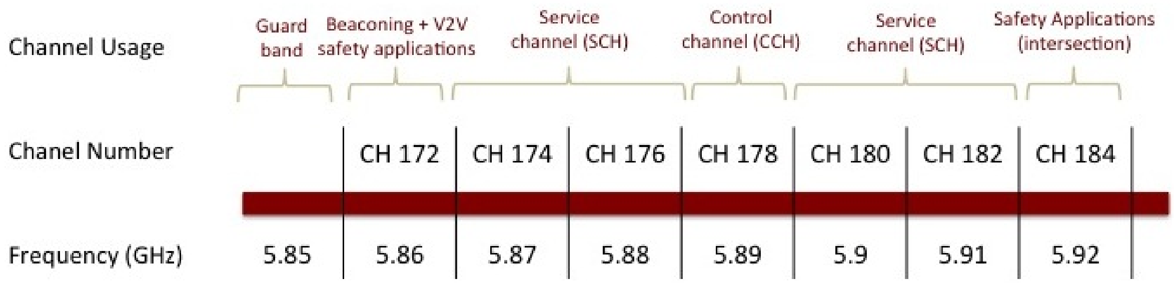


Figure 2.1: WAVE channel assignment

tolerate the high load generated by the periodic transmission of multiple messages from surrounding vehicles, and the high vehicle density during traffic congestion. Another consideration is that, it should allow data on emerging roadway hazards to be gathered from multiple external sources (i.e. other vehicles, infrastructure, or portable devices) and fused with vehicle data. The safety applications should use this data to alert the driver in time to avoid a crash or provide required assistance. It should be uniquely configured to support critical safety applications through continuous, high-speed, trusted and authenticable wireless data communications among moving vehicles and between vehicles and roadway infrastructure or mobile devices.

2.1.1 Spectrum allocation

The U.S. Federal Communications (FCC) allocated 75 MHz of licensed wireless spectrum in the 5.9 GHz band for the Wireless Access for Vehicular Environments (WAVE) technology. This spectrum is divided into seven non-overlapping 10 MHz channels, plus a 5 MHz guard band at the beginning of the frequency range, as shown in Figure 2.1. The term dedicated short range communications (DSRC) is sometimes used in the literatures to refer to radio spectrum or technologies associated with WAVE [37]. [1] The term "Short Range" in DSRC is meant to convey that the communication takes place over hundreds of meters, a shorter distance than cellular service typically support [5]. The V2X is another term used in literatures to refer to technologies associated with WAVE.

The standard defines two mode to access the channel: continuous access mode, which requires no channel coordination [38]. This mode always tuned to channel 172 for broadcasting the BSM and used also for crash avoidance safety applications [1]. The other mode is alternating access, which does require channel coordination. This mode is uses channel 178 as a control channel to manage channel switching to support messages on other service channels. The control channel determine which channel to listen to for specific informa-

[1] The word "Dedicated" in DSRC refers to the dedicated spectrum allocated for DSRC communication.

tion as well as transmitting that same information when the device is ready to transmit information (see Section 2.1.2).

Similar to DSRC, ITS communication system in the European Union (EU) operates in the 5.9 GHz band. The European spectrum allocation is sub-divided into part A to D. ITS-G5A with three 10 MHz channels is the primary frequency band (5.875-5.905 MHz) that is dedicated for safety and traffic efficiency applications.[2] ITS-G5B has 20 MHz (2 channels) for non-safety application, and ITS-G5C is shared with the radio local area network (RLAN) band. Finally, The ITS-G5D which operates in 5.905 to 5.925 band is set aside for future usage of ITS road traffic applications [39].

The key technology features of WAVE and Cooperative Intelligent Transport Systems (C-ITS) stack are the same: At the PHY layer, it applies OFDM. At the MAC layer, ITS-G5 also employs EDCA with CSMA/CA and access categories allow for data traffic prioritization [40]. Also, standards for networking and transport for non-safety applications rely on the IP protocol. All these features focusing WAVE technology is described in detail in the next section.

In Japan, two bands solution has been reserved for ITS applications. The government has deployed 5.8 GHz for electronic Toll System, and some original equipment manufacturers supporting V2X system using 760 MHz communications. The Japanese 5.8 GHz system is not compatible with the IEEE 802.11p protocol used in the US and Europe.

For the benefit of both the public and the motor vehicle industries, it is significant to achieve a broad agreement on harmonization on technologies and spectrum use. This will allow vehicle applications to be interoperable between vehicles from different manufacturers and between vehicles and roadway infrastructure within the areas where the vehicle is likely to travel. In addition, other countries (such as, Australia) that has no native vehicle manufacturing company and wants to apply ITS may discover that they have to choose one approach or the other, if the Japan, Europe, and the US decisions on technologies, spectrum use, and standards differ enough to impact the foundational systems. This will constrain market choices for these countries as well as constrain opportunities for motor vehicle industry and suppliers. Harmonization efforts, including specific areas of focus, stakeholders involved, and various standards being considered, are presented in [41].

2.1.2 WAVE layered architecture

The Wireless Access for Vehicular Environments (WAVE) consists of multiple cooperating standards on the DSRC band. The WAVE standards consist of Institute of Electrical and Electronics Engineers (IEEE) 1609 suit, IEEE 802.11p, the Society of Automotive Engineers (SAE) J2735, and SAE J2945. IEEE 1609 contains a set of standards which are IEEE 1609.2 intended for Security Services for Applications and Management Messages, IEEE 1609.3 for Network Services and WAVE Short Message Protocol (WSMP), and IEEE 1609.4 for multi-channel Operations [42, 43]. The IEEE and SAE standards related to

[2] C-ITS stack covering physical layer and data link layer is termed ITS-G5; the last two letters indicate that it operates in the 5 GHz frequency band.

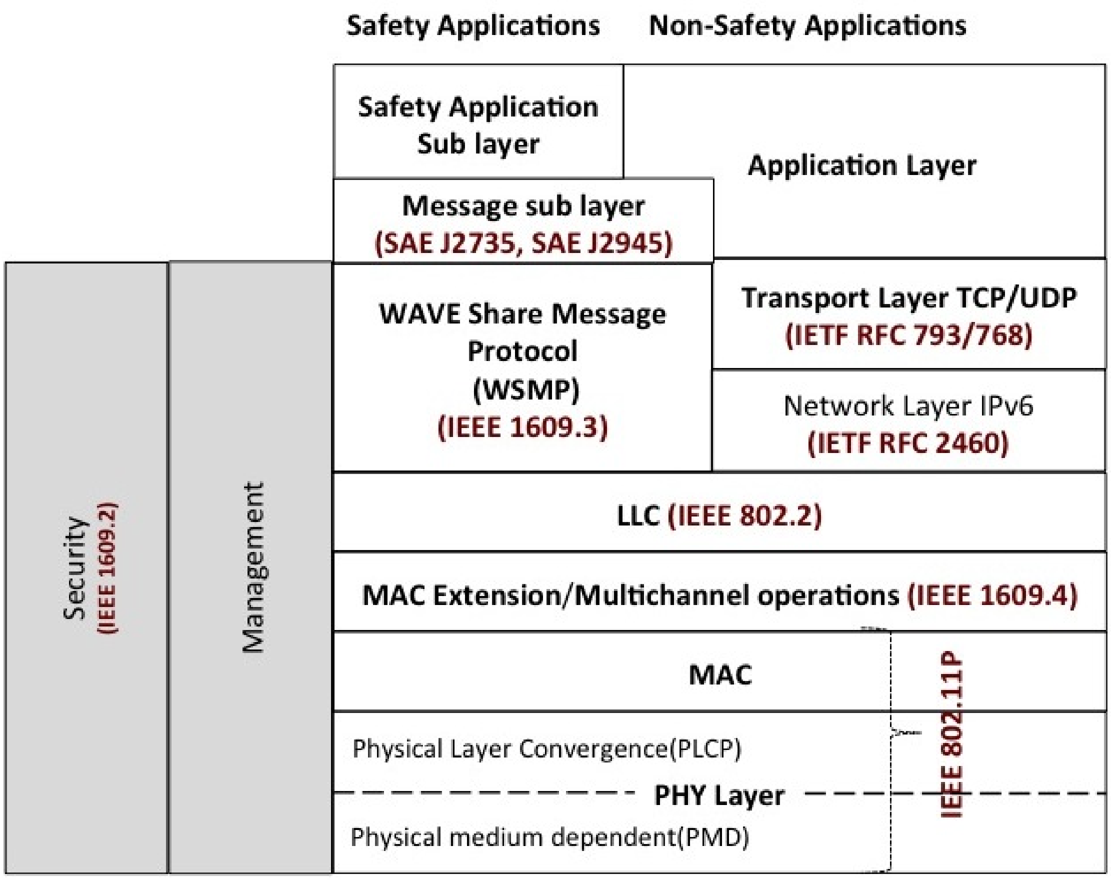


Figure 2.2: WAVE communication protocol layered architecture

WAVE architecture have international scope, but have been developed in close coordination with US automotive and governmental strategic plans [5]. Thus, in this work a description of the core WAVE standards under development for use in the United States is provided. Most of these standards were recently published and reviewed in 2016.

The next several subsections overview the standards in a layered representation similar OSI (Open Systems Interconnection) model order. The presented order is from top to bottom starting with the Message sub layer. This presentation does not correspond to clear layered architecture mentioned by IEEE related documents. However, it facilitates the understanding of the standards roles in WAVE architecture. Figure 2.2 demonstrates the WAVE communication layered architecture, as presented in [37], with the related standards for each layer.

Message sub layer

At the top of the architecture is the Message sub layer, which is defined in SAE J2735 [44] and SAE J2945 standards. SAE J2735 standard specifies different types of messages to support various vehicle-based applications [45, 46]. It defines the content and structure of messages exchanged between applications. The SAE J2735 messages are used for both Vehicle-to-Vehicle (V2V) and Vehicle to Infrastructure (V2I) safety exchanges. The main target for SAE J2735 is to allow vehicle applications to be interoperable between vehicles from different manufacturers and between vehicles and roadway infrastructure within the areas where the vehicle is likely to travel. SAE J2735 messages have been designed to be used with WAVE technology. However, it can be utilized for applications that may be deployed in conjunction with other wireless communications technologies. Table 2.3 lists all the 16 messages identified in SAE J2735 standard [44, 47]. The table summarizes the usage of each message in description column and present it in the same standard order.

This SAE Standard specifies messages and a complete list of all data frames and data elements to allow interoperability at the application layer without the need to standardize applications. SAE J2735 Message Set Dictionary identifies 231 data element and 156 standard frames [44,48]. Data elements are the smallest unit of information to be standardized. Examples of data elements are Acceleration, Speed, Steering Wheel Angle, Vehicle Length, Vehicle Width, Vehicle Height, etc. Data frames are the next level of data structure including several data elements. Ultimately, each message comprise data elements and data frames. This hierarchical structuring is to encourage reuse of data structures in different applications. An example of data elements and data frames is shown in Table 2.4 for basic safety message (BSM). It is informally called heartbeat message, because it is periodically broadcast to surrounding vehicles with the vehicle safety-related information. The BSM message is made up of six constituent parts. It consists of five frames, which are positions frame, motion frame, control frame, vehicle basic frame and vehicle status frame. The others are data elements associated to message identification [43]. Message Set Dictionary in SAE J2735 defined a standard name, description, expressed unit, size, Abstract Syntax Notation revision One (ASN.1) and Extensible Markup Language (XML) representations, and other data structure using it.

Table 2.3: SAE J2735 message set

ID	Name	Description
0	MessageFrame	Used to hold all the defined messages of SAE J2735 standard.
1	Basic Safety Message (BSM)	Contains vehicle state information that is periodically broadcast to surrounding vehicles.
2	Common Safety Request	A vehicle participating in the exchange of BSM can unicast requests to other vehicles for additional information.
3	Emergency Vehicle Alert message	Used for broadcasting warnings to surrounding vehicles that an emergency vehicle is operating in the vicinity.
4	Intersection Collision Avoidance	Warning message is broadcast to DSRC devices in the area of a potential collision with a vehicle that is likely to be entering an intersection without the right of way.
5	Map Data	Currently is used to convey one or more intersection lane geometry maps within a single message.
6	NMEA Corrections	Used to encapsulate NMEA 183 style differential corrections for GPS/GNSS radio navigation signals as defined by the NMEA (National Marine Electronics Association).
7	Personal Safety Message (PSM)	Used to broadcast safety data regarding the kinematic state of various types of Vulnerable Road Users (VRU), such as pedestrians, cyclists or road workers.
8	Probe Data Management (PDM)	Used to control the type of data collected and sent by OBUs to the local RSU.
9	Probe Vehicle Message (PVM)	Used to exchange status about a vehicle with other DSRC devices to allow the collection of information about typical vehicle travelling behaviours along a segment of road.
10	Roadside Alert	Used to send alerts for nearby roadway hazards to travellers.
11	RTCM Corrections	Used to encapsulate RTCM differential corrections for GPS and other radio navigation signals as defined by the RTCM (Radio Technical Commission For Maritime Services).
12	Signal Phase and Timing (SPAT)	Used to convey the current status of one or more signalized intersections. Along with the Map Data message the receiver of this message can determine the state of the signal phasing and when the next expected phase will occur.
13	Signal Request Message (SRM)	Used to either a priority signal or a signal pre-emption
14	Single Status Message (SSM)	Sent by RSU and used to relate the current status of the signal and the collection of pending or active pre-emption or priority requests acknowledged by the controller
15	Traveller advisory message (TIM)	Used to send advisory and road sign types to equipped devices.

SAE J2735 gave specific message syntax, but the minimum communication performance requirements of the message sets are specified in SAE J2945. Each section in SAE J2945 describes a specific message set's requirements [49, 50]. For example, SAE J2945-1 [51] explains BSM Message communication minimum performance requirements for V2V safety applications, for example, message transmission rate, accuracy of BSM data elements, and channel usage.

Network and Transport layer

The next layer in WAVE architecture is Network and Transport layer. This layer supports two protocol stacks. The first protocol is the Internet Protocol version six (IPv6) that supports the transport protocols TCP and UDP. The second protocol is the WAVE Short-Message Protocol (WSMP), which is specified in IEEE Std 1609.3 [8, 9]. WSMP is used to accommodate high-priority, time-sensitive communications, such as safety applications. On the other hand, IPv6+TCP/UDP is used for typical internet applications and for routing packets through a network. It also supports the exchange of safety and other content provider data over a network that can be readily established based on existing communications infrastructure. Examples of IPv6 applications include traveller information, parking payment, toll payment, fleet vehicle monitoring, and remote vehicle diagnostics [43]. WSMP and IPv6 are each selected by registered EtherType hexadecimal values, where the value 0x88DC indicates WSMP protocol and 0x86DD value refers to IPv6 protocol.

The main reason for creating the WSMP is to reduce the overload IPv6 packet. The WSMP packet is shown in Figure 2.3. The WSMP header comprised the WSMP-N-Header and the WSMP-T-Header. In the WSMP-N-Header, the 4 bits Subtype select the networking protocol features. In the last version of the IEEE 1603.3 standard [8] Subtype 0 is the only presented feature. However, the future versions will include different Subtypes, such as Subtype 2 that is reserved for N-hop forwarding. WSMP-N-Header format for Subtype 0 includes 1 bit WSMP-N-Header Option Indicator subfield. It is set to 1 to indicate the presence of the WAVE Information Element Extension field in the WSMP-N-Header. It is set to 0 to indicate that no WAVE Information Element Extension field is present. WSMP-N-Header also includes WSMP Version that indicates the version of the WSMP protocol. A device that receives a WSMP packet with an unsupported version level should discard the packet. The WSMP-N-Header may include channel number, data rate, transmit power, and/or channel load as part of WAVE Information Elements. These optional fields are used by WSMP receipt to allow the WSMP to directly control radio parameters. This enables the application to send short messages with the required services, like being transmitted using a particular power or data rate. This is to maximize the probability that all the implicated parties will receive the messages in time.

The WSMP-T-Header part contains the Address Info, and WAVE Information Element Extension fields which depend on the value of the Transport Protocol ID (TPID) field in the WSMP-N-Header. The TPID values 0, 2, and 4 indicate that WAVE Information Element Extension field is not presented, while TPID values 1, 3, and 5 point out that WAVE Information Element Extension field is presented. For TPID values from 6 through 255 is reserved for future. The address information field in the WSMP-T-Header contains

Table 2.4: Basic safety message verbose

Data Element	Description	Size
Part I,		
msgCnt	A sequence number within a stream of messages with the same msgID and from the same sender.	1 byte
id	Vehicle temp id is used as a means to identify the local vehicles that are interacting during an encounter.	4 bytes
secMark	Time stamp of milliseconds unit	2bytes
lat	Latitude	4 bytes
long	Longitude	4 bytes
elev	Elevation	2 bytes
Positional Accuracy Frame		
semiMajor	The radius (length) of the semi-major axis of an ellipsoid representing the accuracy which can be expected from a GNSS system in 5cm steps.	1byte
semiMinor	Express the radius of the semi-minor axis of an ellipsoid; representing the accuracy which can be expected from a GNSS system in 5cm steps.	1byte
orientation	Used to orientate the angle of the semi-major axis of an ellipsoid representing the accuracy which can be expected from a GNSS system with respect to the coordinate system.	2 bytes
transmission	Current state of the vehicle transmission	3 bits
speed	Speed units of ms	2 bytes
heading	Heading	2 bytes
angle	Steering wheel angle	1 byte
Acceleration set 4 way Frame		
long Acceleration	Acceleration of the vehicle along some known axis in units of 0.01 meters per second squared.	2 bytes
lat Acceleration		2 bytes
vert Acceleration		1 byte
yaw rate		2 bytes
Brake System Status Frame		
wheelBrakes	BrakeAppliedStatus	4 bits
traction	TractionControlStatus	2 bits
abs	AntiLockBrakeStatus	2 bits
scs	StabilityControlStatus	2 bits
brakeBoost	BrakeBoostApplied	2 bits
auxBrakes	AuxiliaryBrakeStatus	2 bits
Vehicle Size Frame		
vehicle length	Measured from the edge of the front bumper to the edge of the rear bumper expressed in centimetres	12 bits
vehicle width	the widest point of the vehicle with all factory installed equipment expressed in centimetres.	10 bits
Part II, optional frames sent when required		
Vehicle Safety Extensions Frame		
Special Vehicle Extension Frame		
Supplemental Vehicle Extensions Frame		
...		

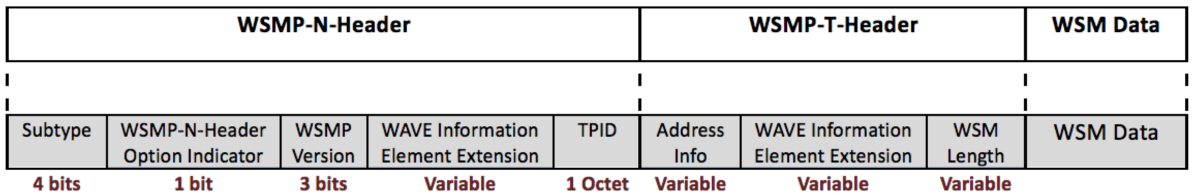


Figure 2.3: The format of a WSMP Packet

Provider Service Identifier (PSID) for TPID 0 and 1, which represents an identifier of an application area. On the other hand, it contains ITS port number for other values of TPID to identify source and destination of an entity above the OSI transport layer. The WSM Length field is mandatory and indicates the length of the WSM Data to be passed up to higher layers. The WSM data field is the SAE J2735 message sent by the upper layer protocol (i.e. application layer).

IEEE 1609.3 also defines a WAVE management Entity (WME), as a set of management functions required to provide WAVE networking services. For instance, WME maintains the Management Information Base (MIB) that contains the required configuration and status information. It also allows the WAVE devices to access the service channels based on service requests

Logical link control (LLC)

The LLC follows the IEEE 802.2 standard. The purpose of LLC is to manage and ensure the integrity of data transmissions. It supports three service types: Service type 1 is unacknowledged connectionless service; Service type 2 is a connection logical service with an acknowledgement of delivery; and Service type 3 is a connectionless service with an acknowledgement of delivery. WSMP uses LLC service type 1 as specified in IEEE Std 802.2. Different Ethernet Type (Ethertype) values identify the different network layer protocols used in WAVE. When the LLC receives an MAC data unit, it checks the Ethertype in the Subnetwork Access Protocol (SNAP) header and extracts the packet. If the Ethertype value is 0x86DD, the LLC delivers the packet to IPv6. If the Ethertype value is 0x88DC, the LLC delivers the packet to WSMP. When IPv6 packets request transmission of a packet, the LLC protocol will set the Ethertype to 0x86DD. Similarly, when WSMP requests transmission of a packet, the LLC protocol will set the Ethertype to 0x88DC.

Media Access Control (MAC)

MAC layer is specified into two standards: IEEE 802.11p and IEEE 1609.4 (MAC multi-channel operation) standards [38]. MAC multichannel sub layer is an extension towards MAC layer to allow a system with one or more radios, for instance, U. S. 5.9 GHz band, to effectively switch among those channels. Recall that the WAVE 5.9 GHz spectrum is divided into smaller operational channels, as shown in Figure 2.1 (see Section 2.1.1). A 75 MHz of the spectrum allocated for WAVE applications, such that 5 MHz for the guard band, 10 MHz for control channel (CCH), and six services channel (SCHs) with 10 MHz each. There are two standard modes to access the channel. First is the continuous access mode which requires no channel coordination. This mode uses channel 172 for broadcasting the BSM and time sensitive and high priority data, for example, crash avoidance safety applications [1]. Allocating one channel dedicated to safety was a result of VSC Consortium testing. The consortium test four channel configurations for operating up to 60 radio units. The channel configurations include three channel switching schemes based on IEEE 1609.4 and one scheme relying on a single channel. They concluded that the use of a full-time channel dedicated to safety provided superior performance to any of the channel switching.

The other mode is alternating access, which does require channel coordination. This mode is using channel 178 as a control channel to manage channel switching to support messages on other service channels. In this case, a typical WAVE device uses the control channel and at least one service channel. The channel switching mechanism uses time division to isolate CCH traffic (e.g. service advertisements) from SCH interference.

The WAVE device has the option to use alternating access mode or to tune to a single channel all the time. Researchers initially tried to use channel 178 as both a control channel and for transmission of the BSM, but the studies proved that it is an unduly restricted BSM transmission. This potentially hinders safety [1, 5, 42, 52]. This is because a radio can only transmit or receive on a single channel at a time; channel switching only solves part of the problem. But, the radio still has to alternate between the BSM and the other necessary messages, which degrades its ability to support the BSM.

The multichannel operation concept is defined in IEEE 1609.4 and it does not exist in traditional wireless LAN station. The multichannel operation supports the following services, which is used to manage channel coordination and to support MAC service data unit (MSDU) delivery [38, 42].

1. The user priority service: that is used to contend for medium access using enhanced distributed channel access (EDCA) functionality derived from IEEE 802.11e. The reference architecture for WAVE MAC is distinguished from the 802.11e architecture by implementing Access Category queues on a per-channel basis. The EDCA mechanism supports differentiated access to the wireless channel using eight different priorities. These priorities are classified into four different access categories (AC), which have independent queues, each with their corresponding parameters (i.e. Different AIFS (Arbitration Inter-Frame Space) and CW (Contention Window)). The parameters for each AC are $CW_{min}[AC]$, $CW_{max}[AC]$, AIFS[AC]. The use of user priority and related access category (AC) governs the required quality of service. For CCH priority, the EDCA parameter set is optimized for WSMP data transfer. A predetermine EDCA parameter set must be used when operating in the CCH. However, for SCH priority, the EDCA parameter received within the WAVE advertisement frame of the provider must be used [42].

2. The channel routing service: it controls the routing of data packets from the LLC to the designated channel and data queue. For WSMs, the channel transmit power, and data rate are set by higher layers on a per-message basis. For IP datagrams, the channel, transmit power, and data rate to be used are stored in a transmitter profile. When the WSMP data is received the packet is placed in the proper transmit queue corresponding to the Channel Identifier and priority. When IP data is received the packet is placed in a data queue that corresponds to the SCH and requested priority.

3. The channel coordination service: coordinates the channel intervals according to the channel synchronization operations of the MAC layer so that data packets from the MAC are transmitted on the proper wireless channel and in the correct time slot.

Physical layer

The physical and MAC functions is specified in IEEE 802.11p standard that result from migrating DSRC-ASTM E2213-03 standard published by The American Society for Testing and Materials (ASTM). IEEE 802.11p is an enhancement draft to the IEEE 802.11 standard, which was published in 2010 [5]. Having IEEE 802.11 under the umbrella of IEEE family is to encourage 802.11 chip vendors to add support for 802.11p, which would help reduce costs [5].

The physical layer is divided into sub layers. The first one is the Physical Medium Dependent (PMD) sub layer that interfaces directly with the wireless medium. It utilizes Orthogonal Frequency Division Multiplexing (OFDM) technique used in 802.11a. The second sub layer is the physical layer convergence procedure (PLCP). The PLCP defines the mapping between the MAC frame and the basic PHY layer data unit by adding PHY layer overhead to the MAC frame to create the PHY protocol Data Unit (PPDU) at the transmitter. In the receiver side, PLCP perform the inverse function to extract a MAC frame from the PPDU. The detailed of PPDU fields have been stable in IEEE 802.11 standard for long time, and not in IEEE 802.11p amendment.

2.1.3 Status of WAVE technology

In July 2015, USDOT has released a report (Status of the Dedicated Short-Range Communications Technology and Applications) to Congress assessing the status of the 5.9 GHz DSCR, as responds to a congressional request for an assessment of 5.9 GHz DSRC technology [1]. This report reveals that no other wireless technology has the ability to provide all of the critical attributes of WAVE needed to support V2V and V2I safety applications. These unique attributes include:

1. Broadcasting messaging capability that does not require network connection. This is an important feature over point-to-point wireless communications, like cellular, for vehicle safety applications. With cellular technology, for example, it would be

difficult to know in advance the cell phone numbers (identity) of other vehicles that may come in close proximity.

2. Messages are small enough to be broadcasted frequently and quickly; WAVE technology latencies of less than 100 milliseconds are achievable. This range of latency is required by many of the vehicle safety applications. Latencies in this range do not appear to be achievable with other wireless communications [34].

3. Anonymous and trusted communications.

4. Robust functionality in rapidly moving environment. It allows all vehicles with OBU to share critical safety information continuously. This is because there are designating portions of the 5.9 GHz DSRC spectrum for high availability access.

According to USDOT [1], WAVE is sufficiently robust to proceed with the preparation for deployment of connected vehicle environments. Consequently, a roadmap has been created with preliminary plans to guide industry and public agency implementation efforts. This roadmap offers three milestones for the year 2040:

1. 90 percent of the US light duty vehicle fleet is DSRC enabled;

2. 80 percent of all traffic signals are DSRC equipped; and

3. DSRC exists at up to 25,000 additional safety-critical roadway locations.

In a similar manner WAVE based technologies and V2V/V2I applications are advancing in Europe, Japan, South Korea, Australia, and Canada. These countries are working to harmonize operational policies and standards to achieve global compatibility that will accelerate the deployment, development, and manufacturing activities [41].

Other commercial wireless communications technologies (such as cellular, satellite, radio, fiber, and Wi-Fi) continue to improve in terms of latency and security. This provides the opportunities to employ such technologies in support of applications that do not require the extreme low latency and fast network access time afforded by DSRC. Examples of these applications include:

1. Mobility and logistics

2. Environmental performance

3. Road weather and traveller information

4. Security credential management

5. Field equipment-to-center (backhaul) communications

6. Agency communications or decision support systems.

Table 2.5: Comparison of two-way communications technologies for V2V requirements [1]

Technologies	Latency (seconds)	Range (meters)	Mobility Design Goal (Relative Speed)	Direct Device-to-Device Mode	Dedicated and Licensed Spectrum
V2V Safety Needs	0.1s	300m	Highway speed	Y	Y
DSRC	0.0002-0.015s	< 1000 m	Highway speed	Y	Y
WI-FI	3-5s	< 300 m	Pedestrian speed	Y	N
WI-FI Direct	5s	<200m	Pedestrian speed	Y	N
WI-FI FILS draft standard	>0.1s	<300m	Pedestrian speed	N	N
LTE Cellular	0.079-0.1s	Wide Area	Highway speed	N	Y
LTE-A Cellular	0.02-0.07s	Wide Area	Highway speed	Proposed	Y
Bluetooth BR/EDR	0.1s	<100m	Stationary	Y	N
Bluetooth LE	0.006s-70min	<50m	Stationary	Y	N
Satellite	>0.015-0.58s	Wide Area	Varies	N	Y

2.1.4 Other wireless communication technologies

The analysis conducted by research institutions and USDOT conclude that DSRC is, up to date, the only viable option for safety-critical applications [1, 53]. Table 2.5 summarizes some of the features of communications technologies that have been examined for use in ITS applications and how their capabilities compare with the needs for V2V safety applications. The blue cells on the table indicate that the requirement is satisfied, cell without shading (i.e. white) is for requirement not satisfied, and gray cells either that there is uncertainty in whether or not the technology could meet the requirement or that it meets it in a less-than-optimal way. Only DSRC meets all the requirements of the V2V safety applications.

However, available wireless data communications technologies (such as, cellular, satellite, radio, and Wi-Fi) can be utilized to support vehicle-to/form-infrastructure applications. According to USDOT report [1], these technologies are expected to be fully leveraged in the upcoming CV Pilot sites [54,55]. The CV Pilot Deployment Program is a program to deploy, test, and operationalize cutting-edge mobile and roadside technologies and enable multiple CV applications in three sites: Wyoming, New York City (NYC), and Tampa. This program worth more than $45 million and is sponsored by the USDOT Intelligent Transportation Systems Joint Program Office (ITS JPO).

The new communications technologies that are in development, such as 5G or LTE (Long-Term Evolution), may also have advantages for various vehicle-to/form-infrastructure application categories [1, 56]. USDOT and the ITS standards community are monitoring and considering these developments to determine it is competent for vehicle applications. However, in order to incorporate these technologies, it should be able to satisfy the security, reliability, and privacy that is compatible with DSCR [1]:

A list of possible wireless technologies that can support ITS applications are presented bellow. This list is acquired from VSCC task 3 final report [34] and USDOT report to U.S.

Congress [1]:

1. Nationwide Differential Global Positioning System (NDGPS)
   Relaying on GPS standalone is not sufficient for safety applications, due to the fact that it shows errors up to ten meters. In addition, GNSS can become inaccurate or unavailable in a number of situations, such as when it is used underground, inside tunnels, at high latitudes, or when electromagnetic interference exist or even when it is cloudy [17]. Therefore, NDGPS can be utilized for more accurate location estimate. The NDGPS system will use differential GPS reference station transmitter systems located at known physical locations to broadcast additional information, such as stations physical location, that can be used by GPS receivers to correct the computed positions estimate. It is expected to have 1-meter positioning accuracy to be widely available from the combination of GPS / NDGPS signal reception and more processing power in receivers.

2. IEEE 802.11 Wireless LAN
   The IEEE 802.11 is a set of standards developed by the IEEE LAN/MAN standards committee (IEEE 802) specifically to support wireless local area network (WLAN) computer communication. The most popular are those defined by the 802.11a, 802.11b and 802.11g protocols, which are collectively known as Wi-Fi technologies. The main drawback of Wi-Fi is its design for stationary terminals. Though Wi-Fi offers higher data rates compared to the other options, it does not work nearly as well in a mobile environment. However, it could support the inclusion of vehicles in wireless home LANs. This offers the opportunity for vehicles to upload and download data through these wireless LANs while the vehicles are within range of the access points.

3. Bluetooth (IEEE 802.15.1)
   Th distance limitation of Bluetooth and the low rate transfer makes Bluetooth not adequate to support vehicle applications. However, Bluetooth may serve as a vehicle to/from infrastructure communications for stationary vehicles in close to the desired communications point [34]. This can be utilize to support commercial applications like electronic payments at fast food drive-thrus, or entertainment-related communications between a vehicle and its garage.

   The preliminary study in [57] shows that Bluetooth 4.0 can be used to propagate information on range less than 100m, from one vehicle to another even while driving. Yet, the range and latency limitations prevent the use of Bluetooth to support vehicle safety applications.

4. Cellular systems
   The advantage of cellular networks is that the infrastructure has already been constructed all over the country. Cellular systems include Global System for Mobile communications/General Packet Radio Service (GSM/GPRS), and the universal mobile telecommunications system /long-term evolution (UMTS/LTE). However, cellular systems are point-to-point wireless communication. In vehicular environment, it

would be difficult to know in advance the identity of other vehicles that may come in close proximity. This makes cellular systems difficult to employ for safety applications. Also, the mobile station in cellular environment normally communicates with another mobile station via base station, which increases the latency for VANETs applications. Another consideration is that data communication has lower priority over these networks compared to voice communications. Thus, data packets are expected to encounter queuing delay if the network is busy with voice traffic, which causes a high latency for VANETs applications. Such latency limitation may prevent the use of cellular communications for the vehicular safety applications. Furthermore, mobile station in cellular environments detached to IVN (e.g CAN, FlexRay) that generate important input to vehicle applications such as speed, and wheel angle.

Finally, the advancement of LTE technology helps to deliver larger amounts of data to cellular users more quickly. Nevertheless, Booz Allen Hamiltons analysis stated that this is less effective when a user is moving, and that the data rate for LTE is often much lower than what is theoretically possible [7]. Although LTE would be able to support the full download of credential revocation list due to the expansiveness of cellular networks, there are areas where cellular networks are not available. Even within coverage areas, there can be dead spots. Another issue that may arise is the fact that any LTE system may suffer from capacity issues in any area that has many LTE users.

However, there are opportunities to use cellular systems in support of applications that do not require the extreme low latency, such as road weather and traveller information application. Cellular systems are expected to be fully leveraged in the upcoming CV Pilot sites [54, 55]

5. Two-way Satellite

   Ubiquitous coverage over the any continental provides a strong argument to consider two-way satellite services for wireless connectivity on vehicles. So far, however, the data services that are available and affordable have rather limited data capacity. Even with these data capacity limitations, there are a fairly wide range of telematics-type applications that could be supported using a short message data structure. For example, low bandwidth packet data services over satellite could be used to support vehicle telemetry applications, such as probe vehicle monitoring. Since the two-way satellite services are designed to operate as point-to-point communications channels, their mode of operation is not compatible with the vehicle safety applications under study by the VSCC. Another serious deficiency of these systems in relation to the vehicle safety applications communications requirements is the large inherent system latency. The expected airtime cost is yet another serious issue.

6. Terrestrial Digital Radio
   The one-way (radio station-to-vehicle) nature of communication for terrestrial digital radio, prevents this technology from meeting the direct wireless communications requirements of the vehicle safety applications. However, there are significant number of telematics-type applications that could potentially use terrestrial digital radio

datacasting to communicate with vehicles. One potentially effective use of datacasting over terrestrial radio systems is the continuous updates of on-board geographical databases, by variable information with low-bandwidth, like work zone locations, lane closures, detours, malfunctioning traffic signals and time-of-day restrictions.

2.2 State of the art

Efficient data dissemination is considered as one of the main significant problems in VANETs. Fast, reliable, and scalable data dissemination in VANET is a key of success for ITS. This requires an efficient relay selection process and an efficient broadcasting mechanism. Though VANETs share some common characteristics with mobile ad-hoc networks (MANET), the proposed solutions for MANETs cannot be applied directly in VANETs. This is because VANETs exhibits its own distinctive characteristics, as presented in Chapter 2.1. Therefore, applying data dissemination proposed for MANETs directly in VANETs will lead to poor networks performance. Such low packet reception rate may happen from intermittent connectivity in sparse environments or from the overhead during high density. Moreover, it may cause unacceptable delay for some VANETs critical applications such as safety applications.

A simple dissemination approach is to use traditional flooding, whereby each node in the network retransmits a message when it is received for the first time, without any information about other nodes in the network. The main advantage of this approach is that it provides very fast data dissemination, if there is no contention or collisions [58]. Furthermore, a vehicle does not need to know a destination address or a route to a specific destination. This eliminates the complexity of route discovery, and topology information management that are difficult in dynamic networks such as VANETs. However, this approach is not suitable for VANET environments, which can be dense or sparse at different times and spaces. In high-density environments, the approach will have severe contention owing to unnecessary redundant retransmissions (i.e. the well-known broadcast storm problem [58]), and it will not be propagated beyond the transmission range in sparse networks. In both cases, the messages will be prevented from reaching all other nodes.

A feasible solution to the broadcast storm problem is to reduce the number of redundant transmissions [25, 58]. This is achieved by controlling the number of nodes that relay the broadcast message. Proper selection of relay nodes governs high delivery ratio, acceptable overall end-to-end communication delays and efficient bandwidth usage. Several protocols have been proposed to identify appropriate relay vehicles.

These protocols can be classified into two main categories: network topology-based protocols and instant-based protocols. The decision to select a vehicle to relay the message in the network topology category is based on neighbourhood information collected at each vehicle [18–21, 59–61]. In contrast, in instant-based protocols, the receiving vehicles make the decision to forward the message based on the information extracted from the message and local information at the receiving node.

2.3 Instant-based protocols

The decision in the instant-based protocols of forwarding the message based on the information contained in the message and the local information at the receiving node such as position coordinates. In this approach, the decision to forward the message is always performed at the receiver side. The receiving nodes decide to transmit or based on a decision function. The value of the function is different from one receiver to another and calculated according to pre-agreed criteria such as distance or density. If value of the function allow the node to relay the message and before retransmission the node receives the same message from other neighbour vehicles, the transmission is suppressed to reduce redundancy. Otherwise, it retransmits the message. Instant-based protocols can be further classified into linear-based and area-based protocols, as described in the subsections below.

2.3.1 Linear-based protocols

In linear-based protocols the receiving vehicles make the decision to forward the message based on how far it is from the preceding forwarder and/or the direction of the message and vehicle movement. Therefore, some vehicles get the highest opportunity to relay the message than the others in the neighbourhood. This is to ensure long hops along the road to speed up the dissemination and cover more nodes.

Distance defer transmission (DDT) [22] is a linear-based approach. The receiving vehicle defers retransmitting the message for a time that is inversely proportional to the distance from the transmitting vehicle; thus, the farthest receiver retransmits first. When the defer time expires and the node has not received the message from other neighbour vehicles, it retransmits the message using the same protocol. It has been shown that DDT outperforms network topology-based protocols in sparse networks, owing to the back-off time used.

The scheme presented in [23, 24] assumes a linear road represented by an x-axis in the direction of the vehicle movement and the message is propagated in the direction opposite to the vehicle movement. When a node receives a message for the first time, it defers transmission for a time proportional to the time necessary to transmit a full message. During the wait, if a node receives another copy propagated in the same direction as the vehicle movement, the receiver can safely avoid forwarding the message. Otherwise, the receiver computes the minimum estimated distance from the received copies and enters a new waiting time. If no new copies of the message are received during the waiting time, the node decides to retransmit the message probabilistically, based on the distance from the closest relay node.

Distance-to-mean (DTM) [62] uses a wait time that is proportional to the distance between transmitter and receiver, to observe the neighbours that retransmit a particular message. Using the positional information, it calculates the spatial mean of those neighbours and the distance from the receiving node to the calculated spatial mean. When the distance is large, the node will cover a larger amount of the additional area by rebroadcasting than when the distance is small. The DTM sets a threshold value such that any node that measures the distance is greater than the threshold will retransmit the message.

Distance-based forwarding (DBF) [63, 64] is an enhanced version of DDT [22]. It integrates hops count with a timer-based approach to avoid possible contention caused by simultaneous transmission. The node suppresses the transmission if the same packet is received twice from different nodes with a greater hop count.

The algorithm proposed in [65] for multi-hop dissemination is also a linear-based approach that computes the deferred time as a function of distance. However, it uses a directional distance (adjacent side) instead of Euclidean distance (hypotenuse side) between the node and the sender. Given the position (x, y) of each eligible node and the position (x_s, y_s) of the source node, then the directional distance, d_d, is calculated as follow:

$$\begin{aligned} & d_d = d_e cos\theta, \text{ where} \\ & d_e = \sqrt{(x-x_s)^2 + (y-y_s)^2}, \text{ and } \quad \theta = arctan\left(\frac{y-y_s}{x-x_s}\right) \end{aligned} \tag{2.1}$$

Another way to select relay node is to use the power of the sensed signal as shown in the research [66]. In this research, the receiving node defer retransmitting for a time that depend on sensed signal level, where each node classify itself into one of the three groups: Preferred group (PG), IN group, and OUT group. The preferred group (PG) consists of the nodes that have signal power greater than OUT group and less than IN group. While IN group contains the nodes with a signal stronger than in PG. After the node classifies itself, it waits for a hold off period before taking a decision whether to rebroadcast a packet or not. The hold off time and the strategy for making a rebroadcasting decision depends on the group the node belongs to, where the priority of rebroadcasting is given to PG group followed by OUT group.

Irresponsible forwarding (IF) [67] is a probabilistic approach that considers inter-vehicle spacing. The rebroadcast is performed in one direction, and the receiving vehicle computes the rebroadcast probability based on the likelihood of having another vehicle downstream to rebroadcast the packet. If the chance of another vehicle downstream is high, then the rebroadcast probabilities should be set to a small value, and vice versa. The probability is computed as follows:

$$P = 1 - F_x(R-d)^{\frac{1}{c}}, \tag{2.2}$$

where $F_x(R-d)$ is the inter-vehicle spacing cumulative distribution function, d is the distance between transmitter and receiver, R is the transmission range, and $c \geq 1$ is a shaping parameter. The higher the value of c , the higher the rebroadcast probability will be. They adapt exponential and lognormal distribution for the inter-vehicle spacing distribution function. The distribution-related parameters (e.g. mean and standard deviation) can be estimated from historical traffic data. In the case of receiving a redundant packet, the node continues with the previously calculated probability, ignoring the new duplicate packet.

The studies in [25, 58, 62–64, 67] use probability as a linear function of distance to reduce the number of redundant retransmissions. In this approach, a higher retransmission probability is given to a vehicle that is farther away from the transmitter, where the probability is computed as follow:

$$p = \frac{d}{R} \tag{2.3}$$

This approach has proven effectiveness in reducing redundancy in dense networks in which multiple vehicles have similar transmission coverage. Thus, having some nodes not re-broadcast is assumed to reduce redundancy and save network resources. Unfortunately, this type of probability function has many shortcomings in heterogeneous environments. For example, if the communication range of the transmitter is large compared with that of the receiver and the distance between the transmitter and the receiver is greater than the receiver's communication range, p will be greater than one and this is against the probability rule. Also, vehicles with the smallest potential coverage area may be given higher probability than vehicles that could cover large areas. This may prevent the message from reaching a large number of vehicles in the vicinity area. Moreover, useless redundant transmissions could be caused by receivers that are completely contained by the transmitter or improper order of transmission.

The choice of farthest neighbouring only as the relay node helps to accelerate the message propagation. However, it may jump over many vehicles in the vicinity. Accordingly, they may not be aware of the message. This may happen in urban areas, where there are a lot of intersections or ramp on/off. Therefore, depending on the farthest conditions only may prevent other vehicles in vicinity to be aware of the message. In addition, the study assumes that messages can be transmitted without collision and congestion. Therefore, it needs to be performed in more realistic road conditions.

All the aforementioned algorithms are intended to reduce the number of redundant transmissions without considering the heterogeneity of vehicle transmission ranges. The difference in transmission ranges could affect the selection of the proper relay node to retransmit the message. For example, the farthest receiver may have a transmission range that is relatively small or enclosed by the sender, which means all neighbourhood vehicles may already be aware of the message. On the other hand, vehicles in between may have larger transmission ranges than the farthest vehicles and if it not relaying the message, many vehicles in the neighbourhood will not be aware of the message or more vehicles will relay the message. This leads to the expectation of more redundancy in the network and/or less delivery ratio. In this case, area is a better criterion than distance to select the next node to relay the message.

2.3.2 Area-based protocols

The concept of using area was initiated in [58] for a mobile ad hoc network (MANET). In that study, the algorithm calculated the area covered by the previous transmission and the amount of area that would be covered by a potential new transmission. If the result was greater than a given threshold, the node relays the message. Unfortunately, that work assumed the same transmission range for all nodes. Therefore, the calculation is not valid for heterogeneous transmission ranges. In addition, it always assumes intersection between two transmission ranges, while in reality there are a variety of possible scenarios. Furthermore, nodes transmissions are not ordered in a way that guarantees high opportunity to nodes that would cover large new areas. All nodes are allowed to relay if the potential coverage area is above the threshold value. This is allowing useless retransmissions and redundancy.

Our recent protocols, Area Defer Transmission (ADT), Area-based Probabilistic Transmission (APT) and an integration of timer and probabilistic area-based approaches ($APTt$) [68–70], enables each vehicle to decide independently to transmit or suppress transmission considering heterogeneous transmission ranges and the amount of area that would be covered by potential new transmissions. The ADT, APT, and $APTt$ protocols are described in more detail in Chapter 3.

2.4 Network topology-based protocols

In network topology-based Protocols, the decision to select relay nodes are based on information collected by beaconing process and prior receiving any messages. The decision to forward the message can be performed at the sender or at the receiver. This approach approve it low latency since no time out or waiting is required at each hop, however, it may suffer from low reception rates, since the candidate relay nodes may not receive the message, or it may not be even a neighbour any more. Therefore, this approach is highly correlated to the beaconing process, which should refresh the data when it is required and always keep the collected data up to date.

Similar to DDT [22], Privileged Inter-vehicle communication Architecture (PIVCA) [71]. It is a linear-based protocol that prioritizes the farthest vehicles in the message's transmission range to become the next forwarder. The receiving vehicles defer transmission for a time that is inversely proportional to the distance from the sender. The defer time is computed based on a contention window (CW), as inspired by classical back-off mechanisms in IEEE 802.11 medium-access control (MAC) protocols. It is measured in slots and varies between a minimum contention window (CWmin) and a maximum contention window (CWmax), depending on the distance from transmitter and estimated transmission range. Estimated transmission range is computed with help of beaconing system. Such that the estimated transmission range is the maximum distance from which the considered vehicle has heard another vehicle, backward or frontward.

The Vehicle Density Based Forwarding (VDF) [72] also, uses the defer time concept that is determined by the contention window in IEEE 802.11p MAC protocols. However, instead of using the farthest vehicle, they use optimal hop distance between the transmitter and the receiver. The optimal hop distance is the distance that minimizes the value of end-to-end broadcast delay. The end-to-end broadcast delay is calculated considering the transmission range, distance and density. The vehicle density in the transmission range is determined by the beaconing process. Thus, when receiving a beacon message, the vehicle counts the vehicle number in its transmission range and then calculates the vehicle density. However, the evaluation is performed in a straight highway road and accordingly they use the lane length instead of transmission range.

The study in [23,24] compare between two different dissemination algorithms. The first algorithm relies on beacons for instantaneous information on vehicle positioning. The node decides to retransmit the message probabilistically based on the distance from the closest relay node and waiting time. The second algorithm relies on neighbours table collected through a beaconing procedure as it will be described in Section 2.5. Neighbours table maintain neighbourhood state information, such as id, timestamps, speed, and position. The entry is removed when the entry age is equals twice the beacon interval. The relay node is selected based on the direction of broadcasting as well as the closest follower among its neighbours (based on the neighbour table and distance). Their research has shown that prior knowledge about network topology approach is more efficient in term of the channel utilization while the redundancy in the instantaneous approach makes it more robust to error, due to the wireless channel.

TRAcking DEtection (TRADE) dissemination protocol is proposed in the study in [22]. The TRADE categorizes the neighbouring vehicles into different road groups, based on their GPS position, and picks a few vehicles from each group for message re-transmission. Neighbours GPS positions are acquired through periodical beacon exchanges. Neighbouring vehicles are categorized into Same-Road-Ahead, Same-Road-Behind, and Different-Road groups using neighbours position information. Then, relay nodes are selected from each group, such that the relay nodes are the farthest vehicles from Same-Road-Ahead and Same-Road-Behind, while all vehicles from Different-Road. Relay nodes ID piggybacked into the message before it is broadcasted. The neighbour, upon receiving the message, determines whether it is responsible for re-broadcasting the message, by checking the ID's in the message. TRADE has been compared to the proposed instant-based protocol Distance Defer Transmission (DDT) that described in 2.3.1. It has been proven that DDT outperform TRADE in sparse network due to the back off time used, while TRADE have higher utilization since it has better knowledge of neighbour topology.

In Non-GPS Data Dissemination (NoG) [18], a node makes a decision by itself whether to be a relay node or not based on the neighbours information gathered by beacon messages. This information includes a number of 1-hop neighbours, a 1-hop neighbour list, and a received packet identifier list. relay node must stratify one of the two conditions: either it has the highest number of 1-hop neighbours or It has at least a neighbour that is not covered by a pair of its neighbours and these two neighbours also are neighbours of each other. If it is a relay node, upon receiving the broadcasting packet, it randomly sets very short backoff delay (<10 ms.). After the delay expires, it immediately rebroadcasts the packet. The nodes that are not relay node set their waiting timeout with longer period than relay nodes. While waiting timeout does not expire, they are listening to rebroadcasting from the other nodes. If they hear any rebroadcasting of the same packet in their waiting list, they will remove this packet from their waiting list to avoid redundant retransmissions. For intermittent connectivity scenarios, NoG can detect a missing packet via an acknowledgement from the beacon. A node will set their waiting timeout, if other nodes do not rebroadcast the packet before its waiting timeout expires, it will retransmit this packet to its neighbours.

The selection of relay nodes in [73] is performed by a control node. This control node is simply a RSU, due to awareness of the vehicle topology within its coverage. To avoid transmission collision, control server(CS) is used to make the scheduling decision for each RSU. This control server is connected with the RSUs with a wired backhaul. The CS then informs the RSUs of the scheduling results, and each RSU just announces the results to the vehicles within its coverage.

Smart Broadcast (SB) [60] is proposed at the MAC layer to maximize the progress of the message along linear propagation line. The road is divided in to sectors based on the position of the vehicles relative to the source. For each sector there is contention window associated with it that do not overlap with other sector contention window, such that the beginning of the contention window starts from the end of the previous sector contention window. This is to ensure nodes in the further regions always transmit before the others. The relay node on the same direction is selected using Request-To-Broadcast (RTB)/Clear-To-Broadcast (CTB) signalling. The source node transmits RTB to one-hop neighbours, containing position, sector width, direction and windows size. Only nodes in the same direction participate on the relay election. The receiving nodes determine the sector they belong to by comparing their coordinates with the source coordinate. Then, nodes randomly pick a back-off time in the contention window associated with the sector they belong to. Whenever a node countdown to zero, it sends CTB to announce its role as relay node and stop other nodes from rebroadcasting. When the source node receive the CTB packet, it starts transmit the packet including the relay node id. The study shows the good performance of the proposed SB, however, it needs to be implemented in more realistic traffic scenario. In addition, one-hop latency is still questionable compared to other algorithm proposed to work in the network layer.

The work [21] proposes DECA protocol to maximize number of neighbours that can receive the message per one transmission. The protocol does not require position information but uses store-and-forward technique and employs number of neighbours to make decision on forwarding. The source node selects one neighbour, which has the highest local density information to be the next relay node. To improve reliability, other neighbours store the message and randomly set their waiting time-out, if they do not hear anyone rebroadcast the message before the time out expiration, they will rebroadcast the message. The protocol uses beaconing to allow nodes to exchange their local density and identifiers of received messages with 1-hop neighbors. A node can discover its neighbours, which have not received the messages and consequently rebroadcast the messages for those neighbours.

In [20, 59], the proposed Distributed Vehicular broadcast protocol(DV-CAST) relies only on one-hop local topology information to decide whether to do retransmission for the message or not. Local topology is built using periodic beaconing (e.g. 1 Hz) of vehicle GPS position. From the local topology, the vehicle determines if the neighbourhood sparsely connected or well-connected neighbourhood. A vehicle in a well connected neighbourhood should immediately apply broadcast suppression algorithm when it receives the broadcast message, while it should resort to a store-carry-forward mechanism in a sparsely connected neighbourhood. In order to determine the local connectivity information, upon receiving the beacon from the neighbour, each vehicle has to compare its GPS information against the neighbour's GPS information and determine whether the neighbour is moving in the same direction or in the opposite direction. In addition, neighbours moving in the same direction must also be further categorized into leading vehicle or following vehicle. For this purpose, DV-CAST maintains three separate neighbour tables, NB-FRONT, NB-BACK, and NB-OPPOSITE, which contains the list of neighbours who are leading, following, or moving in the opposite direction, respectively. A vehicle is said to be in a well connected neighbourhood if it has at least one neighbour in the message forwarding direction. While, a vehicle is operating in a sparse traffic regime if it is the last node in a forwarding direction.

In broadcast suppression mechanism, a node, that is, the farthest node to source node, has the shortest waiting time out. However, if a node meets another node in the same direction of broadcasting packets, it will immediately rebroadcast the packets. This is because a node in the same direction of packets can help source node to forward the packets while it is running. While in store-carry-forward mechanism, upon receiving the message immediately rebroadcast the message. However, a vehicle in opposite direction has to wait until the packet timer expires or it receives a beacon from a new neighbour in the original message forwarding direction. Also, if the vehicle is the last vehicle in the direction of the message, it has to wait until packet timer expires or it receives for the beacon from vehicles in any direction to do rebroadcast.

Receiver consensus algorithm [19] is based on geographical information collected from beaconing process. Beacons also include acknowledgement of unexpired disseminated message. For each disseminated message, each node divides its neighbour nodes into three sets, according to their reception status: R (affirmatively received, nodes that attach ACK in their beacons), $\mathbb{P}$ (potentially received), and $\mathbb{N}$ (not received, nodes without ACK in their beacons). Potentially received is a transient status before receiving ACK. If a new beacon received from a node without acknowledge for the message, the neighbour is updated to be in $\mathbb{N}$ (not received) set. If $\mathbb{N}$ becomes non-empty from empty, retransmission of message will start, using location-based ranking algorithm. In location-based ranking algorithm, all neighbours that affirmatively or potentially received the message are ranked in the order of the distance to the ideal location, for instance r. The ideal location is the centroid of neighbours in the set $\mathbb{N}$ (neighbours who do not receive the message). The smaller the distance is, the higher the ranking. The node will retransmit in the upcoming r^{th} slot if all lower ranked neighbours remained silent in previous slots (when they were expected to forward).

Distributed Multi-hop Broadcast (LDMB) [74] is a time-slotted multi-hop broadcast protocol that trying to reduce number of retransmissions. The protocol allocates separate time slots for the multi-hop warning message dissemination to avoid the interference with the single-hop messages. In addition, It is divide the highway into fixed-size road segments that smaller than the beacon transmission range. The vehicle that will stay in the segment longer time than other is selected as relay node. This protocol has been compared with DV-CAST [20,59] and SB [60]. The result show reduction on the number of retransmissions and dissemination delay.

2.5 Periodic beaconing process

Beaconing is the way of the communications required for most of VANET applications. VANET literatures often discuss beaconing as a mean to solve information dissemination challenges. Also, it has been made as an assumption in different literatures [16,17,75–89], as well as in the Safety Communications Consortium (VSCC) final report [34] to help in identifying vehicle position in the road way. The term beaconing indicate the process of periodically broadcasting a short message, with important information, to neighbouring vehicles in the same transmission range, i.e. single hop neighbours. Accordingly, a beacon means the short message that required to be transmitted with some regularity. An example is the Basic Safety Message (BSM) that contains vehicle state information, which is periodically broadcast to surrounding vehicles.

On the other hand, the term message is used as a general term that either indicate beacon or event driven message, which may need to be disseminated to multi hop neighbours. There are a set of short messages defined in SAE J2735 standard as shown Table 2.3. The messages specified in SAE J2735 standard are used for both Vehicle-to-Vehicle (V2V) and Vehicle to Infrastructure (V2I) exchanges. The information included in these messages is different according to the type of the message and the applications that require the message.

Beacons often used to provide instantaneous information on vehicle operational status. It also may be used to maintain longer-term knowledge about network topology. Beacon messages must be received up to a certain distance with a strict timeline in order to be beneficial to VANET applications. Improper assignment for beacon frequency or beacon schedule time interval my cause overhead or outdated information. Often beacons are generated at static periodic rate for example, BSM. This represents a communication challenge considering that all communication partners must transmit data generated at a potentially high rate. This increases the load on the wireless channel, which in turn reduces the performance of the global communication systems and presents a challenge to a reliable and successful delivery.

The work in [90] investigates channel utilization with respect to different values of nodes number, beacon generation rate, and the size of a beacon message. They have shown that a beaconing system can have many nodes transmitting at a low rate or few nodes transmitting at a high rate. In addition, the beacon size affects the number of nodes and rate that can be achieved.

The performance of single-hop beaconing under different communication range values, beacon generation intervals, and beacon sizes is shown in [91]. This research has shown that it is very difficult to meet the safety application QOS requirements in a congested environment. The research also shows that in order to obtain certain QOS, these parameters should be tuned with respect to one another. For example, in order to obtain high packet delivery ratio for a 100 ms beacon interval, the transmission range should be significantly reduced (e.g. <200m). In addition, choosing an optimal transmission range and beacon interval for higher throughput depends on message size. Moreover, research [48] has shown that only a few dozen vehicles can communicate with one another, even without any collision on the communication channel, when multiple safety applications are running on vehicles.

The issue of wireless channel congestion, especially the congestion that is caused by periodic beacons, has gained a lot of attention and researchers have come up with many fundamentally different solutions. In [48, 92] the authors are not explicitly proposing a strategy for controlling the beaconing rate. Instead they proposed a central unit to coordinate all safety application transmissions with the goal of reducing the redundancy of the broadcast data. This is because many of the data requirements for various vehicular safety applications either partially or completely overlap. In addition, research [48] proposes the use of frame aggregation and compressing before transmission. In spite of the fact that these techniques improved vehicle number limit in VANETs, the number is still insufficient to cover the fluent communication in congestion roads.

In [11] the authors investigated whether the load on the wireless channel can be reduced if the periodic beacon messages are transmitted over multiple hops with reduced transmit power instead of being transmitted over one hop with high transmit power. In this method, beacon messages are relayed and piggybacked by neighbouring nodes until the desired dissemination range is covered. By piggybacking one or several to-be-forwarded messages into the next beacon transmission, a node could save the overhead of multiple message headers and thereby reduce the load on the channel. Their research proves that load reduction can be achieved in the one-dimensional and optimal scenario. However, reduction of the channel load cannot be exploited under non-perfect channel conditions and when suboptimal relaying is considered. It also has been proven that multi-hop beaconing is in general not able to provide a better neighbourhood awareness than single-hop beaconing.

CRCP (Collision Ratio Control Protocol) [93] adjusts the packet beaconing interval based on the number of surrounding packet collisions to a void broadcast storm problem. The target is to bring the actual collision ratio to a pre-defined target collision ratio regardless of the vehicle density.

The authors in [94], design distributed beacon scheduling schemes that assign the time slot to the node by means of a TDMA-like transmission. In this method, each node forms a virtual time frame (VTF) independently based on the received beacon messages. Each beacon message contains a node identifier (ID), time stamp, location, speed, direction and topology information (TI). The TI contains the information of N number of time slots that include an identifier of a road segment for the relative distance vector, a status bit for a reserved time slot, and a flag bit. When an event is triggered for a beacon message transfer, the node checks its VTF table to see if there is any reserved time slot. If there is a reserved time slot, the node generates a beacon message and sends it to the lower layer. Otherwise, the node reserves one of the available time slots to itself and uses it for the next beacon transfer. If there is no reserved time slot, the node will wait for the time duration of a random back off and search its VTF table again to get an available time slot. VTFs operate in both synchronous and asynchronous modes. Synchronization among the nodes is done through a Global Navigation Satellite System. In the asynchronous mode, vehicles maintain their own frame boundaries and therefore the slots are also asynchronous.

In decentralized beacon dissemination control scheme (DBDCS) [95], control channel interval (CCHI) is adjusted dynamically based on traffic condition. Estimated beacon reception ratio is compared to target value of reception rate. If estimated value is smaller than the target value, CCHI will be extended to reduce channel access contentions. Otherwise, CCHI will be shortening to provide more time for SCH. Although, the proposed solution manages to provide good results, CCHI synchronization is still an open issue. This is because CCHI is adjusted for each vehicle individually. Therefore, the switching point between CCH and SCH may differ between neighbouring vehicles.

Research [12] proposes SuRPA (Successive Rate and Power Adaptation) algorithm that is inspired from binary search. In this solution the rate adaptation is applied until the minimum required rate is reached. Once the rate adaptation limit has been reached and density of vehicles still increasing, the power adaptation is performed. The adaptation of rate and power are based on collision rate, and busy ratio. The collision rate is read out by checking the sequence number on the MAC header. The busy ratio, on the other hand, retrieved by sensing the channel and adding up the time periods each vehicle spent in the state receive.

The study in [21] proposes an adaptive beacon interval to be used with DECA protocol that has been discussed earlier in this section:

$$f(n) = min(MinInv + (Cxn), MaxInv), \tag{2.4}$$

where $f(n)$ is an optimum beacon interval (second/beacon), $MinInv$ and $MaxInv$ are constant values analysed from experimental results, n is number of neighbours, and C is a constant for adjusting function slope.

Recently, USDOT are testing two algorithms for congestion alleviation. The first algorithm is a transmission control protocol supports adaptive control of the message transmission rate and transmission power. The second algorithm controls message transmission rate based on reported Channel Busy Percentage (CBP) from the neighbouring vehicles and that measured by the host vehicle. The algorithm adapts the message rate up and down in order to maintain a desired level of channel utilization [7]. In European, the ETSI specified a set of Decentralized Congestion Control (DCC) mechanisms that adapt the transmission parameters based on channel load measures. However, DCC still under investigation and enhancements.

Chapter 3

Relay Selection for Heterogeneous Transmission Ranges

Relay selection protocols reported in the literature generally assume equal maximum transmission range for all vehicles in the network. Whereas, vehicle transmission ranges are typically heterogeneous owing to their different transmission power values. ETSI included transmit power control (TPC) per packet as a component of the decentralized congestion control (DCC) mechanisms for the channels of ITS station [10]. Also, USDOT are considering transmission control protocol for scalable V2V safety communications that supports adaptive control of the message transmission rate and transmission power [7]. There are also many scholars have proposed dynamic adjustment of transmission power for vehicles to prevent congestion in high density networks such as [11–15]. This will create an environment with heterogeneous transmission powers and accordingly heterogeneous ranges. The difference in transmission powers/transmission ranges could affect the selection of the proper relay node to retransmit the message. For example, in instant-based protocols, the receiving vehicles make the decision to forward the message based on how far it is from the preceding forwarder (for more detail about instant-based protocols refer to Section 2.3). The purpose is to give the farthest vehicle the highest opportunity to relay the message. This ensures long hops along the road to speed up the dissemination and cover more nodes.

However, the decision to relay the message based only on the distance in heterogeneous transmission ranges will not be sufficient as illustrated in the example shown Figure 3.1.

Example:

Figure 3.1 shows that after transmission by vehicle A, vehicle B will be the next relay node according to the distance value. Although, vehicle B has a smaller transmission range than vehicle C, it will retransmit before vehicle C. If vehicle C cancels the transmission after receiving a redundant copy of the message from vehicle B, many vehicles in the transmission range of vehicle C will not be aware of the message. Thus, farthest receiver may have a transmission range that is relatively small or enclosed by the sender, which means all neighbourhood vehicles are already aware of the message. On the other hand, vehicles in between may have larger transmission range than the farthest vehicles and if

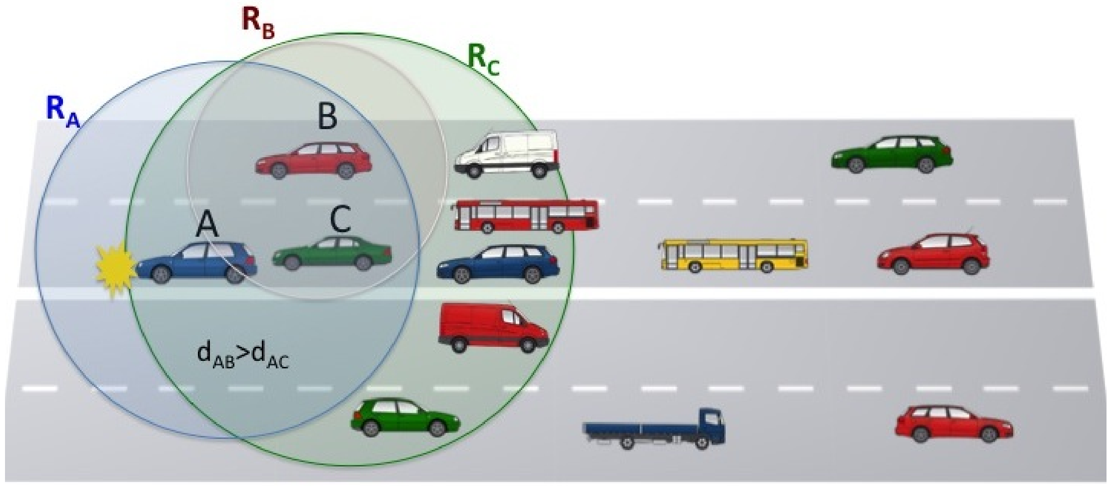


Figure 3.1: Distant-based relay selection in heterogeneous transmission ranges

not relaying the message, many vehicles in the neighbourhood will not be aware of the message or more vehicles will relay the message. This means more redundancy is expected in the network and/or less delivery ratio.

In this case, area is a better measure than distance to select the next node to relay the message. The concept of using area was initiated in [58] for a mobile ad hoc network (MANET). In this study, the algorithm calculates the area covered by the previous transmission and the amount of area that would be covered by a potential new transmission. If the result is greater than a given threshold, the node retransmits. Unfortunately, this work assumes the same transmission range for all nodes. Therefore, the calculation is not valid for heterogeneous transmission ranges. In addition, it always assume intersection between two transmission ranges, while in reality there are variety of possible scenarios. Further, node transmissions are not ordered in a way that guarantees high opportunity to nodes that would cover large new areas. All nodes are allowed to retransmit if the potential coverage area is above the threshold value. This allows useless retransmission and redundancy. Whereas, ordering the transmission according to the size of the potential coverage area increases the chance of reducing redundancy and retransmissions.

In light of the above, our contribution is to introduce area-based dissemination protocols for heterogeneous transmission powers. Rather than distance, the proposed approaches will consider the overlapping transmission area of the sender and the receiver. Where, each vehicle decides to independently transmit or suppress transmission considering the amount of area that would be covered by potential new transmissions. The new amount of area that would be covered by new transmission could be computed by different methods such as Monte Carlo Sampling Methods [96]. However, the value of new potential coverage will be computed exactly using trigonometry.

The protocols will be implemented using actual road map with complex road scenarios and realistic movement traces, and compared with Distance Based Forwarding (DBF) [63] and directional distance defer time (DdDT) [65] approaches, both of which are different versions of a distance-based approach.

3.1 System Model

Relay node selection for the proposed transmission protocols is based on the new potential coverage area. The new potential coverage area can be determined as a function of the common area between the sender and the receiver transmission ranges. The common area, A_{ij}, is computed in the receiver side based on information inside the event driven message (e.g. sender position, and sender transmission range) received from the sender, v_i, in addition to the local information of the receiving vehicle, v_j. The A_{ij} between vehicle v_i and vehicle v_j transmission areas can be one of four cases, as shown in Equation 3.1.

$$A_{ij} = \begin{cases} 0, & \textit{if } d_{ij} >= R_i + R_j \\ \pi * R_j^2, & \textit{if } R_i - d_{ij} \geq R_j \textit{ and } R_j < R_i \\ \pi * R_i^2, & \textit{if } R_j - d_{ij} \geq R_i \textit{ and } R_i < R_j \\ \frac{\theta_j R_j^2 - R_j^2 sin(\theta_j) + \theta_i R_i^2 - R_i^2 sin(\theta_i)}{2}, & \textit{if } |R_j - R_i| < d_{ij} < R_j + R_i \end{cases} \tag{3.1}$$

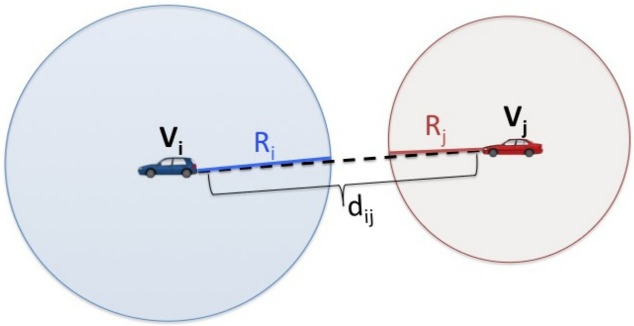
subject to:
$\theta_j = 2cos^{-1}\left(\frac{R_j^2 + d_{ij}^2 - R_i^2}{2R_j d_{ij}}\right)$, $\theta_i = 2cos^{-1}\left(\frac{R_i^2 + d_{ij}^2 - R_j^2}{2R_i d_{ij}}\right)$, and $d_{ij} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}$.

The parameters θ_i and θ_j will be derived in more detail later in this section. The important aspects of the system model are presented below:

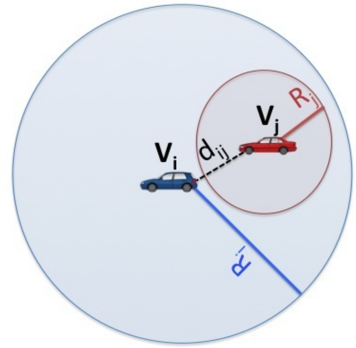
- Vehicle position is determined by using GPS chips as component in the vehicle [1]. However, GPS position measurement contains some errors. Thus, the error in position (x_i, y_i), (x_j, y_j) is modelled as Gaussian distribution with mean μ and standard deviation σ. Such that $x_i = \bar{x_i} + N(\mu, \sigma)$, $y_i = \bar{y_i} + N(\mu, \sigma)$, and $x_j = \bar{x_j} + N(\mu, \sigma)$, $y_j = \bar{y_j} + N(\mu, \sigma)$, where $(\bar{x_i}, \bar{y_i})$,$(\bar{x_j}, \bar{y_j})$ is actual position of v_i and v_j respectively.

- The mobility is not considered in this equation. This is because the required overlap area is at the time when the transmitter sends the message regardless of its movement later on. This is beside the area is computed immediately after the node receives the message and the difference between the send time and the receiving time is very small.

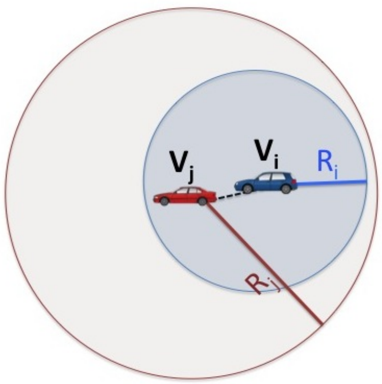
An example of each case of Equation 3.1 is presented in Figure 3.2, where v_i is the sender and v_j is the receiver. Figure 3.2a depicts the first case of Equation 3.1, where the two vehicles went out of transmission range after receiving the message, owing to mobility. In this case, there is no intersection area between the two vehicles (i.e. $A_{ij} = 0$). However, such case will not occur in this approach because the receiver computes the overlapped



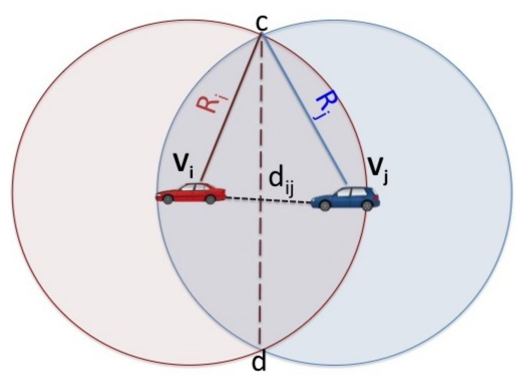
(a) $d_{ij} > R_i + R_j$



(b) $R_i > R_j$ & $R_i - d_{ij} > R_j$



(c) $R_i < R_j$ & $R_j - d_{ij} > R_i$



(d) $|R_j - R_i| < d_{ij} < R_j + R_i$

Figure 3.2: Cases of common area between two heterogeneous transmission ranges

area immediately after receiving the message and does not wait for a time that may cause the receiver to exit from the sender's transmission range. The second case in the equation represents the scenario when the transmission range of the receiver, v_j, is less than the transmission range of the sender, v_i, and the receiver's transmission range is enclosed by the sender's transmission area, as shown in Figure 3.2b. In this case, the overlapping area is equal to the receiver's maximum transmission area. Accordingly, the potential coverage area equals zero. However, the receiver will be given the lowest priority to retransmit. The receiver will be allowed to relay the message only in sparse networks, when there are no other vehicles in the region to relay the message before the maximum defer time expires.

Figures 3.2c and 3.2d illustrate the case of the sender covering part of the receiver transmission area. Figure 3.2c depicts the third case of Equation 3.1, where the overlapping area is equal to sender transmission area. This means that the sender's transmission area is enclosed by the receiver's transmission area. In contrast, Figure 3.2d illustrates when

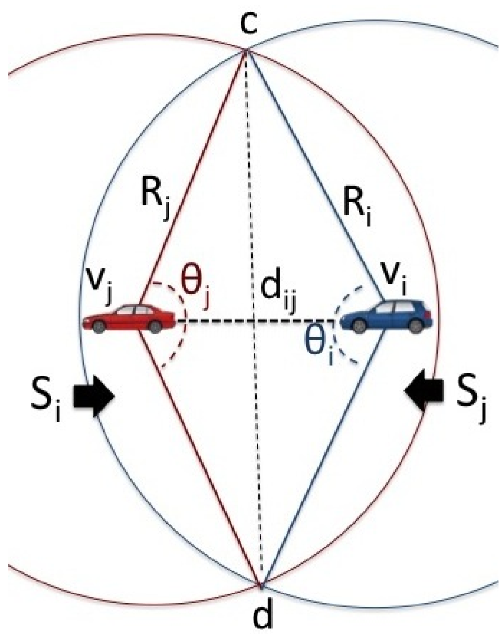


Figure 3.3: Common area of two partially overlapped transmission ranges

part of the sender and receiver transmission ranges overlap, as shown in the fourth case of Equation 3.1. Referring to the example shown in Figure 3.3, this formula is derived by using basic geometry of triangles and circles as follows:

Assume we have two vehicles v_i and v_j with different transmission ranges of R_i and R_j respectively. If we consider the transmission area to be circular, then the radius of v_i and v_j transmission areas is R_i and R_j respectively. Let v_i be the center of the first transmission area with coordinate (x_i, y_i) and v_j be the center of the other transmission area with coordinate (x_j, y_j). Then, the overlapped area is formed by two segments that bisected by the chord cd that belongs to sectors S_i and S_j. The area of circle sectors S_i and S_j are given by:

$$S_i = \frac{\theta_i}{2} * R_i^2 \ , \ S_j = \frac{\theta_j}{2} * R_j^2$$

In order to find the area of the two sector segments (i.e. the overlapped area), we first need to find the area of the triangles cv_id and cv_jd. Then, the area of each segment can be determined by the difference in area between the sector and the associated triangle. To obtain the area of the triangles, the angles θ_i and θ_j must be calculated using a cosine formula, as follows:

$$
\begin{aligned}
R_i^2 &= R_j^2 + d_{ij}^2 - 2 * R_A * d_{ij} * cos(\alpha_j) \\
cos(\alpha_j) &= \frac{R_i^2 + d_{ij}^2 - R_j^2}{2 * R_i * d_{ij}} \\
\alpha_j &= cos^{-1}\left(\frac{R_i^2 + d_{ij}^2 - R_j^2}{2 * R_i * d_{ij}}\right) \\
\theta_j &= 2 * \alpha_j \\
&= 2 * cos^{-1}\left(\frac{R_i^2 + d_{ij}^2 - R_j^2}{2 * R_A * d_{ij}}\right)
\end{aligned}
$$

Similarly,

$$\theta_i = 2 * cos^{-1}\left(\frac{R_j^2 + d_{ij}^2 - R_i^2}{2 * R_j * d_{ij}}\right)$$

Then, the overlapped area is given by subtracting the area of each sector from the respective triangles as follows:

$$A_{ij} = \frac{\theta_j R_j^2 - R_j^2 sin(\theta_j)}{2} + \frac{\theta_i R_i^2 - R_i^2 sin(\theta_i)}{2} \tag{3.2}$$

3.2 Area Defer Transmission (ADT) Scheme

Area Defer Transmission (ADT) enables each vehicle to decide independently to transmit or suppress transmission considering heterogeneous transmission ranges and the amount of area that would be covered by potential new transmissions. The ADT dissemination protocols do not rely on network topology information. Instead, each node decides independently based on the information contained in the message (such as, position and sender transmission range) and local information at the receiving vehicle. ADT orders the retransmission of a message among nodes, using timer concept. The value of the timer is based on the overlap between the receiving vehicle and the sender's transmission areas, and the ratio of receiver transmission range to the smallest value of transmission ranges. Thus, the retransmission is ordered in a way that ensures the node with high potential coverage area will transmit first. This ensures useless retransmissions with small coverage areas that can be covered by other transmission are eliminated. Accordingly, the network overload will be reduced.

The rationale behind letting the time depends on the overlapped area and the relative size of the receiver transmission range is that when a node hears the message for the first time, and its overlapped area with the transmitting node is small compared to the total transmission area of the receiving node, the additional coverage that can be achieved by retransmitting the message will be significant for receiver with large transmission range. Thus, the decision to forward the message should be taken with high priority and, accordingly, with the transmission deferral proportional to the overlap area between the sender

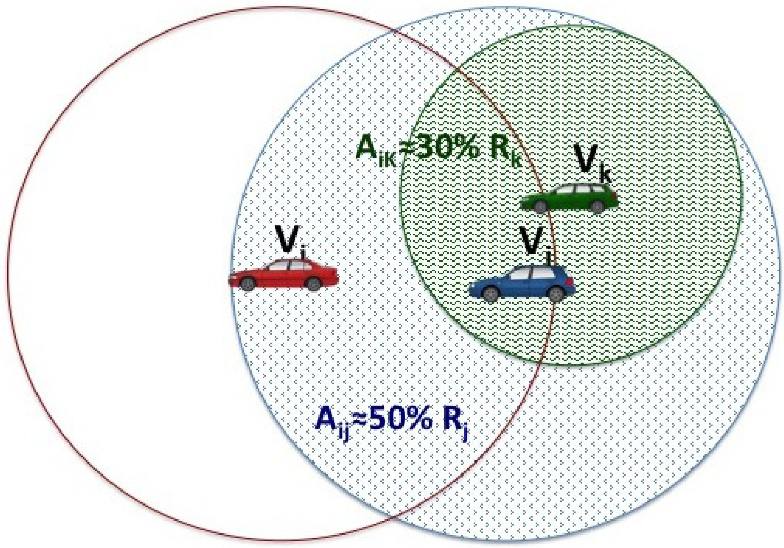


Figure 3.4: Illustrative example of ADT

and receiver. Thus, when a vehicle, say v_i broadcasts a message to the surrounding area, vehicles in its radio transmission range receive the message. The transmission area of the sender vehicle covers a circular area with a radius equal to its transmission range, R_i. The vehicle that receives the message, say v_j, checks if the message has been received before, as illustrated in Algorithm 1 Line 10. If not, v_j starts a timer before transmission, as shown in Equation 3.3. If the timer expires before receiving another copy of the same message, the vehicle proceeds with the transmission. Otherwise, it suppresses the scheduled transmission for the same message to reduce redundancy, as shown in Algorithm 1 Lines 31-37.

$$\tau = \begin{cases} T_{max}(\frac{A_{ij}}{\pi * R_j^2} * \frac{\gamma}{R_j}) + \delta, & if\ A_{ij} \neq \pi R_j^2 \\ \\ T_{max} + \delta, & if\ A_{ij} = \pi R_j^2, \end{cases} \tag{3.3}$$

where T_{max} is the time required to ensure the receiving vehicle can observe if other vehicles are forwarding the message and thus decide to refrain from transmission. A_{ij} is the intersection area between transmitter and receiver transmission areas, which is computed using Equation 3.1, for more detail refer to Section 3.1. δ is a random variable. The random variable component is used to avoid collisions caused by simultaneous transmissions from two or more vehicles within the transmission range of the sender. Though, the MAC layer uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme to access the shared media. CSMA/CA is known to perform well in uncongested networks, but degrades dramatically with a strong increase in network load. The importance of the random number concept has been discussed by a number of scholars, including [24,65]. In this case, the transmission is delayed by a uniform random amount within the distributed coordination function inter-frame space (DIFS), as proposed by [65].

The parameter γ is the allowed minimum transmission range. In this research the minimum transmission range for vehicles is set to $100m$. The rationale behind using the fraction $\frac{\gamma}{R_j}$ in the equation is to ensure that the receiver with the largest additional coverage among all vehicles in the sender transmission range has the shortest waiting time. Accordingly, it has the highest opportunity to retransmit the message. Without this fraction vehicles with different transmission range will have the same timer and accordingly transmission priority, in case they have the same ratio of the overlapped area with the transmitter. Also, vehicles with large potential coverage and less overlapped area will have large waiting time than vehicles with small transmission ranges but large overlapped area with the transmitter. Illustrative example is shown in Figure 3.4.

Example:

In Figure 3.4, we assume vehicle v_i relay the message to vehicle v_j, and v_k. Vehicles v_j, and v_k have transmission ranges of $0.5km$ and $0.1km$ receptively. If we assume that the overlapped area of vehicles v_j, and v_k with the transmitter v_i is 50% and 30% respectively, then the potential coverage area for v_j is $0.395km^2$, while it is equal to $0.0217km^2$ for v_k. In spite of that the re-transmission decision for v_j is deferred to $T_{max} * 0.5$ seconds, which is greater than the defer time for v_k that is equal to $T_{max} * 0.3$ seconds. This means that vehicle v_k, which has smaller potential coverage area than v_j, is given high priority to relay the message than v_j. This may suppress v_j transmission and allow more vehicles that do not hear from v_k to re-transmit the message. To overcome such problem, we multiply the ratio of overlapped area between the transmitter and the receiver with the relative size of the minimum allowed transmission range to receiver transmission range. As a result, the defer time will be ordered according to the size of potential coverage area, such that vehicles with larger potential coverage area will wait less time than vehicles with smaller potential coverage area. Applying this to the same example in Figure 3.4, vehicle v_j will defer re-transmission decision to $0.1 * T_{max}$ seconds and v_k defer re-transmission decision to $0.3 * T_{max}$ seconds. This complies with the potential coverage area size.

If the overlap area is equal to receiver transmission area, as shown in the second part of the Equation 3.3, then the receiver will wait at least T_{max} seconds. This means v_j will be given lowest priority to relay the message since all vehicles on v_j transmission ranges already receive the same message. Thus, repeating the transmission will be useless, unless it is in sparse networks and no vehicles in the vicinity to relay the message. This waiting time will increase the chance of disseminating the message to new neighbours arriving later.

3.3 Area-based Probabilistic Transmission (APT) Scheme

A probabilistic approach has been used in studies to reduce the number of redundant retransmissions [25, 58, 62, 63, 67]. It has proven to be effective in reducing redundancy in dense networks in which multiple vehicles share similar transmission coverage. Thus, randomly having some nodes not rebroadcast is assumed to reduce redundancy and save network resources.

Algorithm 1 *ADT*, *APTt*, and *APT* scheme at vehicle j

```
Notation:
$\mathbb{M}$: Set of distinct received messages.
$\mathbb{W}$: Set of messages scheduled for transmission.
$m_k$: Message $k$ received from vehicle $i$.
$A_{ij}$: Overlap transmission area between the transmitter $i$ and receiver $j$.
$\tau_k$: Defer time for message $k$ before transmission.
$t_m$: timer mode, ($t_m = 0$ no timer is used, $t_m = 1$ use timer).
$p_m$: probability mode ($p_m = 0$ no probability is used, otherwise allow probability).
$P_{ij}$: probability of transmission.
if $m_k \notin \mathbb{M}$ and message life time not expired then
    $\mathbb{M} = m_k \cup \mathbb{M}$
    compute $A_{ij}$ using Equation 3.1
    if ($p_m == 0$) then
        $p_{ij} = 1$
    else
        $p_{ij} = 1 - \frac{A_{ij}}{\pi * R_j^2}$
    end if
    if ($P_{ij} >= rand(0, 1)$) then
        if ($t_m == 1$) then
            if ($\hat{A}_j != \pi * R_j^2$) then
                $\tau_k = T_{max}(\frac{A_{ij}}{\pi * R_j^2} * \frac{\gamma}{R_j}) + \delta$
            else
                $\tau_k = T_{max} + \delta$
            end if
        else
            $\tau_k = 0$ /* No waiting time */
        end if
        $\mathbb{W} = \mathbb{W} \cup m_k(\tau_k$+current time);
    end if
else
    /* Redundant message */
    if ($m_k \in \mathbb{W}$) then
        /* Suppress scheduled message for transmission */
        $\mathbb{W} = \mathbb{W} - m_k$;
    end if
    drop $m_k$;
end if
/* Broadcast scheduled messages when deferred time expired */
for each $msg_L \in \mathbb{W}$ do
    if $\tau_L$==now then
        broadcast($msg_L$);
        $\mathbb{W} = \mathbb{W} - msg_L$;
    end if
end for
```

The simple approach is to allow each node to generate a random number and compare it with a particular threshold; if it is less than the threshold, the node retransmits the message [58,63]. The performance of such approach is highly dependent on the threshold. The large value of the threshold will result in excessive retransmissions of the same packet. In contrast, if the threshold value is too low, the packet might not be able to reach the distant vehicles. Another type of probabilistic approach is to give a higher retransmission priority to a vehicle that is farther away from the transmitter. In particular, the retransmission probability should be set as a linear function of distance, in the following form:

$$P = \frac{d}{R}$$

Unfortunately, this type of probability function has many shortcomings in heterogeneous environments. For example, if the communication range of the transmitter is large compared with that of the receiver and the distance between the transmitter and the receiver is greater than the receiver's communication range, P will be greater than one and this is against the probability rule. Also, vehicles with the least potential coverage area may be given higher probability than vehicles that could cover large areas. This may prevent the message from reaching a large number of vehicles in the vicinity area. Moreover, useless redundant transmissions could be caused by receivers that are completely contained by the transmitter or improper order of transmission.

In our proposed APT scheme, the shortcomings were eliminated, where each node calculates the retransmit probability as a function of the overlap area between the receiving vehicle's and the sender's transmission areas, as follows:

$$P = 1 - \frac{A_{ij}}{\pi * R_j^2} \tag{3.4}$$

where R_j is the receiver's transmission range and A_{ij} is is the overlap area between the transmitter v_i and the receiver v_j as shown in Equation 3.1. The node that receives the message for the first time retransmits the message with probability P and drop out the message with probability $1 - P$. No retransmission is performed when a duplicate message is received, and any scheduled retransmission is suppressed similar to ADT, as illustrated in Algorithm 1 Lines 31-37. In Algorithm 1, APT is the approach with probability mode (i.e. $p_m = 1$) and no timer mode (i.e. $t_m = 0$).

3.4 Area-based Probabilistic and Timer-based Transmission (APT_t)

In this approach, identified as (APT_t), area-based probabilistic approach is joined with area-based timer approach. When a vehicle receives a message for the first time, it decides to retransmit it with probability P, as illustrated in Equation 3.4. Thus, with probability P, the vehicle acts as a relay node and retransmits the message after it is deferred τ seconds. The deferred time τ is computed using Equation 3.3. On the other hand, with probability $1 - P$, the receiving vehicle drops out the message and gives up forwarding the message. When a duplicate message is received, no retransmission is performed and any scheduled retransmission is suppressed similar to ADT and APT, as illustrated in Algorithm Lines 31-37. In Algorithm 1, $APTt$ is the approach with probability mode (i.e. $p_m = 1$) and no timer mode (i.e. $t_m = 1$).

3.5 Area-based transmission protocols properties

Proposed area-based transmission approaches (i.e. ADT, APT, $APTt$) characterized by the following properties that prove their efficiency of relay selection process:

1. The protocols ensure that each selected relay vehicle covers new additional area not covered by any other relay node. This is because the selected relay nodes for the same hop never overlapped together, as will be demonstrated in the lemma 1.

   ***lemma 1*:** let vehicle v_i, v_j, and $v_k \in S_m$, where S_m is the ordered set of vehicles that retransmit the message m, and A_i, A_j, and A_k are the transmission area of vehicles v_i, v_j, and v_k respectively. Then, if $(A_i \cap A_j \neq \varnothing) \wedge (A_i \cap A_k \neq \varnothing) \Rightarrow (A_j \cap A_k = \varnothing)$.

   ***proof* :** $(A_i \cap A_j \neq \varnothing) \wedge (A_i \cap A_k \neq \varnothing)$ means that v_j and v_k are within the transmission range of v_i. Thus, if v_i relays the message m it will be received by both vehicles v_j and v_k. If we assume the contradiction that is $(A_j \cap A_k) \neq \varnothing$, then any transmission of v_j will reach v_k or vice versa. This means one of them will receive a redundant copy of the message. Recall that in area-based transmission protocols, any vehicles receiving a redundant copy will suppress scheduled transmission. Thus, either vehicles v_j, or v_k will not relay the message, and accordingly $(v_j \vee v_k) \notin S_m$, which contradicts the original assumption that both v_j, and v_k are relay vehicles.

2. As lemma 1 guarantees that relay vehicles for the same hop are disjointed, this reduces the common area between relay nodes, which ensures the reduction of useless redundancy and overhead in networks.

3. lemma 1 also ensures that vehicles in all directions will get the message. This eliminates the need to determine specific relay node for each direction.

4. In ADT, non-relay vehicles receive at least two copies of the message transmitted from distinct relay nodes. This redundancy of packet transmission improves dissemination reliability.

5. In sparse networks, if no additional coverage is achieved in ADT and $APTt$, at least one relay node will wait for the maximum defer time to retransmit. This waiting time will increase the chance of disseminating the message to new neighbours arriving later.

Figure 3.5: Map used in the simulation

3.6 Simulation set-up and performance metrics

Results in this section were obtained using the NS2 network simulator. The simulation is based on data from a real map of down-town Ottawa streets (see Figure 3.5), which was generated from OpenStreetMap. The map area is $2064mX2102m$. It includes details such as highways and secondary roads, intersections, highway junctions and traffic lights to represent realistic scenarios. The real movement traces are generated using Simulation of Urban MObility (SUMO) [97], a microscopic road traffic simulation package that combines vehicle movement with lane changing and intersection control, and constrains vehicle movements to selected streets. The speed for each vehicle is limited to the maximum speed allowed in each road that is configured in OpenStreetMap. In addition, it is defined in relation to the vehicle ahead. Also, vehicles may decide to slow down in order to execute a lane-change manoeuvre or aid other vehicles with lane changing.

The MAC (media access control) and the physical layers are based on the IEEE 802.11p model presented in [98]. The configuration parameters for the physical (PHY) and medium access control (MAC) layers of the IEEE 802.11p that is used in simulator is presented in Appendix B. The default carrier sense threshold is $-85dBm$ with heterogeneous transmission power. Transmission power for each vehicle was selected randomly, to achieve maximum transmission range of $100m$ to $600m$. Event-driven messages were generated every $1s$ second and assigned to a source node randomly chosen from the entire pool of network nodes. A list of simulation parameters used in this work is given in Table 5.1. The confidence interval calculation that is adopted for the performance metrics in this thesis is presented in Appendix A. The performance metrics used to evaluate dissemination approaches with a confidence level of 95% are listed below.

- *Relay ratio*: measures the ratio of vehicles in the network that retransmit the source message.
- *Relay coverage rate*: evaluates the quality of the selected relay vehicles, by quantifying the number of vehicles receiving the message from a single relay vehicle transmission.

Table 3.1: ADT, APT, and APT_t Simulation Parameters

Parameter name	**Value**
Network simulator	NS2.35
Propagation model	TwoRayGround
Mac and physical layer	IEEE 802.11p
Noise floor	-99 dBm
Carrier sense threshold	-85 dBm
Antenna	OmniAntenna
Mobility/Traffic generator	SUMO
Transmission range (R)	Randomly selected from 100 to 600 m
Number of vehicles (N)	50-500 vehicles
Message lifetime	700 ms
T_{max}	300 ms

- *Saved retransmission ratio*: the ratio of of the number of vehicles receiving but not retransmitting the message, to the total receiving vehicles (i.e. excluding relay vehicles).

- *Redundancy rate*: measures the number of duplicate messages in the network per one source message.

- *Delivery ratio*: measures the proportion of vehicles in the network that successfully receive the message.

- *Maximum hops traversed*: the average number of maximum hops the messages traversed.

- *Average propagated distance*: the average distance traversed by the messages in the network.

- *Average end-to-end delay*: represents the difference between the time when the message initiated and the received time.

3.7 Performance evaluation

The first part of the experiments evaluates the performance behaviour of the area-based protocols compared to distance-based protocols. The second part of the experiments assesses the ADT protocol under different T_{max} values, as shown in Equation 3.3.

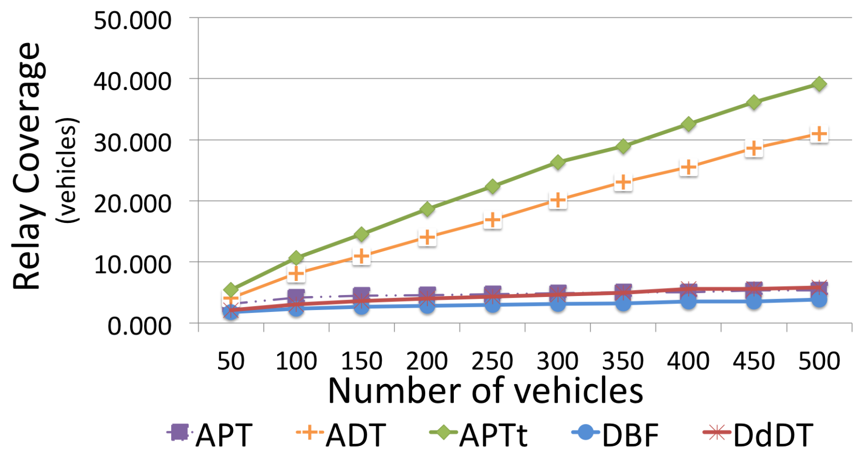


Figure 3.6: Area-based relay coverage comapred to distance-based protocols

3.7.1 Area-based compared to distance-based protocols

ADT, APt, and $APTt$ are compared with Distance Based Forwarding (DBF) [63], and distance version algorithm presented in [65], will be referred as $DdDT$. DBF is an enhanced version of the timer-based approach DDT [22]. It has integrates hop count with a timer-based approach, to avoid contention due to simultaneous transmission. The hop count is used to suppress transmission if the same packet is received from one hop greater than the previously received message. The algorithm in [65] is also a timer-based approach that computes the timer as a function of distance. However, it uses a directional distance, d_d, between the node and sender, rather than Euclidean distance, d_e. The directional distance d_d is computed as follows:

$$\begin{aligned} &d_d = d_e cos\theta, \text{ where} \\ &d_e = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}, \text{ and} \quad \theta = arctan\left(\frac{y_j - y_i}{x_j - x_i}\right) \end{aligned} \tag{3.5}$$

Both approaches start a timer, τ, before transmission, where τ is calculated as follows:

$$\tau = T_{max}\left(1 - \frac{d_{ij}}{R_j}\right),$$

where R_j is the receiver's transmission rang. The distance $d_{ij} = d_e$ in BDF, while $d_{ij} = d_d$ in the DdDT approach. The vehicle whose timer is due in the $DdDT$ approach, retransmits the message after a brief random time in DIFS. The purpose of the short time is to avoid possible collisions caused by concurrent transmissions from two or more vehicles with the same defer time.

The relay coverage rate is presented in Figure 3.6. The figure illustrates number of vehicles receiving one source message from one relay node. It measures the quality of

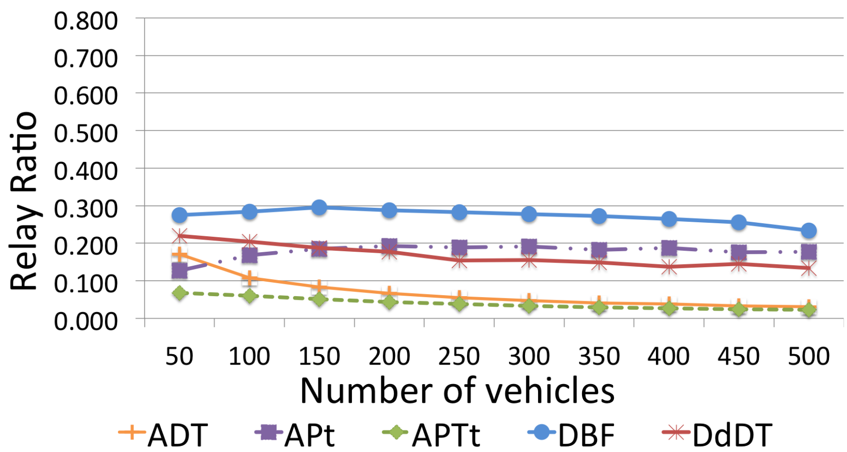


Figure 3.7: Area-based relay nodes ratio comapred to distance-based protocols

the selected node to relay the message in terms of the number of vehicles receiving the transmitted message. The figure shows that relay selection of timer-based approaches ADT and $APTt$ outperform other approaches. The vehicles that relay the message reach more vehicles than other approaches, and the number increases almost linearly when the number of vehicles increases. This is because the decision of ADT and $APTt$ is based on the potential coverage area and it is not performed stochastically. In addition, the back-off time helps the receiving node to decide with high certainty to relay the message or not, such that if the node does not receive a copy during the back off time, it is more certain that it will cover a new area.

Less coverage per relay node yields more vehicles relaying the message. Thus, the relay ratios for distance-based algorithm are larger than other approaches, as illustrated in Figure 3.7. The ratio of vehicles relaying the message in ADT, $APTt$ are 4%, and 6% consequently, on average for all densities, whereas it reaches 27% for DBF and 17% for $DdDT$ and APT.

The increase in ratio of relay vehicles will increase the hops traversed, as shown in Figure 3.8. In Figure 3.8, the effect of increasing the number of vehicles into the number of hops the messages traversed is demonstrated. The figure shows an increase in the number of hops traversed with the increase of total number of vehicles in the network for the distance-based approaches and APT, whereas it is more stable for area-based timer (e.g. ADT, $APTt$) approaches, particularly with respect to high density. This proves that area-based approaches are more scalable to the increase in density than distance-based. With the increase of vehicles in the network, messages in the ADT and $APTt$ approaches traversed less hops than the DBF and $DdDT$ approaches, and also propagated to a greater distance than others, as shown in Figure 3.9. This is because DBF and $DdDT$ are based on the distance to defer retransmission. Thus, vehicles with small potential coverage area may transmit first, causing other vehicles with large potential coverage to suppress their transmission.

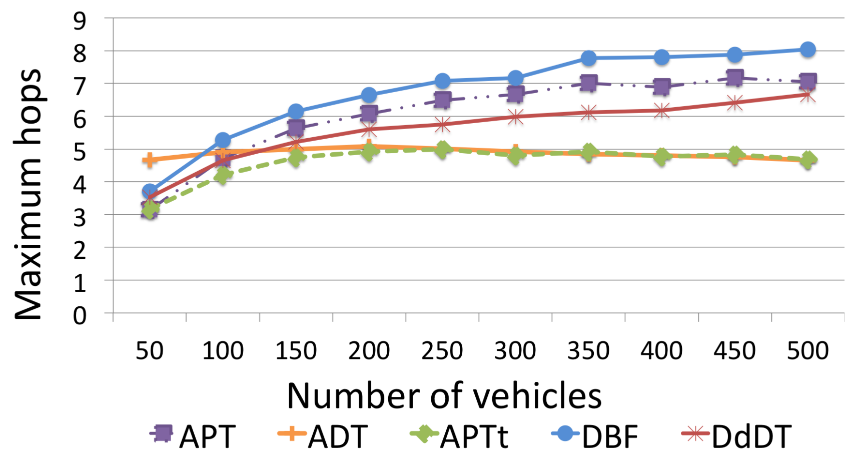


Figure 3.8: Area-based hops count comapred to distance-based protocols

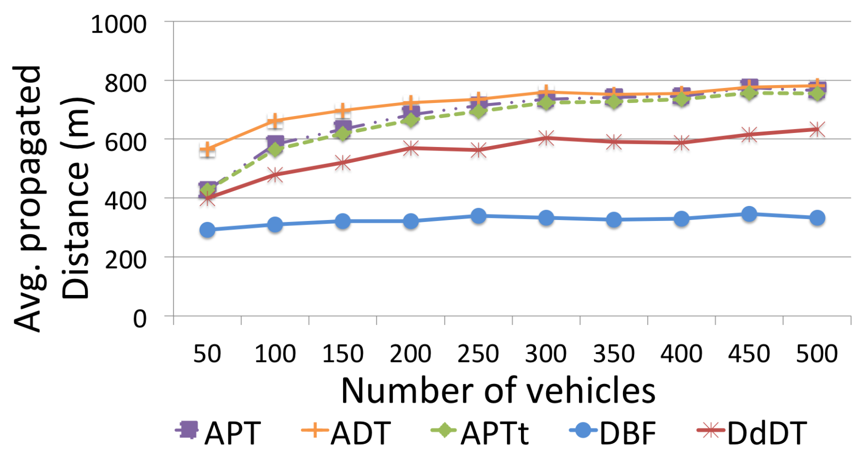


Figure 3.9: Area-based average propagated distance comapred to distance-based protocols

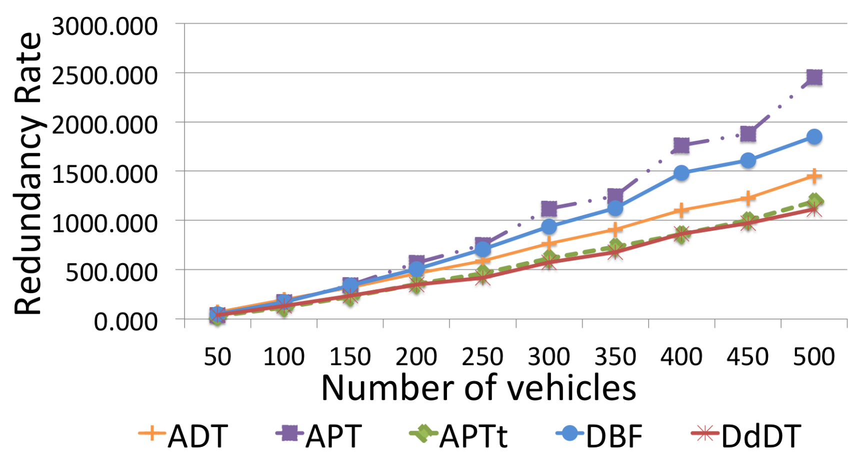


Figure 3.10: Area-based redundancy rate comapred to distance-based protocols

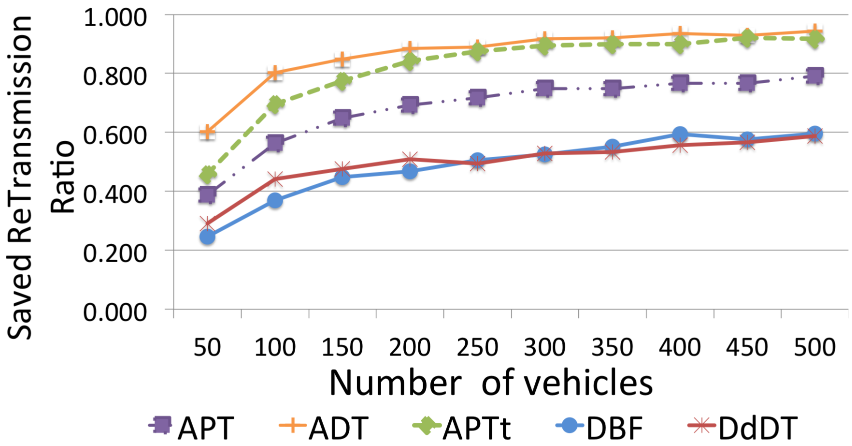


Figure 3.11: Area-based saved retransmission comapred to distance-based protocols

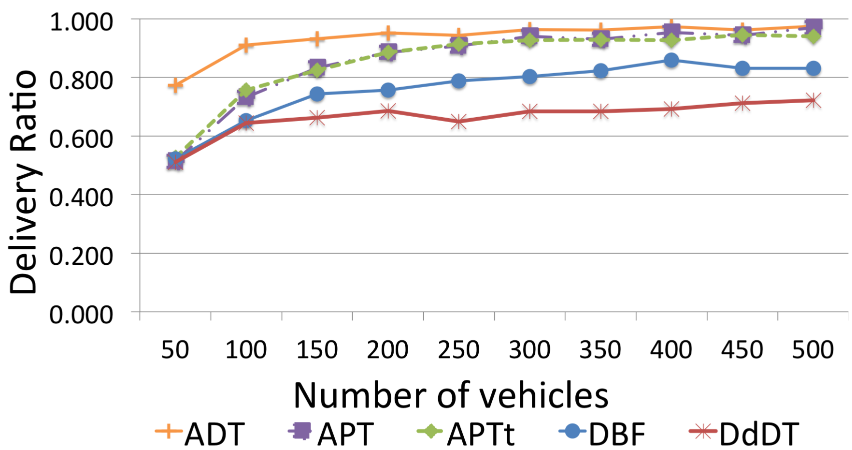


Figure 3.12: Area-based delivery ratio comapred to distance-based protocols

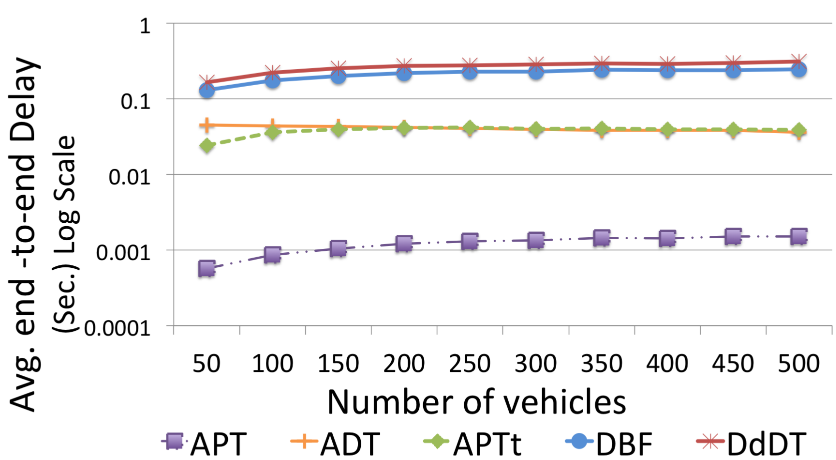


Figure 3.13: Area-based average end-to-end delay comapred to distance-based protocols

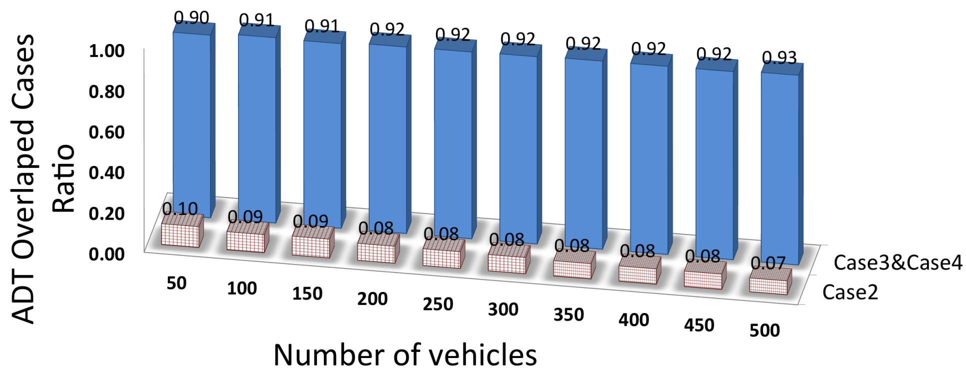


Figure 3.14: Ratio of *ADT* overlap cases.

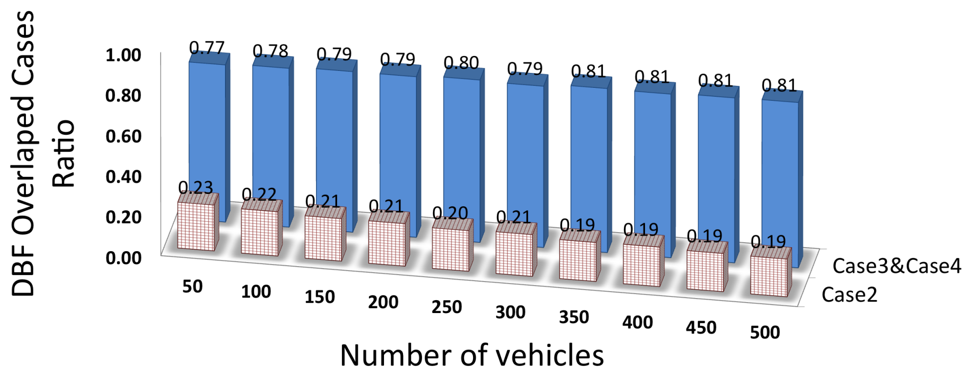


Figure 3.15: Ratio of DBF overlap cases.

Figure 3.10 measures the number of duplicate messages in the network per one source message. The figure shows that *DBF* and APT have the highest redundancy in the network, whereas *ADT* and *DdDT* have the lowest redundancy in the network. Nevertheless, the saved retransmission ratio for *ADT* and *APTt* are the highest, whereas it is lower than other approaches, as illustrated in Figure 3.11. This indicates that *DBF* and *APT* have useless retransmission, and *DdDT* and *APTt* suppress important transmissions. This is also depicted in Figure 3.12, which shows that the proportion of vehicles in the network that successfully receive the message in *ADT* which is much higher than with *APT* and *APTt*.

In *APT* there is no back-off time, while in other approaches the defer time is proportional to potential coverage area. As consequence, *APT* has the lowest average end-to-end delay, as shown in Figure 3.13. Whereas, the distance-based approaches have the highest end-end delay even though they cover less distances and less nodes than area-based approaches. On the other hand, the average end-to-end delay for *ADT* and *APTt* are less than $0.04s$, which is in the range of safety applications requirements.

Figure 3.14, Figure 3.15, and Figure 3.16, demonstrate the ratio of overlapped cases

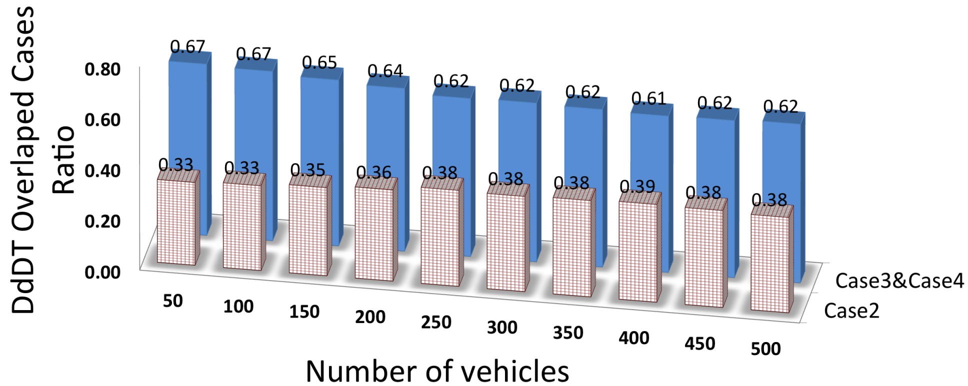


Figure 3.16: Ratio of DdDT overlap cases.

with different total number of vehicles in the network. Four cases are shown in Equation 3.1. Case 1 represents the scenario with the receiving vehicle become out of sender transmission area or vis versa. The percent of this case is zero for all the protocols, because the receiving vehicle computes the defer time immediately after receiving the message and does not wait for a time that may cause both vehicles exit each other transmission area. Thus, it was removed from the graphs. However, Case 2 represents the scenarios of the transmission area of the receiver already covered by sender transmission area and no benefit from retransmitting the message again. In this case ADT outperforms other protocols because it has only 8%, while it is 20% for DBF protocol and 36% for $DdDT$. It is noticed that ADT in Case 2 is not prevented totally from retransmission, thus the percentage of this case is low but not zero. This is because in ADT, if no additional coverage is achieved (such as, sparse networks) at least one relay node will wait for the maximum defer time to retransmit. This waiting time will increase the chance of disseminating the message to new neighbours arriving later. Therefore, Case 2 percentage is reduced with the increase of total number of vehicles in the network for ADT and DBF, while it is not for $DdDT$. Consequently, ADT in Case 2 and Case 3 percentages, which represent the scenario when the sender covers part of the receiver transmission area, outperforms other protocols.

3.7.2 ADT with different T_{max} values

Here, we report the results of comparing the performance of ADT approach with different T_{max} values. Figure 3.17 displays the number of vehicles receiving the message from one relay node. The figure shows that the relay coverage for ADT approach is almost the same when T_{max} has large values (i.e. 500ms, 300ms, and 100ms), while it is degrade when the T_{max} value is equal 5ms. The relay coverage degrades when T_{max} value is equal 5ms because the average value of the waiting time to hear from other vehicle in the vicinity will be very small. Accordingly, many vehicles that should suppress their scheduled transmission retransmit before having enough time to listen to other neighbours that may have larger potential coverage. On the other hand, the values 500ms, 300ms, and 100ms increase the

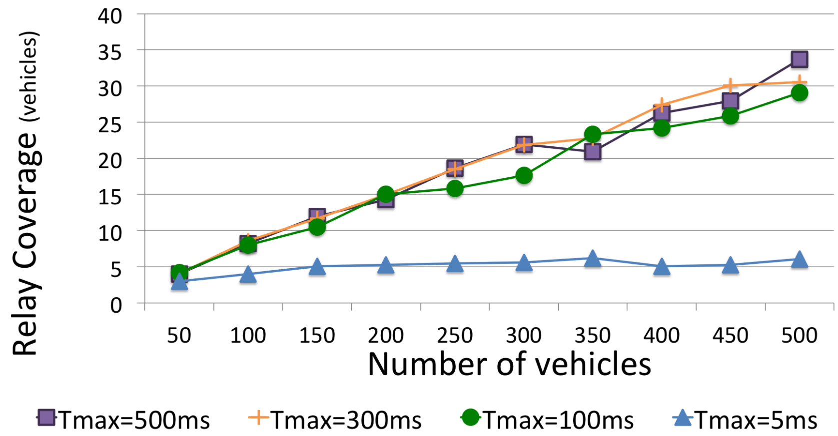


Figure 3.17: *ADT* relay Coverage with different T_{max} values.

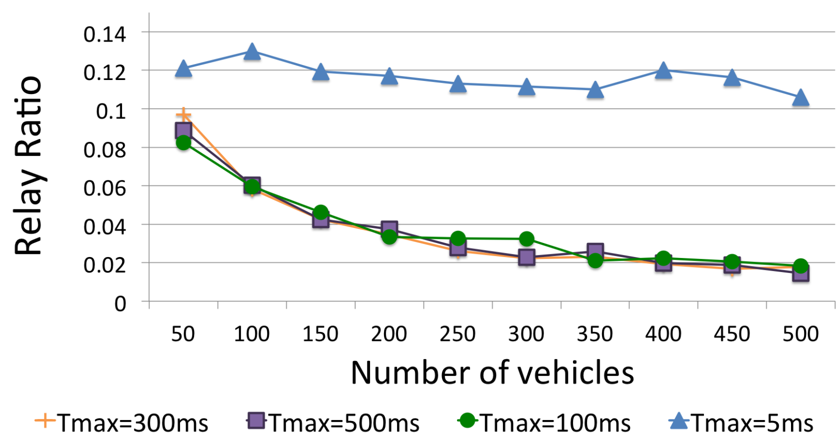


Figure 3.18: *ADT* relay ratio with different T_{max} values.

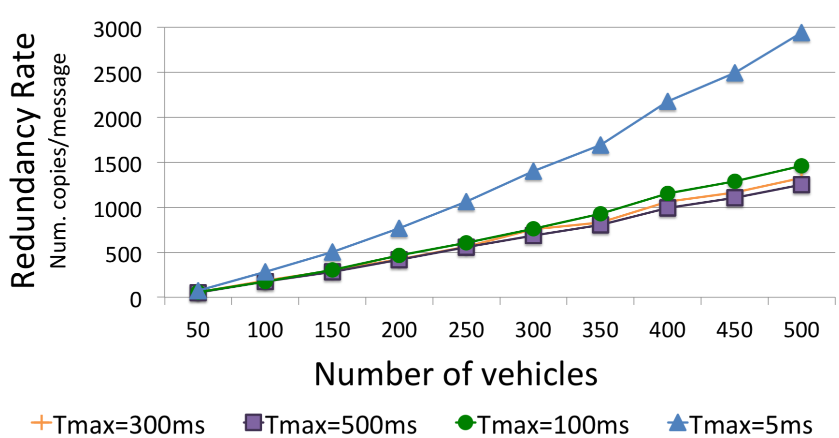


Figure 3.19: *ADT* redundancy rate with different T_{max} values.

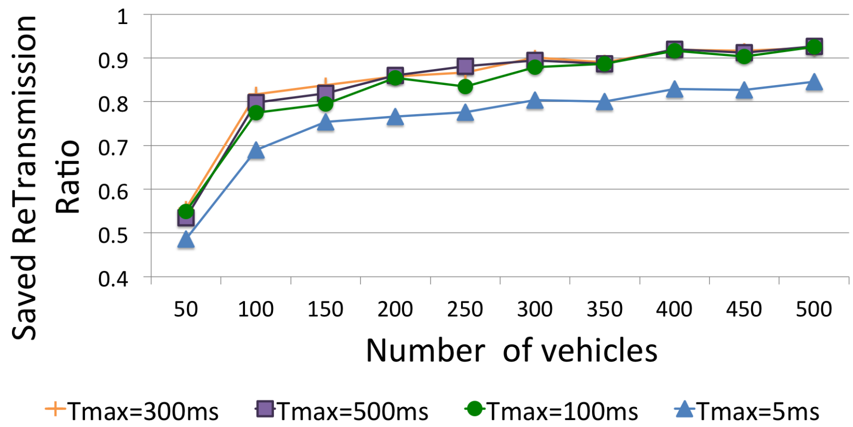


Figure 3.20: *ADT* saved re-transmission with different T_{max} values.

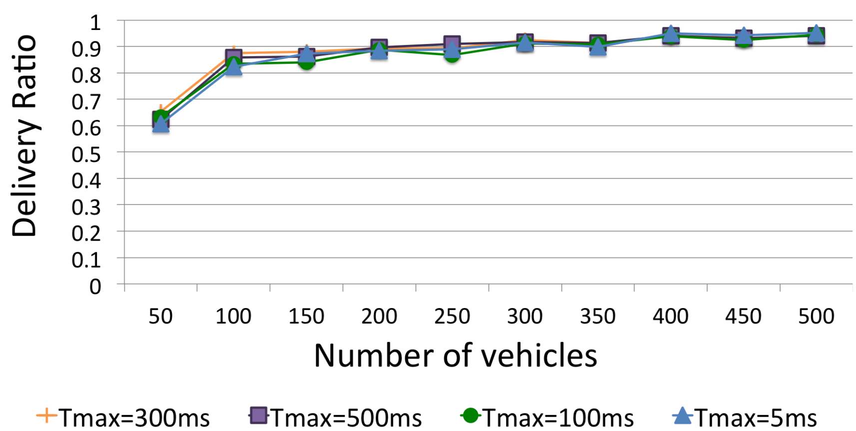


Figure 3.21: *ADT* delivery ratio with different T_{max} values.

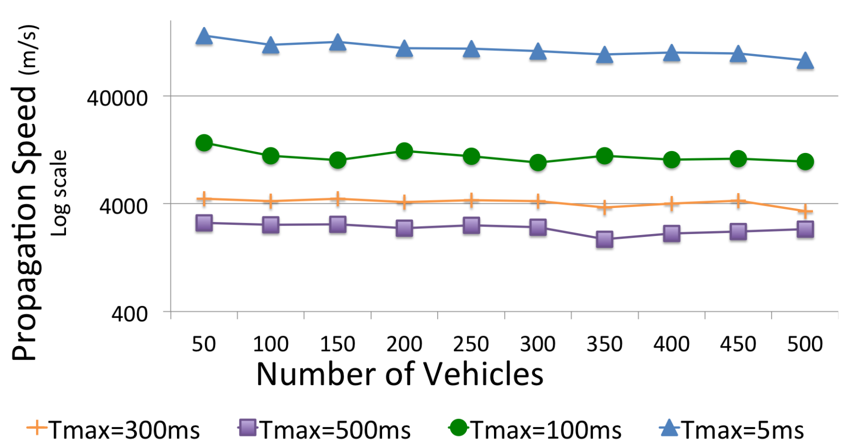


Figure 3.22: *ADT* average propagation speed with different T_{max} values.

waiting time for the vehicles. This means vehicles have enough time to hear from the neighbours before deciding to retransmit, which will give the chance of suppressing more useless retransmission. At certain point the increase of T_{max} will not affect the coverage value. This is because the priority to relay the message in ADT ordered according to the potential coverage area and the increase of the T_{max} will not affect this order. Such that if the node does not receive a copy during the defer time, it is more certain that it will cover new area.

Less coverage per relay node yields to more vehicles relaying the message, as shown in Figure 3.18. Thus, it is noticed that the relay ratio when T_{max} value is 5ms has the worst performance. The ratio of vehicles that relay the message decreases with the increase of vehicles density, when T_{max} has large value (i.e. 500ms, 300ms, and 100ms). The proper value of T_{max} yields to more scalable protocol. This is also predicated in Figure 3.19, and Figure 3.20, where redundancy rate reduced and saved retransmission ratio increase with the increase of T_{max} value. This is because the increase of T_{max} value for ADT will give the receiving vehicle more time to detect if other vehicles are forwarding the message, and thus decide to refrain from re-transmission.

Figure 3.21 shows that the proportion of vehicles in the network that successfully receive the message for all T_{max} values are almost the same. The changes of defer time due to the change of T_{max} value has a big impact on the speed, where the increase of the T_{max} value reduces the speed and vice versa, as shown in Figure 3.22.

3.8 Summary

In this chapter the following interesting works is done: First, an algebraic expression for a timer to be used by each vehicle receiving an event message is defined. The value of this timer will allow the vehicle to determine if it is the next to act as relay node or not. This expression orders vehicles transmission according to the amount of new area that would be covered by potential new transmissions, considering the heterogeneity in vehicle transmission ranges. This ensure unwanted retransmission or retransmission with small coverage areas that would be covered by other transmissions will be eliminated. Accordingly, Area Defer Transmission (ADT) protocol for data dissemination in heterogeneous transmission ranges is introduced. Next, the area-based concept are adopted to develop probabilistic area-based transmission (APT) and an integration of timer and probabilistic area-based transmission method ($APTt$) for heterogeneous transmission ranges in vehicle networks. Area-based approaches order nodes transmission according to the amount of area that would be covered by potential new transmissions, considering the heterogeneity in vehicle transmission ranges. Finally, the performance of the proposed techniques (i.e. ADT, APT, and $APTt$) has been thoroughly investigated and compared with other distance-based algorithms.

The following interesting findings were drawn from the results. First, more vehicles receive a message transmitted by a single relay vehicle with ADT than with other distance versions. This confirms the hypothesis that relay nodes selected by area-based timer are more effective than others, owing to their higher delivery ratios, end-to-end delay and the fewer hops with long distance hops. Second, the probabilistic area-based approach without timer concept increase redundancy, however, it is very fast at disseminating data compared with other approaches. Third, redundancy and retransmission are reduced more with controlling defer time in timer area-based approaches than with a probabilistic approach, without affecting reachability in the network and the delivery ratio. Fourth, $APTt$ can be utilized in high number of vehicles in the network because it achieves less redundancy than ADT with almost the same delivery ratio and propagated distance.

Chapter 4

Reliable Area-based Relay Selection for Heterogeneous Transmission Ranges

In VANET, Vehicle-to-Vehicle (V2V) multi-hop data dissemination has been considered a promising technology to support safety-related applications that have strict quality-of-services requirements such as low latency, high-reliability, and scalability. This has been increasing with the need to alleviate congestion in high-density networks. One way proposed by scholars is to dynamically adjust transmission power for vehicles. This leads to heterogeneous transmission ranges environments, which require multi-hop for data dissemination. The efficiency of multi-hop dissemination is related to the selection criteria of relay nodes. Reported data dissemination protocols in literature generally assume an equal transmission ranges for all vehicles in the network.

In this chapter, reliable area-based transmission protocols that work in heterogeneous transmission ranges are introduced. Reliable message transmissions in a timely manner is the primary concern in vehicular applications. This concern become more severe in an environment with heterogeneous transmission powers. The major problems that prevent reliable transmission protocol include the collisions caused by concurrent transmissions, high node mobility, sparse network and non-line of sight problem.

The proposed reliable protocols allow retransmission of duplicate received message are introduced. The transmissions between relay vehicles are ordered in a way that ensures the node with high potential coverage area transmits first. This eliminates useless transmission and retransmission that could be contained by other transmission. The new potential coverage area is computed as a function of the common overlap areas. Thus, a geometric taxonomy for all possible overlap patterns is introduced. In addition, the criteria used to define each pattern and relevant algebraic expression to compute the potential additional coverage area are deduced. Moreover, probability formula in probabilistic approaches is enhanced to order transmission according to potential coverage areas in the network. This is to ensure that useless retransmission, or retransmission with small coverage areas that would be covered by other transmissions, will be eliminated.

4.1 Analysis of retransmitting redundant message

In ADT, vehicles suppress their scheduled transmission of the message, if it is receives redundant copy from other vehicles in the same region. This section explains the benefit and costs of retransmitting the message after it have been received f times. The study is conducted using simulation. The map and simulation set up is the same what we are present in Section 4.4. The results are averaged on different traffic densities from 50-500 vehicles. Vehicles transmission ranges are heterogeneous configured randomly within a range of $100m - 600m$. We measure the proportion of vehicles in the network that receive the message for the first time from a relay vehicle that receives $f - 1$ copies of the same message from different relay vehicles before it decide to retransmit it. This value is denoted by ADR(f), which stand for additional delivery ratio. Also, we measure the cost in term of message redundancy caused by each redundant transmission.

The $ADR(f)$ for different f values is shown in Figure 4.1. The figure also demonstrates, in the first column, the total delivery ratio achieved by allowing relay vehicle to retransmit the message even if it is receive number of copies that is less than f. The first row depicts ADT when no redundancy is allowed (i.e. $ADT(1)$). It shows that the message is delivered up to 93%. In $ADT(2)$, the total delivery ratio is increased to 97%. However, it is noticed that the first copy, when $f = 1$, delivery ratio is reduced to 88%; while the second copy reaches 9% achieving total of 97%. For $ADT(f)$, with $f > 2$, no additional delivery ratio is achieved. However, the delivery ratio for earlier copies of the message is reduced and later copies are increased. This means allowing retransmission for a message that it is received multiple times will change ADT order of transmission. Thus, it may give the later copies the priority over the earlier copies, which leads to more redundancy as shown in Figure 4.2. The Figure demonstrate that the redundancy rate is increased to 50% for $ADT(2)$ compare to $ADT(1)$ and the value is increasing with the increase of f till it gets to 235% for $ADT(6)$.

In light of these results, it is concluded that if a vehicle receives more than two copies of the message, it is more likely that earlier relay vehicles cover all its transmission area and retransmitting the message will not propagate to new vehicles. On the other hand, new vehicles can be reached by relaying a message that has been received two times or less. But it will be at the expense of more redundancy. Thus, to reduce redundancy it is important to examine if part of the receiver area is not covered by earlier relay vehicles before relaying the message. In addition, we should ensure the order of transmissions is still based on the new potential coverage size.

4.2 ADT and Retransmission of Redundant message

In light of the results obtained in the previous section, Area Defer Transmission with relaying Redundant received message ($ADTr$) is proposed. $ADTr$ allows relaying one redundant copy as long as the retransmission is predicted to cover a new area of the receiver not covered previously by earlier relay vehicles. At the same time, it is intended to

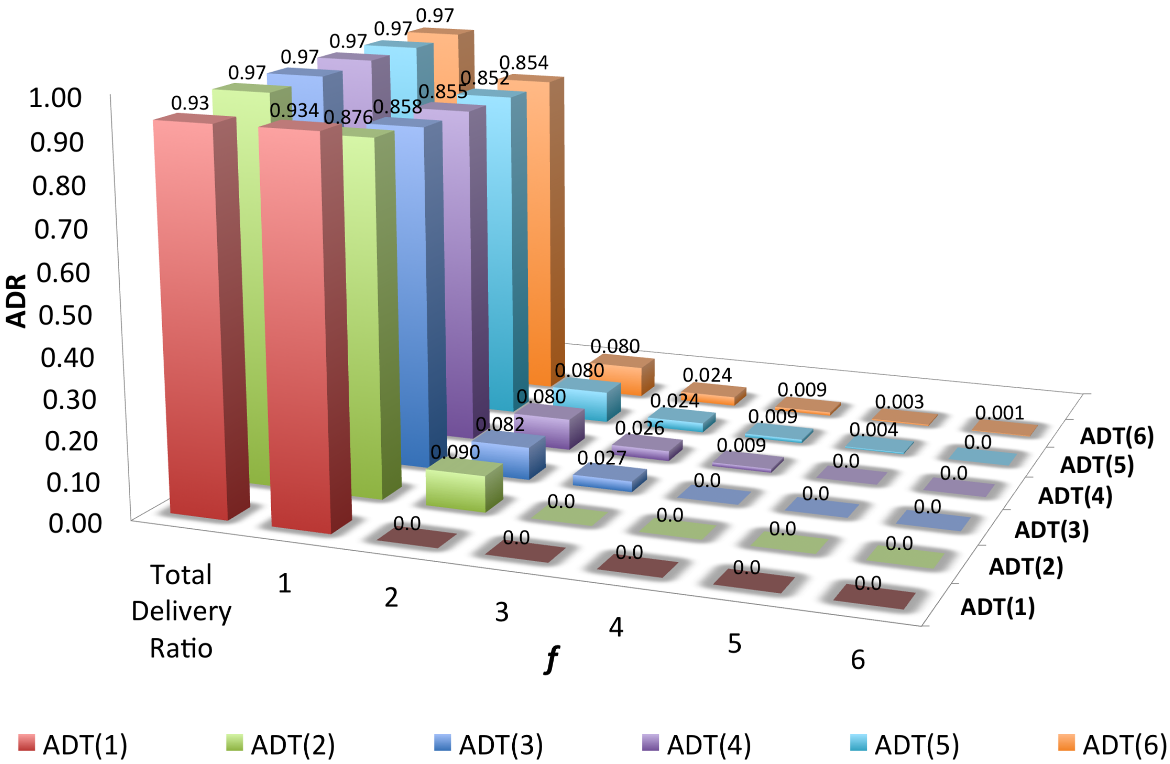


Figure 4.1: Additional delivery ratio vs. message copy number

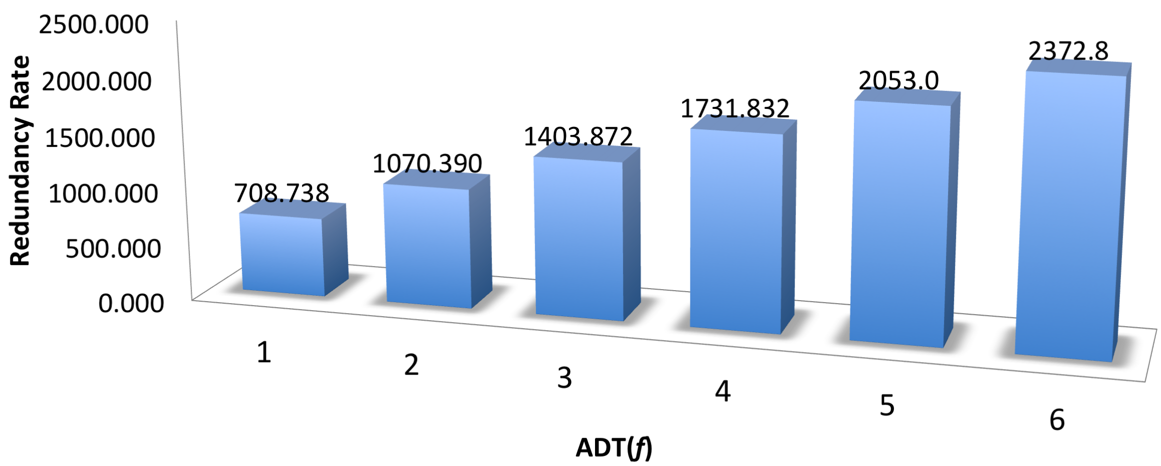


Figure 4.2: Redundancy rate vs. message copy number

Algorithm 2 ADT scheme considering redundant retransmission by vehicle k (ADTr)

Notation:
$\mathbb{P}$: Set of distinct received messages.
$\mathbb{P}_2$: Set of distinct received messages for the second time.
$\mathbb{W}$: Set of messages scheduled for transmission.
msg_m: Message m received from vehicle j.
A_{kj}: Overlap transmission area between the transmitter k and receiver j.
$\hat{A}_k$: Non covered transmission area of vehicle k by earlier relay nodes.
τ_m: Defer time for message m before transmission.
if $msg_m \notin \mathbb{P}$ and message life time not expired **then**
    $\mathbb{P} = msg_m \cup \mathbb{P}$
    compute A_{kj} using Equation 3.1
    if $A_{kj} \neq A_k$ **then**
        $\tau_m = T_{max}(\frac{A_{jk}}{\pi R_k^2} * \frac{\gamma}{R_k}) + \delta$
    else
        $\tau_m = T_{max}\frac{A_{jk}}{\pi R_k^2} + \delta$
    end if
    $\mathbb{W} = \mathbb{W} \cup msg_m$;
else
    /* Redundant message */
    if $msg_m \in \mathbb{W}$ **then**
        /* Suppress scheduled message for transmission */
        $\mathbb{W} = \mathbb{W} - msg_m$;
    end if
    if $msg_m \notin \mathbb{P}_2$ and message life time not expired **then**
        $\mathbb{P}_2 = msg_m \cup \mathbb{P}_2$
        compute $\hat{A}_k$ using Algorithm3
        if $\hat{A}_k > \upsilon$ **then**
            $\tau_m = T_{max}(\frac{\pi R_k^2 - \hat{A}_k}{\pi R_k^2} * \frac{\gamma}{R_k}) + \delta$
            $\mathbb{W} = \mathbb{W} \cup msg_m$;
        end if
    else
        drop msg_m;
    end if
end if
/* Broadcast scheduled messages when deferred time expired */
for each $msg_L \in \mathbb{W}$ **do**
    if $\tau_L ==$ current time **then**
        broadcast(msg_L);
        $\mathbb{W} = \mathbb{W} - msg_L$;
    end if
end for

keep the order of transmission between candidate relay vehicles according to the potential coverage area. This is to avoid large overlapping area that may overwhelm the network with redundant data. To achieve this, the common area of the three transmission areas relative to vehicles locations is specified, and determine the area of the receiving vehicle that is not covered by previous relay nodes taking into account the heterogeneous transmission ranges, dynamic movements of vehicles, and vehicles positions relative to one other.

The *ADTr* is shown in Algorithm 2. The vehicle that receives the message checks if the message has been received before, if not the receiver starts a timer before it relay the message, as illustrated in Algorithm 2 statement number 9. The timer value is computed using Equation 3.3. If the timer expires before receiving another copy of the same message, the vehicle proceeds with the transmission. Otherwise, it suppresses the scheduled transmission for the same message. Then, it checks if it is the second copy of the message and there is an area not covered by previous relay vehicles (refer to Lines 24-29 in Algorithm 2), it will restart the timer with value proportional to non-covered area and receiver transmission size, as shown in Equation 4.1.

$$\tau = T_{max}(\frac{\pi R_k^2 - \hat{A}_k}{\pi R_k^2} * \frac{\gamma}{R_k}) + \delta, \tag{4.1}$$

where $\hat{A}_k$ is the non-covered transmission area of vehicle k by earlier relay nodes, while δ is a random variable used to avoid collisions caused by simultaneous transmissions from two or more vehicles within the transmission range of the sender. On the other hand, γ is the allowed minimum transmission range. In this research the minimum transmission range for vehicles is set to $100m$. The rationale behind using the fraction $\frac{\gamma}{R_j}$ in the equation is to ensure that the receiver with the largest additional coverage among all vehicles in the sender transmission range has the shortest waiting time. Accordingly, it has the highest opportunity to retransmit the message. For more detail of the parameter γ and δ refer to Section 3.2.

The threshold υ value, shown in Line 27, Algorithm 2, is configured to any value that suit the application requirements and network status. However, in this study, the value is configured to be zero assuming dissemination is used for safety applications.

Vehicle v_k is assumed to receive a message m from both vehicle v_i followed by the same message from vehicle v_j. Then, vehicle v_k decide to retransmit the message or not, based on the amount of the non-covered area, $\hat{A}_k$, of v_k transmission area. This area can be determined as a function of the intersection between the different combination of the three vehicles v_i, v_j, and v_k transmission areas as follow:

$$\hat{A}_k = A_k - ((A_k \cap A_i) + (A_k \cap A_j) - (A_i \cap A_j \cap A_k))$$

For simplicity it will be rewritten it as follow:

$$\hat{A}_k = A_k - A_{ik} - A_{jk} + A_{ijk} \tag{4.2}$$

, where $A_k = \{(x, y) \in \mathbb{R} : \wedge(x_k, y_k) - R_k \leqslant (x, y) \leqslant (x_k, y_k) + R_k\}$, that is the set of positions (x,y) in the plane that are with at most R_k distance from the center (x_k, y_k).

4.2.1 Overlapped area of three transmission ranges

Before tackling this problem, one must first recognize the difficulty of finding the intersection between the three vehicles transmission areas, A_{ijk}, due to two aspects. The first aspect is the movement of the vehicles, which will be discussed in more detail in the following subsection. The second aspect is that the intersection between the three areas does not follow the same pattern. Hence it is necessary to first explore the variety of possible scenarios, when a vehicle is within two of its neighbours' transmission range. We should be able to identify situations where an area of common overlap exists as subset of transmission area of one or more of participants and, when it is as results of partially intersection among the three vehicles.

4.2.2 Virtual position

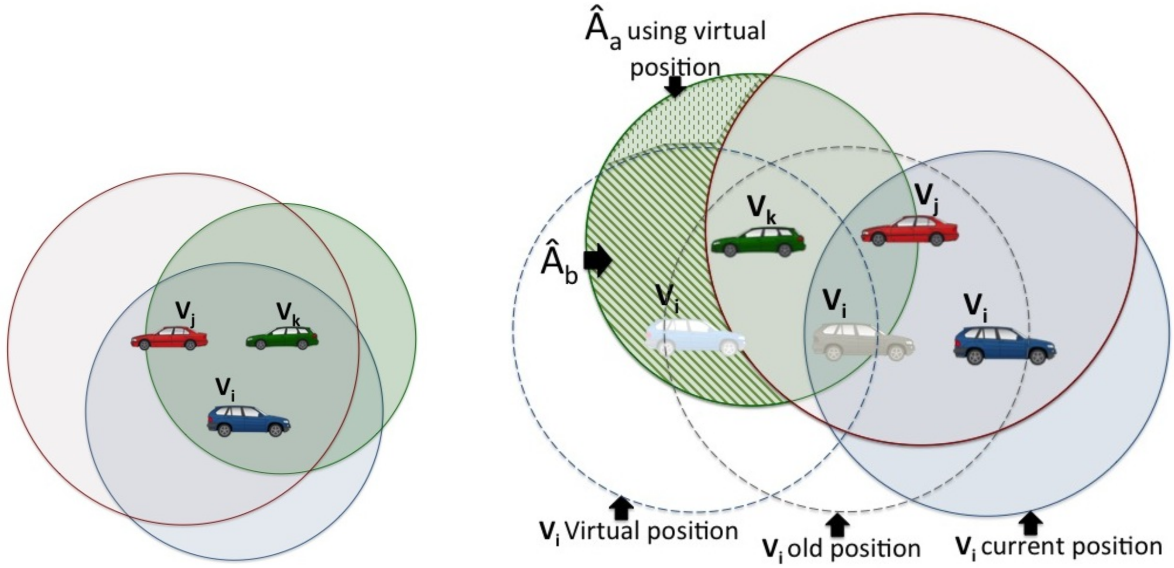
Due to mobility, it may happened that by the time vehicle v_k receives a second copy of the warning message form vehicles v_j, vehicle v_i will be in different position and/or vehicle v_k become out of vehicle v_i transmission range. In this case, A_{ijk} will not be accurate if we depend on neither the old position nor the current position of vehicle v_i.

Example: illustrative example is shown in Figure 4.3, where Figure 4.3a shows the positions of the three vehicles before time t, and Figure 4.3b after time t. If the potential coverage area is computed, $\hat{A}_k$, using the position of vehicle v_i after time t, $\hat{A}_k$ value will be both areas $\hat{A}_a$ and $\hat{A}_b$, as shown in Figure 4.3. While the correct value is the area which is not covered by both relay vehicles, which is only $\hat{A}_a$. The same thing if we consider the position of vehicle v_i before time t, the value of $\hat{A}_k$ will count in addition to $\hat{A}_a$ part of $\hat{A}_b$. To overcome this problem, it is suggested to create a virtual position for vehicle v_i, $(\breve{x}_i, \breve{y}_i)$. This virtual position depends on the speed (s_k) and orientation (ϑ_k) of vehicle v_k. Such that vehicle v_i takes the same position with respect to vehicle v_k before movement, as shown in Equation 4.3. By doing that, the exact area of vehicle v_k covered by vehicle v_i is known and the potential coverage area not covered by previous relay vehicles v_i and v_j can be computed.

$$\breve{x}_i = x_i + ts_k sin(\vartheta_k), \quad \breve{y}_i = y_i + t * s_k cos(\vartheta_k) \tag{4.3}$$

4.2.3 Geometric taxonomy for three overlapped transmission ranges

Analysing all possible variations of three transmission areas in the plane, we come up with three groups as shown in Figure 4.4, Figure 4.5, and Figure 4.6. Further cases can be derived from the same presented groups by proper displacements of vehicles. Based on these groups, Algorithm 3 is used to compute the potential coverage area, $\hat{A}_k$, of vehicle v_k transmission area, after receiving the message from vehicle v_i, followed by the same message from vehicle v_j.



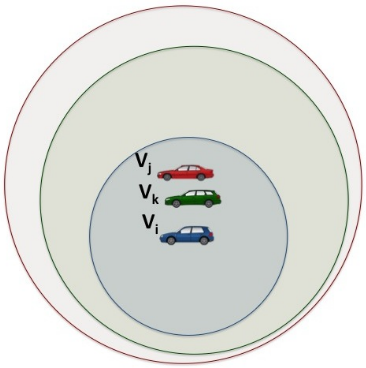
(a) Before time t

(b) After time t

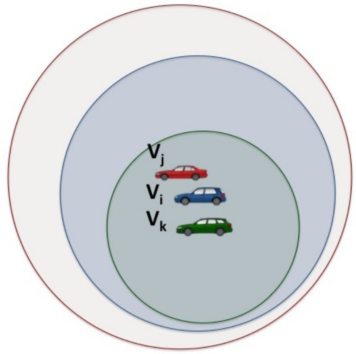
Figure 4.3: Virtual position and potential coverage

- First set of scenarios is depicted in Figure 4.4, where vehicle v_k transmission area is a subset of v_i transmission area or v_j transmission area. The tuples in the examples shown in Figure 4.4 represent the values of A_{ik}, A_{jk}, and A_{ijk} respectively. If Equation 4.2 is solved for any case in this category, the potential coverage will be gotten, $\hat{A}_k$, is equal to zero. This means all vehicles within the transmission range of vehicle v_k are expected to receive message m from previous relay nodes v_i and/or v_j. Accordingly, there is no benefit from redundant retransmission by vehicle v_k. Hence, vehicle v_k should suppress any scheduled transmission for message m to prevent useless transmission. All the cases in this category should satisfy the condition in Line 1 in algorithm 3.

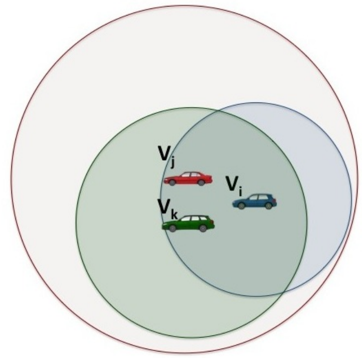
- The second group of scenarios, as shown in Figure 4.5 and Lines 4-12 in Algorithm 3, represent the cases when v_k transmission area is not a subset of other transmission areas, however, it could be a superset. At the same time, at least one transmission area of other vehicles should be a subset, i.e., $\{(A_k \not\subseteq A_i) \wedge (A_k \not\subseteq A_j) \wedge ((A_i \subset A_j) \vee (A_j \subset A_i) \vee (A_i \subset A_k) \vee (A_j \subset A_k))\}$. For instance when part of v_k transmission area intersect with part of v_i and v_j transmission areas, and at the same time, v_i transmission area is enclosed by v_j transmission area or vice versa (refer to Figure 4.5a, Figure 4.5b). In this case, potential coverage area is equal to v_k transmission area excluding the intersection area between v_k and the superset among v_i and v_j transmission areas. Another example is when A_k is a superset. In such case, the intersection of the three transmission areas is equal to intersection between the two other transmission areas, i.e., $A_{ijk} = A_{ij}$ as shown in Figure 4.5c, then $\hat{A}_k$ is computed accordingly.



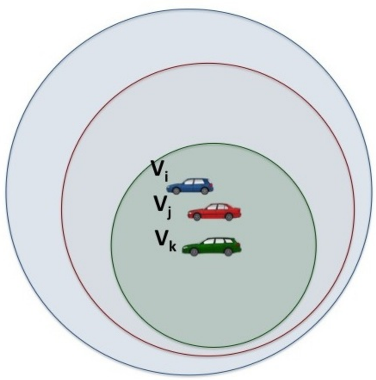
(a) $(A_i,\ A_k,\ A_i)$



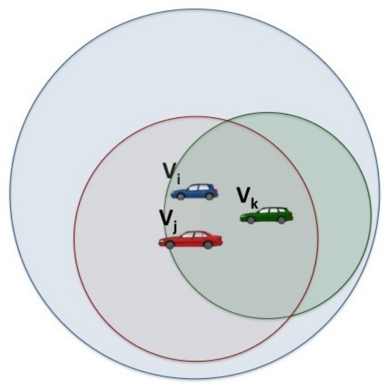
(b) $(A_k,\ A_k,\ A_k)$



(c) $(A_{ik},\ A_k,\ A_{ik})$

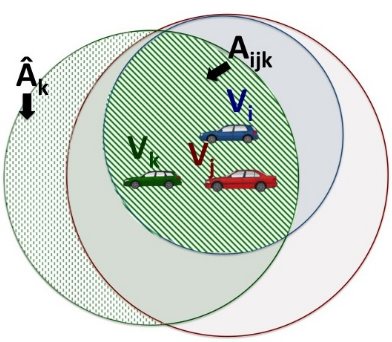


(d) $(A_k,\ A_k,\ A_k)$

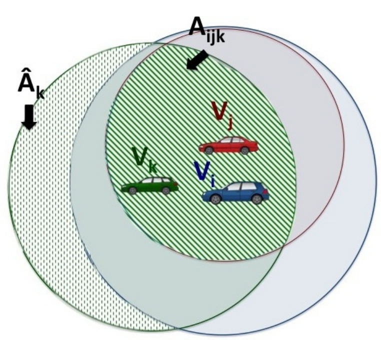


(e) $(A_k,\ A_{jk},\ A_{jk})$

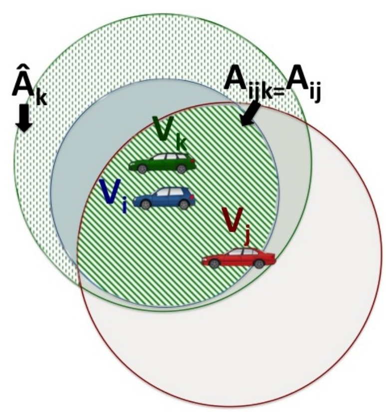
Figure 4.4: Group one of overlapping scenarios ($\hat{A}_k = 0$). The tuples represent the values of A_{ik}, A_{jk}, and A_{ijk} respectively



(a) $A_{ijk} = A_{ik}$



(b) $A_{ijk} = A_{jk}$



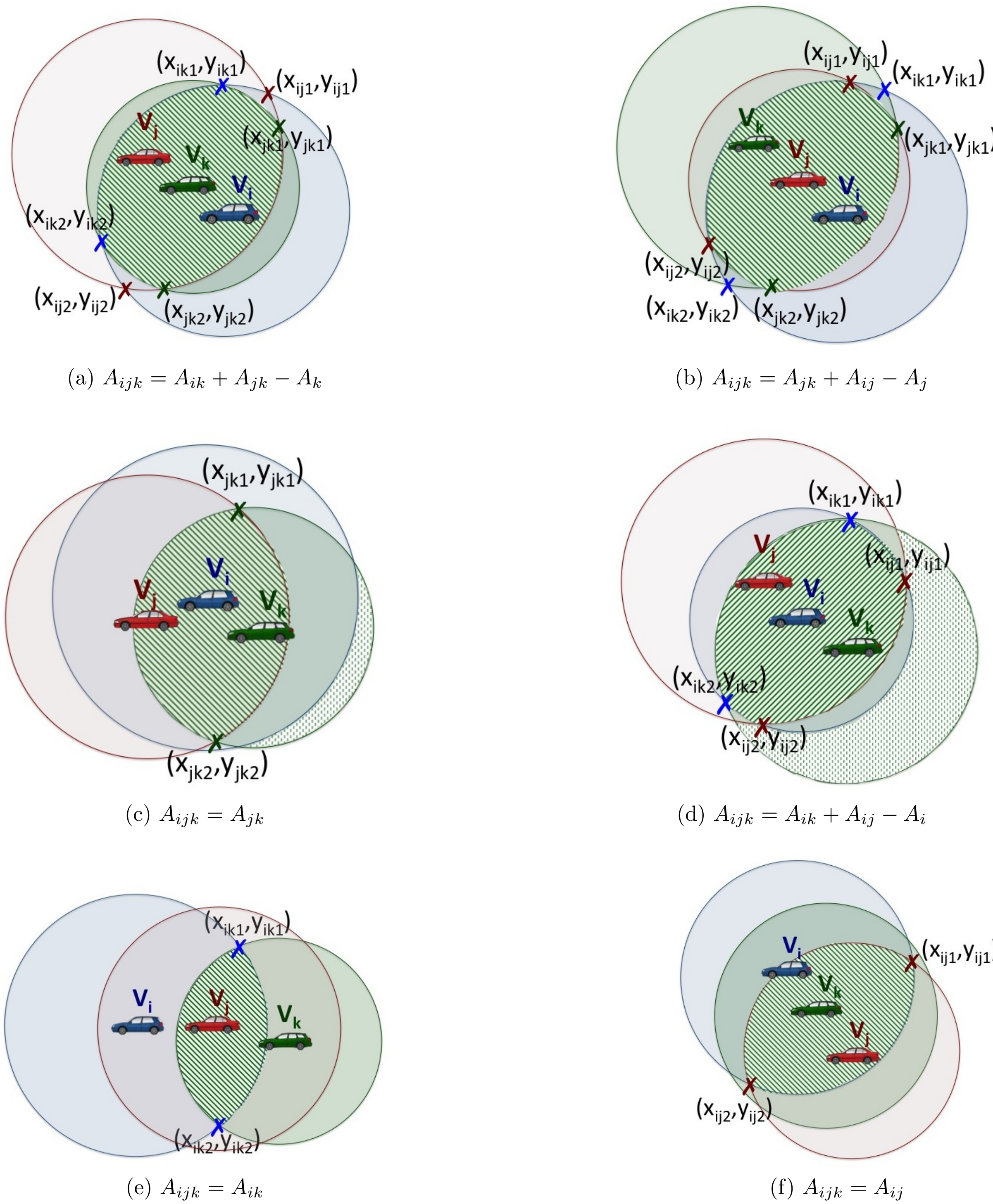
(c) $A_{ijk} = A_{ij}$

Figure 4.5: Group two of overlapping scenarios

Algorithm 3 $\hat{A_k}$, potential coverage area of vehicle v_k not covered by relays v_i and v_j.

Input: Vehicles coordinates: $(\breve{x}_i, \breve{y}_i)$,$(x_j, y_j)$, and (x_k, y_k), and transmission ranges: R_i, R_j, R_k.
Output: $\hat{A_k}$

/*Group one: A_k is a subset of A_j or A_i*/
if $((R_k < R_i)$ & $(R_i - d_{ik}) >= R_k)$ OR $((R_k < R_j)$ & $(R_j - d_{jk} >= R_k))$ **then**
  return(0); /*$\hat{A_k} = 0$;*/
end if
/*Group Two: A_k intersect with A_j and A_i. A_i constrained by A_j or vis versa.*/
if $(|R_k - R_j| < \breve{d}_{ij} < R_j + R_k)\&(R_i < R_j$ & $R_j - \breve{d}_{ij} >= R_i)$ **then**
  return$(A_k - A_{jk})$; /*$A_{ijk} = A_{ik}$*/
end if
if $(|R_k - R_i| < d_{ik} < R_i + R_k)\&(R_j < R_i$ & $R_i - \breve{d}_{ij} >= R_j)$ **then**
  return$(A_k - A_{ik})$ /*$A_{ijk} = A_{jk}$*/
end if
if $(R_i < R_k$ & $R_k - d_{ik} >= R_i)||(R_j < R_k$ & $R_k - d_{jk} >= R_j)$ **then**
  return$(A_k - A_{ik} - A_{jk} + A_{ij})$ /*$A_{ijk} = A_{ij}$*/;
end if
/* Group Three: All the three ranges R_i, R_j and R_k intersect together */
if $(|R_i - R_k| < d_{ik} < R_i + R_k)\&(|R_j - R_k| < d_{jk} < R_j + R_k)\&(|R_i - R_j| < \breve{d}_{ij} < R_i + R_j)$ **then**
  * /* Calculate intersection points between R_i and R_j*/
  $S_{ij} = \frac{\sqrt{(\breve{d}_{ij}+R_i+R_j)(\breve{d}_{ij}+R_i-R_j)(\breve{d}_{ij}-R_i+R_j)(R_i+R_j-\breve{d}_{ij})}}{4}$
  $x_{ij1,2} = \frac{(\breve{x}_i+x_j)}{2} + \frac{(x_j-\breve{x}_i)(R_i^2-R_j^2)}{2\breve{d}_{ij}^2} \pm \frac{(\breve{y}_i-y_j)}{\breve{d}_{ij}^2} 2S_{ij}$;
  $y_{ij1,2} = \frac{(\breve{y}_i+y_j)}{2} + \frac{(y_j-\breve{y}_i)*(R_i^2-R_j^2)}{2\breve{d}_{ij}^2} \mp \frac{(\breve{x}_i-x_j)}{\breve{d}_{ij}^2} 2S_{ij}$;
  /* Calculate intersection points between R_i and R_k*/
  $S_{ik} = \frac{\sqrt{(d_{ik}+R_i+R_k)(d_{ik}+R_i-R_k)(d_{ik}-R_i+R_k)(R_i+R_k-d_{ik})}}{4}$
  $x_{ik[1,2]} = \frac{(\breve{x}_i+x_k)}{2} + \frac{(x_k-\breve{x}_i)(R_i^2-R_k^2)}{2d_{ik}^2} \pm \frac{(\breve{y}_i-y_k)}{d_{ik}^2} 2S_{ik}$;
  $y_{ik[1,2]} = \frac{(\breve{y}_i+y_k)}{2} + \frac{(y_k-\breve{y}_i)*(R_i^2-R_k^2)}{2d_{ik}^2} \mp \frac{(\breve{x}_i-x_k)}{d_{ik}^2} 2S_{ik}$;
  $S_{jk} = \frac{\sqrt{(d_{jk}+R_j+R_k)(d_{jk}+R_j-R_k)(d_{jk}-R_j+R_k)(R_j+R_k-d_{jk})}}{4}$
  $x_{jk[1,2]} = \frac{(x_j+x_k)}{2} + \frac{(x_k-x_j)(R_j^2-R_k^2)}{2d_{jk}^2} \pm \frac{(y_j-y_k)}{d_{jk}^2} 2S_{jk}$;
  $y_{jk[1,2]} = \frac{(y_j+y_k)}{2} + \frac{(y_k-y_j)*(R_j^2-R_k^2)}{2d_{jk}^2} \mp \frac{(x_j-x_k)}{d_{jk}^2} 2S_{jk}$;
  /* The distance between the intersection point of R_i with R_k and center of R_j*/
  $d_{ik[1,2]-j} = \sqrt{(x_{ik[1,2]} - x_j)^2 + (y_{ik[1,2]} - y_j)^2}$;
  $d_{jk[1,2]-i} = \sqrt{(x_{jk[1,2]} - \breve{x}_i)^2 + (y_{jk[1,2]} - \breve{y}_i)^2}$;
  $d_{ij[1,2]-k} = \sqrt{(x_{ij[1,2]} - x_k)^2 + (y_{ij[1,2]} - y_k)^2}$;
  /*G3:1 One of the areas is surrounded by the other two areas */
  if $(d_{jk1-i} <= R_i)\&(d_{jk2-i} <= R_i)\&(d_{ik1-j} <= R_j)\&(d_{ik2-j} <= R_j)$ **then**
    return(0); /*$A_{ijk} = A_{ik} + A_{jk} - A_k$;; */
  end if
  if $(d_{jk1-i} <= R_i)\&(d_{jk2-i} <= R_i)\&(d_{ij1-k} <= R_k)\&(d_{ij2-k} <= R_k)$ **then**
    return$(A_k - A_{ik} - A_j + A_{ij})$ /*$A_{ijk} = A_{jk} - A_j + A_{ij}$*/;
  end if
  if $(d_{ik1-j} <= R_j)\&(d_{ik2-j} <= R_j)\&(d_{ij1-k} <= R_k)\&(d_{ij2-k} <= R_k)$ **then**
    return$(A_k - A_{jk} - A_i + A_{ij})$; /*$A_{ijk} = A_{ik} - A_i + A_{ij}$*/;
  end if
  /*G3:2*/
  if $(d_{jk1-i} <= R_i)\&(d_{jk2-i} <= R_i)$ **then**
    return$(A_k - A_{ik} + A_{ijk})$ /*$A_{ijk} = A_{jk}$*/;
  end if
  if $(d_{ik1-j} <= R_j)\&(d_{ik2-j} <= R_j)$ **then**
    return $(A_k - A_{jk} + A_{ijk})$ /*$A_{ijk} = A_{ik}$*/
  end if
  if $(d_{ij1-k} <= R_k)\&(d_{ij2-k} <= R_k)$ **then**
    return$(A_k - A_{ik} - A_{jk} + A_{ij})$; /*$A_{ijk} = A_{ij}$*/;
  end if
  /*G3:3*/
  if $(d_{ij1-k} <= R_k)\&(d_{ij2-k} > R_k))||((d_{ij1-k} > R_k)\&(d_{ij2-k} <= Rk))\&((d_{ik1-j} <= Rj)\&(dik2 - j > Rj))||((d_{ik1-j} > R_j)\&(d_{ik2-j} <= R_j))\&((d_{jk1-i} <= Ri)\&(d_{jk2-i} > Ri))||((d_{jk1-i} > R_i)\&(d_{jk2-i} <= R_i)$ **then**
    A_{ijk}=Algorithm 4($(\breve{x}_i, \breve{y}_i)$,$(x_j, y_j)$,$(x_k, y_k)$,$(x_{ijh}, y_{ijh})$,$(x_{jkh}, y_{jkh})$, (x_{ikh}, y_{ikh}), d_{ijh-k},d_{ikh-j}, d_{jkh-i}, where $h = \{1, 2\}$);
    return $(\hat{A_k} = A_k - A_{ik} - A_{jk} + A_{ijk})$;
  end if
end if



(a) $A_{ijk} = A_{ik} + A_{jk} - A_k$

(b) $A_{ijk} = A_{jk} + A_{ij} - A_j$

(c) $A_{ijk} = A_{jk}$

(d) $A_{ijk} = A_{ik} + A_{ij} - A_i$

(e) $A_{ijk} = A_{ik}$

(f) $A_{ijk} = A_{ij}$

Figure 4.6: Group three and an example of A_{ijk} values

- In the third group, as shown in Figure 4.6, transmission areas of the three vehicles are partially intersect with each another. In other words, each two transmission-areas are intersected in two places, such that the following conditions must be satisfied:

$$(|R_k - R_i| < d_{ik} < R_i + R_k) \& |R_k - R_j| < d_{jk} < R_j + R_k$$
$$\wedge (|R_i - R_j| < \breve{d}_{ij} < R_i + R_j)$$

The intersection between the three transmission areas of v_i, v_j, and v_k, A_{ijk} is difficult to compute. This is because, the intersection do not follow the same pattern. Examination of possible variations guides us to depend on the coordinates of the intersection points between each two transmission areas. The position of the intersection points between two transmission areas with respect to the third transmission area will help to define the pattern and accordingly compute the common area between the three transmission areas precisely.

The coordinates of intersections between the two transmission area of vehicle v_i, and vehicle v_j, i.e, (x_{ij1}, y_{ij1}), (x_{ij2}, y_{ij2}), can be given using the following equation [99].

$$\begin{aligned}
S &= \frac{1}{4}\sqrt{(\breve{d}_{ij} + R_i + R_j)(\breve{d}_{ij} + R_i - R_j)(\breve{d}_{ij} - R_i + R_j)(R_i + R_j - \breve{d}_{ij})} \\
x_{ij1} &= \frac{\breve{x}_i + x_j}{2} + \frac{(x_j - \breve{x}_i)(R_i^2 - R_j^2)}{2\breve{d}_{ij}^2} + \frac{(\breve{y}_i - y_j)}{\breve{d}_{ij}^2}2S \\
x_{ij2} &= \frac{\breve{x}_i + x_j}{2} + \frac{(x_j - \breve{x}_i)(\breve{R}_i^2 - R_j^2)}{2\breve{d}_{ij}^2} - \frac{(\breve{y}_i - y_j)}{\breve{d}_{ij}^2}2S \\
y_{ij1} &= \frac{\breve{y}_i + y_j}{2} + \frac{(y_j - \breve{y}_i)(R_i^2 - R_j^2)}{2\breve{d}_{ij}^2} - \frac{(\breve{x}_i - x_j)}{\breve{d}_{ij}^2}2S \\
y_{ij2} &= \frac{\breve{y}_i + y_j}{2} + \frac{(y_j - \breve{y}_i)(R_i^2 - R_j^2)}{2\breve{d}_{ij}^2} + \frac{(\breve{x}_i - x_j)}{\breve{d}_{ij}^2}2S
\end{aligned} \tag{4.4}$$

In the same way the coordinates of intersections between vehicle v_i, and vehicle v_k transmission areas is found, i.e. (x_{ik1}, y_{ik1}), (x_{ik2}, y_{ik2}), and vehicle v_j, with vehicle v_k transmission areas, i.e. (x_{jk1}, y_{jk1}), (x_{jk2}, y_{jk2}). The position of the intersection points between two transmission areas, for example (x_{ik1}, y_{ik1}), with the respect to the third transmission area (e.g. A_j) is determined by computing the distance between the intersection points and the center of the third transmission area, e.g. (x_j, y_j). If the distance is less than the transmission range, e.g. R_j, then the intersection points located inside the transmission area. Otherwise, it will be outside the transmission area as shown in the example below:

Example:

$d_{ik1-j} = \sqrt{(x_{ik1} - x_j)^2 + (y_{ik1} - y_j)^2}$;
if $d_{ik1-j} <= R_j$ **then**
/*The intersection point located inside the v_j transmission area */
$(x_{ij1}, y_{ij1}) \in A_j$
else

$(x_{ij1}, y_{ij1}) \notin A_j$
end if

Accordingly, any scenario should satisfy one of the following three conditions:

1. First case is when one of the transmission areas of the three vehicles is enclosed by the two transmission areas of other vehicles, as shown in 3 Lines 26-35. In other words, two pairs of two intersection points between two transmission areas are located inside the third transmission area, which can be recognized if the following condition is satisfied:
$\{\big((x_{ikh}, y_{ikh}) \in A_j \wedge (x_{jkh}, y_{jkh}) \in A_i\big) \vee \big((x_{ijh}, y_{ijh}) \in A_k \wedge (x_{jkh}, y_{jkh}) \in A_i\big) \vee \big((x_{ijh}, y_{ijh}) \in A_k \wedge (x_{ikh}, y_{ikh}) \in A_j\big), \forall h = \{1, 2\}\}$

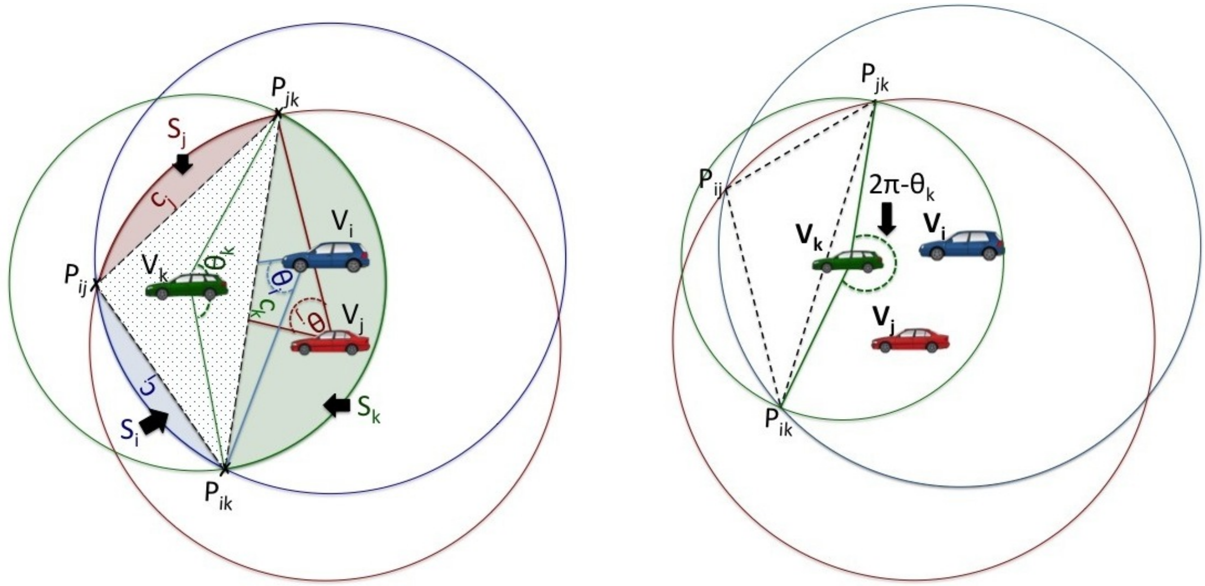
   In this case, the overlap between the three transmission areas equals the sum of the intersection between the contained transmission area with the other two transmission areas separately and deducting the transmission area of contained transmission area. Examples of such case are shown in Figures 4.6a, 4.6b, and 4.6d. For Example in Figures 4.6a, the two intersection points of A_i with A_k, i.e. (x_{ik1}, y_{ik1}), and (x_{ik2}, y_{ik2}), are located inside the transmission area of vehicle v_j. In addition, the two intersection points of A_j with A_k, i.e., (x_{jk1}, y_{jk1}), and (x_{jk2}, y_{jk2}), are located inside A_i. This means v_k transmission area is constrained by the two vehicles v_i and v_j transmission areas. Accordingly, $A_{ijk} = A_{ik} + A_{jk} - A_k$, which implies $\hat{A}_k = 0$. Another example is shown in Figure 4.6b, where v_j transmission area is constrained by the two vehicles v_i and v_k transmission areas, which imply $A_{ijk} = A_{jk} - A_j + A_{ij}$.

2. The second case in this group is when only two intersection points between two transmission areas are located inside the third transmission area, as demonstrated in the condition below:
$\big((x_{ijh}, y_{ijh}) \in A_k \wedge (x_{ikh}, y_{ikh}) \notin A_j \wedge (x_{jkh}, y_{jkh}) \notin A_i)\big) \vee \big((x_{ijh}, y_{ijh}) \notin A_k \wedge (x_{ikh}, y_{ikh}) \in A_j \wedge (x_{jkh}, y_{jkh}) \notin A_i\big) \vee \big((x_{ijh}, y_{ijh}) \notin A_k \wedge (x_{ikh}, y_{ikh}) \notin A_j \wedge (x_{jkh}, y_{jkh}) \in A_i)\big), \forall h = \{1, 2\}\}$

   In such case, the common area, A_{ijk}, is equal to the common area between the two transmission areas with intersection points located inside the third transmission area, as shown in 3 Lines 35-44. Examples of such case are shown in Figure 4.6c, Figure 4.6e, and Figure 4.6f. For example in Figure 4.6c, the two intersection points of A_j and A_k are inside A_i. However, A_i and A_j intersection points are outside A_k. Also, the intersection points of A_{ik} are not inside A_j. In this case, $A_{ijk} = A_{jk}$.

3. The last case is when the common area, A_{ijk}, has three vertices. Such that one of the intersection points between two transmission areas is located inside the third transmission area and the other does not, as shown in Figure 4.7. In this category, the common area, i.e. A_{ijk}, is equal to the area of segments S_i, S_j, and S_k plus the area of triangle $\triangle P_{ij} P_{ik} P_{jk}$ (i.e.$A_\triangle$), as shown in Equation 4.5:

$$A_{ijk} = A_\triangle + S_i + S_j + S_k; \tag{4.5}$$



(a) $\breve{d}_{ij} > R_i + R_j$

(b) $R_k < R_i, R_k < R_j$ $\&(x_k, y_k)$ between P_{ij} and $\overline{p_{ik}p_{jk}}$

Figure 4.7: A_{ijk} with three vertices

The details of Equation 4.5 parameters computations are provided in Section 4.2.4.

4.2.4 Common area with three vertices

In group three, each two transmission areas are intersect in two places; There are six intersection coordinates. Three coordinates out of the six will represents the vertices for the common area, A_{ij}. The vertex is the intersection coordinate between two transmission area that is located inside the third transmission area. Thus, the relevant coordinate (Px_{ij}, Py_{ij}) of the intersection A_{ij} is the coordinates that is located inside the transmission range of vehicle v_k. Such that the distance between the vertex and the center (x_k, y_k) is less than or equal the transmission range R_k. In the same way, we define the relevant coordinates of the intersection between vehicle v_j and vehicle v_k transmission areas and relevant coordinates of intersection between vehicle v_i and vehicle v_k transmission areas, as shown in Algorithm 4 Lines1-15. After this point we will have the vertices coordinates for the common area, A_{ijk}, between the transmission areas of the vehicles. This area is called circular triangles in reference [100]. The author solve the problem assuming $R_i > R_j > R_k$ and the origin of coordinates plane is placed on the center of A_i. In addition, the direction of the y-axis is chosen so that the y_k coordinate is positive. In this documents, the overlapped area, A_{ijk}, is computed without considering these assumptions and by using the real coordinates of the vehicles, as described by the following steps:

First is to compute the area of the triangle $\triangle P_{ij}P_{ik}P_{jk}$ that is performed between the transmission areas of the three vehicles. Heron's formula is used for triangle area as follow:

$$A_{\triangle} = \frac{1}{4}\sqrt{(ci+cj+ck)(ci+cj-ck)(ci-cj+ck)(cj+ck-ci)}$$

, where c_i, c_j, and c_k are the triangle sides that can be computed using the distance formula as follow:

$$c_i = \sqrt{(Px_{ik} - Px_{ij})^2 + (Py_{ik} - Py_{ij})^2}$$
$$c_j = \sqrt{(Px_{jk} - Px_{ij})^2 + (Py_{jk} - Py_{ij})^2}$$
$$c_k = \sqrt{(Px_{jk} - Px_{ik})^2 + (Py_{jk} - Py_{ik})^2}$$

After which, the areas of segments S_i, S_j, and S_k are computed. The area of any segment equal to circular sector minus the related triangle is calculated using Equation 4.6 (see Figure 4.7a).

$$\frac{R_h^2}{2} acos(1 - \frac{c_h^2}{2R_h^2}) - \frac{c_h}{4}\sqrt{4R_h^2 - c_h^2}, \tag{4.6}$$

where $h = \{i, j, k\}$. However, there are situations where the area of sector can not be computed using Equation 4.6. For example if we try to compute S_k in Figure 4.7b the formula $acos(1 - \frac{c_k^2}{2R_k^2})$ will provide the opposite angle, which related to different circular sector. The analysis of Figure 4.7b and its variations leads to the intuition that the situation can arise only when the vehicle transmission range is the smallest among the other two vehicles transmission ranges. Moreover, its' position is located between the intersection point of the other two vehicles transmission areas and the line that join its' intersection points with other vehicles transmission areas. For example, in Figure 4.7b R_k is less than R_i and R_j and the position (x_k, y_k) located between P_{ij} and the line joining P_{ik} and P_{jk}. This is so to satisfy the following conditions:

$$\begin{aligned}
&(R_k < Ri)\&(R_k < Rj) \ and \\
&\big(y_k < Py_{ik} + m_k(xk - Px_{ik}) \ \& \ Py_{ij} > Py_{ik} + m_k(Px_{ij} - Px_{ik})|| \\
&y_k > Py_{ik} + m_k(x_k - Px_{ik}) \ \& \ Py_{ij} < Py_{ik} + m_k(Px_{ij} - Px_{ik})\big),
\end{aligned} \tag{4.7}$$

where $m_k = \frac{Py_{jk} - Py_{ik}}{Px_{jk} - Px_{ik}}$. Accordingly, S_i equal to case one in Equation 4.8 if the condition true, Otherwise, it is equal to the second case.

$$S_k = \begin{cases} \frac{R_k^2}{2} acos(1 - \frac{c_k^2}{2R_k^2}) - \frac{c_k}{4}\sqrt{4R_k^2 - c_k^2}, & \text{(Eq. 4.7 true)} \\ \frac{R_k^2}{2}(2\pi - acos(1 - \frac{c_k^2}{2R_k^2})) + \frac{c_k}{4}\sqrt{4R_k^2 - c_k^2}, & \text{(Eq. 4.7 false)} \end{cases} \tag{4.8}$$

In the same way S_i and S_j are computed, as shown in Algorithm 4, Lines 22-36.

Algorithm 4 A_{ijk} with three vertices

Input: Vehicles coordinates: (x_i, y_i),(x_j, y_j), and (x_k, y_k).
Intersection coordinates: (x_{ijh}, y_{ijh}), (x_{jkh}, y_{jkh}), (x_{ikh}, y_{ikh}), d_{ijh-k}, d_{ikh-j}, and d_{jkh-i} where $h = 1, 2$
Output: A_{ijk}
/* Determine Aijk vertices*/
if $(dij1 - k <= R_k)$ **then**
    $Px_{ij} = x_{ij1}; Py_{ij} = y_{ij1};$
else
    $Px_{ij} = x_{ij2}; Py_{ij} = y_{ij2};$
end if
if $(d_{ik1-j} <= R_j)$ **then**
    $Px_{ik} = x_ik1; Py_{ik} = y_ik1;$
else
    $Px_{ik} = x_{ik2}; Py_{ik} = y_{ik2};$
end if
if $(d_{jk1-i} <= R_i)$ **then**
    $Px_{jk} = x_{jk1}; Py_{jk} = y_{jk1};$
else
    $Px_{jk} = x_{jk2}; Py_{jk} = y_{jk2};$
end if
/* determine Aijk triangle sides */
$c_i = \sqrt{(Px_{ik} - Px_{ij})^2 + (Py_{ik} - Py_{ij})^2)};$
$c_j = \sqrt{(Px_{jk} - Px_{ij})^2 + (Pyjk - Py_{ij})^2)};$
$c_k = \sqrt{(Px_{jk} - Px_{ik})^2 + (Py_{jk} - Py_{ik})^2};$
$A_{\triangle} = \frac{\sqrt{(c_i+c_j+c_k)(c_i+c_j-c_k)(c_i-c_j+c_k)(c_i+c_j-c_k)}}{4};$
$m_i = \frac{Py_{ij}-Py_{ik}}{Px_{ij}-Px_{ik}};$
if $(R_i < R_k \& R_i < R_j)\&((\breve{y}_i < Py_{ik} + m_i(\breve{x}i - Px_{ik}))\&(Py_{jk} > Py_{ik} + m_i(Px_{jk} - Px_{ij})))\|(\breve{y}_i > Py_{ik} + m_i(\breve{x}_i - Px_{ik}))\&Py_{jk} < (Py_{ik} + m_i(Px_{jk} - Px_{ik})))$ **then**
    $\theta_i = 2\pi - acos(1 - \frac{c_i^2}{2R_i^2});$
    $S_i = \frac{R_i^2}{2}\theta_i + \frac{c_i}{4}\sqrt{4R_i^2 - c_i^2};$
else
    $\theta_i = acos(1 - \frac{c_i^2}{2R_i^2});$
    $S_i = \frac{R_i^2}{2}\theta_i - \frac{c_i}{4}\sqrt{4R_i^2 - c_i^2};$
end if
$m_j = \frac{Py_{ij}-Py_{jk}}{Px_{ij}-Px_{jk}};$
if $(R_j < R_k \& R_j < R_i)\&((y_j < Py_{jk} + m_j(xj - Px_{jk}))\&(Py_{ik} > Py_{jk} + m_j(Px_{ik} - Px_{jk})))\|(y_j > Py_{jk} + m_j(x_j - Px_{jk}))\&Py_{ik} < (Py_{jk} + m_i(Px_{ik} - Px_{jk})))$ **then**
    $\theta_j = 2\pi - acos(1 - \frac{c_j^2}{2R_j^2});$
    $S_j = \frac{R_j^2}{2}\theta_j + \frac{c_j}{4}\sqrt{4R_j^2 - c_j^2};$
else
    $\theta_j = acos(1 - \frac{c_j^2}{2R_j^2});$
    $S_j = \frac{R_j^2}{2}\theta_j - \frac{c_j}{4}\sqrt{4R_j^2 - c_j^2};$
end if
$m_k = \frac{Py_{jk}-Py_{ik}}{Px_{jk}-Px_{ik}};$
if $(R_k < R_i \& R_k < R_j)\&((y_k < Py_{ik} + m_k(xk - Px_{ik}))\&(Py_{ij} > Py_{ik} + m_k(Px_{ij} - Px_{ik})))\|(y_k > Py_{ik} + m_k(x_k - Px_{ik}))\&Py_{ij} < (Py_{ik} + m_k(Px_{ij} - Px_{ik})))$ **then**
    $\theta_k = 2\pi - acos(1 - \frac{c_k^2}{2R_k^2});$
    $S_k = \frac{R_k^2}{2}\theta_k + \frac{ck}{4}\sqrt{4R_k^2 - c_k^2};$
else
    $\theta_k = acos(1 - \frac{c_k^2}{2R_k^2});$
    $S_j = \frac{R_j^2}{2}acos(\theta_j) - \frac{c_j}{4}\sqrt{4R_j^2 - c_j^2};$
end if
$A_{ijk} = S_i + S_j + S_k + \frac{\sqrt{(c_i+c_j+c_k)(c_i+c_j-c_k)(c_i-c_j+c_k)(c_i+c_j-c_k)}}{4};$
return A_{ijk};

4.3 Area-based Probabilistic Transmission with Relaying Redundant Received message

A probabilistic approach has been examined in Chapter 3. It has shown that it is effective in reducing redundancy if it is joined with timer approach. Introduced here is an enhancement of the approach to give vehicles with larger potential coverage area high priority to relay the message than the one with small potential coverage area or small communication range. Moreover, it allows retransmitting of a duplicate received message, if the retransmission is predicted to cover a new area of the receiver not covered previously by the earlier relay vehicles. This ensures that the priority of the transmission between candidate relay vehicles is not disordered and performed according to the potential coverage area. When a vehicle receives a message, it decides to retransmit it with probability p, as illustrated in Equation 4.9.

$$p = \begin{cases} (1 - \frac{A_{ij}}{\pi R_j^2}) * \frac{R_j}{\beta} & \text{if newly received message,} \\ \frac{\hat{A}_j}{\pi R_j^2} * \frac{R_j}{\beta} & \text{if it is a duplicate message,} \end{cases} \tag{4.9}$$

where $\hat{A}_j$ is the transmission area of vehicle j not covered by earlier relay nodes and A_{ij} is the overlap area between the transmission area of vehicle j and the transmitter i, computed using Equation 3.1. The fraction $\frac{R_j}{\beta}$ is the relative size of the receiver k to the maximum allowed transmission range β. The purpose of this fraction is to ordered transmission between all vehicles in the network according to the size of potential coverage area.

Thus, with probability p the vehicle acts as a relay node and with probability $1 - p$ the receiving vehicle drops out and gives up forwarding the message. Accordingly, there are two versions of the approach. The first one is area-based probabilistic joined with area-based timer, which is identified as (APT_{tr}). In APT_{tr}, the vehicle retransmits the message with probability p, but after it's deferred τ seconds. Deferred time, τ, is computed using Equation 3.3. The second version is area-based probabilistic ($APTr$), where the vehicle retransmits the message with probability p without deferring transmission.

4.4 Simulation set-up and performance metrics

Results in this research were obtained using the NS2 network simulator. The simulation is based on data from a real map of down-town Ottawa streets (see Figure 3.5), which was generated from OpenStreetMap. The map area is $2064m\ X\ 2102m$. It includes such details as highways and secondary roads, intersections, highway junctions and traffic lights to represent realistic scenarios. The movement traces are generated using SUMO [97], a microscopic road traffic simulation package that combines vehicle movement with lane changing and intersection control, and constrains vehicle movements to selected streets. The speed for each vehicle is limited to the maximum speed allowed in each road that is configured in OpenStreetMap. In addition, it is defined in relation to the vehicle ahead. Also, vehicles may decide to slow down in order to execute a lane-change manoeuvre or aid other vehicles with lane changing.

Table 4.1: Simulation Parameters used for Reliable Area-based Data Dissemination Protocols

Parameter name	**Value**
Network simulator	NS2.35
Antenna	OmniAntenna
Propagation model	Shadowing
path-loss exponent	2.7
shadowing deviation	4.0 dB
Mac and physical layer	IEEE 802.11p
Noise floor	-99 dBm
Carrier sense threshold	-85 dBm
receiver sensitivity	-84 dBm
Mobility/Traffic generator	SUMO
Transmission range (R)	Randomly selected from 100 to 600 m
Number of vehicles (N)	50-500 vehicles
Message size	300 bytes
Beacon Frequency	1 Hz
Event driven message	1 Hz
Message lifetime	700 ms
T_{max}	300 ms

The MAC (media access control) and the physical layers are based on the IEEE 802.11p model presented in [98], with receiver sensitivity of $-84\ dBm$, and heterogeneous transmission power. The configuration parameters for the physical (PHY) and medium access control (MAC) layers of the IEEE 802.11p that is used in simulator is presented in Appendix B. Transmission power for each vehicle was selected randomly, to achieve a transmission range of $100 - 600\ m$. The propagation model is shadowing propagation model with path-loss exponent equal to 2.7 and shadowing deviation equal to 4.0 dB, as recommended by [101, 102]. Event-driven messages were generated every 1 s and assigned to a source node randomly chosen from the entire pool of the network nodes. Also, periodic beacons were generated every 1 s by all the nodes in the network to one-hop neighbours. A list of simulation parameters used in this work is given in Table 5.1. The confidence interval calculation that is adopted for the performance metrics in this thesis is presented in Appendix A. The performance metrics used to evaluate dissemination approaches with a confidence level of 95% were:

- *relay ratio*, which represents the ratio of vehicles in the network that retransmit the source message.
- *relay coverage rate*, which evaluates the quality of the selected relay vehicles, by quantifying the number of vehicles receiving the message for the first time from a single relay vehicle transmission.
- *redundancy rate*, which measures the number of duplicate messages in the network per one source message.
- *delivery ratio*, which measures the proportion of vehicles in the network that successfully receive the message.
- *maximum hops traversed*, which refers to the average number of maximum hops the messages traversed.
- *maximum propagated distance*, the average maximum distance traversed by the messages in the network.
- *average end-to-end delay*, which represents the difference between the time when the message is initiated and when is received.

4.5 Performance evaluation

The first part of the experiments evaluates the performance behaviour of the area-based timer approaches (i.e. $ADT(2)$, and $ADTr$), allowing retransmission of duplicate received message. The second part of the experiments assesses the performance of retransmission strategy in area-based probabilistic approaches (i.e. $APT(2)$, $APTr$, $APTt(2)$, and $APTtr$). The section ends up with a summary and a comparison of area-based timer approach with area-based probabilistic approaches.

4.5.1 Area Defer Transmission with Retransmission of Redundant Received message

This section reports the results of comparing the performance of the $ADTr$ compared to ADT and $ADT(2)$. The ADT [68] is described in Section 2.3.2 and used in the comparison to measure the amount of enhancement achieved by transmission of redundant received message. The $ADT(2)$ is an ADT technique that allows the vehicle to retransmit a duplicate message received from different relay vehicle considering the potential coverage area based on the last relay vehicle ignoring the covered area by the earlier relay vehicle, refer to Section 4.1. In contrast, $ADTr$, which is presented in Section 4.2, allows retransmission of a duplicate message as long as the retransmission is predicted to cover a new area not covered by all previous relay vehicles. At the same time, it ensures the transmission does not impact the order of transmissions, which are performed according to the potential coverage area.

Figure 4.8 demonstrates the effect of increasing number of vehicles into the maximum number of hops required for disseminating the message. The figure shows that the maximum hops count for the three approaches almost the same, where the maximum number of hops required to disseminate the message is between four to five hops. In spite of that, the ratio of vehicles that relay the message in $ADTr$ is less than $ADT(2)$, as shown in Figure 4.9. This proves that there are useless transmissions in $ADT(2)$ that are mitigated in $ADTr$. The ratio of vehicles that relay the message in ADT is less than $ADTr$ and $ADT(2)$, this is because it does not allowing redundancy. The relay ratios for all algorithms are gradually reduced with the increase of total number of vehicles, which reveals that area-based timer algorithms are scalable to the increase of the total number of vehicles in the network.

The rate of vehicles receiving the message from a single relay vehicle transmission is demonstrated in Figure 4.10. It measures the quality of the selected node to relay the message in terms of number of vehicles receiving the message for the first time. The figure illustrates that relay selection in $ADTr$ outperforms $ADT(2)$ approach, where $ADTr$ relay vehicles transmissions reach more vehicles than $ADT(2)$. This is because in $ADT(2)$ vehicle relaying a received duplicate message consider only the potential coverage of the latest relay node ignoring what has been covered by earlier vehicle. Thus, the order of retransmissions in $ADT(2)$ is distracted leading to more relay ratio with less coverage. The rate of relay coverage in both approaches increases almost linearly as the number of vehicles increases. This is another indication that area-based timer schemes are more scalable to the increase of the total number of vehicles in the network. The reason is because the back-off time helps the receiving node to decide with high certainty to relay the message or not, such that if the node does not receive another copy during the back-off time, it is more certain that it will cover a new area.

Since $ADTr$ has less relay ratio than $ADT(2)$, it has also less redundancy, as shown Figure 4.11. The difference between $ADTr$ and $ADT(2)$ increases as the number of vehicles increase. Nonetheless, all the three algorithms have the same average end-to-end delay and reach the same maximum distance, as shown in Figure 4.12, and Figure 4.13 respectively. Despite the fact that $ADTr$ has less redundancy than $ADT(2)$, the proportion of

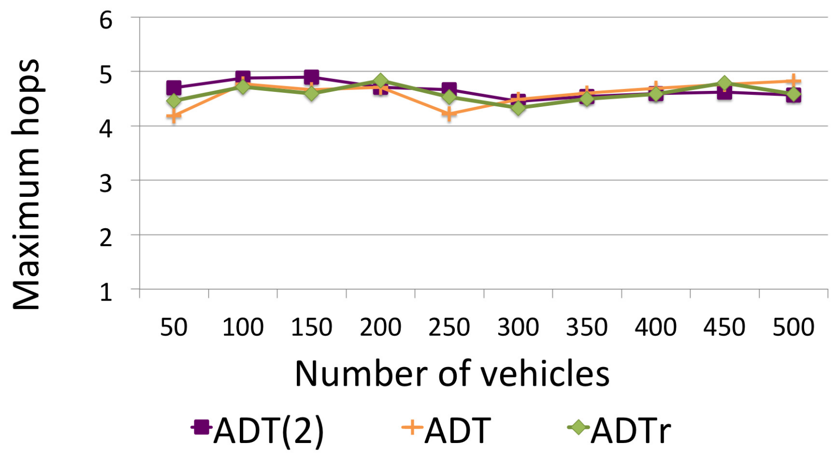


Figure 4.8: Hops count vs. number of vehicles

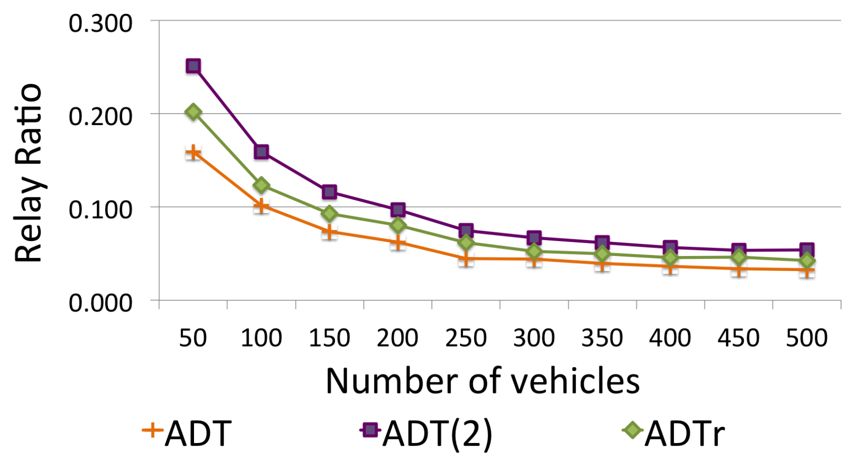


Figure 4.9: Ratio of relay nodes

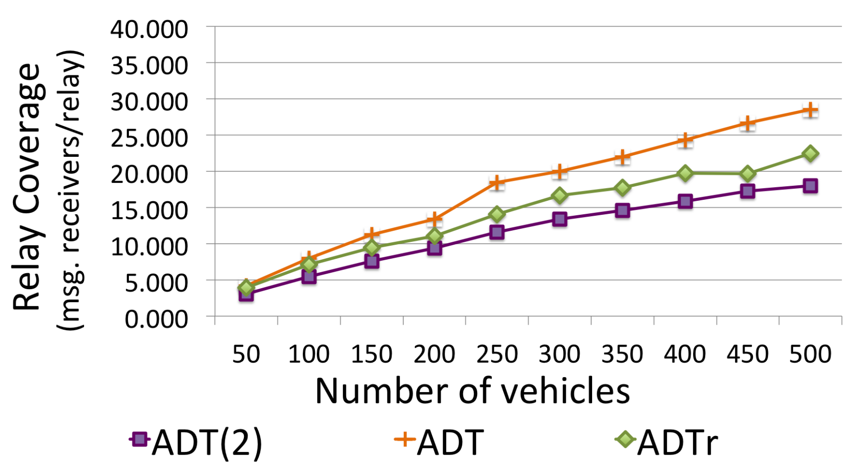


Figure 4.10: Average number of vehicles receiveing the message per relay

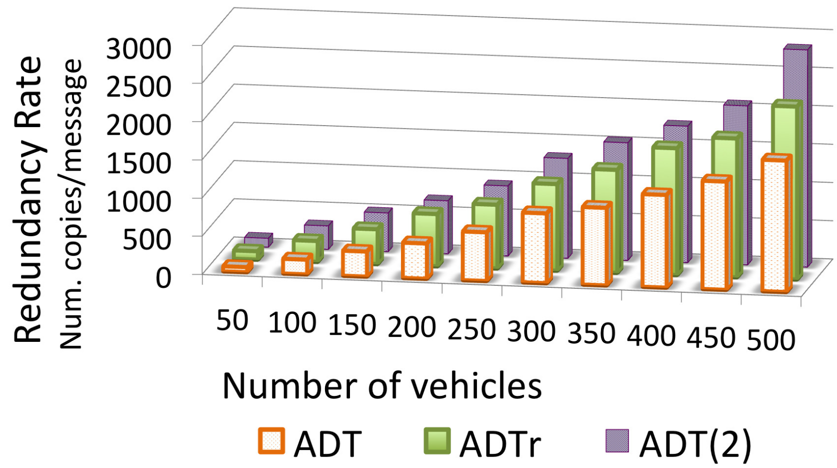


Figure 4.11: Redundancy rate vs. number of vehicles

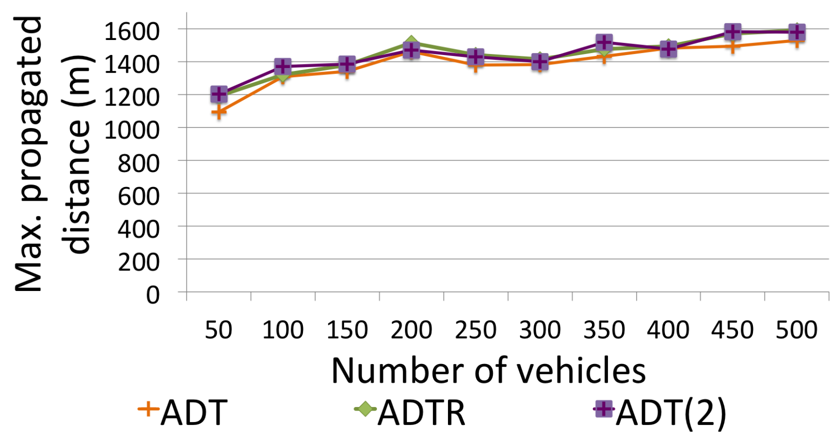


Figure 4.12: Maximum distance achieved

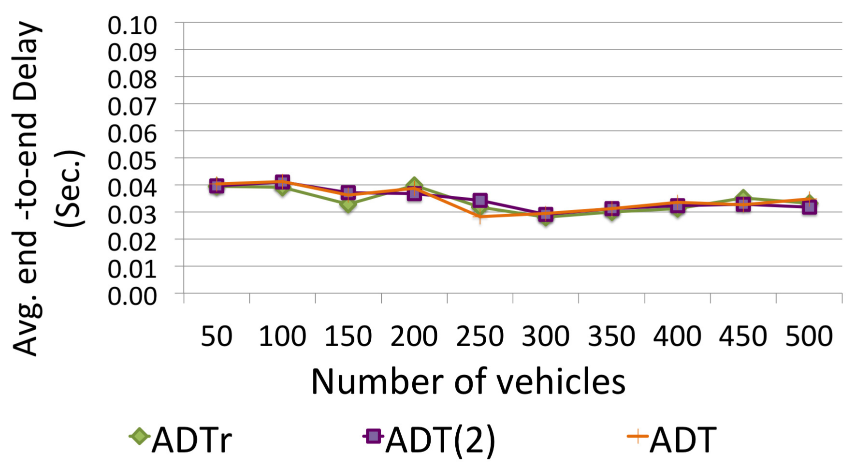


Figure 4.13: Average end-to-end delay.

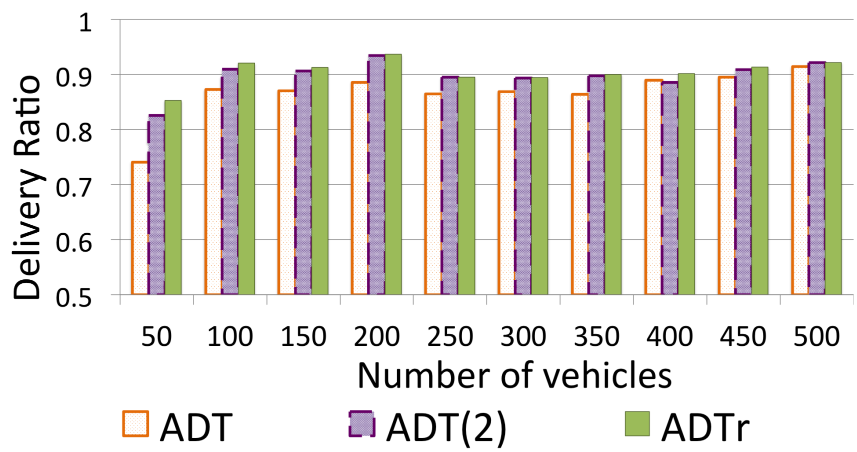


Figure 4.14: Delivery ratio

vehicles in the network that successfully receive the event message is the same with slight enhancement. The delivery ratio of $ADTr$ and $ADT(2)$ outperform ADT especially in low number of vehicles. This confirms the hypothesis that relay nodes selected by $ADTr$ are more effective than $ADT(2)$ owing to their low relay ratio, redundancy, and high coverage rate. It has also high delivery ratio compared to ADT

4.5.2 Area based probabilistic approaches with Relaying Redundant Received message

The second part of the experiments examines the probabilistic approaches $APTr$ and $APTtr$ as described in Section 4.3. The $APTr$ and $APTtr$ are compared to the original algorithms, i.e., APT and $APTt$, that do not allow retransmitting redundant received message.

The difference between the ratio of vehicles that relay the message for $APTt$, and $APTtr$ approaches is almost negligible particularly in high number of vehicles, as shown Figure 4.15. On the other hand, the relay ratio for $APTr$ is increased compared to APT, where it gets to 60% for $APTr$. Accordingly, the maximum hops count for $APTr$ is increased compared to APT, as shown in Figure 4.16. The hops count value for $APTr$, and APT exceed the expected value of hops that is equal 5.64, given the map area is $2064m$ X $2102m$ and the transmission ranges vary within $100m - 600m$. On the other hand, number of hops for $APTt$, and $APTtr$ almost the same in particularly with respect to high density, where the maximum hops the message traversed is less than five.

The dramatic increase in relay ratio and hops count for APT, and $APTr$ lead to considerable increase in the redundancy rate, as shown in Figure 4.17. Also, the figure shows that there are big difference in redundancy rate between APT and $APTr$. Whereas, there is reasonable increase in redundancy rate for $APTtr$ compared to $APTt$.

The maximum distance traversed by the messages in the network is illustrated in Fig-

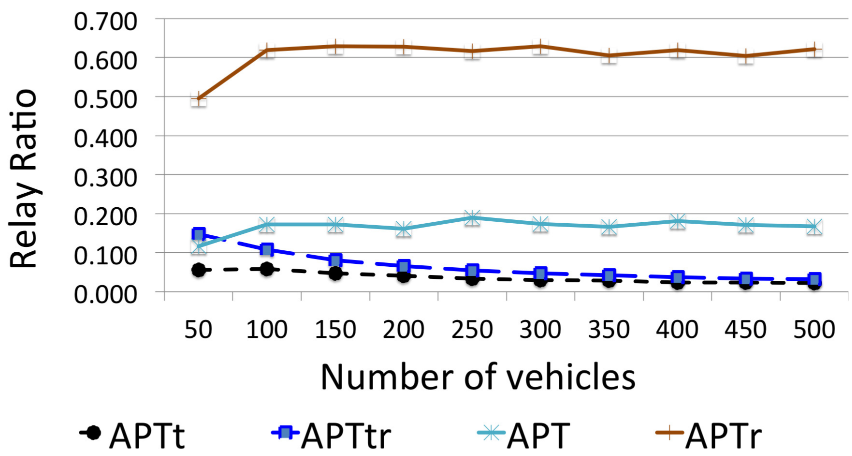


Figure 4.15: Ratio of relay nodes

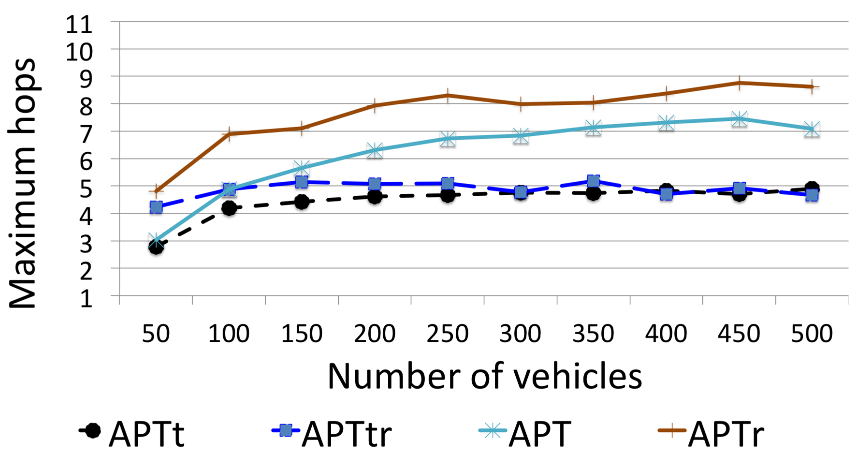


Figure 4.16: Hops count vs. number of vehicles

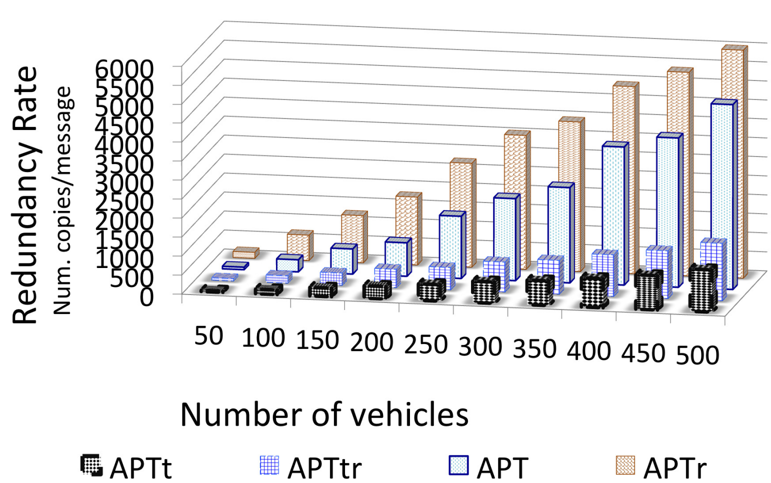


Figure 4.17: Redundancy rate vs. number of vehicles

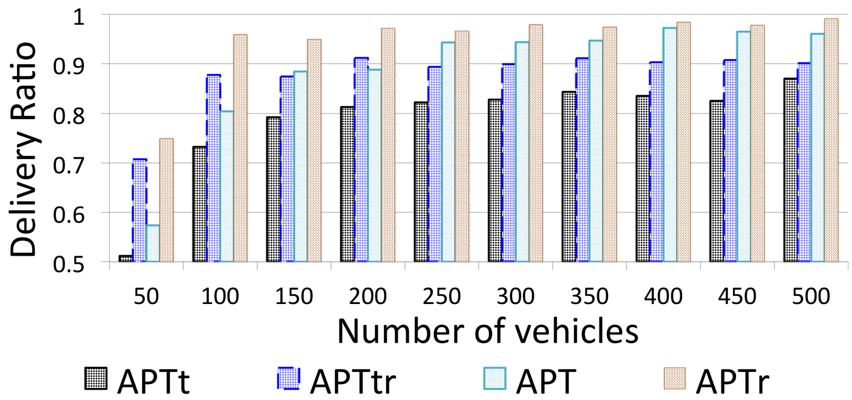


Figure 4.18: Delivery ratio

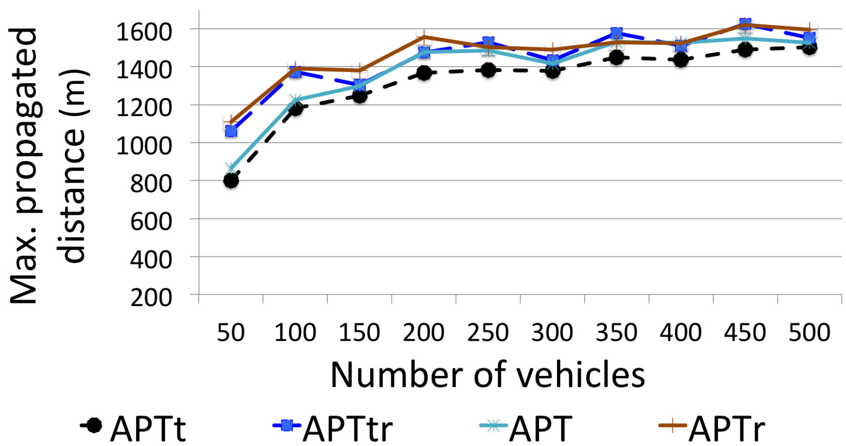


Figure 4.19: Maximum distance achieved

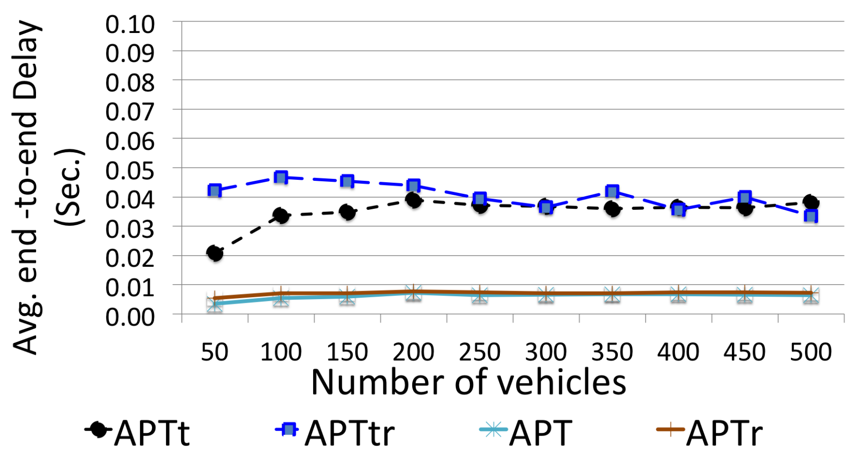


Figure 4.20: Average end-to-end delay.

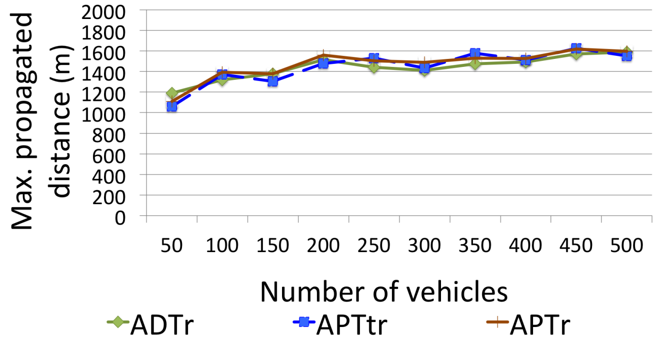
ure 4.19. The figure shows that $APTr$ outperform APT in low number of vehicles. The same thing is applied to $APTtr$, which outperform $APTt$ in low number of vehicles in the networks. However, all probabilistic approaches converge to the same distance with the increase of vehicles in the network.

The $APTtr$ approach outperforms $APTt$ in delivery ratio, as shown in Figure 4.18. The same thing is applied to $APTr$, which outperforms APT in delivery ratio. The $APTr$ delivery ratio outperforms $APTtr$. However, the enhancement of in delivery ratio for $APTr$ compared to $APTtr$ comes at the expense of useless transmissions that overwhelmed the network with large number of redundant data.

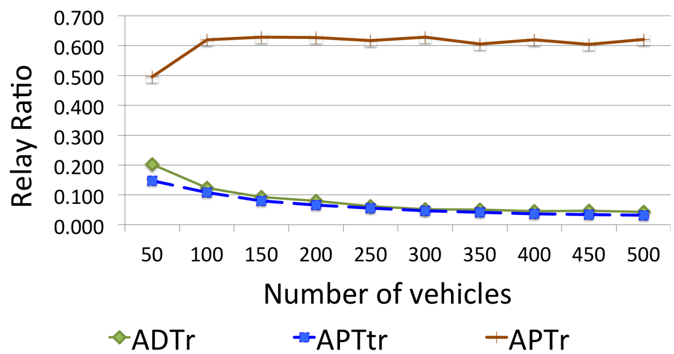
4.5.3 $ADTr$, $APTr$, and $APTtr$ Comparison

In the previous section, each protocol is studied separately. In this section, comparison is made on all the approaches that allow retransmission of a duplicate received message, i.e. $ADTr$, $APTr$, and $APTtr$, and the results are summarize. The maximum propagated distance traversed by the messages in the network is almost the same for $ADTr$, $APTr$, and $APTtr$, as shown in Figure 4.21a. Nevertheless, maximum hops count for $APTr$ is larger than other approaches, and increases with the increase of vehicle numbers as shown in Figure 4.21c. On the other hand, the values of hops count for $ADTr$, and $APTtr$ are more stable with the increase in the total number of vehicles in the network. This means that retransmission probabilistically without back-off time, such as in $APTr$, is not scalable to vehicles density. This is because back-off time helps the receiving node decide with high certainty to relay the message or not, such that if the node does not receive another copy during the back-off time, it is more certain that it has the larger potential coverage area. Otherwise, recalculation is performed based on the information inside the received duplicate message. This can be also confirmed in Figure 4.21b, where the relay ratio of $APTr$ is very large, which is equal on average 60% of the total number vehicles in the network. In contrast, it is less than 10% for $ADTr$ and $APTtr$. As consequence, the redundancy for $APTr$ increased dramatically with the increase of the total number of vehicles, as shown Figure 4.17. Furthermore, it has the worst performance, in terms of number of redundant message in the network, compared to other timer approaches.

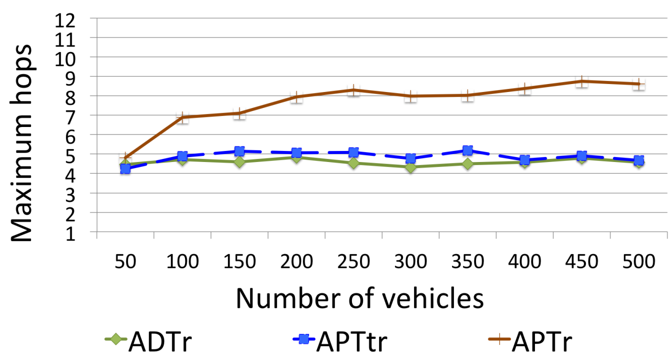
Referring to Figure 4.22 and Figure 4.23, we can summarise our observation as follow. First, $APTr$ outperforms $ADTr$, $APTtr$ in delivery ratio, but at the expense of huge useless transmissions that may overwhelm the network with redundant data. Second, $ADTr$ is better than $APTtr$ in delivery ratio. However, $APTtr$ superior in low redundancy rate, which can be utilized in a congested environments, where the redundancy is a big issue. Finally, area-based data dissemination protocols with timer (i.e. $ADTr$ and $APTtr$) are more scalable to the increase of total number of vehicles than probabilistic approach, owing to the stable hops count, and the decrease of relay ratio with increase of vehicles in the network.



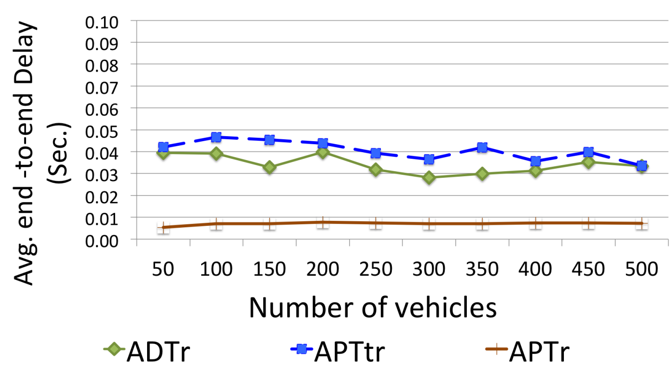
(a) Maximum distance achieved



(b) Ratio of relay nodes



(c) Hops count vs. number of vehciles



(d) Average end-to-end delay.

Figure 4.21: $ADTr$, $APTr$, and $APTtr$

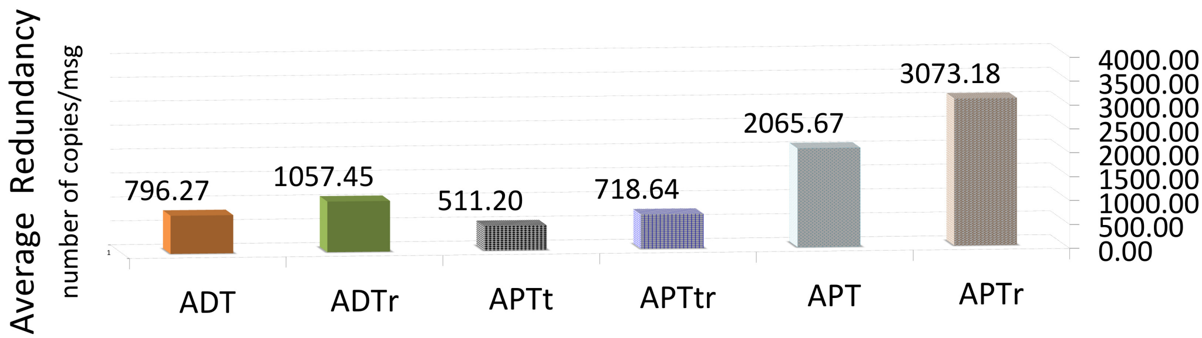


Figure 4.22: Average redundant copies per message

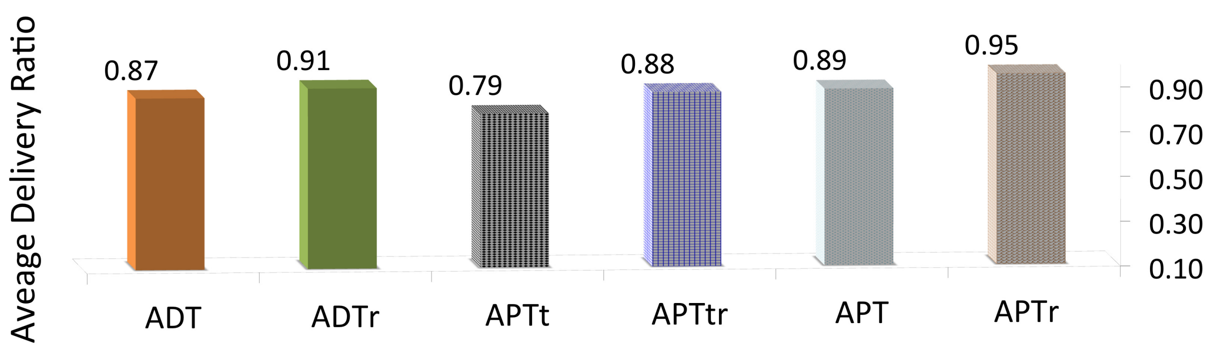


Figure 4.23: Average delivery ratio

4.6 Summary

In this chapter, it is proven that retransmitting a message that is received for the second time achieves 4% increase on delivery ratio with 50% increase in redundancy. While, retransmitting a message that is received more than two times has a dimmer prospect of expectancy to reach new vehicles in the network. Nonetheless, it will increase the message redundancy rate in the network, above 100%, without any clear benefits. Accordingly, ADT is updated to allow transmission only for the second duplicate copy if there is a new area is not covered. Finally, to address the above issue, we develop geometric expressions to compute the area between three transmission areas. The common overlap area includes diverse variety of patterns, thus, we determine the criteria used to define each pattern and relevant algebraic expression.

The performance of the proposed techniques has been evaluated using an actual road map with complex road scenarios and realistic movement traces. The criteria of computing potential coverage that is based on previous relay nodes overlap areas outperform the method of computing the potential coverage based on the last relay vehicle, owing to higher delivery ratio and low redundancy rate. The results presented here have a general significance in VANETs, and could be used in many VANET applications in specific safety applications. They can also be utilized for routing protocols in route discovery and maintenance mechanisms. Merging area-based protocols with network topology protocols can be done for future works.

Chapter 5

Adaptive Expiration Time for Dynamic Beacon Scheduling

SAE J2735 standard specifies different types of short messages to support different vehicle-based applications [45]. The Basic Safety Message (BSM), informally called heartbeat message, is the short message used for beaconing process. BSM contains information about vehicle position, vehicle motion (e.g. speed, acceleration, heading, and steering wheel angle), and other vehicle control information [43]. Beacon messages must be received up to a certain distance with a strict timeline in order to be beneficial to VANET applications. Improper assignment for beacon-scheduling interval and beacon lifetime my cause overhead or outdated information, and consequently poor awareness of the surrounding environment.

Most testing and trials that are performed for VANETs applications have used a fixed beacon generation interval. However, this represents a communication challenge considering that all communication parties must generate data at the same rate. This rate is different from one application to other, but it is typically high for safety applications as presented in [34]. This increases the load on the wireless channel, which in turn reduces the performance of the global communication systems. Research [48] has shown that only a few dozen vehicles can communicate with one another, even without any collision on the communication channel, when multiple safety applications are running on vehicles. Eenennaam et al. [90] examined channel utilization with respect to different values of number of nodes, and beacon generation rate. They have shown that a beaconing system can have many nodes transmitting at a low rate or few nodes transmitting at a high rate. This problem gains a lot of attention and researchers started to come up with many fundamentally different solutions to adjust beacons rate for better scalability.

However, the effort of adjusting beacons rate should be performed in coordination with determining the lifetime of the beacon data. Especially, for the applications and services that require knowledge about network topology, e.g. routing, dissemination protocols, positioning protocols, etc. The lifetime of the beacon data in literature depend on beacon rate, such that the entry is removed from the neighbours-table if the vehicle does not receive any new beacon messages from neighbouring vehicles within two or more consecutive beacon intervals. However, this approach with dynamic adjustment of beacon interval may contain obsolete data when beacon interval adjusted to large value or incomplete data when beacon interval is set to short value. This is may affect the efficiency of the applications decisions.

Thus, we introduce a mathematical formula to compute Adaptive Expiry Time (AET) for each entry individually, which is independent from beacon generation interval and based on the movement information of the neighbour. Furthermore, we introduce a Dynamic Beacon Scheduling (DBS) instead of Static Beacon Scheduling (SBS), as a function of vehicle speed, to alleviate unnecessary overhead, even before any congestion that could lead to loss of important beacons.

The rest of the chapter is organized as follows. Section 5.1 introduces an Adaptive Expiry Time (AET) that determine the life time for each beacon. Section 5.2 presents the proposed Dynamic Beacon Scheduling (DBS) mechanism. Performance evaluation of the proposed approaches is presented in Section 5.3, followed by summary in Section 5.4.

5.1 Adaptive Expiry time (AET)

Vehicles broadcast beacon messages to identify their location, and provide status information to one hop neighbours. Receiving beacons allows a vehicle to build a neighbours-table, and when a new beacon is received the neighbours-table is updated. Vehicles must also be able to determine when to remove an entry from the neighbours-table. In literature, the entry is removed from the table if the vehicle does not receive a new beacon message from neighbouring vehicles within two or more consecutive beacon intervals. We, however, determine the expiry time for each entry individually independent of the beaconing interval, based on information collected from the beacon (for instance, position, speed, orientation).

Assume that we have two vehicles (v_0 and v_1), v_1 sends a beacon to v_0 with v_1 information such as speed s_1, orientation θ_1, and position (x_1, y_1). Vehicle v_0 already knows its current position (x_0, y_0), and the movement information such as speed s_0, and orientation θ_0. Using the information received from v_1, v_0 creates an entry in the neighbours-table and calculates the expiry time (t) for this entry. Expiry time (t) is defined as the time when the distance between the two vehicles v_0 and v_1 reaches the maximum distance achieved by transmission power of vehicle v_0, i.e., vehicle v_0 transmission range R. If the coordinates of vehicle v_0, and vehicle v_1 after t seconds are $(x_0^t - y_0^t)$, $(x_1^t - y_1^t)$ respectively. Then, the distance between the two vehicles coordinates $(x_0^t - y_0^t)$, $(x_1^t - y_1^t)$ after t seconds is:

$$R^2 = (x_1^t - x_0^t)^2 + (y_1^t - y_0^t)^2 \tag{5.1}$$

v_0 and v_1 coordinates after t seconds are calculated as follow:

$$\begin{aligned} x_0^t &= x_0 + t * s_0 sin\theta_0, \quad & y_0^t &= y_0 + t * s_0 cos\theta_0 \\ x_1^t &= x_1 + t * s_1 sin\theta_1, \quad & y_1^t &= y_1 + t * s_1 cos\theta_1 \end{aligned} \tag{5.2}$$

By substituting the coordinates shown in Equation 5.2 into Equation 5.1 we get Equation 5.3. Solving the quadratic Equation 5.3 (following the steps shown in Equations 5.4a till

5.6b) we get the expiry time formula as shown in Equation 5.7.

$$(x_1 - x_0 + t * s_1 sin\theta_1 - t * s_0 sin\theta_0)^2 + (y_1 - y_0 + t * s_1 cos\theta_1 - t * s_0 cos\theta_0)^2 - R^2 = 0 \quad (5.3)$$

Substituting the variables in equations 5.4a-5.4c into equation 5.3 will lead to equation 5.4e:

$$X = x_1 - x_0, \qquad Y = y_1 - y_0, \quad (5.4a)$$
$$S_{x0} = s_0 sin\theta_0, \quad S_{y0} = s_0 cos\theta_0, \quad (5.4b)$$
$$S_{x1} = s_1 sin\theta_1, \quad S_{y1} = s_1 cos\theta_1, \quad (5.4c)$$
$$\Rightarrow (X + t * S_{x1} - t * S_{x0})^2 + (Y + t * S_{y1} - S_{y0})^2 - R^2 = 0 \quad (5.4d)$$
$$X^2 + Y^2 - R^2 + 2X(S_{x1} - S_{x0}) + 2Y(S_{y1} - S_{y0}) + t(S_{x1} - S_{x0})^2 + (S_{y1} - S_{y0})^2 = 0 \quad (5.4e)$$

Defining:

$$c = X^2 + Y^2 - R^2 \quad (5.5a)$$
$$b = 2X(S_{x1} - S_{x0}) + 2Y(S_{y1} - S_{y0}) \quad (5.5b)$$
$$a = (S_{x1} - S_{x0})^2 + (S_{y1} - S_{y0})^2 \quad (5.5c)$$

Substituting 5.5a-5.5c into 5.4e, we get:

$$\Rightarrow at^2 + tb + c = 0 \quad (5.6a)$$
$$\Rightarrow t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (5.6b)$$

The negative root is ignored because it indicates the past time.

$$\therefore t = -\big(2X(S_{x1} - S_{x0}) + 2Y(S_{y1} - S_{y0})\big) + \frac{\sqrt{\big(2X(S_{x1} - S_{x0}) + 2Y(S_{y1} - S_{y0})\big)^2 - 4\big((S_{x1} - S_{x0})^2 + (S_{y1} - S_{y0})^2\big)\big(X^2 + Y^2 - R^2\big)}}{2\big((S_{x1} - S_{x0})^2 + (S_{y1} - S_{y0})^2\big)} \quad (5.7)$$

Algorithm 5 illustrates how to determine expiry time for a new entry. If the two vehicles have the same speed and direction, regardless of the position, the denominator will be zero, as shown in lines 18-20. This indicates that vehicle i will always be in the transmission range of vehicle j. Therefore, the expiry time will be equal to the beacon interval β times three. The same is applied when one of the vehicles is stopped for a while, as shown in lines 22-25.

5.2 Dynamic Beacon scheduling (DBS)

This section illustrates the procedure for generating beacon dynamically to avoid unnecessary overhead. Beacon generation interval (β) value is determined by looking at the

Algorithm 5 Calculate expiry time for an entry received from vehicle i to vehicle j

Input: BeaconPacket {Received Beacon packet from vehicle i to vehicle j}
Output: T_{expiry} {Expiry Time for i entry}

{Get the required data from the received packet.}
$S_j = packet.speed$
$x_j = packet.x$
$y_j = packet.y$
$\theta = packet.\theta$
$T_{snd} = packet.sendTime$
$T_{rcv} = now$
{Update neighbour coordinate due to time difference}
$x_j = x_j + S_j * (T_{rcv} - T_{snd}) * sin(\theta)$
$y_j = y_j + S_j * (T_{rcv} - T_{snd}) * cos(\theta)$
{Get the receiver j data}
$getCoordinate(x_j, y_j)$;
$read(S_j)$
$read(\theta_j)$
{Compute expiry time for neighbour i entry}
if $(S_i \neq 0 \ and \ S_j \neq 0)$ **then**
  $a = (s_i sin\theta_i - s_j sin\theta_j)^2 + (s_i cos\theta_i - s_j cos\theta_j)^2$
  $b = 2(x_j - x_i)(s_i sin\theta_i - s_j sin\theta_j) + 2(y_j - y_i)(s_i cos\theta_i - s_j cos\theta_j)$
  $c = (x_j - x_i)^2 + (y_j - y_i)^2 - R^2$
  if $a \neq 0$ **then**
    $T_{expiry} = \frac{-b+\sqrt{b^2-4ac}}{2a}$
  else
    compute β using Equation 5.8
    $T_{expiry} = 3 * \beta$
  end if
  {Else if one vehicle is paused}
else
  compute β using Equation 5.8
  $T_{expiry} = 3 * \beta$
end if

speed of each individual vehicle since speed can be thought of as the rate at which a vehicle covers distance. A vehicle that is travelling at high speed covers a relatively large distance in a given amount of time while a slow-moving vehicle covers a small distance in the same amount of time. Thus, it is likely that nearby neighbours and surrounding road condition of the fast moving vehicles will change more frequently than slow moving vehicles. Therefore, the faster a vehicle is moving, the more frequent it will send beacons. The proposed solution is based on four parameters: slow speed (S_{slow}), fast speed (S_{fast}), minimum interval (β_{min}), and maximum interval (β_{max}). Where beacon scheduling interval is computed as follow as follow:

$$\beta_i = \begin{cases} \beta_{min} & \text{if } S_i \geq S_{fast} \\ \frac{S_{fast}}{S_i} * \beta_{min} & \text{if } S_{slow} < S_i < S_{fast} \\ \beta_{max} & \text{if } S_i \leq S_{slow} \end{cases} \tag{5.8}$$

Minimum scheduling interval and maximum scheduling interval are configured differently form one application to another and vary according to application communication requirements. For example, beacon frequency for collision warning is defined as 10 Hz according to VSCC and USDOT [34]. Therefore, minimum interval for such application is set as 0.1 second and maximum interval as 1 second.

5.3 Simulation and Analysis

The performance of Adaptive Expiry Time (AET) for Dynamic Beacon Scheduling (DBS) has been evaluated with respect to different traffic density, and different transmission range. It has been compared with Static Beacon Scheduling (SBS) where beacon frequency is fixed per application. In SBS, the neighbour vehicle entry is removed from neighbours-table if no beacon is received within three consecutive beaconing intervals. In addition, different approaches of expiry time, such as Constant Expiry Time (CET), Variable Expiry Time (VET), and Adaptive Expiry Time (AET) are compared with DBS approach. In CET expiry time is constant for entries. It is equal to three times minimum scheduling interval (e.g. 3*0.1). While in VET, the expiry time for each entry is three consecutive dynamic beacon intervals determined by each neighbour vehicle individually (e.g. 3*β). On the other hand, AET is adaptive and computed according to equation 5.7, as discussed earlier.

5.3.1 Simulation Setup and Performance Metrics

Results in this section are obtained using NS2 network simulator. The simulation is based on a real map of Ottawa-downtown streets data, which is generated from Openstreetmap, as shown in Figure 5.1. This map includes high way, secondary roads, traffic lights, intersections, etc. to represent realistic scenarios. The real movement traces are generated using Simulation of Urban MObility (SUMO) [97]. Beacons are sent every β seconds, where the value of β in DBS is adaptive to vehicle speed (see Equation 5.8) and fixed for SBS approach during simulation time. Neighbours-table entries expiry time, t, in DBS is

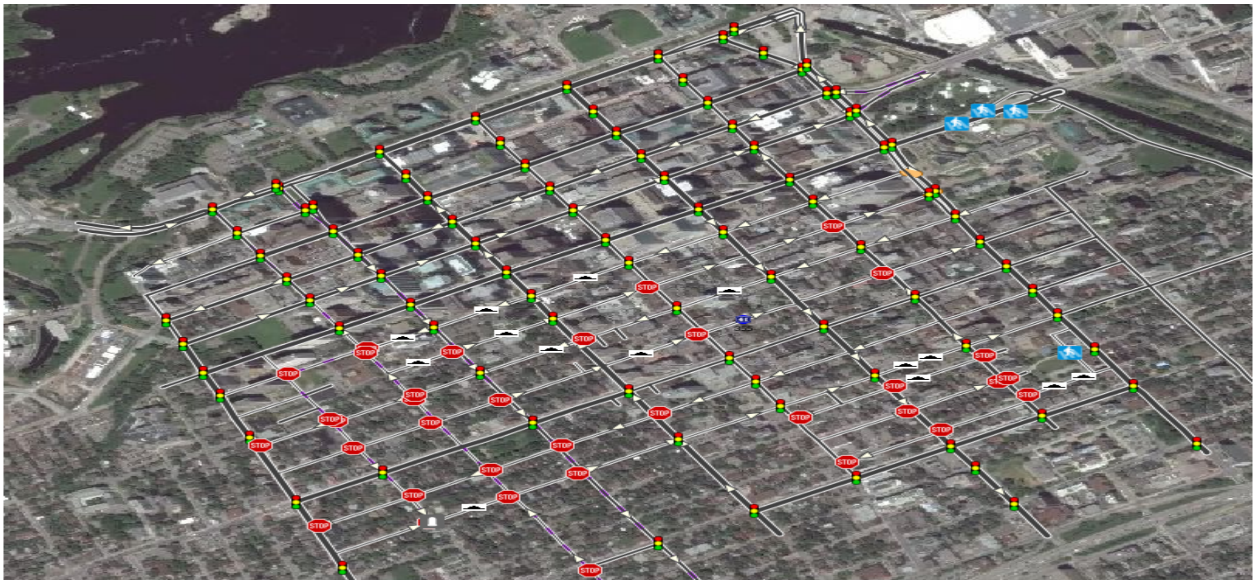


Figure 5.1: Ottawa downtown map

Table 5.1: AET Simulation Parameters

Parameter name	**DBS**	**SBS**
Network simulator	NS2.35	
Propagation Model	TwoRayGround	
Mac and physical Layer	IEEE 802.11p	
-Noise floor	-99dBm	
-Carrier sense threshold	-85dBm	
Antenna	OmniAntenna	
simulation Time	500s	
Mobility/Traffic Generator	SUMO	
Transmission Range (R)	50,100,150,250,350m	
Number of vehicles (N)	50-500 vehicles	
Beacon schedule interval (β)	dynamic	0.1 sec
Entry Expiry Time (t)	AET/VET/CET	$3 * \beta$
Fast speed parameter	70km/hr	-
Slow speed parameter	30km/hr	-
Minimum scheduling interval parameter	0.1 second	-
Maximum scheduling interval parameter	1 second	-

determined individually according to the speed, direction and position of the sender and the receiver vehicle as described in Algorithm 5. On the other hand, in SBS the neighbour vehicle entry is removed from neighbours-table if no beacons is received within three consecutive interval of beaconing, i.e. $t = 3 * \beta$. The list of simulation parameters used in this work is given in Table 5.1. The performance metrics that are used to evaluate the performance of the DBS and SBS approaches are listed below with a confidence level of 95%:

- Average beacon scheduling interval: This metric is used to measure the increase in beacon scheduling interval. $\mu_\beta = \frac{\sum_{i=0}^{N}\beta_i}{N}$, where β_i is the average beacon scheduling interval for vehicle i.
- Coverage, which represents average number of one-hop vehicles that receive the beacons.
- Early expired ratio (EER), which refers to the ratio of vehicles entries that is expired early to the total entries in neighbours-table. A vehicle entry is considered expired early in vehicle i table, when it is removed due to the end of expiry time value, though the vehicle still neighbour to vehicles i and within the transmission range.
- Beaconing overhead, which measures number of generated beacons per one vehicle at the end of simulation.
- Awareness (α), which is the metric measures the average level of awareness of the surrounding neighbouring vehicles. The vehicle is aware of its neighbour if it has an entry of this neighbour in the neighbours-table. This is computed as follow:

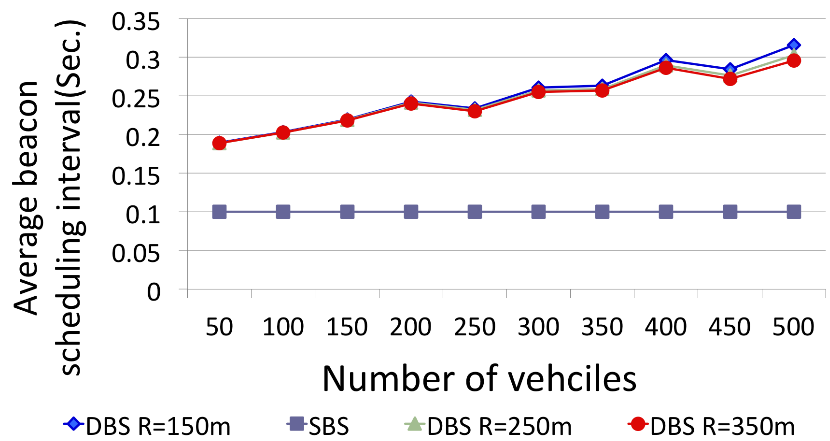
$$\alpha = \frac{\sum_{i=0}^{m}\alpha_i}{m}$$

  , where $\alpha_i = \frac{E_i}{N_i}$ is the average number of neighbours that vehicle i is aware of. It is calculated each time an entry is expired and need to be removed from the table, with total frequency equal m. N_i is the total number of actual neighbours and E_i is the total number of neighbours have an entry in vehicle i table.

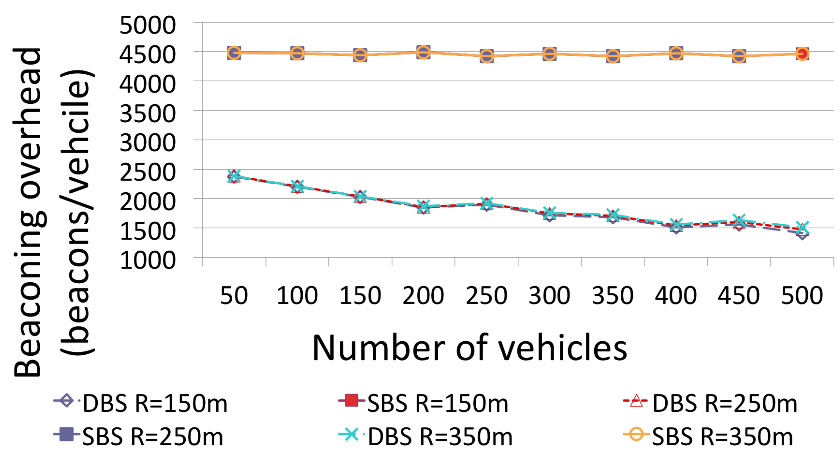
5.3.2 Results

In this section, the results obtained to evaluate the performance of the DBS approach and AET approach are report. The first part of the experiments compares DBS using AET with SBS approach. It demonstrates how much reduction on beacon overhead is achieved and how this reduction affects the coverage and awareness level. In the second part, the awareness of DBS with different expiry time approaches is compared.

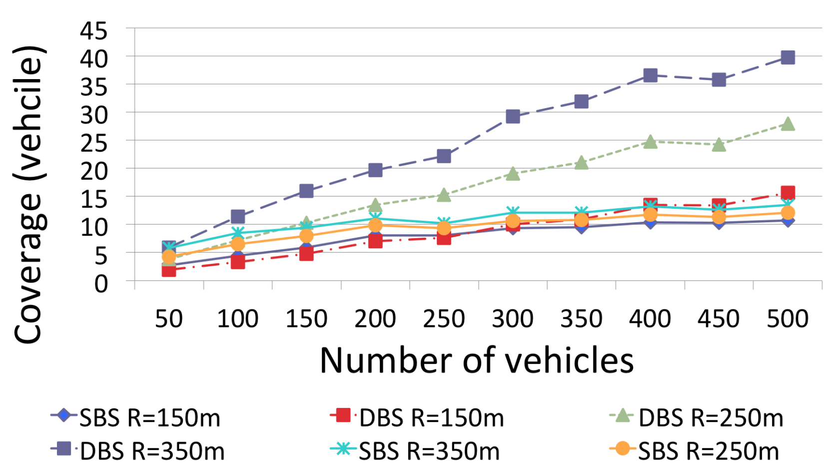
In Figure 5.2a, we observe the effect of increasing number of vehicles into beacon scheduling interval in DBS compared to SBS that is equal to $0.1s$. The figure demonstrates that with the increase of vehicle density the beacon scheduling interval for DBS is increased.



(a) β vs number of vehicles



(b) Beacon rate vs number of vehicles



(c) Coverage vs number of vehicles

Figure 5.2: Assessment of DBS and SBS

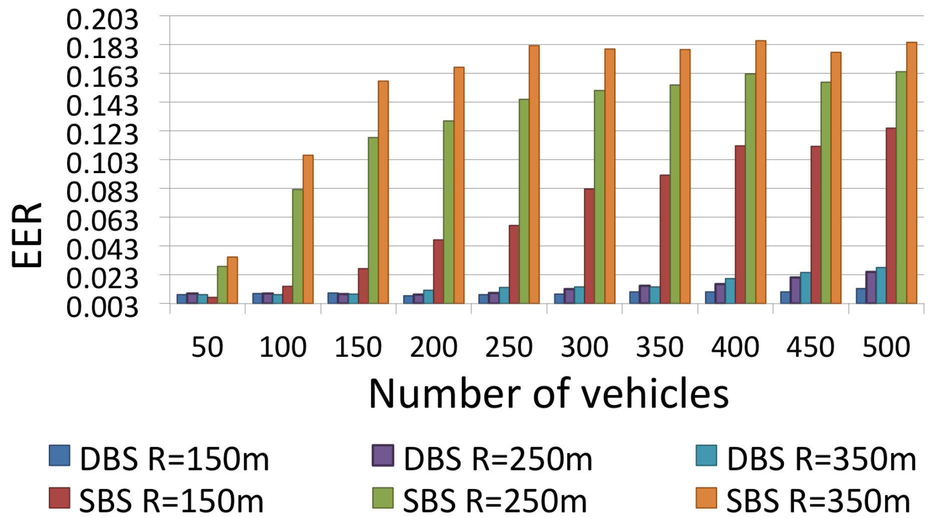


Figure 5.3: EER vs number of vehicles

Because when number of vehicles increases, vehicles speed will decrease and accordingly beacon scheduling interval will increase. As consequence, beacons overhead will be reduced. This is clear in Figure 5.2b, in which the reduction of beacon overhead per vehicle in DBS is about $30\% - 50\%$ compared to SBS for all densities. The increase on the maximum transmission range has no effect on beacon scheduling interval as shown in both approaches, DBS and SBS, as demonstrated in Figure 5.2a and Figure 5.2b.

The reduction achieved on beaconing overhead in DBS reflected on number of vehicles receives the beacons as shown in Figure 5.2c. DBS outperform SBS when transmission range is 250 m or 350 m for all traffic densities. However, when transmission range is equal to 150 m DBS is better than SBS for high densities. This indicates that due to the high rate of beacons in SBS, especially in high density, beacons are lost/dropped due to overhead. This is proving that DBS is more scalable to total number of vehicles in the network than SBS.

Figure 5.4 and Figure 5.3 illustrate vehicle conception to the network topology when longer-term knowledge is used. Figure 5.3 measures the ratio of vehicles entries removed from the neighbours-table, i.e. expired early, though they are still neighbours and within the transmission range. We notice that the information in DBS is more comprehensive than SBS for different densities with different values of transmission ranges. Recall that in SBS record is removed if it is not refreshed within three consecutive beacon intervals, this means beacons are lost due to unnecessary overhead (as shown in Figure 5.2b and Figure 5.2c) or blocked due to temporal non-line-of-sight areas. This also give us indication if instantaneous beaconing is used in SBS the vehicle will not be aware about other vehicles due to overhead especially in high density traffic.

Figure 5.4 depicts the awareness ratio as function of vehicle numbers. The awareness level in DBS is much better than SBS for all traffic densities with different values of transmission range. DBS aware of most surrounding neighbours especially when transmission range is equal to 150 m or 250 m. While in SBS the ratio is sharply degrade when the

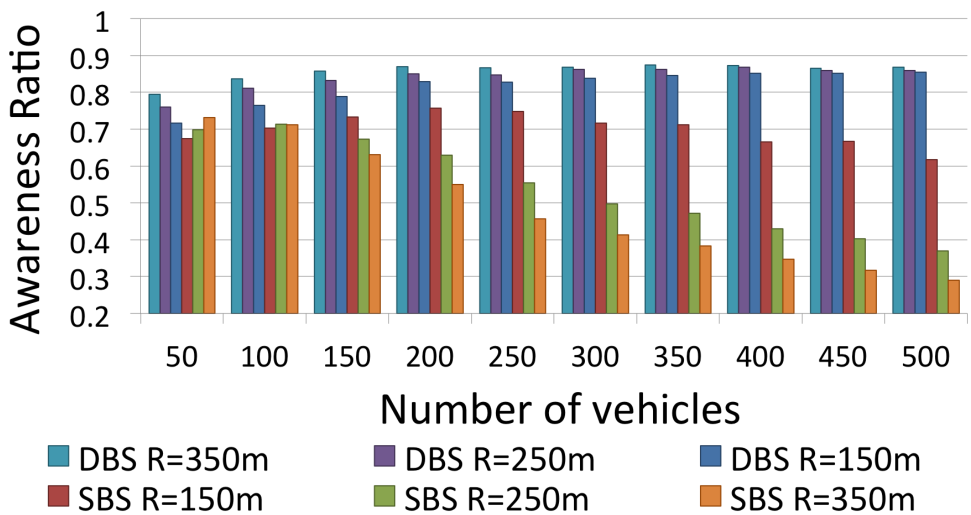


Figure 5.4: Awareness vs number of vehicles

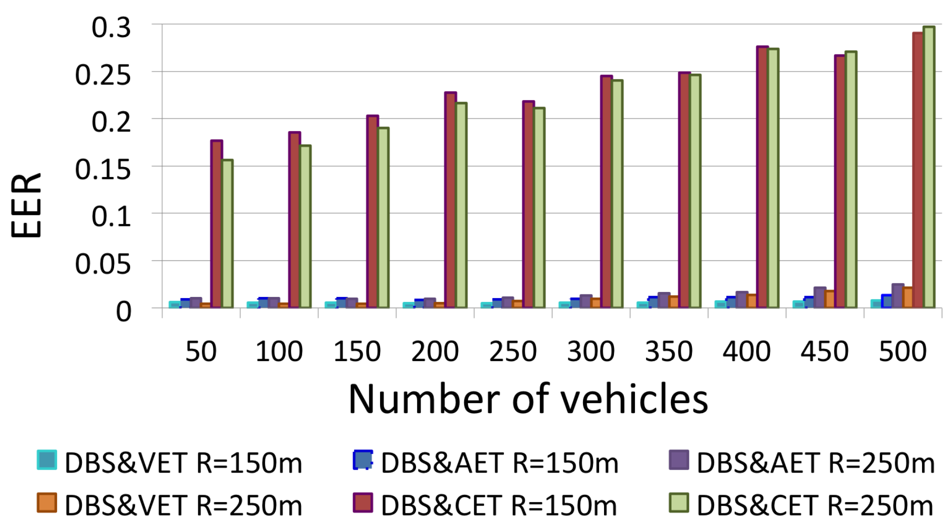


Figure 5.5: DBS EER for different expiry time approaches

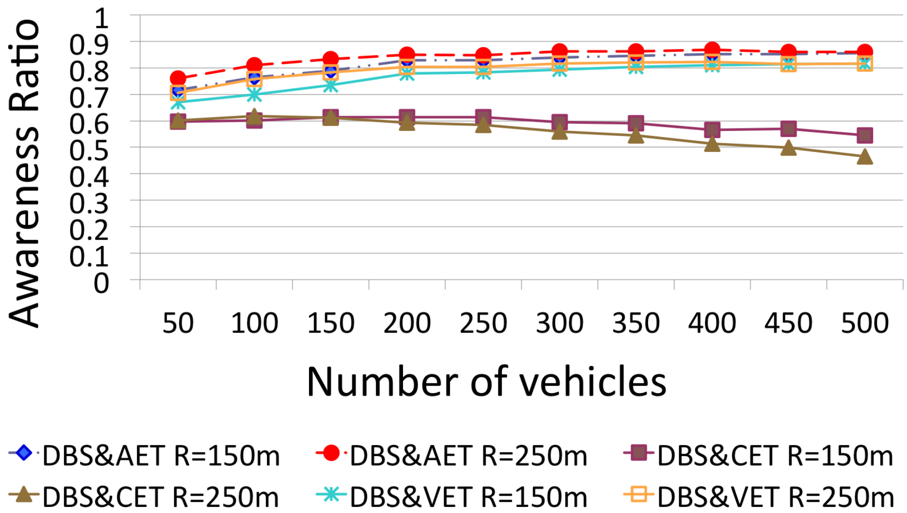


Figure 5.6: DBS awareness for different expiry time approaches

density is increased. This is due to early expired entries as shown in Figure 5.3 beside the unnecessary overhead that cause loss or blockage of beacons.

Figure 5.5 and Figure 5.6 illustrate the behaviour of DBS with different expiry time, such as AET, VET, and CET. In Figure 5.5 the ratio of vehicles entries removed from the neighbours-table for AET and VET are almost negligible compared to CET. In CET the EER is increased with the increase of vehicle density. Because setting up the expiry time constant, while the beacon interval is scheduled dynamically will lead to fast expiry of entries compared to beacon interval especially in high density. Figure 5.6 portrays the awareness ratio of the surrounding neighbouring vehicles for DBS with different expiry time. The figure demonstrates that AET outperforms other approaches, CET and VET approaches.

5.4 Summary

The efforts of trying to control the beaconing rate should be performed in sync with a good estimate of the beacon information lifetime. Especially when knowledge about network topology is required. The vehicle should be able to determine the time at which to remove an entry from a neighbours-table. To the best of our knowledge, all adopted approaches in literature depend on the beaconing rate of vehicles [16–25]. In such approaches, the entry is removed from the neighbours-table if the vehicle does not receive any new beacon messages from neighbouring vehicles within two or more consecutive beacon intervals. Therefore, neighbours-table may contain outdated data if the consecutive beacon period chosen is too long or a valid entry may be removed from the table if the next beacon lost or blocked, due to short scheduling interval or temporal non-line-of-sight areas.

In this chapter, we explore the visibility of having adaptive expiry time for neighbours-table entries that harmonizes with dynamic beacon scheduling. The expiry time is calculated for each entry individually based on neighbour position, speed, orientation, and independent from beacon scheduling interval. It has been evaluated using fixed beacon scheduling and dynamic beacon scheduling that adjusts beacon interval according vehicle speed. Also, it is compared to traditional approach of expiry time that is beacon information expired when no new beacon messages from neighbouring vehicles within two or more consecutive beacon intervals. The results show that the awareness ratio of the surrounding neighbouring vehicles using adaptive expiry time outperforms traditional approach.

Chapter 6

Conclusion and Future Work

In connected vehicles environment, V2V multi-hop relay selection has been considered a promising technology to support ITS applications. It is also effective in safety related applications that have strict quality-of-services requirements such as low latency, high-reliability, and scalability. However, the heterogeneous transmission powers in connected vehicles environment influences the selection of the proper relay vehicles to retransmit the messages. Consequently, it will have an impact on the effectiveness of ITS applications. It may also affect the performance of some safety applications that require one-hop periodic transmission. In such situation, switching to multi-hop relay selection will be the best candidate solution to dissemination data to vehicles in the vicinity. The efficiency of multi-hop dissemination is related to the selection criteria of relay vehicles. The proper selection of relay nodes governs high delivery ratio, acceptable overall end-to-end delay and efficient bandwidth usage. Reported relay selection protocols in literature generally assume an equal transmission powers for all vehicles in the network.

This work define mathematical formulas for a timer and decision probability functions that can be used by each vehicle receiving an event message. The two functions are based on all possible scenarios of the overlapping between transmitter and receiver transmission ranges in a wireless environment. Each scenario is uniquely identified by mathematical conditions to differentiate it from others. The value of the timer or the probability functions allow the vehicle to determine if it is the next to act as relay node or not. These values order vehicles transmission according to the amount of new area that would be covered by the potential retransmissions, considering the heterogeneity in vehicle transmission ranges. Accordingly, area-based data dissemination protocols for environments in which vehicles transmission ranges are heterogeneous are developed. These protocols are Area Defer Transmission (ADT) protocol, Area-based Probabilistic Transmission (APT), and an integration of timer and probabilistic area-based transmission method ($APTt$). The proposed area-based approaches are instant-based protocols that do not rely on network topology information. Instead, each vehicle decides independently based on information contained in the message (such as, position and sender transmission range) and local information at the receiving vehicle. These protocols eliminate useless retransmission or retransmission with small coverage areas that would be covered by other transmissions.

The performance of the proposed protocols has been thoroughly investigated and compared with other distance-based algorithms.

Moreover, more reliable approaches (i.e. $ADTr$ and $APTtr$) are proposed by relaying duplicate received message. Thus, we introduce a geometric taxonomy for all possible overlap patterns in wireless environment, which is an apparently hitherto unsolved geometrical problem. Accordingly, the criteria used to define each pattern and relevant algebraic expression to compute the potential additional coverage area is deduced.

In addition, we explore the visibility of having adaptive estimate of the beacon information lifetime for neighbours-table entries that can harmonizes also with dynamic beacon scheduling. The expiry time estimate is calculated for each entry individually based on neighbour position, speed, orientation, and independent from beacon scheduling interval. Thus, the vehicle is able to determine the time to remove an entry from a neighbours-table. This is to avoid outdated data if the consecutive beacon period is chosen too long or removing a valid entry may from the table if the next beacon lost or blocked, due to short scheduling interval or temporal non-line-of-sight areas. The proposed expiry time formula can be applied to a number of single hope safety applications. An example of such safety application is Cooperative Collision Warning application. Cooperative collision warning collects surrounding vehicle locations and dynamics, along with its own position, dynamics, and roadway information (map data), and warns the driver when a collision is likely. It also can be exploited in the area of routing as well as dissemination protocols based on network topology, to transmit a message over multi hop neighbours located within a range of few kilometres from the source.

6.1 Thesis Conclusion

The performance of the proposed techniques has been evaluated using simulation. It has been compared to other protocols. Actual road map with complex road scenarios and realistic movement traces is used in the simulation. The following interesting findings were drawn from the results. First, more vehicles receive a message transmitted by a single relay vehicle with ADT than with other distance versions. This confirms the hypothesis that relay nodes selected by area-based timer are more effective than others, owing to their higher delivery ratios, end-to-end delay and the fewer hops with long distance hops. Second, the probabilistic area-based approach without timer concept increase redundancy, however, it is very fast at disseminating data compared with other approaches. Third, redundancy and retransmission are reduced more with controlling defer time in timer area-based approaches than with a probabilistic approach, without affecting reachability in the network and the delivery ratio. Fourth, $APTt$ can be utilised in high number of vehicles in the network because it achieves less redundancy than ADT with almost the same delivery ratio and propagated distance. Fifth, proposed approach for more reliable dissemination (i.e. $ADTr$) outperform the method of computing the potential coverage based on the last relay vehicle, owing to higher delivery ratio and low redundancy rate. Finally, area-based data dissemination protocols with timer (i.e. $ADTr$ and $APTtr$) are more scalable to the increase of total number of vehicles than probabilistic approach, owing to the stable hops count, and the decrease of relay ratio with increase of vehicles in the network.

For Adaptive Expiry Time (AET) for neighbours-table entries increases the awareness ratio of the surrounding neighbouring vehicles.

The results presented here have a general significance in connected vehicle technology, and could be used in many ITS applications in particular safety applications. They also can be utilized for routing protocols in route discovery and maintenance mechanisms. It can also utilize in V2I/I2V considering the infrastructure unit as stationary vehicle.

6.2 Future Work

Meantime, connected vehicles technology target is to mitigate roads congestion and improve safety. The V2V communications using DSCR/WAVE technology enable vehicles to talk to each other in the road, automatically transmitting data such as speed, position, and direction, and send alerts to each other if a crash seems imminent. This technology is already in the action list of the U.S. Department of Transportation (USDOT) and stakeholders. USDOT announced late in 2015 the roadmap with the preliminary plans to guide industry and public agency implementation efforts. Steps are taking to enable V2V communication after it has been confirmed that the DSCR/WAVE is the only viable option for safety-critical and other low latency mobility and environmental applications.

At the same time, communities are working to widen the scope of connected vehicle, by integrating DSCR/WAVE technology with other available wireless data communications technologies, such cellular, satellite, and Wi-Fi. The integration with multiple systems will enable the connected vehicle to support vehicle-to/form-infrastructure applications, interacting with other smart devices on the road or inside the vehicle, and provides more services such as the Internet access to all the smart devices used by the driver and passengers. Thus, it will be important to ensure that heterogeneous wireless technologies and the diversity of the provided services do not somehow compromise the effectiveness of the safety applications. Future research is required to be conducted to ensure the interoperability. Thus, the followings lay out some of future research in the same area:

1. Explore the proposed techniques in heterogeneous wireless technologies, such as WAVE technology, cellular networks, and Wi-Fi. By tuning the parameters to fit the integration of such technologies.

2. Integration of other wireless technologies and/or V2I applications with V2V would require additional data elements to be broadcast to, and processed by vehicles. Broadcasting additional data has the potential of leading to communication congestion. Channel congestion may impact WAVEs effectiveness, which may in turn impact the effectiveness of supported V2V safety applications. Thus, it is critical that safety messaging should not be compromised due to broadcasting more data for other services or other technologies integration. The issue of wireless channel congestion has

gained a lot of attention and researchers have come up with many fundamentally different solutions. In US, USDOT are considering two algorithms for congestion mitigation. The first algorithm is a transmission control protocol for scalable V2V safety communications that supports adaptive control of the message transmission rate and transmission power. The second algorithm controls message transmission rate based on reported CBP from the neighbouring vehicles and that measured by the host vehicle. The algorithm adapts the message rate up and down in order to maintain a desired level of channel utilization. In European, the ETSI specified a set of Decentralized Congestion Control (DCC) mechanisms that adapt the transmission parameters based on channel load measures. Relaying event-driven messages are required to be investigated in the presence of congestion control mechanism. The study should evaluate how congestion control affects event driven message dissemination and how congestion control will perform in the presence of event driven messages.

3. Merge area-based protocols with network topology-based protocols. In the network topology-based protocols, the decision of selecting relay nodes are based on information collected by periodic beacons/hello messages. It is highly correlated to the periodic beaconing process, which should refresh the data when it is required and always keep the collected data up to date.

4. Exploits the combination of V2V and V2I communications and specify the common area of transmission area relative to vehicles locations and the sides of non-covered vehicle transmission area.

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APPENDICES

Appendix A

Confidence Interval

This appendix describes the confidence interval calculation that is adopted for the performance metrics in this thesis. There is a sequence of n independent movement traces files, which are generated for a real map of downtown Ottawa streets. This is done using SUMO [97]. SUMO is a microscopic road traffic simulation package that combines vehicle movement with lane changing and intersection control, and constrains vehicle movements to selected streets. If it is assumed that performance metric is z generated from the simulation run of one trace file, then we have a sequence of n data points $\{z_1, z_2, ..., z_n\}$. Each trace file is run m times, $\{z_{11}, z_{12}, ..., z_{1m}\}$, $\{z_{21}, z_{22}, ..., z_{2m}\}$,..., $\{z_{n1}, z_{n2}, ..., z_{nm}\}$. Given that the data is collected once the simulation has achieved steady state, then, the estimated mean is computed as follow for each map:

$$\bar{z}_1 = \frac{\sum_{i=1}^{m} z_1}{m},\ \bar{z}_2 = \frac{\sum_{i=1}^{m} z_2}{m},\ ...,\ \bar{z}_n = \frac{\sum_{i=1}^{m} z_n}{m} \tag{A.1}$$

Now the data sequence in the set of m observations $\{\bar{z}_1, \bar{z}_2, ..., \bar{z}_n\}$.

$$\mu = \frac{\sum_{i=1}^{n} \bar{z}_i}{n} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} z_{ij}}{m * n} \tag{A.2}$$

The variance is computed as follow:

$$\sigma^2 = \frac{\sum_{i=1}^{n} (\bar{z}_i)^2 - n * (\mu)^2}{n(n-1)} \tag{A.3}$$

With enough samples, the Central Limit Theorem is used to construct the confidence interval for the mean. With confidence level 95%, the confidence interval is the estimated mean, ± 1.96 estimated standard deviations. Where, the standard deviation is the square root of the variance. This is mean with probability 95%, the true mean lies within the range $[\mu\ -\ 1.96\sigma,\ \mu\ +\ 1.96\sigma]$.

Appendix B

Source Code

B.1 IEEE 802.11p parameters in NS2.35

The configuration parameters for the physical (PHY) and medium access control (MAC) layers of the IEEE 802.11p that is used in N2.35 simulator.

```
#802.11p parameters

Phy/WirelessPhyExt set CSThresh_              3.162e-12  ;#-85 dBm Wireless interface sensitivity
Phy/WirelessPhyExt set Pt_                    0.001     ;# The value is different for each vehicle
Phy/WirelessPhyExt set freq_                  5.9e+9
Phy/WirelessPhyExt set noise_floor_           1.26e-13   ;#-99 dBm for 10MHz bandwidth
Phy/WirelessPhyExt set L_                     1.0        ;#default radio circuit gain/loss
Phy/WirelessPhyExt set PowerMonitorThresh_    6.310e-14  ;#-102dBm power monitor  sensitivity
Phy/WirelessPhyExt set HeaderDuration_        0.000040   ;#40 us
Phy/WirelessPhyExt set BasicModulationScheme_ 0
Phy/WirelessPhyExt set PreambleCaptureSwitch_ 1
Phy/WirelessPhyExt set DataCaptureSwitch_     0
Phy/WirelessPhyExt set SINR_PreambleCapture_  2.5118;     ;# 4 dB
Phy/WirelessPhyExt set SINR_DataCapture_      100.0;      ;# 10 dB
Phy/WirelessPhyExt set trace_dist_            1e6         ;#PHY trace until distance of 1 Mio. km
Phy/WirelessPhyExt set PHY_DBG_               0

Mac/802_11Ext set CWMin_                      15
Mac/802_11Ext set CWMax_                      1023
Mac/802_11Ext set SlotTime_                   0.000013
Mac/802_11Ext set SIFS_                       0.000032
Mac/802_11Ext set ShortRetryLimit_            7
Mac/802_11Ext set LongRetryLimit_             4
Mac/802_11Ext set HeaderDuration_             0.000040
Mac/802_11Ext set SymbolDuration_             0.000008
Mac/802_11Ext set BasicModulationScheme_      0
Mac/802_11Ext set use_802_11a_flag_           true
Mac/802_11Ext set RTSThreshold_               2346
Mac/802_11Ext set MAC_DBG                     0
```