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Title Achieving Reliable and Enhanced Communication in Vehicular Ad-Hoc Networks (VANETs)

Name Elias Chinedum Eze

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Elias Chinedum Eze

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Achieving Reliable and Enhanced Communication in Vehicular Ad-Hoc Networks (VANETs)

by

Elias Chinedum Eze

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Centre for Wireless Research
Institute for Research in Applicable Computing
Department of Computer Science and Technology
University of Bedfordshire
Luton, Bedfordshire, LU1 3JU, UK

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Dr Sijing Zhang (Supervisor)

Dr Enjie Liu (Second Supervisor)

Abstract

With the envisioned age of Internet of Things (IoTs), different aspects of Intelligent Transportation System (ITS) will be linked so as to advance road transportation safety, ease congestion of road traffic, lessen air pollution, improve passenger transportation comfort and significantly reduce road accidents. In vehicular networks, regular exchange of current position, direction, speed, etc., enable mobile vehicle to foresee an imminent vehicle accident and notify the driver early enough in order to take appropriate action(s) or the vehicle on its own may take adequate preventive measures to avert the looming accident. Actualizing this concept requires use of shared media access protocol that is capable of guaranteeing reliable and timely broadcast of safety messages. This dissertation investigates the use of Network Coding (NC) techniques to enrich the content of each transmission and ensure improved high reliability of the broadcasted safety messages with less number of retransmissions. A Code Aided Retransmission-based Error Recovery (CARER) protocol is proposed. In order to avoid broadcast storm problem, a rebroadcasting vehicle selection metric η, is developed, which is used to select a vehicle that will rebroadcast the received encoded message. Although the proposed CARER protocol demonstrates an impressive performance, the level of incurred overhead is fairly high due to the use of complex rebroadcasting vehicle selection metric. To resolve this issue, a Random Network Coding (RNC) and vehicle clustering based vehicular communication scheme with low algorithmic complexity, named Reliable and Enhanced Cooperative Cross-layer MAC (RECMAC) scheme, is proposed. The use of this clustering technique enables RECMAC to subdivide the vehicular network into small manageable, coordinated clusters which further improve transmission reliability and minimise negative impact of network overhead. Similarly, a Cluster Head (CH) selection metric $\mathcal{F}(j)$ is designed, which is used to determine and select the most suitably qualified candidate to become the CH of a particular cluster. Finally, in order to investigate the impact of available radio spectral resource, an in-depth study of the required amount of spectrum sufficient to support high transmission reliability and minimum latency requirements of critical road safety messages in vehicular networks was carried out. The performance of the proposed schemes was clearly shown with detailed theoretical analysis and was further validated with simulation experiments.

Declaration

I, Elias C. Eze, declare that this dissertation is my own unaided research. It is being submitted for Doctor of Philosophy (PhD) degree at the University of Bedfordshire, UK.

This thesis has not been submitted before for any degree or examination in any other educational establishment, except where appropriate acknowledgement (or reference) is made in the dissertation.

Name of candidate: Signature:

Date:

Dedication

This dissertation is dedicated to my lovely family.

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List of Publications

Award and Honour

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Published Journal Papers

[P.1] Eze E. C., Zhang S., Liu E., and Eze J. C., "Advances in Vehicular Ad-hoc Networks (VANETs): Challenges and Road-map for Future Development," *International Journal of Automation and Computing*, vol. 13, no. 1, pp. 1-18, 2016.

[P.2] Eze E. C., Zhang S., Liu E., Nweso E. N. and Eze J. C., "Timely and Reliable Packets Delivery Over Internet of Vehicles for Road Accidents Prevention: A Cross-Layer Approach," *IET Networks*, vol. 5, no. 5, pp. 127-135, 9 2016.

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[P.3] Eze E. C., Zhang S., Liu E., Nweso E. N. and Joy E. C., "RECMAC: Reliable and Efficient Cooperative Cross-Layer MAC Scheme for Vehicular Communication Based on Random Network Coding Technique," *in the Proceedings of 2016 22nd International Conference on Automation and Computing (ICAC)*, (Colchester, UK), 2016, pp. 342-347.

[P.4] Joy E. C., Zhang S., Liu E., Theresa E. E. and Elias E. C., "Cognitive Radio Aided Vehicular Ad-Hoc Networks with Efficient Spectrum Allocation and QoS Guarantee," *in the Proceedings of 2016 22nd International Conference on Automation and Computing (ICAC)*, (Colchester, UK), 2016, pp. 156-161.

- [P.5] Eze E. C., Zhang S. and Liu E., "Improving Reliability of Message Broadcast over Internet of Vehicles (IoVs)," *in the Proceedings of 2015 IEEE International Conference on Computer and Information Technology; Ubiquitous Computing and Communications; Dependable, Autonomic and Secure Computing; Pervasive Intelligence and Computing (CIT/IUCC/DASC/PICOM),* (Liverpool, UK), 2015, pp. 2321-2328.

- [P.6] Eze E. C., Zhang S. and Liu E., "Estimation of Collision Probability in A Saturated Vehicular Ad-Hoc Networks," *in the Proceedings of 2015 Fourth International Conference on Future Generation Communication Technology (FGCT),* (Luton, UK), 2015, pp. 1-7.

- [P.7] Eze E. C., Zhang S., Liu E., Eze J. C., and Yu H. Q., "Cognitive Radio Aided Internet of Vehicles (IoVs) for Improved Spectrum Resource Allocation," *in the Proceedings of 2015 IEEE International Conference on Computer and Information Technology; Ubiquitous Computing and Communications; Dependable, Autonomic and Secure Computing; Pervasive Intelligence and Computing (CIT/IUCC/DASC/PICOM),* (Liverpool, UK), 2015, pp. 2346-2352.

- [P.8] Eze E. C., Zhang S. and Liu E., "Message Dissemination Reliability in Vehicular Networks," *in the Proceedings of 2015 21st International Conference on Automation and Computing (ICAC),* (Glasgow, Scotland), 2015, pp. 1-6.

- [P.9] Eze E. C., Zhang S. and Liu E., "Achieving Reliable and Efficient Message Broadcast in Vehicular Networks using Network Coding Concept," *in the Proceedings of International Conference on Computing and Technology Innovation (CTI 2015),* (Luton, UK), May 27 – 28, 2015

- [P.10] Eze E. C., Zhang S. and Liu E., "Vehicular Ad Hoc Networks (VANETs): Current State, Challenges, Potentials and Way Forward," *in the Proceedings of 2014 20th International Conference on Automation and Computing (ICAC), (*Cranfield, UK), 2014, pp. 176-181.

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[P.11] Eze E. C., Zhang S. and Liu E., "Transmission Reliability Measures for Efficient Vehicular Communication through Cooperative Cross-layer MAC Scheme and Random Network Coding," *in the Proceedings of International Conference on Internet of Things (IoTs), Data and Cloud Computing (ICC'17)*, (Cambridge, UK), March 2017

[P.12] Eze E. C., Zhang S. and Liu E., "Radio Spectrum Support for Timely and Reliable Communication over Vehicular Ad-Hoc Networks (VANETS)," *in the Proceedings of International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 2017),* (Porto, Portugal), 2017.

Accepted Conference Papers (awaiting presentation and indexing)

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[P.14] Eze E. C., Zhang S., Liu E., and Eze J. "Cognitive Radio Technology Assisted Vehicular Ad-Hoc Networks (VANETs): Current Status, Challenges, and Research Trends" *peer reviewed and accepted for presentation at the 23rd IEEE International Conference on Automation & Computing*, (University of Huddersfield, Huddersfield, UK), 7-8 September 2017

Journal Papers under Review

[P.15] Eze E. C., Zhang S., Liu E., and Eze J. C., "Reliable and Efficient Cooperative Cross-layer MAC Scheme for Vehicular Communication based on Random

Network Coding and Vehicle Clustering Technique," *IEEE Transaction on Vehicular Technology* (Still under review).

[P.16] Eze E. C., Zhang S., Liu E., and Eze J. C., "Cognitive Radio-Aided Internet of Vehicles (IoVs) Paradigm: An Adaptive Cooperative Spectral Resource Sensing and Allocation for Vehicle Communication," *Digital Communications and Networks, Elsevier/Science Direct* (Still under review).

List of Acronyms

AFR	Asynchronous Fixed Repetition
AGC	Automatic Gain Control
AIFS	Arbitration Inter-Frame Spacing
AIFSN	Arbitration Inter-Frame Space Number
AP	Access Point
API	Application Programming Interface
APR	Asynchronous p-Persistent Repetition
AODV	Ad hoc On-Demand Distance Vector Routing
ARQ	Automatic Repeat reQuest
ASTM	American Society for Testing and Materials
AWGN	Additive White Gaussian Noise
BCH	Basic Channel
BEC	Backward Error Correction
BMMM	Batch Mode Multicast MAC
BMW	Broadcast Medium Window
BP	Belief propagation
BPSK	Binary Phase-Shift Keying
BSMA	Broadcast Support Multiple Access
CAM	Cooperative Awareness Message
CARER	Coding Aided Retransmission-based Error Recovery
CB	Coherence Bandwidth
CCA	Clear Channel Assessment

CCH	Control Channel
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CLTF	Cross-Layer Tree Formation
CNCDS	Compressed NC based Distributed data Storage
CPF	Cooperative Positive Orthogonal Codes (POC) based Forwarding
CRB	Conditional Reception Probability
CS	Compressed Sensing
CSI	Channel State Information
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTB	Clear To Broadcast
CTS	Clear To Send
CVSS	Cooperative Vehicle Safety System
CW	Contention Window
CWC	Constant Weight Code
DCF	Distributed coordination function
DCU	DFS Control Unit
DENM	Decentralized Environment Notification Message
DDS	Distributed Data Storage
DIFS	DCF Inter Frame Space
DoF	Degree of Freedom
DP	Data Pouring protocol
DP-BP	DP with Buffering Paradigm
DSR	Differential Successive Relay
DSRC	Dedicated Short Range Communications
EDCA	Enhanced Distributed Channel Access

ECC	Error Correcting Codes
EIRP	Effective Isotropic Radiated Power
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FI	Frame Information
GAC	German Aerospace Center
GDP	Gross Domestic Product
GI	Guard Interval
GPS	Global Positioning System
HAL	Hardware Abstract Layer
HARQ	Hybrid ARQ
HIVE	HybrId Video DissEmination protocol
IEEE	Institute of Electrical and Electronics Engineers
I2V	Infrastructure-to-Vehicle
IoTs	Internet of Things
IP	Internet Protocol
ISI	Inter Symbol Interference
ITS	Intelligent Transportation System
IVC	Inter-Vehicle Communication
LAA	Location-Aware Algorithm
LAMM	Location Aware Multicast MAC
LBP	Layered Belief Propagation
LDPC	Low-Density Parity Check
LFSR	Linear Feedback Shift Register
LLR	Log-Likelihood Ratio
MAC	Medium Access Control

MANETs	Mobile Ad Hoc Networks
MCTRP	Multi-Channel Token Ring MAC Protocol
MFL	Maximum Freedom Last
MQAM	Multiple Quadrature Amplitude Modulation
MRF	Message Reception Failure
MTM	Map Throughput Metric
NAV	Network Allocation Vector
NC	Network Coding
NTS	Nominal Transmission Slot
OBU	On Board Unit
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiplexing Access
PCD	Popular Content Distribution
PDF	Probability Density Function
PDP	Power Delay Profile
PF	Persistence Factor
PHY	Physical Layer
PLCP	PHY Layer Convergence Procedure (or Protocol)
POC	Positive Orthogonal Code
PRNG	Pseudo Random Number Generator
QAM	Quadrature Amplitude Modulation
QoE	Quality of user Experience
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RECMAC	Reliable and Efficient Cross-layer MAC scheme
RF	Radio Frequency
RGG	Random Geometric Graphs

RLNC	Random Linear Network Coding
RMS	Root Mean Square
RNC	Random Network Coding
RSU	Road Side-Unit
RTB	Request To Broadcast
RTS	Request To Send
RXNC	Random XORed Network Coding
SBP	Shuffled Belief Propagation
SCH	Service Channel
SFR	Synchronous Fixed Repetition
SI	Selection Interval
SIFS	Short Inter-Frame Space
SLNC	Symbol-Level Network Coding
SNR	Signal-to-Noise Ratio
SPCR	Synchronized p-Persistent Coded Repetition
SPR	Synchronous p-Persistent Repetition
STDMA	Synchronized Time Division Multiple Access
SUMO	Simulation of Urban MObility
TDD	Temporal Data Dissemination
TDMA	Time Division Multiple Access
TXOP(or TOs)	Transmission Opportunities
UDP	User Datagram Protocol
USDOT	United States Department of Transportation
UWSN	Under-Water Sensor Network
V2V	Vehicle to Vehicle
V2I	Vehicle to Infrastructure
V2X	Vehicle to X (X = other pedestrians multi-types hand-held devices)

VANET	Vehicular Ad Hoc Network
VC-MAC	Vehicular Cooperative MAC
WAVE	Wireless Access in Vehicular Environment
WLAN	Wireless Local Area Network
WSM	Wave Short Message
WSN	Wireless Sensor Network
XOR	Exclusive OR operation

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Chapter one

Introduction

1.1 Motivation

The United Nations announced the launch of Decade of Action (2011 – 2020) for Road Safety across the globe on 11th May 2011. According to the United Nations' report on road safety, someone is killed or maimed on the world's roads in every six seconds [168]. Similarly, according to 2010 World Bank's Global Road Safety Facility report, over 1.3 million people were estimated to have died in 2010 alone due to road traffic accidents, accounting for over 3% of all deaths world over. In other words, road accidents across the world have been adjudged as the eighth leading cause of death today [64]. Likewise, World Health Organization's Global Status Report on road safety in 2013 maintained that, if unchecked, the death toll due to road traffic accidents could surpass death rate due to HIV/AIDS by 2030 and become the fifth-leading cause of death [199]. According to UK Department for Transport's June 2015 reports, vehicle traffic levels increased by 2.4 percent between 2013 and 2014 with a total of 194,477 casualties of all severities in reported road traffic accidents during 2014 alone [161]. In a similar case, a recent report by WHO on road traffic deaths in selected African countries says Nigeria accounts for the highest fatalities with 33.7 percent per 100,000 population every year. It is estimated that the volume of traffic in Nigeria will increase from eight million at present, to 40 million by 2020 [2]. This growing death toll is the basic motivation for researchers in both academia and industry to design innovative technologies that will improve the safety on our current roads and highways of the future.

Despite the introduction of several innovative in-vehicle safety-oriented devices such as anti-locking braking system (ABS), seatbelts, airbags, rear-view cameras, electronic stability control (ESC), many road users worldwide continue to die annually from road traffic accidents [47]. Recent estimations by experts opine that there will be 25 billion connected devices by the end of this year, and 50 billion devices by 2020 [59]. Obviously, smart vehicles will constitute a significant portion of these connected 50 billion devices. This shows that unless a solution is proffered, there may be more death resulting from road traffic accidents due to increased traffic on the roads. Most of these traffic accidents are avoidable by using Intelligent Transportation Systems (ITSs), and safety vehicular communication systems. Statistics have shown that over 60 percent of chain traffic accidents could be prevented if drivers are informed about an automobile accident at least 500 milliseconds (ms) ahead of time [47]. Vehicular ad-hoc networks (VANETs), which allow smart vehicles to directly exchange both safety-related and non-safety-related information such as location, direction of movement, velocity, acceleration, and other kinematic data with each other, has been seen as a promising communication technology that could significantly reduce road traffic accidents. For instant, a suddenly decelerating mobile vehicle in a busy traffic will end up having a collision with vehicles behind, unless the decelerating vehicle transmits warning (i.e., safety) packets to all the approaching vehicles. In addition to road safety as the leading application of vehicular networks, many other areas of benefits include improvement in road traffic management which will eventually save the economy in billions of dollars, positive change of climate through reduction in: 1) carbon emissions, 2) fuel consumption, and 3) man-hours usually wasted on traffic jams. Finally, VANET will make long distance travelling a bit fun through infotainment services incorporated into vehicular networks.

In the recent years, car manufacturing industries, academia and government agencies have started putting much efforts towards realizing the concept of vehicular communications in wide scale. Some frameworks are already worked out with the first landmark of standardization processes made by US Federal Communications Communication (FCC) by allocating 75 MHz of dedicated short-range communication (DSRC) spectrum [183] basically to accommodate V2V and V2I communications for safety-related applications. Potentials (i.e., possibilities) envisaged in VANETs have led to numerous vehicular communications research with their associated standardization projects in many countries across the world. These projects include DSRC development by Vehicle Safety Communications Consortium (VSCC) [109] (USA), European automotive industry project co-funded by the European Communication Commission to improve road safety through the development and demonstration of preventive safety-related applications/technologies called PReVENT project [7, 126] (Europe), Internet ITS Consortium [88] and Advanced Safety Vehicle project [174] (Japan), Car-2-Car Communications Consortium (C2C-CC) [104], Vehicle Infrastructure Integration program (VII) [55], Secure Vehicle Communication (SeVeCOM) [97], and Network on Wheels project [1] (Germany). IEEE and ASTM adopted DSRC standard (ASTM E 2213-

03) [6] also called Wireless Access in Vehicular Environment (WAVE) in 2003 in order to provide wireless communications for vehicles at normal highway speeds within the range of 1000m.

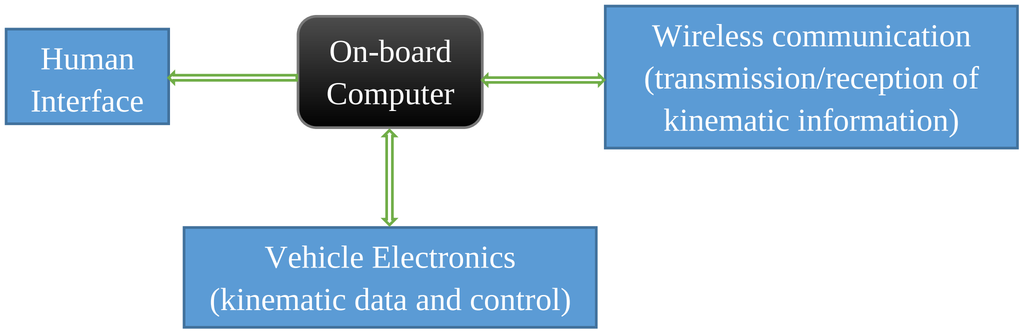


Fig. 1.1: Basic architecture of the embedded On-Board Unit (OBU) in smart vehicles

1.2 Background of Vehicular Networks

Vehicular networks are wireless communication networks empowered by DSRC technology, which is a basic enabling technology for the next generation of wireless communication-based road safety systems. VANETs are made-up of radio-equipped smart vehicles equipped with communication radios, (i.e., On-Board Units (OBUs)), wireless sensors, and road-side units (RSUs) that serve as fixed access points (APs). Fig. 1.1 shows the basic architecture of OBU with its features such as location awareness, kinematic data awareness, communication ability, collision avoidance, and human interface. The aforementioned features of the embedded OBU are discussed below:

- **Location awareness** – the embedded OBUs enable each vehicle to get its current location with the help of in-built positioning devices such as the Global Positioning System (GPS).
- **Communication ability** – the embedded OBUs enable direct exchange of the acquired location and other kinematic data in real-time with neighbouring vehicles.
- **Kinematic data awareness** – the embedded OBUs can access the kinematic information from each vehicle's electronics.
- **Collision avoidance** – by processing the acquired location and other kinematic data such as vehicle speed, direction of movement, acceleration, etc from

neighbouring vehicles, the embedded OBUs can avoid a potential road traffic accident.

- **Human interface** – when a potential road traffic accident is detected, the embedded OBUs can either visually or acoustically warn the driver to take informed actions that can prevent traffic accident.

The different types of wireless communications in vehicular networks as depicted in Fig. 1.2 can be categorized as follows:

- **Vehicle-to-Vehicle (V2V) communication** – direct wireless communication between the embedded OBUs in different vehicles without the aid of RSUs.
- **Vehicle-to-Infrastructure (V2I) communication** – wireless communication between the embedded OBUs in different vehicles and the stationary RSUs.
- **Vehicle-to-devices (V2X) communication** – direct wireless communication between vehicles and other pedestrians' consumer electronics such as handheld devices, PDAs, etc.
- **Infrastructure-to-Infrastructure (I2I) communication** – direct information exchange between different stationary RSUs.

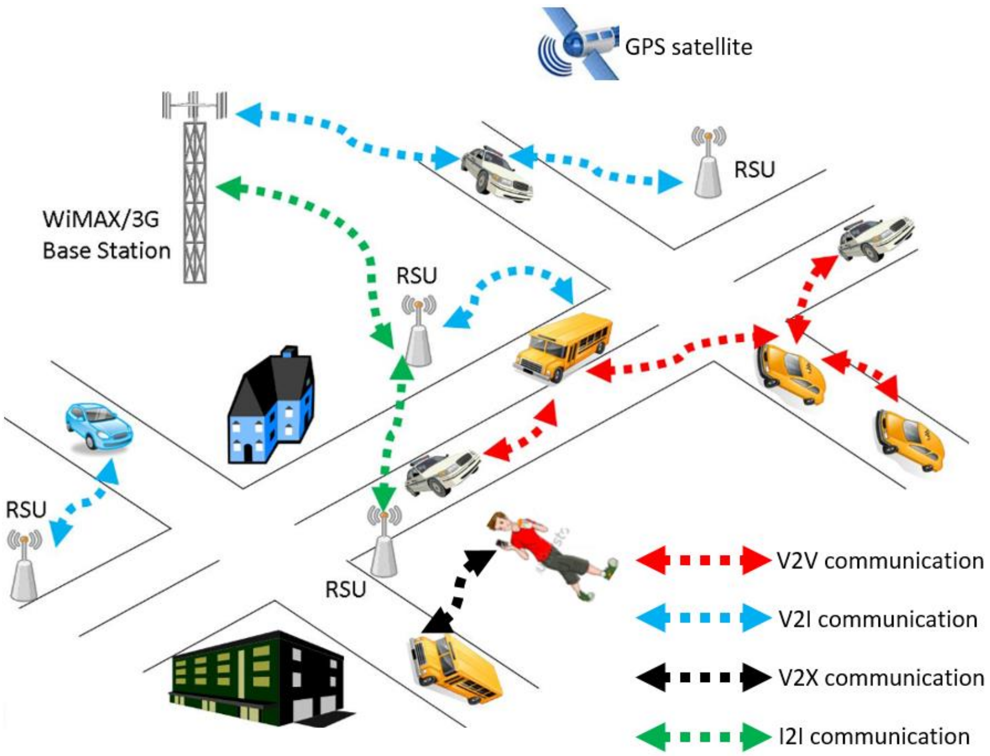


Fig. 1.2: The different categories of wireless communications in vehicular networks

Vehicular networks can be considered as a form of Mobile Ad-hoc Networks (MANETs). However, the peculiar characteristics associated with VANETs generally make the existing MANET approaches, protocols and solutions unfit for use in VANETs. Some of these peculiar properties of VANETs are listed as follows [48]:

- **High vehicular mobility**: Unlike the moderate mobility observed in MANET nodes, vehicular stations are associated with very high speeds. For instance, in urban areas, the typical speed limit for vehicles is usually between 40 kmph up to 60 kmph, and on motor highways, the typical speed limit is generally between 80 kmph up to 110 kmph.
- **Highly dynamic topology**: The high mobility of vehicles coupled with the existence of multiple road lanes of opposite directions for vehicular traffic flows leads to regular changes of vehicular network topology.
- **Non-random vehicular mobility**: The vehicular mobility is rigidly restricted to the road layout patterns, human driver behaviour, subject to traffic rules and regulations.
- **Varying network density**: During the rush hours, the vehicular traffic density becomes very high, especially on major unban roads and highways, but usually very low in rural areas, and generally low at night in cities.
- **Recurrent network fragmentation**: Low traffic density, change of lane, and irregular high mobility most times result in frequent network fragmentation in VANETs because nodes tend to move far apart from each other, thereby moving out of radio communication coverage of one another.
- **Harsh operating environment**: The high mobility of vehicles, and the existence of many buildings and trees especially in urban areas can often create extremely harsh fading and shadowing effects on the communication channels between mobile vehicles. This may worsen the already unreliable nature of wireless channels, particularly in vehicular communication environment.
- **Unconstrained energy capacity**: The embedded OBUs, the multi-sensors, and other communication electronic elements which the smart vehicles are equipped with, use the power reserve of the node's battery. Hence, unlike MANETs, energy and power constraints do not constitute a limiting design challenge in vehicular networks.

1.3 Problem Statement

In vehicular networks, road traffic safety system is solely based on real-time wireless communication between the stationary nodes (i.e., RSUs), mobile nodes (e.g., cars, buses, trains, etc), and other pedestrian's handheld devices (e.g., PDAs, smart phone, iPads) so as to detect and prevent accidents. However, the effectiveness of this road safety system heavily depends the underlying communication protocol's ability to guarantee the reliability of the exchanged communications. Guaranteeing the reliability of each transmitted safety packet must be ensured given that each safety-related packet contains some life-saving information, and the loss of such packet may possibly lead to road accident and eventual loss of life or property. However, the currently approved communication protocol (IEEE 802.11p) by IEEE working group for vehicular networks coordinates nodes access to the shared transmission medium through a distributed Medium Access Control (MAC) protocol. In other words, the lack of central controller in this protocol to coordinate data transmissions from many vehicles makes VANETs transmissions collision-prone. As a result, incessant transmission collisions make error-free packets reception extremely difficult. The probability of transmission collision increases drastically as the number of vehicles contending for the wireless channel access increases. Hence, in road safety communication systems, where each vehicle is required to periodically broadcast its status (i.e., safety beacon messages) at least once in every 100ms [48], rampant transmission collisions can possibly result in total communication collapse [183, 114]. Obviously, increased transmission collisions due to absence of central controller reduce the reliability of vehicular networks, especially during rush hours when vehicular traffic safety is of greatest concern.

Although conventional wireless communication applications usually suffer poor quality of service (QoS) due to interference, variations due to node mobility, channel noise, and packet collision worsens the vehicular network QoS and may lead to loss of safety packets which can be the difference between life and death. Thus, to improve reliability of transmitting safety packets in vehicular networks, a formidable error recovery technique capable of recovering lost packets especially for safety communications must be designed and implemented.

1.3.1 Error Recovery Technique for Vehicular Networks

Generally, the conventional mechanism, often used for error recovery in traditional data communication networks when a packet is lost (or damaged), is for the sender to retransmit the original data after receiving a negative acknowledgment (NACK) frame from the receiver. Reliable communication based on repeat of the original transmission when the receiver explicitly conveys the status of packets reception to the sender is known as Automatic Repeat reQuest (ARQ) [103]. In typical wireless networks, the ARQ approach has proved very effective in guaranteeing transmission reliability of one-to-one unicast communication between nodes and APs. Although traditional wireless networks are known to use one-to-many, broadcast communication technique, guaranteeing reliable or timely delivery of such transmission is not imperative since it is only required for best-effort delivery such as address resolution. However, unlike conventional wireless networks, effective road safety in VANETs with high reliability requirement depends on each mobile node transmitting their status periodically to all neighbouring vehicles within their one-hop transmission range, which results in one-to-many, broadcast communication. In such one-to-many, broadcast communication scenario, guarantee of transmission reliability is required at all the receivers within one-hop coverage. Therefore, adopting ARQ technique to ensure transmission reliability in vehicular networks becomes significantly unfeasible due to three reasons, namely: 1) The source vehicle may not know the exact number of recipient vehicles so as to know the number of acknowledgments (ACKs) to expect; 2) even when the number of neighbouring vehicles within one-hop range is known (like in a cluster scenario), sending multiple ACKs from more than one receiver at the same time will eventually lead to collision; and 3) ACKs from many receivers can lead to excessive channel congestion especially during rush hours with high traffic density, thereby creating overwhelming overhead capable of worsening the network QoS, which is very necessary for timely delivery of life-saving, time-sensitive safety messages. Thus, for efficient traffic safety in VANETs, the challenge of emergency message broadcast reliability is still an unresolved problem both in academia and industry.

Although forward error correction (FEC) mechanism [175, 19] has been successfully used to improve transmission reliability in wireless networks (even in broadcast scenarios), due to the fact that unlike ARQ technique which uses retransmissions to ensure reliability, FEC appears attractive since it does not incur extra communication load. However, several studies have shown that FEC cannot work effectively in vehicular networks especially for transmission reliability requirement or timely safety message delivery guarantee, simply because FEC is not applicable in vehicular communication environments as is already established by several studies [43, 203-204]. Unlike FEC that works with readily awaiting streams of packets to improve transmission reliability by adding redundant data to the transmission, in VANETs each vehicle regularly creates status packet(s) periodically or automatically in the face of emergency and broadcasts to other neighbouring vehicles within one-hop communication range.

Since the classical error recovery mechanisms such as ARQ and FEC have been seen to be unfit for use in guaranteeing message broadcast reliability through error recovery in harsh vehicular communication environments, it is expedient to devise other feasible ways of ensuring high broadcast reliability of safety packets in VANETs. Some researchers have proposed a repetition-based error recovery protocols for vehicular networks to ensure transmission reliability of safety (or emergency) messages [207-208, 201]. Some other results have also been published on retransmission-based error recovery mechanisms [52, 209] for VANETs. Unlike error recovery via ARQ mechanism, these proposed retransmission protocols enable proactive retransmission of original packets without requiring acknowledgments from the receivers, thereby reducing the chances of collision from multiple ACKs been sent to the sender at the same time. The key aim of repetition-based error recovery technique is to allow each node[1] to repeat the transmission of its original packet(s) within the timeout period thereby giving the nodes within their transmission range multiple chances of receiving the packets not correctly received, damaged or lost at the receivers. Since retransmission increases network overhead and after a given number of consecutive repeats may lead to excessive channel congestion thereby resulting in further degradation of QoS, further novel refinements and improvements are needed to overcome the challenge of increasing network overhead due to increased number of broadcast retransmissions associated with retransmission-based error recovery schemes especially in high density vehicular networks during rush hours. Consequently, the need for novel approaches and techniques that will guarantee improved road traffic data packet broadcast efficiency, high transmission reliability with minimum tolerable (or acceptable) delay so as to meet the transmission deadline, in the case of safety

[1] Nodes, stations, and vehicles are used interchangeably in this write-up.

related packets transmission in vehicular safety communication. These and many more challenges are extensively studied in Chapters 3, 4, and 5 of this thesis.

1.3.2 Radio Spectrum Enhancement for Reliable Inter-Vehicle Communication

Recent research on the analysis of WAVE-based Inter-vehicle communication system has identified its reliability and scalability challenges especially in high density vehicular networks [38, 106, 104]. One of the possible explanations responsible for these reliability and scalability issues is inadequate and insufficient allocation of spectrum for vehicular communication systems. The FCC of US has allocated 75MHz bandwidth to WAVE-based ITS services within the 5.850GHz – 5.925GHz band (see Fig. 1.3) where only 10MHz radio spectrum is dedicated to road safety vehicular communication system. In Europe, just like in US, a similar trend is repeated where radio spectrum of 10MHz control channel (CCH) is allocated for the transmission of life-saving safety messages out of the 30MHz bandwidth available in the allotted 5.875GHz – 5.905GHz band for vehicular communication systems [167]. Unfortunately, there are no well-established literatures yet on this issue to ascertain whether this allocated 10MHz bandwidth would be sufficient for the transmission of life-saving safety-related packets in CCH except a maiden study conducted by CEPT [35]. Hence, carrying out an in-depth study of the required amount of radio spectrum sufficient to guarantee reliable and minimum latency requirement of critical road safety messages is highly imperative.

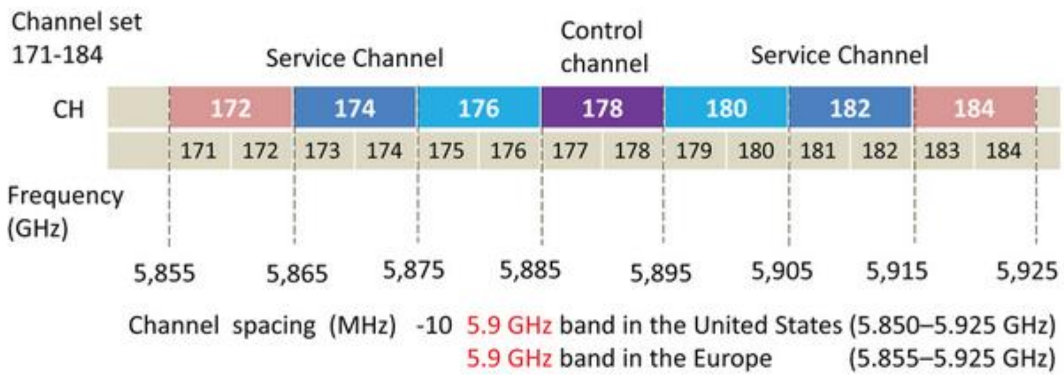


Fig. 1.3: The channels (i.e., one CCH and six service channels (SCHs)) available for IEEE 802.11p radio communication [167]

1.4 Contributions of the Research

The aim of this research is to study how reliable and efficient vehicular communication systems can be achieved in VANETs; and hence, establish theoretical framework for future development and deployment of effective road traffic safety communication systems for our increasingly overcrowded motorways. In order to achieve this aim, this thesis documents three key original contributions as shown below.

1.4.1 Improved Broadcast Reliability through Network Coding (NC)

Chapter 3 of this thesis applied the concept of NC [3], and offered original analysis to explain how its fundamental innovations can improve packet retransmission mechanism to ensure high reliability through lost data recovery in vehicular networks for effective road traffic safety systems. Furthermore, the possibility of reducing the number of broadcast retransmissions while increasing the content and efficiency of each retransmission by introducing smart NC of multiple original packets before transmission is studied. With the analysis, the study in Chapter 3 demonstrates that NC can improve broadcast reliability with less number of retransmissions by ensuring that more lost safety packets are recovered with a single retransmission of the enriched packet content.

Likewise, as opposed to the existing solutions on improving broadcast reliability of VANETs through NC and retransmission-based error recovery schemes, the proposed Code-Aided Retransmission-based Error Recovery (CARER) scheme requires the receivers to reply with acknowledgement frame so that the sender will have knowledge of the broadcast transmission's reception status. However, unlike the existing solutions, where acknowledgement is expected from all the receivers, which leads to transmission collision and increased overhead due to increased contention and channel load (i.e., many ACK packets) among the vehicle, a rebroadcasting vehicle selection metric η is designed to determine and select the most suitably qualified vehicle to rebroadcast the encoded packets to enable the vehicles outside the radio range of the source node to receive the encoded packets. Only the selected vehicle is required to send acknowledgement to the sender on behalf of the other receivers within one-hop range before rebroadcasting the received encoded packet to widen the penetration coverage of the message. Since ACK is sent from only one vehicle, the case of high rate of transmission collision and the increased overhead become completely resolved and eliminated. Finally, the efficient retransmission achieved through the proposed CARER scheme improves the recovery performance of lost packets through NC in two ways 1) less bandwidth consumption due to the reduced number of retransmissions, and 2) improved QoS due to reduced retransmission overhead and low rate of transmission collision. The theoretical results were validated through extensive simulation experiments.

1.4.2 Reliable and Enhanced Cooperative Cross-layer MAC Scheme for Vehicular Communication based on Random Network Coding (RNC)

In order to guarantee high broadcast reliability and to maintain maximum achievable network throughput with low overhead and low algorithmic complexity due to the use of rebroadcasting metric η in CARER scheme (as contained in Chapter 3), a novel cluster based vehicular communication scheme, named Reliable and Enhanced cooperative Cross-layer MAC (RECMAC), is proposed in Chapter 4 for vehicular communication based on RNC technique aiming to further improve the encoded message broadcast transmission reliability. RECMAC scheme is the product of combining RNC, vehicle clustering technique and cooperative communication with the aim to further improve the bandwidth efficiency, maximize the achievable network throughput, enhance transmission reliability, and minimize the network overhead. Specifically, a vehicle clustering technique is applied in the RECMAC scheme to segment the whole vehicular network into separate manageable groups (or sub-networks) primarily for boosting the overall network performance. In order to ensure effective node clustering, an efficient vehicular cluster formation algorithm is designed, which uses the Euclidean distance to segment the network into smaller manageable groups of vehicles (i.e. clusters) to achieve high reliability with very low overhead. The algorithm allows only vehicles moving in the same direction to group together so as to ensure durability and stability in the life cycle of the vehicular clusters. A dynamic Cluster Head (CH) selection metric $\mathcal{F}(j)$, which is used to determine and select the most suitably qualified candidate to become the CH is also designed. In order to maintain low communication overhead and low rate of packet collision, the successfully selected CH is responsible for inter-cluster communication to avoid the problem of broadcast storm due to more than one vehicle communicating between different clusters at the same time.

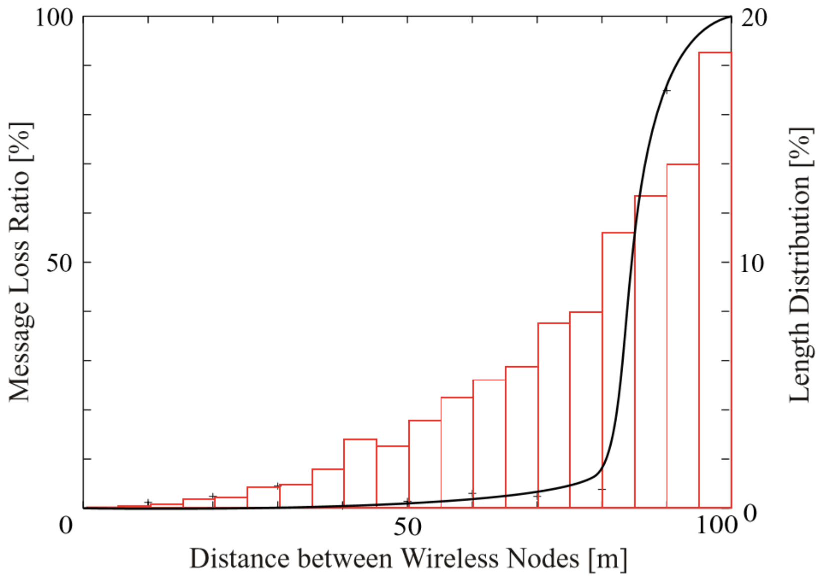


Fig. 1.4: Message loss rate as a function of length distribution of wireless communication links

1.4.3 Investigation of Radio Spectrum Requirement for Reliable Inter-Vehicle Communication

Furthermore, an in-depth study of the required amount of radio spectral resource sufficient to guarantee high transmission reliability and minimum latency requirements of critical road safety messages in vehicular networks is carried out in Chapter 5 of this thesis. Thus, a feasibility analysis of radio spectrum requirement for scalable and reliable vehicular safety communication is carried out. In the feasibility analysis, the synchronized STDMA MAC protocol is compared with the DSRC/WAVE and European standard ITS-G5, which are based on IEEE 802.11p specification generally known for its unbounded media access delay and best-effort quality, as well as scalability and reliability issues. Additionally, two different types of access protocols, namely STDMA and CSMA/CA based MAC schemes were implemented so as to effectively provide balanced assessment of the minimum spectrum requirement necessary for reliable road safety vehicular communication with a guaranteed acceptable minimum latency. Finally, in order to investigate the impact of available radio spectral resource on the transmission reliability and its associated MAC-to-MAC delay of safety packet transmission, the channel bandwidth of the CCH is varied from 10MHz up to 40MHz.

1.5 Research Method and Methodology

The proposed schemes and a range of components were designed and their simulation experiments carried out in MATLAB® software. MATLAB® software offers an excellent interactive environments and fast mathematical algorithms. It supports efficient matrix handling, plotting of functions and data, and easy algorithm implementations.

1.5.1 Choice of Simulation Software

In this research, MATLAB® (a generic software) is used for simulation experiments as opposed to domain-specific software such as VanetMobiSim, OPNET Modeller, TraNS, FreeSim, GrooveNet, and NCTUns software due to the following benefits.

i. MATLAB® offers a development environment with high-performance numerical computation, development tools, data analysis, and visualisation capabilities.
ii. In MATLAB®, statements are written and calculated instantly so they are tested as you go.
iii. MATLAB® allows instant access to thousands of written fundamental and speciality functions by experts in addition to the special functions developed by yourself as well as your research colleagues.
iv. The in-built GUI builder and graphing tools available in MATLAB® allow one to customise one's data and models so as to be able to easily interpret data for the purpose of quicker decision-making.

1.6 Thesis Organization

The remaining part of the thesis is arranged as follows: Chapter 2 contains a detailed literature review and a background overview on vehicular communication networks and the NC concept. Chapter 3 dwells on novel approaches of guaranteeing vehicular communication broadcast reliability through network coding. A network code aided solution was proposed, and the overall performance was further evaluated through a detailed analytical study of the proposed CARER protocol. Chapter 4 discusses other possible ways of achieving broadcast reliability over vehicular networks through random network coding and a cross-layer MAC scheme. In this chapter, a vehicle clustering based vehicular communication scheme, named RECMAC scheme, is proposed and evaluated through analytical study and extensive simulation experiments. Chapter 5 investigates the radio spectrum required for timely and reliable vehicular safety communication. The chapter further focusses on feasibility analysis of radio spectrum requirement for scalable and reliable vehicular safety communication. In the feasibility analysis, the synchronized STDMA MAC protocol is compared with the DSRC/WAVE, which is based on IEEE 802.11p specification. Chapter 6 draws the conclusions from this dissertation and explores the possible directions to extend the work presented in this thesis in future research.

Chapter Two

Literature Review*

2.1 Error Recovery through Classical Approaches

Recently, wireless mobile networks consisting of mobile vehicles with wireless communication technologies are currently been researched widely using a new refined protocol stack called IEEE 802.11p from the legacy wireless local area network (WLAN) protocols like IEEE 802.11a [195]. Table 2.1 shows the technical difference between the approved amended IEEE 802.11p and the legacy IEEE 802.11 family. Generally, wireless communication links between neighbouring mobile stations are less reliable as opposed to wired communication links. In other words, the loss rate of transmitted data messages through wireless communication links is usually higher than wired communication links. With wireless communication links, the loss rate largely depends on: 1) the distance between the senders and the receivers, 2) the noise effect in the communication environments, and 3) the rate of collisions with the other data transmissions [177]. In order to guarantee low packet loss rate (i.e., improve transmission reliability) and achieve higher end-to-end network throughput of data messages in such communication environments, various error recovery techniques have been widely adopted.

The two classical approaches widely used for error recovery in error-prone, unreliable communication channels to remedy packet loss during transmission are ARQ and FEC. In this section, these two classical methods are reviewed with their merits and demerits briefly highlighted. Particularly, the qualities that render both ARQ and FEC techniques unfit for error recovery in vehicular networks especially for road traffic safety communication systems during rush hours are also discussed.

2.1.1 Error Recovery through ARQ Technique

ARQ [175, 122], also sometimes referred to as backward error correction (BEC) [107], is an error control technique for data transmission, which uses error detection codes, acknowledgment and/or negative acknowledgment frames as well as pre-set time-

*Part of this chapter has been peer reviewed and published in [P.1] and [P.10] as shown in list of publications.

Table 2.1: Basic PHY Parameters of IEEE802.11p and IEEE802.11a [79, 219, 214].

Parameters	**IEEE 802.11a**	**IEEE 802.11p**
OFDM symbol duration	$4\mu s$	$8\mu s$
Modulation	BPSK, QPSK, 16 QAM, 64 QAM	BPSK, QPSK, 16 QAM, 64 QAM
FFT period	$3.2\mu s$	$6.4\mu s$
Guard time	$0.6\mu s$	$1.6\mu s$
Subcarrier frequency spacing	0.3125MHz	0.15625MHz
Preamble duration	$16\mu s$	$32\mu s$
Coding rate	$1/2, 1/3, 3/4$	$1/2, 1/3, 3/4$
Data rates (Mbps)	6, 9, 12, 18, 24, 37, 48, and 54	3, 4.5, 6, 9, 12, 18, 24, and 27
Number of subcarriers	52 (i.e., 48+4)	52 (i.e., 48+4)

outs to ensure transmission reliability. An *acknowledgment (ACK)* is a short message sent by a receiver to inform the sender that transmitted data frame has been correctly received. Usually, when the sender does not receive the ACK message before the timeout elapses, it assumes that the transmission is not successful and retransmits the data frame until it either receives an ACK message from the receivers to show that the transmission has been correctly received or the error persists beyond a pre-set number of retransmissions. In other words, the data frame will be retransmitted when the sender detects reception failure at the receiver by either receiving a negative ACK (NACK) from the receiver or not receiving an ACK within the pre-set timeout period.

The ARQ method has been widely applied in the design of communication protocol to improve the reliability of one-to-one, unicast communications like the Transport Control Protocol (TCP) [25, 11, 113], wireless ad-hoc networks [206, 36, 30, 188, 110, 205], and the legacy IEEE 802.11 WLAN MAC protocol [189, 76, 14]. Conversely, in the case of one-to-many (i.e., multicast and broadcast) communication environments, an attempt to ensure transmission reliability by sending the reception status from all the receivers to the transmitter by way of NACKs or ACKs leads to poor QoS due to drastic increase in communication overhead [16, 41]. Particularly, the adverse effect of the use of ACKs and NACKs on broadcast oriented wireless networks with shared medium to guarantee transmission reliability usually result in unhealthy medium contention and high rate of packet collisions [48, 197, 126, 225, 88, 147].

Several studies have been carried out and many solutions for minimizing the number of receivers sending ACKs or NACKs to the sender have been proposed to overcome the aforementioned reliability issues bothering on one-to-many, broadcast communication scenarios. One of the existing solutions is to choose only one node (i.e., a leader) from amongst the receivers to send the transmission reception status to the transmitter using ACKs or NACKs [88, 147, 66, 100, 20]. Consequently, this approach avoids multiple transmissions of ACKs and NACKs messages from all the receivers thereby significantly minimizing the number of unhealthy contention for shared medium access as well as the resultant packet collisions due to indiscriminate transmissions from many nodes at the same time. Other studies conducted by both Jun Peng [153] and Liang *et al.* [120] proposed a different approach where each receiver is assigned a time-slot so that each of them only sends their ACK or NACK frame in their own assigned time-slots. Although these existing approaches and proposed solutions have shown an improved transmission reliability especially in broadcast oriented WLANs and MANETs, none of them has taken into consideration the peculiar characteristics of vehicular networks, which makes the existing ARQ schemes for conventional wireless networks unfit for effective road traffic safety applications in VANETs.

2.1.2 Forward Error Correction Mechanism

Contrary to the ARQ scheme, which uses data transmission reception status awareness to overcome data loss or data errors through message retransmission, the FEC approach improves transmission reliability through the use of data redundancy. FEC or channel coding [175, 18] is a technique used for controlling data errors in packet transmission over unreliable (error-prone) or noisy communication channels. This techn-

Table 2.2: Access Class Parameters for IEEE802.11p CCH

AC No.	Access Class	CWmin	CWmax	AIFSN
0	Background Traffic (BK)	15	1023	9
1	Best Effort (BE)	7	15	6
2	Voice (VO)	3	7	3
3	Video (VI)	3	7	2

ique allows for error recovery by transmitting redundant data alongside the original data. The receivers use the redundant data to correct and recover any detected data error without any need for original data retransmission. FEC enables the receivers to recover from errors due to data loss (or corrupt packets) without the need for a reverse channel to request retransmission of the original data, though at the cost of higher forward channel bandwidth. Usually, FEC is most suitable in situations where retransmissions are either costly or impossible, such as data transmission to multiple receivers in a multicast communication scenario, and one-way communication links. Typically, the size of the redundant data, which the transmitter encodes by the use of an error-correcting codes (ECC) [109, 228] such as turbo code [192] and Reed-Solomon code [139], is usually small compared to the original data.

The use of FEC technique has been widely adopted for error correction in various wireless networks such as in the PHY layer of vehicular networks. For instance, in the recently amended IEEE 802.11p standard [105] for WAVE [202, 190], the convolutional FEC coding [156, 4, 229] is adopted for bit error correction during the processing of the received signals. Although convolutional coding has been widely applied for bit error correction due to channel noise and fading in wireless communications, its use can only correct a certain amount of errors as opposed to high rate of packet losses associated with many one-to-many, broadcast communication scenarios in vehicular networks as a result of transmission collisions [183, 15, 186, 92, 215, 42]. It is noteworthy to mention that this high percentage of packet losses as a result of transmission collisions is partly due to the fact that the default MAC protocol for channel access in IEEE 802.11p standard is equivalent to the Enhanced Distribution Coordination Function (EDCF) IEEE 802.11e [78]. EDCF IEEE 802.11e has four categories of Access Classes (ACs) [42]. Table 2.2

shows the four categories of ACs and the service contention parameters of the IEEE 802.11p standard CCH where each AC maintains a different Arbitration Inter-Frame Space Number (AIFSN) to ensure that high priority class has less waiting time for channel utilization. This channel access method uses a random-access scheme based on carrier sense multiple access with collision avoidance (CSMA/CA) mechanism. The CSMA/CA mechanism is known to perform best in a one-to-one, unicast communication environment as opposed to vehicular communication which uses broadcast communication [48, 42]. In a typical broadcast communication environment, when transmission collision occurs, a continuous chunk of bits is corrupted as a result of timely-overlapping of two signals. Consequently, it will be nearly impossible to correct the errors through FEC technique since FEC is usually ineffective in recovery of data losses that are not evenly dispersed [14, 140, 5, 150]. Thus, packet losses due to transmission collisions at the MAC layer cannot be corrected by the bit-level FEC approach in the PHY layer.

In order to overcome the short-comings of bit-level FEC, packet-level FEC has been studied by researchers [202, 190, 164, 218, 26, 74, 121, 149]. With the packet-level FEC technique, redundant packets are added to a stream of original data in contrast to bit-level FEC where redundant bits are added to the original data as is exemplified with the use of convolutional coding in the PHY layer of IEEE 802.11p standard. Furthermore, studies have shown that packet-level FEC is more effective in communication scenarios where streams of data are readily available to be transmitted [164, 218] like in the case of file transfer or multi-media streaming. On the contrary, in vehicular communication, especially in road traffic safety communication, there are usually no readily available stream of data awaiting transmission since every emergence messages are time-constrained and delay-sensitive. Similarly, each vehicle periodically generates status messages (or beacons) at least every 500 ms or automatically in the face of emergency [43]. These messages contain the vehicle's current location and kinematics data, for onward broadcasting to other vehicles within their vicinity. The content of these periodic packets becomes obsolete once new status packets are generated since the location and other kinematics information of the vehicle must have changed, thereby making it unnecessary to accumulate stream of packets in vehicular networks. Thus, neither bit-level FEC nor packet-level FEC can be effectively applied in road traffic safety communication in vehicular networks.

2.1.3 Hybrid ARQ Technique

Hybrid ARQ (HARQ) is the combination of high-rate FEC and ARQ error-control methods. In traditional FEC method, the transmitter adds redundant information to the original data before transmission using an error-detecting code (EDC) like Cyclic Redundancy Check (CRC) as oppose to traditional ARQ method, which is packet retransmission-based. On the other hand, the HARQ technique involves the encoding of the original data with a FEC code, and immediate transmission of the parity bits alongside the message or transmitted when requested by a receiver upon detecting an erroneous message. When a code that can perform both FEC in addition to error detection such as a Reed-Solomon code [139] is used, the EDC is usually omitted. Generally, in the HARQ method, an expected sub-set of all data losses that may occur can be corrected using the FEC code, while the ARQ technique will be used as a fall-back to correct data losses that could not be corrected using only the redundant bits added to the initial transmission.

Several studies have proposed the HARQ approach for efficient error recovery in wireless communication [37, 221, 27, 95, 34, 168, 191] through the use of both FEC and ARQ method in a hybrid manner. Firstly, FEC is used as the default data error recovery mechanism. Secondly, ARQ method will be applied, so that a NACK frame will be sent by the receiver to request a retransmission of the original data from the transmitter if the error bits/packets cannot be corrected by the ECC. Consequently, HARQ out-performs both ordinary ARQ and FEC especially in poor signal conditions, but this comes at the cost of significantly lower network throughput than ordinary ARQ or FEC in good signal conditions. Notwithstanding, the hybrid error recovery approach (i.e., the HARQ technique) can only be feasible if: 1) the original data is transmitted in a stream to enable the transmitter to add redundancy through ECC so that FEC can work, and 2) the receivers can send NACK packets to the transmitter when ECC cannot correct the detected errors, so that ARQ method can work. However, none of the above stated conditions is true in road traffic safety communication in vehicular networks. Thus, the above discussion has made it abundantly clear that classical error recovery approaches cannot be effectively feasible in vehicular communication environments especially for road traffic safety communication.

2.2 Overview of Network Coding (NC) Concept for Error Recovery

In traditional wireless networks, data packets are transmitted through store-and-forward mechanisms where the intermediate stations (such as routers or relays) forward an exact copy of the received original data packets. However, NC enables a network node to combine several self-generated or received packets into one or several outgoing packets. The original study carried out by Ahlswede *et al*. [3] clearly demonstrated how the utility of NC can be applied for multicast in wireline networks. Originally, NC is a concept designed to enable routers to intelligently mix different packets from different sources in order to increase the information content of each transmission as well as increase the overall network throughput. Recently, NC has received significant research attention as a tool for improving network capacity as well as coping with unreliable wireless links [128, 194]. Similarly, other interesting studies have also suggested that NC can actually improve transmission reliability through error recovery in wireless networks [61, 60]. As a matter of fact, the broadcast and error-prone nature of wireless links make wireless networks a natural setting for NC. Unfortunately, in spite of several significant research that have been carried out on the capacity gain of NC, the reliability gain of NC is still largely unknown. In this section, some relevant related literature on NC techniques and existing proposed NC based error recovery schemes are reviewed.

It is noteworthy to mention that the original work on NC by Ahlswede *et al*. [3] was followed by the theoretic study on linear NC (LNC) carried out by Li *et al*. [119] to show that LNC can be used to guarantee maximum capacity bound of wireless multicast communications. With LNC, each router combines (or encodes) n independent number of different packets into one packet (i.e., a linear combination of n independent packets) to improve the bandwidth efficiency of wireless links. Each station that receives the n linear combinations will be able to decode the mixed n number of different packets. Furthermore, the LNC was extended to random NC (RNC) to enable each station to select the coefficients of the linear combinations randomly in a non-centralised manner [72, 71, 180, 12, 22, 220]. Several other studies have applied RNC to achieve efficient broadcast flooding in wireless networks [56, 10, 138].

In other related studies, Katti *et al*. [98, 97] proposed a different NC approach called opportunistic coding. With opportunistic coding, each relaying node leverages on the shared nature of wireless medium to acquire the knowledge of "*what the neighbouring* *nodes have and what they want*". Using the acquired knowledge, the relaying node decides which group of packets to encode through exclusive OR (XOR). The receiver of the end result of the XOR operation (i.e., the coded packet) will be able to decode the coded packet if it has at least $(n-1)$ of the n different packets. Furthermore, the XOR based NC has been studied under different wireless communication settings such as one-hop and multi-hop unicast communications [39, 55, 118, 62, 157, 176, 115, 144-145], and one-hop and multi-hop broadcast communications [10, 123, 127, 163].

One of the advantages of XOR based NC over LNC is that each receiver of the coded packet can decode it immediately without having to wait for another $(n-1)$ linear combinations, which results in low latency [117]. Particularly, this feature of low latency in XOR based NC is highly required in road traffic safety applications of vehicular networks given the critical time-sensitive nature and low delay requirements of the safety communications.

2.2.1 Network Coding Enabled Error Correction Based on Reception Status Information

Several studies have proposed NC enabled error recovery solutions for a conventional wireless communication scenario, where APs coordinate and communicate with many nodes [144, 127, 102, 162, 49, 159]. Fortunately, these error recovery schemes show improved performance in terms of error recovery with the help of transmission reception status compared to the conventional ARQ method. In other words, with NC, the total number of retransmissions required to achieve correction of all errors are significantly reduced (up to 47%) due to the increased content of each transmission as opposed to conventional approaches [49].

Some researchers have studied how to ensure that lost broadcast packets are recovered from APs to their clients with reduced number of packet retransmissions [144, 145, 127, 49]. The error correction is based on the assumption that each AP always gets the knowledge of each node's reception status of the broadcasted packets from the feedbacks received from the receivers (i.e., the destination nodes) such as ACK or NACK frames. Using the reception status awareness, the AP knows which set of packets to retransmit from the virtually maintained buffer, which contains stream of packets to be broadcast. The intuition behind the proposed schemes in [144, 145, 127, 49] is based on the reception status received by AP from the clients (i.e., the knowledge of "which node received what"). As a result, each AP draws two important inferences from the reception status information, namely: 1) each AP is able to ascertain the set of corrupted (or lost) packets that require retransmission, and 2) each AP becomes aware of the set of packets to encode via XOR operation to enable the receivers to easily decode them after retransmission. Although the results of these proposed schemes demonstrated that they improved error recovery with reduced number of packet retransmissions, the schemes rely on the broadcasted packets reception status (i.e., feedbacks) from the clients through ACK/NACK frames, and are only applicable to communication scenarios where streams of packets in a virtual buffer are maintained. Thus, the proposed solutions cannot be efficient in vehicular networks, especially in road traffic safety applications, which are known to be dependent on critical delay and time-sensitive messages generated periodically, or automatically in the face of emergency (i.e., road accidents or situations that may lead to an eventual vehicle crash) and broadcasted to other neighbouring vehicles within one-hop communication range to enable the driver to take proactive actions to avert such incidents.

Similarly, in their study, Kuo *et al*. [112] investigated unicast session from the AP to each client with the aim of reducing the number of required retransmissions to recover lost packet. The proposed solution only encodes known lost packets selected from different sessions into a single packet retransmission, which also leads to reduction of signalling overhead. Through Bayesian-learning method, the APs use each received ACK or NACK frame from the client to estimate the probability that a given client has some self-generated packets. Finally, the APs use the estimated probabilities to efficiently choose the right set of packets to encode for a particular client, thereby increasing the chances of decoding the retransmitted coded packets at the receiver. The results of their simulation experiments show that the proposed NC scheme outperforms a similar proposed solution by Rozner *et al*. [162], which explicitly depends on reception status reports received from the clients.

In summary, the above reviewed existing/proposed NC schemes have shown clearly that NC is a promising concept that will efficiently improve data error recovery schemes based on packets reception status awareness. Notwithstanding, none of these existing proposals can effectively be adopted in vehicular networks for the purpose of guaranteeing packets broadcast reliability. The fact that they are dependent on the receivers' reception status report through ACK or NACK frame transmissions already renders all of them unfit for road traffic safety communications because of the broadcast nature of vehicular communication networks. In order words, the use of ACK/NACK messages to achieve transmission reliability in a one-to-many, broadcast communication scenarios like vehicular networks is known to result in high rate of transmission collision, overwhelming network overhead, and QoS deterioration. On the other hand, successful application of the NC technique for efficient error correction and recovery in vehicular networks, especially for reliable road traffic safety communications, entails that coded packets broadcast reliability must not be dependent on the receivers' reception status awareness, unless there is a way of estimating the receivers' reception status information without relying on ACK/NACK messages.

2.2.2 Network Coding Enabled Error Correction with no Reception Status Information

Several studies have also been carried out on NC enabled error recovery, which are not based on packet reception status information from the receivers through the exchange of ACK or NACK short messages [134, 212, 65, 211, 105]. Most of the loss recovery solutions proposed in these studies adopted LNC and the results from their simulation experiments demonstrated that their proposals outperform the traditional FEC technique in terms of the percentage of successful packet delivery rate. Guo *et al* [65] proposed an efficient error recovery scheme based on NC to guarantee reliability of one-to-one unicast communication in an under-water sensor networks (UWSNs), where the packet transmission (i.e., communication) starts from the source to a sink node. Between the source and the sink node, there are multiple paths through which packets are forwarded via multi-hop transmission using the intermediate nodes along the multiple paths to the sink node. Prior to packets transmission, stream of K individual packets are encoded into coded packets through the LNC technique by the use of a K dimensional vector. Each of the intermediate nodes (which are randomly distributed along the multiple paths between the source node and the sink node) also uses a K dimensional vector to encode the received packets. Finally, when the K coded packets reach the sink node through the multi-paths of the intermediate nodes, the sink node gets the original packets by decoding the received

K coded packets. Although both the theoretical and simulation results of the proposed NC based error recovery scheme in [65] demonstrate the efficiency of the proposed scheme in UWSNs, its efficiency in vehicular network environment may not be feasible due to the special characteristics associated with VANETs as opposed to wireless sensor networks (WSNs), even though both of them are forms of wireless ad-hoc networks. This can also be attributed to the fact that streamed packets are required to be encoded and transmitted through multi-hop (i.e., multi-paths) unicast communication using the intermediate nodes to reach the sink node as opposed to road traffic safety communications, which is based on one-hop broadcast communication with no requirement for availability of streamed packets.

Similarly, Yang *et al*. [212] combined the compressed sensing (CS) with the NC theories to solve the challenge of power consumption, which is one of the most critical factors that adversely affect the life-time of WSNs, through the use of NC based CS recovery mean squared error reduction without reception. A Compressed NC based Distributed Data Storage (CNCDS) scheme is proposed to achieve energy efficiency of distributed data storage (DDS) in WSNs by taking advantage of the correlation of sensor readings. The key aim of the study is to improve energy efficiency by careful reduction of the total number of transmissions N_{ttot} and receptions N_{rtot} during the dissemination process of the sensor readings (i.e., the sensed data) from the CS and NC technique, which guarantees good CS recovery performance as well as the reduction of the CS recovery mean squared error. The authors theoretically verified the efficiency of the proposed CNCDS scheme by deriving the expressions for N_{ttot} and N_{rtot} based on the random geometric graphs (RGG) theory [212]. Furthermore, the authors also proposed an adaptive CNCDS scheme based on the derived expressions in order to further reduce the total number of transmissions N_{ttot} and receptions N_{rtot}. Although the Simulation results actually show that the proposed CNCDS and the adaptive CNCDS schemes significantly reduced the total number of transmission N_{ttot}, receptions N_{rtot}, and the CS recovery mean squared error by up to 55%, 74%, and 76%, respectively, it has been shown that none of the WSN schemes can be effectively adopted for application in road traffic safety communications due to the special features of VANETs as opposed to other conventional WSNs.

In a closely related work based on the use of a backbone connection and the NC approach, Wu *et al*. [199] designed an efficient data dissemination scheme for vehicular networks in order to overcome the challenging issue of broadcast reliability in VANETs, which is usually as a result of high vehicle mobility, lossy features of wireless communication, and limited wireless resources associated with vehicular networks. In their work, a protocol is proposed which employs backbone vehicles to disseminate broadcast messages in vehicular networks. The backbone vehicles are autonomously selected with the aid of a "*hello message*" exchange between the neighbouring nodes by taking into account the vehicular network link qualities and vehicles mobility dynamics. The basic aim of using the backbone vehicles connection is to reduce the MAC-layer contention time at each vehicle while maintaining a high rate of packet dissemination. The proposed protocol also adopts NC technique to achieve light-weight coded packets forwarding and retransmissions. The backbone forwarding algorithm enables different traffic flows to use the same backbone vehicles, which leads to a more efficient MAC layer contention by efficiently reducing the total number of sender vehicles. Both their theoretical results and simulation results show the advantage of the proposed protocol, which integrates backbone based forwarding with the NC technique, over other existing alternatives by significantly reducing the end-to-end delay and the total number of required retransmissions. However, in vehicular networks, especially in road traffic safety vehicular communications, it is not usually practicable to have a steady line-up moving vehicles through which a backbone connection can be maintained upon which the joint inter-flow and intra-flow NC approach depends on. This is partly due to the apparent frequent network disconnection in VANETs as a result of vehicle branching at road segment intersections, high vehicle mobility, and frequently changing network topology.

Similarly, a sizable number of studies have also investigated the potentials of applying the NC technique to enhance performance in mobile wireless broadcast communication systems in terms of improving packets dissemination reliability [94, 181, 210, 178, 216]. Nevertheless, none of these studies is specifically designed with full consideration of the peculiar characteristics of vehicular networks. Some other studies have investigated the performance impacts of NC theories on vehicular networks. Li *et al*. [118] studied how to maximize popular content distribution (PCD), which is one of the basic services offered by vehicular networks, by applying network coding concept. In their study, a push-dependent PCD scheme called CodeOn is introduced, where contents are actively broadcasted to vehicles from road side APs, and further distributed amongst vehicles with the aid of cooperative VANET communication. In the proposed CodeOn, the authors employ a symbol level NC (SLNC) technique to combat the lossy wireless transmissions and improve content transmission reliability. Amerimehr and Ashtiani [8] investigated the issue of content distribution between the vehicles belonging to a particular cluster in a VANET by exploiting the benefits of NC technique. The vehicles cooperatively disseminate the encoded packets, which are received from a roadside (RS) info-station based on IEEE 802.11 access control protocol. The authors considered two categories of NC, namely: 1) random LNC (RLNC) over a large finite field, and 2) random XORed NC (RXNC) [8]. In order to resolve the issue of random access MAC and the correlation between the received encoded messages over the performance of the content distribution, the authors proposed analytical model [8]. The authors adopted and used a p-persistent CSMA approximation for IEEE 802.11 MAC to estimate the expected amount of duration required for the successful delivery of the complete data file to the vehicles, (i.e., the total content distribution delay), based on RLNC [8]. Finally, Amerimehr and Ashtiani [8] assessed the success of content distribution process in a typical vehicular network for an erasure channel. Although, the solutions proposed in the above reviewed studies show improved performance as indicated by both the analytical and simulation experiment results, they can only be applicable in efficient dissemination of non-safety messages (infotainment services), which are not time or delay-sensitive as opposed to time-critical, delay-constrained road traffic safety messages.

Additionally, amongst the few existing studies that have incorporated the NC technique into vehicular networks to improve transmission reliability and enhance overall network performance, the study conducted by Hassanabadi and Valaee [201] directly falls in the category of the solutions proposed in this thesis. The authors designed a scheme that uses rebroadcasting of network coded safety messages to significantly improve the overall reliability of data dissemination. Although, the scheme the authors designed provides transmission reliability for small safety packets with low overhead, large and saturated network scenario will undeniably incur heavy network overhead. Such heavy overhead can become a serious drawback due to the ensuing excessive channel congestion, which can produce high rate of collisions and lead to unacceptable reliability measures especially for safety applications. In this thesis, this issue is resolved by combining RNC with vehicle clustering technique to divide large and dense network into different separate manageable vehicle clusters, primarily for boosting performance by maintaining low network overhead while RNC leads to high transmission reliability and maximizes the total achievable network throughput. Some other studies also applied deterministic NC to improve transmission reliability [52, 209]. Furthermore, the vehicle clustering technique is a crucial network management task for vehicular communication networks to resolve even the challenge of broadcast storm and to cope with the rapidly changing topology, which is very common in vehicular networks. The only merit of applying deterministic NC over RNC is that it offers better performance in terms of decoding messages successfully. Nevertheless, it is not easy to find the deterministic encoding vectors required for the deterministic NC. Consequently, as opposed to RNC, the algorithmic complexity of deterministic NC is always high, which makes it unwise to implement it in resource-constraint vehicular networks. Although, the issue of maximizing the overall achievable network throughput and improving reliability of conventional wireless transmission have been deeply studied in the network community, many unique characteristics of the VANET bring out new research challenges.

In summary, the above outlined reviews of some similar existing studies on the adoption of NC related approaches to improve message transmission reliability show that the NC mechanism is a very promising approach to improve the error recovery performance of both ARQ and FEC based solutions. However, none of these reviewed existing solutions is directly applicable to vehicular networks, especially for road traffic safety communication owing to the several special features and demands of safety packets dissemination in the harsh vehicular environments. To this extend, these reviews of related literature show that: 1) the application of the conventional classical error recovery mechanisms to guarantee error-free communication in a typical one-to-many, broadcast based road traffic safety communication in vehicular networks only result in further loss of packets due to rampant transmission collisions, over-bearing effects of heavy signalling overhead, unhealthy contention for shared medium access, excessive channel congestion, and consequently the degradation of overall network QoS; and 2) the NC technique has a promising potential that is capable of improving error correction capabilities of classical error recovery methods such as ARQ, FEC, or HARQ technique. However, none of the above reviewed studies is directly applicable to road traffic safety communications in vehicular networks. Nevertheless, few recent studies have actually proposed non-classical data lost recovery mechanisms that are directly applicable to vehicular network. These non-classical data lost recovery solutions are critically discussed in detail in the next section.

2.3 Error Recovery Techniques for Vehicular Safety Communication

In this section, a detailed review of some of the related existing wireless communication error recovery mechanisms, which are specifically designed for road traffic safety communications in vehicular network environments are presented [207, 208, 201, 52, 209, 53, 73, 32, 99, 131, 152]. Table 2.3 shows a survey summary of the existing studies on error recovery techniques for vehicular networks. These error recovery techniques are retransmission based, and are classified into different categories such as repetition, and relay based error recovery techniques.

Table 2.3: Survey Summaries of Existing Studies on Error Recovery Techniques for Vehicular Networks.

Algorithms/Schemes	**Variation factors**	**Traffic scenario**	**Network simulator**	**Mobility Generator**	**Application type**	**Propagation loss model**	**Performance parameters**
Safety Message dissemination scheme [207]	Different vehicle densities	Urban	NS-2	SHIFT	Safety message	Obtained directly from experimental data	Probability of Reception Failure, Channel Busy Time
Safety Message Broadcast Reliability system [208]	Node densities	Highway lanes	NS-2	Not mentioned	Warning/Safety and periodic messages	Nakagami	Reception Rate, Delay, collision rate
Real-time Safety Message dissemination system [201]	Different vehicle densities	Highway lanes	NS-2	Not mentioned	Safety message	Nakagami	Packet Reception Rate
Message Broadcast Reliability system [52]	Node densities	Urban/ highway lanes	Not mentioned	Not mentioned	Warning/Safety and periodic messages	Obtained directly from experimental data	Probability of success, Delay
Message Broadcast Reliability [209]	Node densities	Highway lanes	NS-2	Not mentioned	Safety and periodic messages	Nakagami	Reception Rate, Delay, collision rate
Reliable Broadcast of Safety Messages [53]	Different vehicle densities	Highway lanes	MATLAB	Not mentioned	Safety message	Not mentioned	Probability of success, average delay
Reliable MAC Scheme [73]	Node densities	Highway lanes	MATLAB	Not mentioned	Safety and entertainment messages	Not mentioned	Probability of frame failure

Reliable multi-hop safety message broadcast [32]	Different node densities	Highway lanes	MATLAB	Not mentioned	Safety-critical message	Not mentioned	Throughput, Packets delivery rate (PDR)
Guaranteed delivery of safety messages [99]	Packet generation rate	Highway and urban traffic	NS-3	TraNS	Safety message	Not mentioned	Packets reception rate, delay
Robust safety message broadcast scheme [131]	Different vehicle densities	Highway scenario	NS-2 and MATLAB	Not mentioned	Safety message	Nakagami-*m*	Packets reception rate (PRR), delay
VeMAC [152]	Node densities	City scenario	NS-2	Vissim	Safety message	Not mentioned	Periodic message goodput, delay, etc
Priority Based Inter-Vehicle Communication [172]	Number of packet repetitions	Highway lanes	OPNET Modeler	Not mentioned	Safety message	Not mentioned	Throughput, delay
Safety applications and position information dissemination [41]	number of retransmis-sions attempts	3-lane highway	Not mentioned	Not mentioned	Safety message	Nakagami	Message loss probability, delay
Reliable dual-radio based DSRC channel assignment scheme and application-level based receiver-oriented repetition (AROR) scheme [130]	Different vehicle densities	Highway lanes	Not mentioned	Not mentioned	Safety message	Nakagami	Packet transmission delay, PDR, PRR
Reliable Periodic Safety Message Broadcasting [96]	Distance, Node densities	Highway and urban traffic	NS-2 and MATLAB	Not mentioned	Safety and periodic message	Nakagami	Loss probability, Reception probability

2.3.1 Repetition Based Error Recovery Techniques for Vehicular Safety Communication

In Section 2.1.2, it is clearly shown that packet-level FEC cannot be efficiently adopted for reliable road traffic safety communication due to the fact that the error recovery opportunity of packet-level FEC solely depends on added redundant data, that is, through inspection of a stream of packets. In vehicular networks, especially in the case of road traffic safety communications, safety (i.e., emergency) packets are urgently broadcasted once generated without delay, since only few seconds are required to alert the drivers of other neighbouring vehicles to take necessary actions that may avert an impending road accident. In other words, in road traffic safety communications, those few seconds could be the difference between life and death. Consequently, with vehicular safety communication systems, there is no availability of ECC that can be applied to work out the required redundancy necessary for effective packet-level FEC based error recovery solutions. However, a form of redundancy without the use of any ECC may still be feasible and applicable for error recovery in road traffic safety communication by transmitting redundant packets after the original packets have been broadcasted. The authors in [41] first proposed this type of approach in a road traffic safety communication environment, where redundant information of the same packets is repeated multiple times. The intuition behind this approach is to provide additional opportunities for vehicles that do not receive the original data transmission to recover the packets lost or incorrectly received during the first attempt of broadcasting the original data packets by repeating the transmission within the timeout period.

Recently, several other studies have adopted the same packets repetition (i.e., retransmission) based schemes to achieve safety message transmission reliability in vehicular networks [172, 9, 69, 130, 68, 193]. Although repetition guarantees transmission reliability by making multiple retransmission attempts of the original packets so as to give the nodes within the communication range multiple chances of receiving the packets not correctly received, it also leads to excessive channel congestion, increased network overhead, and may finally result in packets collision. Hence, it ends up becoming counter-productive after a given number of attempts, and reduces the probability of receiving the original packets. Particularly, the results of simulation experiments in [69] clearly substantiated the fact that transmission reliability gain for an optimum number of repetition attempts exists, beyond which the use of packet repetitions becomes counter-productive and leads to QoS deterioration. This simple retransmission approach is the first loss recovery solution proposed for efficient road traffic safety communication, and after its publication in 2004, several works have adopted it as an accurate *bench mark scheme* for effective comparison purposes against newly proposed error recovery protocols for vehicular road traffic safety communications.

Although wireless communication in vehicular networks is built upon legacy IEEE 802.11 MAC, the simple repetition method is applicable to other MAC protocols. Hence, the IEEE 802.11 MAC dependence has inspired several studies on finding ways to improve the simple repetition based error recovery through other MAC protocols such as Code Division Multiple Access (CDMA), Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), and Self-organized Time Division Multiple Access (STDMA) MAC protocols [52, 53, 47, 83, 67, 146, 151]. Even though the alternative MAC scheme like TDMA based channel access scheme is fast becoming one of the most widely adopted approaches in MANET, it is a much more challenging work to design such architectures for a single carrier, where data communication and control is performed via the same channel. Similarly, other challenging issues include time synchronization in a distributed environment like road traffic safety communication with high QoS requirements, slot allocation bottle-neck, provision of race-free operation as well as incorporating dynamic range bandwidth reservation [90]. Hence, further details of existing studies on these alternative MAC protocols were not reviewed.

2.3.2 Relay Based Error Recovery Techniques for Vehicular Safety Communication

The studies carried out by Yang *et al*. [145] and Quadros *et al*. [155] show that relay based error recovery approaches offer performance gain over conventional repetition based loss recovery schemes [207, 172, 9], which were discussed in the previous section. With relay based error recovery approaches, each vehicle retransmits (i.e., relays) the received data packets from other vehicle located far away from themselves as opposed to repetition based loss recovery mechanisms, where each vehicle repeats its own packets until the packets timeout period expires.

In order to resolve the issue of stringent demands of video streaming and the challenges of high dynamic topology associated with VANETs, Naeimipoor and Boukerche [142] conducted a study to investigate the designing of an efficient communication scheme for reliable dissemination of high quality video over vehicular networks. The authors proposed a relay based error recovery protocol called Hybrid Video Dissemination Protocol (HIVE), which deploys a receiver-based relay vehicle selection mechanism in addition to a MAC congestion control technique [142]. With a MAC congestion control technique, the proposed protocol in [142] is able to avoid high packet collision, and maintains a low latency with respect to vehicular traffic conditions. Unlike other related existing relay based error recovery protocols, the HIVE protocol [142] integrates various promising mechanisms in an optimal manner so as to guarantee high quality video streaming by carefully considering the special vehicular network features.

The combination of a receiver-based relay vehicle selection mechanism with MAC congestion control techniques in an integrated manner enables the HIVE protocol [142] to achieve a reasonably high packet delivery ratio. In addition to these techniques, the authors applied the erasure coding technique on the application layer in order to further enhance the error recovery performance of HIVE protocol. The results of HIVE's simulation experiments clearly show that the proposed protocol is robust, efficient, and guarantees high quality of transmitted videos over a vehicular network in terms of high QoS and Quality of user Experience (QoE) [142]. Although the HIVE protocol outperforms the other similar existing video streaming protocols in a vehicular communication environment in terms of reconstructed video quality while complying with scalability, and delay requirements of a real-time video streaming, like most other existing relaying protocols, it is built on the assumption that the quality of each relay vehicle is the same. Nevertheless, this assumption is not always true due to the different quality and workload of the devices. Moreover, the quality of the link must be put into consideration in the process of relay nodes selection.

Cheng and Yamao [23] carried out a related study to analyse and optimize the potential of the carrier sense multiple access with collision avoidance (CSMA/CA) broadcast relay network to overcome the reliability challenge of CSMA/CA V2V communication over actual road environment due to the hidden terminal problem, fading and shadowing effects. The authors proposed a V2V broadcast protocol with relay vehicles to achieve guaranteed improved V2V communication reliability in a typical vehicular environment. In their study, a theoretical model is also proposed to critically analyse the performance of such network. For a realistic vehicular communication environment, the theoretical model assumes a typical crossroad and takes into consideration the required safe distances between moving vehicles, hidden terminal problem, fading, shadowing, and capture effects. Likewise, the effect of other relevant system parameters on the transmission reliability of the broadcast oriented wireless network such as RF frequency band and carrier sense threshold is also investigated through in-depth theoretical analysis. From both theoretical and simulation results, the authors suggested that the performance of V2V communication in terms of broadcast reliability can be improved by applying relay vehicles to obtain path diversity gain, and locate them close to the transmitting vehicles. In a similar study, Das *et al*. [33] investigated the challenging issue of transmission reliability in wireless communication over vehicular networks as a result of incessant, frequent network disruption due to highly dynamic, interference-prone, and noisy wireless links in V2V communications. A relay node based novel wireless communication algorithm, called Cross-Layer Tree Formation (CLTF) is proposed to achieve efficient shared medium access. With the proposed CLTF algorithm, a tree architecture is formed to connect the receiver vehicle with the cooperative relay vehicle in MAC-level packet retransmission. Each relay vehicle in the network serves a neighbouring destination vehicle. The simulation experiments show improved performance of the proposed protocol over similar existing schemes. However, the relay node based CLTF algorithm was not implemented in the MAC layer of a realistic vehicular environment. Moreover, none of the above proposed solutions/approaches actually applied the concept of NC based retransmission, which is known for guaranteeing very high rate of transmission reliability through efficient error recovery by the way of enriching the information content of each transmission.

In a closely related study, Ren *et al*. [158] investigated the potentials of combining a form of coding called superposition coding with differential modulation and relay based vehicular communication reliability. A differential successive relays (DSRs) scheme is proposed to resolve the challenges created by the high-speed mobility associated with nodes in vehicular networks that results in worsened situation of imprecise channel estimation, and unstable direct links, thus posing critical impediments to reliable and timely data delivery in road traffic safety communication. Particularly, the key aim of the DSRs scheme is to achieve high-speed full-duplex relaying vehicular communication connectivity specifically for unstable direct communication links and, to guarantee fast and reliable information detection in vehicular networks without depending on precise channel state information (CSI). With the proposed scheme, a full-duplex relaying vehicular communication connectivity is achieved by the use of DSRs at RSUs or inside other moving vehicles. Additionally, the authors applied efficient blind interference cancellation that will ensure improve robustness of DSR without specific CSI by mitigating inter-relay interference. Meanwhile, the proposed DSRs scheme uses the superposition coding with a differential modulation technique to guarantee reliable and fast information detection in vehicular communication without precise CSI. The authors equally discussed the advantages, and the real-world implementation complexities of the application of DSR, while the ergodic capacity and the bit error probability (BER) were theoretically obtained. Both the theoretical and numerical results verify significant improvements in the BER performance and capacity of the proposed DSRs scheme as opposed to conventional schemes with half-duplex relays and frequent channel estimation in vehicular networks. However, like the relaying protocol proposed in [142], this scheme is built on the assumption that the quality of each relay vehicle is the same, which is not always true as a result of the different quality and workload of the devices.

In general, the intuition behind the relay based error recovery mechanisms is based on that notion that if Vehicle A receives a data packet from another vehicle, say, Vehicle X, which is far away from the location of A, then it is likely that the data packet may not be correctly received by Vehicle X's neighbours considering the lengthy distance between the transmitter (Vehicle A) and the receiver (Vehicle X). Thus, Vehicle X retransmitting (i.e., relaying) the same data packet received from far away Vehicle A is more useful than X retransmitting any other data packets received from other vehicles closer to it (i.e., Vehicle X's neighbouring vehicles). In other words, this intuition is built on the assumption that the packet reception rate is not fully correlated, which means that, for a transmitted data packet from a faraway node, it is possible that two nodes closely located to each other may not always have the same message reception status. However, the only drawback that is common to all the above proposed relay based error recovery protocols is lack of relay vehicle selection metric, which should help in ensuring that the most suitably qualified relay candidate is chosen to guarantee reliability as well as widen the packets transmission coverage. In essence, the degree of performance of a relay based network is highly dependent on the choice of best positioned relaying node, since retransmitting a data packet by a closely located node to the original transmitter may not show any performance difference (or performance gain) in terms of transmission coverage as well as reliability.

By comparing repetition based error recovery techniques against relay based error recovery techniques, it is obvious that the relay based approach outperforms the simple repetition based approach. This is partially due to the fact that unlike repetition based transmission reliability schemes which solely depend on the receivers' reception status information, relay based communication protocols does not depend on reception status information. In other words, the retransmissions in relay based error recovery mechanisms are solely based on the intuition that if a packet is received by vehicles A from another vehicle that is faraway, then, there exist a low probability that the packet is correctly received by Vehicle A's neighbours. The results of theoretical analysis and simulation experiments in [69], [172], [9], particularly the simulation results of [69], show that relay based error recovery schemes maintain significant performance gain over repetition based error recovery schemes especially in a case where the distance between the transmitter and the receiver is beyond 100m. Thus, in order to achieve optimal broadcast reliability over a long-distance motor highway for efficient road traffic safety communication, the relay based error recovery mechanisms must be utilized. For analytical point of view, detailed potentials of both repetition and relay based error recovery protocols can be identified and unlocked by applying innovative concepts like network coding, relay vehicle selection metric and algorithm to further guarantee their error recovery performance improvement.

2.3.3 Network Coding for Road Traffic Safety Communication

Unlike ARQ, FEC or HARQ communication techniques, the NC technique is known to significantly improve the rate of packet dissemination without increasing the message communication overhead. Following the pioneer work in [3], NC has been seen as an innovative concept that is capable of unlocking the full potential of classical error recovery mechanisms such as ARQ, FEC or HARQ to achieve reliable packets broadcast in vehicular networks. Although several research studies have applied the NC concept to different classical error recovery methods for vehicular communication services, the literature on its application in road traffic safety communication to guarantee reliable and fast transmission of safety packets in vehicular environment is still quite scanty. More so, to the best of our knowledge, no study has been reported on the application of the combination of wireless communication techniques such as NC and cooperative communication, node clustering concept and classical error recovery approaches for timely and error-free safety packets broadcast in road traffic safety communication (this is studied in Chapter 3 and 4 of this thesis). However, Zhang *et al*. [224], Wu *et al*. [200], and another group of researchers at the University of Michigan – Dearborn [208], [201] have recently studied the potentials of applying the NC concept to relay based data loss recovery for reliable safety packets transmission in vehicular networks.

Based on the work reported in [209] on relay based data loss recovery, Yang and Guo [208] investigated the benefit of combining the NC technique and relay based data loss recovery for safety packets transmission reliability in vehicular networks. With the network coded relay based error recovery protocol proposed in [208], safety packets separately received from two different vehicles are combined into one packet by the use of the NC technique and relayed in order to widen the transmission coverage and improve the safety message transmission reliability. Any vehicle that receives the relayed coded packets will be able to decode the coded packets if the vehicle has at least one of the encoded packets. Furthermore, in [201], an improved version of the protocol is proposed, which increases the chances of decoding each received coded packet by encoding one packet from each of the relay vehicles in a typical linear motor road topology. Similarly, Zhang *et al*. [224] improved upon the work reported in [223], and proposed a novel cooperative forwarding solution, referred to as Cooperative Positive Orthogonal Codes (POC) based Forwarding (CPF) scheme to extend the POC-MAC for multi-hop communication in a typical highway vehicular networks. In [223], the dissemination of a data packet at each hop is retransmitted within a transmission frame of L time-slots, but the proposed CPF protocol deterministically schedules the retransmission of each data packet according to the POC code-words. Furthermore, the CPF exploits the spatial diversity by distributing the multiple forwarding transmissions among all the cooperating relay vehicles at each hop as clearly depicted in Fig. 2.1. More so, in order to ensure proper penetration of the coded packet using the multi-hop dissemination, each of the multiple relay vehicles is assigned additional transmission opportunities (TOs) by the CPF protocol for each multi-hop flow to guarantee efficient data forwarding across the network. In Fig. 2.1, the dashed arrows represent the TOs assignment to the virtual relay members, while TOs correspond to POC code-words. Although the results reported in their published study show that CPF protocol outperforms other similar existing solutions, the authors did not specify how the multiple relay vehicles are selected, or the metrics used in the process to ensure that only suitable relay candidates that will guarantee optimal results are selected to perform the relaying functions.

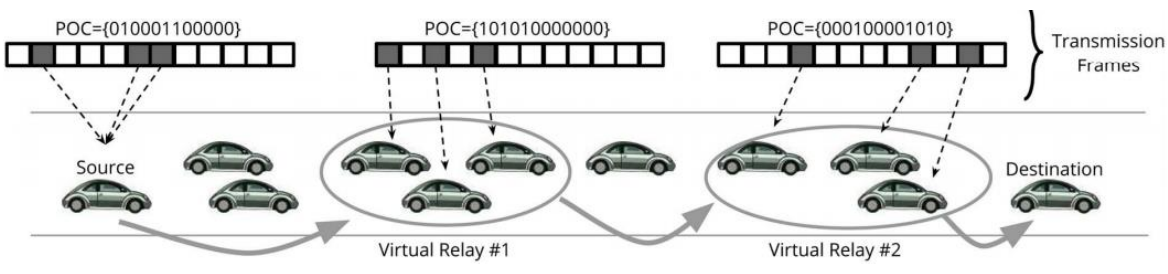


Fig. 2.1: Reliable cooperative coded packets forwarding using multiple vehicles as virtual relays [224].

The overall performance of the relay based data loss recovery schemes proposed in [208] and [201] in terms of the rate of coded packets transmission reliability is compared with the performance of the repetition based protocol proposed by Xu *et al*. [207].

Although no study has investigated the reliability performance comparison between conventional relay based error recovery protocol and network coded relay based error recovery protocol, it is obvious that the NC enabled relaying approach will certainly outperform the conventional relaying approach. This is because the NC technique enriches the content of each packet transmission by combining two or more packets into one prior to dissemination and subsequent multiple relays. Upon careful examination of the results of simulation experiments reported in [207], [208] and [201], it is obvious that the simulation settings and parameters of the three studies are the same apart from the fact that the vehicular densities used in [207] and [208] are slightly smaller than the vehicular density used in [201]. Hence, it is possible to directly compare the performance of the three studies using the results of the simulation experiments presented in the papers. Finally, the comparison of their results show that relay based protocols in [208] and [201] outperform the repetition based scheme in [207]. Furthermore, it is noteworthy to mention that the results of simulation experiments in [225] clearly show that the NC aided relay based scheme offers the highest performance in terms of transmission reliability of the coded safety packets.

2.3.4 Application of Random Network Coding, Vehicle Clustering, and Cooperative Cross-layer MAC Communication Techniques for Reliable Safety Communication

Some of the recent studies on efficient application of NC over vehicular networks generally addressed the challenges of improving vehicular communication reliability and quality at the MAC layer. The authors in [53] proposed a medium access control (MAC) protocol for reliable transmission of safety-critical packets in vehicular communication networks. The authors implemented a topology-transparent message broadcast by applying positive orthogonal codes (POC) to ensure time-sensitive message broadcast reliability in a dynamic vehicular communication environment. Fallah *et al.* [51] studied efficient message dissemination in cooperative vehicle safety systems (CVSS) by extensively analysing two basic controllable parameters that affect vehicular network condition and overall performance such as the data transmission rate (frequency) and communication radio transmission range. The authors used the findings reached after analysing the effects of different choices of data transmission rate and range to design robust feedback control schemes for efficient transmission range adaptation in VANETs. Similarly, the authors in [222] have proposed a vehicular cooperative MAC (VC-MAC) scheme, which exploits the potentials of V2V communication to increase the overall achievable system throughput by taking of V2V message sharing for serving nodes which are beyond the RSU's radio service coverage. Bi *et al.* [13] also proposed a multi-channel token ring MAC protocol (MCTRP) for inter-vehicle communications (IVC). The authors adopted asynchronous carrier sense multiple access with collision avoidance (CSMA/CA) mechanism to guarantee emergency message delivery with low delay. Additionally, the authors designed a token-based packet exchange protocol to further improve the network throughput for non-safety multimedia applications. The above studies provide a solid foundation for enhancing wireless communication efficiency and qualities in vehicular communication networks. However, none of them has taken into consideration the peculiar application requirements and communication constraints in vehicular networks. More so, none of the above works considered the benefits of combining the network coding concept with the vehicle clustering technique. This is because, aside from the reliability functionalities of network coding (as discussed in the previous sections), the vehicle clustering technique is known to primarily eliminate heavy communication overhead and boost the overall network performance by segmenting the whole network into separate small manageable group (or sub-networks).

Several studies have investigated the design of scheduling algorithms for easy message dissemination, minimized network overhead, and improved reliability in vehicular networks. Chang *et al.* [17] conducted a study aimed at ensuring minimum communication overhead as a result of infrastructure-to-vehicles (I2V) handoff process for packets dissemination when an on-going transmission is not completed before the vehicle leaves the current RSU's radio coverage. The paper proposed a scheduling algorithm called Maximum Freedom Last (MFL) to ensure minimum system handoff rate under the maximum acceptable delay constraint. The proposed MFL schedules the service ordering of the on-board units (OBUs) according to their degree of freedom (DoF), which is based on performance parameters such as remaining transmission time, queueing delay, remaining dwell time of service channel (SCH), and maximum acceptable delay. The results from simulation experiments show that the proposed MFL scheduling algorithm performs better than the conventional earliest-deadline-first and first-come-first-serve approaches in terms of minimized system handoff and service failure rates. In [101], Kim *et al.* investigated the problem of using the data dissemination technique to improve the reliability of data delivery services from the cloud data center to vehicles through roadside wireless access points (APs) with local data storage. A vehicular route-dependent data prefetching scheme was devised to boost performance in terms of maximizing the rate of data dissemination success probability especially when the wireless connectivity is stochastically unknown with a limited size of local data storage. The authors proposed a greedy algorithm, and an online learning algorithm for deterministic, and stochastic cases, respectively. These algorithms were used to determine how a set of data can be prefetched from a data center to roadside wireless APs. Similar study was carried out by Zhao *et al.* [226] to address the challenge of efficient data dissemination and transmission reliability in VANETs. The authors proposed a data pouring (DP) and DP with buffering paradigm (DP-BP), which can significantly improve data delivery ratio through the use of relay stations that rebroadcast data at the intersections in order to offload data dissemination workload at data centers. Likewise, efficient data dissemination as one of the intrinsic requirements to enable emerging road safety applications in vehicular cyber–physical systems is presented in [124]. The authors studied real-time data services empowered by I2V communication by taking into consideration the time constraint of data dissemination and the freshness of data items, and formulated a temporal data dissemination (TDD) problem. The TDD problem is formulated by introducing the snapshot consistency requirement on serving real-time requests for temporal data items. Furthermore, a heuristic scheduling algorithm is proposed to maximize the overall system performance. As opposed to these reviewed related studies, the study presented in Chapter 4 of this thesis investigates how to apply the combination of RNC and vehicle clustering techniques with the aid of cooperative packet dissemination in vehicular communication environments with the aim of improving the bandwidth efficiency, maximizing the achievable network throughput, and enhancing transmission reliability.

Interestingly, a sizable number of studies have investigated the potentials of applying NC to enhance performance in mobile wireless broadcast communication systems [94, 181, 210, 178, 216]. Nevertheless, none of them is specifically designed with full consideration of the peculiar characteristics of vehicular networks. Some other studies have investigated the performance impacts of NC on vehicular networks. Li *et al.* [118] studied how to maximize popular content distribution (PCD), which is one of the basic services offered by vehicular networks, by applying the NC concept. In their study, a push-dependent PCD scheme called CodeOn is introduced, where contents are actively broadcasted to vehicles from road side APs, and further distributed amongst vehicles with the aid of cooperative communication in VANETs. In the proposed CodeOn, the authors employ a symbol level network coding (SLNC) technique to combat the lossy wireless transmissions and improve content transmission reliability. Wu *et al.* [199] addressed the challenges of designing an efficient data dissemination protocol for vehicular networks. These challenges are caused by high vehicle mobility, error-prone characteristics of wireless communication, and the limited wireless resources in VANETs. The authors proposed a protocol to provide a light-weight, and reliable data dissemination in vehicular networks by employing dynamically generated back-bone vehicles to: 1) disseminate broadcast messages that will minimize the MAC layer contention time at each vehicle, and 2) maintain high percentage of data dissemination rate by taking into consideration the vehicle mobility dynamics, and the link quality between vehicles for the back-bone selection. The protocol employs the NC technique to minimize protocol overhead and improve packet reception probability. Amongst the most recent existing studies that have incorporated the NC into vehicular networks to improve transmission reliability and enhance overall network performance, the study conducted by Hassanabadi and Valaee [68] directly falls in the category of the RECMAC scheme proposed in Chapter 4 of this thesis. The authors designed a scheme that uses rebroadcasting of network coded safety packets to significantly improve the overall reliability of safety data dissemination. Although, the scheme which the authors designed provides transmission reliability for small safety packets with low overhead, large and saturated network scenario will undeniably incur heavy network overhead, which will in turn, counter the performance gain achieved by the scheme. Such heavy overhead can become a serious drawback due to the resultant excessive channel congestion, which can produce high rate of packet collisions, as well as lead to unacceptable reliability measures especially for safety applications. In Chapter 4 of this thesis, this issue is resolved by combining RNC and vehicle clustering technique to divide a large and dense network into different separate small manageable vehicle clusters primarily to boost the network performance by maintaining low network overhead. Moreover, the application of RNC as discussed in Chapter 4 of this thesis results in high transmission reliability and maximizes the total achievable network throughput.

Few studies also applied deterministic NC to improve transmission reliability [64, 93]. The only merit of applying deterministic NC over RNC lies in the fact that deterministic NC offers higher probability of successful packets decoding performance gain over RNC. Nevertheless, finding the required deterministic coding vectors for efficient application of deterministic NC is a complex task. Consequently, as opposed to RNC, the high algorithmic complexity associated with deterministic NC renders it nearly unprofitable to implement in typical resource-constraint networks like vehicular networks. Although, the issue of maximizing the overall achievable network throughput and improving reliability of conventional wireless transmission have been deeply studied within the network community, many unique characteristics of the VANET bring out new research challenges. Furthermore, in a typical one-to-many packet broadcast-oriented vehicular communication networks, the vehicle clustering technique can be a crucial network management task that can be used to resolve even the challenge of broadcast storm and cope with the rapidly changing topology, which is very common in vehicular networks.

Chapter Three

Broadcast Reliability through Network Coding*

3.1 Introduction

As was discussed in Chapter Two, multiple retransmission attempts of the original safety packets through retransmission-based error recovery method has been found to guarantee high probability of successful reception in error-prone wireless road traffic safety communication. In other words, the key aim of retransmission-based error recovery technique is to allow each node to repeat the transmission of its raw packet(s) within the timeout period thereby giving the nodes within their transmission range multiple chances of receiving the packets not correctly received during the previous transmission. However, since retransmission increases network overhead and after a given number of consecutive repeats may lead to excess channel congestion due to channel overload, this chapter investigates the possibility of reducing the number of retransmissions while increasing the content and efficiency of each transmission attempt. Hence, it enables all the vehicles within the radio range to receive the combined original packets using NC concept [3] and reduces contention with the aid of a relay vehicle selection metric, η to rebroadcast the coded messages to ensure that the vehicles that are beyond one-hop communication reach of the transmitter also receive the broadcasted encoded packets. Chapter 3 of this thesis exploits the manifold potentials of NC technique to achieve reliable and efficient communication in vehicular networks by proposing a protocol called Coding Aided Retransmission-based Error Recovery (CARER) communication scheme. The CARER scheme enables each vehicle to perform an exclusive OR (XOR) operation on its packet pool, ρ[4] and to retransmit the XORed packets in one-hop broadcast to other vehicles within their vicinity. By broadcasting the XORed version instead of the raw packets creates ample opportunity for high rate of lost packets recovery from each transmission. Furthermore, the performance of the proposed CARER protocol is evaluated with the aid of an analytical study, and validated through extensive simulation experiments.

* Part of this chapter has been peer reviewed and published in [P.2], [P.5] and [P.6] as shown in list of publications.

[4] The set of packets, $[P_1, P_2, P_3, \ldots, P_n]$ contained in a virtual buffer, which are heard by the vehicle within the last T seconds.

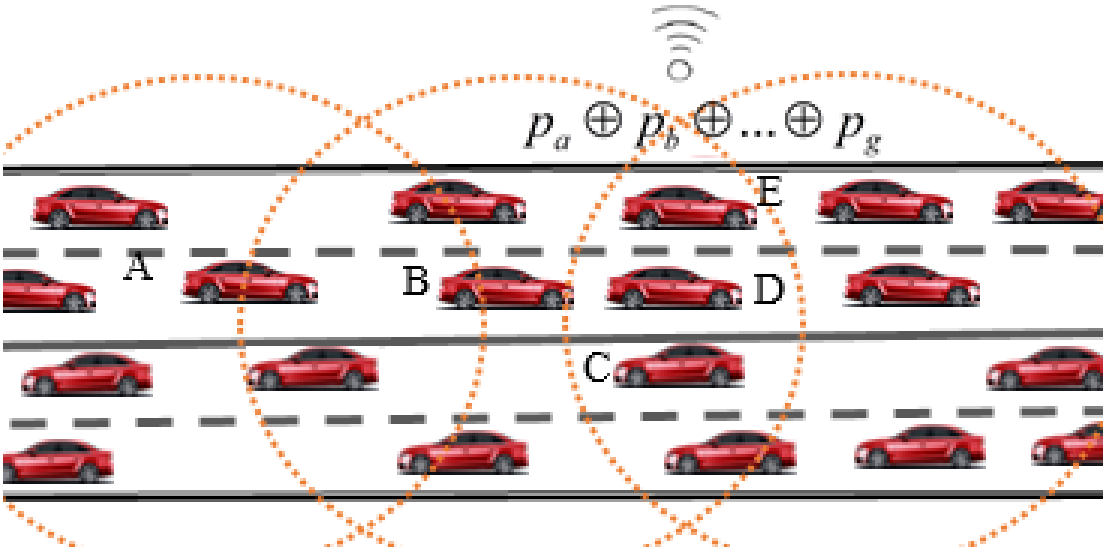


Fig. 3.1: CARER: Vehicle A selects Vehicle B to retransmits the XORed message ($P_a \oplus P_b \oplus \cdots P_g$) to enable the vehicles within one-hop broadcast range of A to recover lost packets, and those beyond its one-hop broadcast range to receive the encoded message.

3.2 Theoretical Basis of Network Coded Retransmission

3.2.1 Proposed CARER System Model

A vehicular highway of 4 lanes with two lanes each dedicated to nodes moving in one and opposite directions is considered. The vehicles maintain directional velocity (because nodes only move in two different directions in highways) which is distributed arbitrarily over a discrete set $S = \{(30 + 10 * k)m/s,\ \forall k \in [0,5]\}$. Mobile nodes are equipped with a GPS that is used to obtain the node position information, direction and velocity, and a half-duplex transceiver for wireless communication. The CSMA/CA-based IEEE 802.11e MAC [196, 227] is used for service differentiation and shared media access with some modification. In order to enhance transmission reliability of the broadcasted encoded packets, the traditional three-way handshake of CSMA/CA-based MAC is adopted with certain modifications by using request-to-broadcast and clear-to-broadcast (RTB/CTB) frame exchanged before encoded messages are transmitted. Additionally, the proposed CARER protocol enables the selection of one vehicle for rebroadcasting the encoded message towards the intended direction with the aid of a rebroadcasting metric η specifically devised for vehicular communications.

3.2.2 Safety Message Coding for Error Recovery

With the proposed CARER scheme, each mobile node will perform an exclusive OR (XOR) operation over its own generated raw packets and any other packets contained in ρ (i.e., where ρ denotes packets received from other vehicles in *T* ms). Then, using location-aware algorithm (LAA) and the metric η, another node is selected to retransmit the encoded packets instead of the source vehicles repeating their raw packets indiscriminately. Here, nodes $i + 1$ and $i - 1$ retransmit the encoded versions of the packets $[i \oplus (i + 1)]$ and $[(i - 1) \oplus i]$ for $m + 1$ times respectively to enable every vehicle within their vicinity to recover any packet(s) they may have lost.

Packet recovery probability (PRP) is defined as the probability that a raw packet is lost but recovered with CARER scheme after m number of retransmissions. Analytical study is used to derive PRP as a function of the total error probability. Let $P_l(CARER)$ be the loss probability of CARER protocol. Then, $P_l(CARER)$ can be expressed as

$$P_l(CARER) = \in_i [(1 - \alpha_i)(1 - \beta_i)] \qquad (3.1)$$

where $\in_i$ represents the packet error probability, α_i and β_i represent the probability that node i can successfully recover raw packet i after successfully decoding the encoded retransmitted packets $[(i - 1) \oplus i]$ and $[i \oplus (i + 1)]$ respectively. $P_l(C)$ implies that: 1) node i lost the raw packet i; 2) node $i - 1$ cannot recover raw packet i from the encoded packet retransmission $[(i - 1) \oplus i]$; and (3) node $i + 1$ cannot recover raw packet i from the encoded packet retransmission $[i \oplus (i + 1)]$ as well. Considering that node $i - 1$ repeats the encoded packets $[(i - n) \oplus ni]$ for a total number of $m + 1$ times before all the vehicles within the radio range of vehicle $i - 1$ are able to successfully recover their lost packet(s), it follows that α_i is the probability that at least a single packet was received out of the $m + 1$ retransmitted encoded packet $[(i - n) \oplus ni]$ by vehicle $(i - 1)$. Hence, the encoded retransmission $[(i - n) \oplus ni]$ by vehicle $(i - 1)$ can be recovered as shown in the formula:

$$\alpha_i = \mu_i \left(\frac{(1 - \epsilon_{i-n}^{m+1})}{1 - (1 - \epsilon_{i-n})} \right) \qquad (3.2)$$

where μ_i represents the probability that vehicle $(i - 1)$'s retransmitted encoded packets, $[(i - n) \oplus ni]$ can be decoded by node i when successfully received. Since vehicle $i - 1$, $i - 2, \ldots, i - n$ must have at least one of $i - 1, i - 2, \ldots, i - n$ raw packets to be able to decode any of the encoded packets such as $[(i - 1) \oplus i]$, $[(i - 2) \oplus 2i]$, $\ldots, [(i - n) \oplus ni]$ retransmissions, μ_i as well means that vehicle $i - n$ already has at least one of the $[(i - 1) \oplus i]$, $[(i - 2) \oplus 2i]$, $\ldots, [(i - n) \oplus ni]$ packets and therefore can decode the retransmissions of the encoded packets. So, that

$$\mu_i = 1 - \epsilon_{i-n} \qquad (3.3)$$

where ϵ_{i-n} represent the loss probability of the encoded packets $[(i - n) \oplus ni]$. Hence, Eq. (3.3) can now be rewritten as:

$$\alpha_i = \left(\frac{(1 - \epsilon_{i-n})(1 - \epsilon_{i-n}^{m+1})}{1 - (1 - \epsilon_{i-n})} \right) \qquad (3.4)$$

With the encoded safety messages, the area of interest for retransmission is the immediate transmission range of vehicle i and $i - n$ which is successfully selected to rebroadcast it for the reach of the immediate cluster of vehicles within its range but out of range of the source node (see as exemplified in Fig. 3.1). From Eq. (3.4), it is observed that α_i strongly depends on $\alpha_{i-1}, \alpha_{i-2}, \alpha_{i-3}$, and so on till α_{i-n}. However, it is assumed that the difference between $i - 1, i - 2, \ldots, i - n$ is trivial and insignificant. Hence, substituting $i - n$ with $i - 1$ in Eq. (3.4), gives a linear equation of α_i which can be solved as

$$\alpha_i = \left(\frac{(1 - \epsilon_{i-1})(1 - \epsilon_{i-1}^{m+1})}{1 - (1 - \epsilon_{i-1})}\right) \tag{3.5}$$

Following the above analysis for $[(i - n) \oplus ni]$, encoded message $[ni \oplus (i + n)]$ retransmission by vehicle $(i - n)$ can be decoded by using the formula

$$\beta_i = X_i \left(\frac{(1 - \epsilon_{i+n}^{m+1})}{1 - (1 - \epsilon_{i+n})}\right) \tag{3.6}$$

where X_i represents the probability that vehicle $(i + 1)$'s retransmitted XORed packets, $[ni \oplus (i + n)]$ can be decoded by node i when successfully received. Again, following the steps that lead to the derivation of Eq. (3.3), X_i is given as

$$X_i = 1 - \epsilon_{i+n} \tag{3.7}$$

Then, putting Eq. (3.7) into Eq. (3.6) gives us

$$\beta_i = \left(\frac{(1 - \epsilon_{i+n})(1 - \epsilon_{i+n}^{m+1})}{1 - (1 - \epsilon_{i+n})}\right) \tag{3.8}$$

Hence, substituting $i + n$ with $i + 1$ in Eq. (3.8) gives a linear equation of β_i which can be solved as

$$\beta_i = \left(\frac{(1 - \epsilon_{i+1})(1 - \epsilon_{i+1}^{m+1})}{1 - (1 - \epsilon_{i+1})}\right) \tag{3.9}$$

Finally, putting Eq. (3.6) and Eq. (3.9) into Eq. (3.1), $P_l(CARER)$ can be rewritten as

$$P_l(CRER) = \in_i \left(\left(1 - \frac{[(1 - \in_{i-1})(1 - \in_{i-1}^{m+1})]}{1 - (1 - \in_{i-1})}\right) \times \left(1 - \frac{[(1 - \in_{i+1})(1 - \in_{i+1}^{m+1})]}{1 - (1 - \in_{i+1})}\right)\right) \tag{3.10}$$

Once more, with reference to the assumed triviality of the difference between vehicles $i-1, i-2, \ldots, i-n$ and $i+1, i+2, \ldots, i+n$ with respect to vehicle i, both the loss probability of the encoded safety messages $i-1$ (i.e. $\in_{i-1}$) and $i+1$ (i.e. $\in_{i+1}$) can be represented as $\in_i$. Hence, Eq. (3.10) can be simplified and expressed as a function of m and $\in_i$, resulting in

$$P_l(CRER) = \in_i \left(\left(1 - \frac{[(1 - \in_i)(1 - \in_i^{m+1})]}{1 - (1 - \in_i)}\right) \times \left(1 - \frac{[(1 - \in_i)(1 - \in_i^{m+1})]}{1 - (1 - \in_i)}\right)\right) \tag{3.11}$$

Then, the recovery probability (P_r) of CARER scheme will be given as:

$$P_r(CARER) = 1 - P_l(CARER)$$

$$= 1 - \left[\in_i \left(\left(1 - \frac{[(1 - \in_i)(1 - \in_i^{m+1})]}{1 - (1 - \in_i)}\right) \times \left(1 - \frac{[(1 - \in_i)(1 - \in_i^{m+1})]}{1 - (1 - \in_i)}\right)\right)\right] \tag{3.12}$$

Consequently, the overall measure of performance improvement in terms of Packet(s) loss recovery potential of the proposed network coding assisted scheme can be determined by the results obtained from Eq. (3.12), as is shown in Section 6.3.2 (Results and Discussion).

3.2.3 RTB/CTB Handshake

In order to overcome the hidden node problem and reduce packets collision as well as minimize the overall network overhead, sender nodes engage in RTB/CTB handshake with the recipients within the radio transmission coverage of the sender. If the furthest vehicle away can be selected with RTB/CTB packets, then other nodes in between can overhear the transmission as well. The source node adheres to all the rules of CSMA/CA transmission associated with IEEE 802.11 while attempting to broadcast an RTB packet.

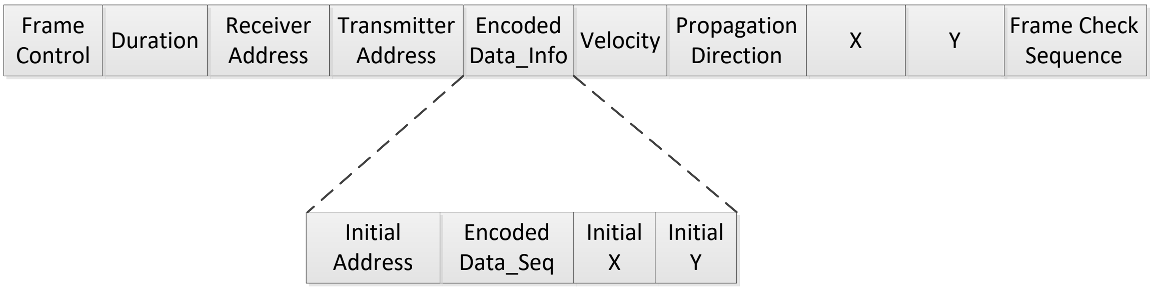


Fig. 3.2: An RTB frame structure

Fig. 3.2 shows the structure of an RTB frame with an additional five fields (*Encoded Data_Info, Velocity, Propagation Direction, X* and *Y*) as opposed to conventional RTS frame. The *Encoded Data_Info* field holds the information about the source node that initially broadcasted the encoded packets. The other fields include *Velocity* which is the relative moving velocity of the sender, *Propagation Direction* which is the encoded packet desired propagation direction, while *X* and *Y* represent the coordinates of the transmitter. *Encoded Data_Info* field, in turn, contains: 1) the address of the source node *Initial Address*, 2) the initial coordinates (*Initial X* and *Initial Y*) of the source node, and 3) the encoded message's sequence number, *Encoded Data_Seq*.

The source node with the encoded packet that is meant for broadcasting will first broadcast a short RTB packet and obeys CSMA/CA-based MAC procedure by starting a retransmission timer with value set as $T_{RTB\_r} = T_{DIFS} + T_{RTB} + T_{CTB}$, where T_{DIFS} represents time period of the Distributed coordination function Inter-Frame Space (DIFS), and T_{RTB} and T_{CTB} represent the transmission time durations of an RTB and a CTB frame, respectively. In the event of collision with no CTB response from an eligible candidate within T_{RTB_r} time duration, the sender (i.e. the source) vehicle will immediately start contending for shared media access to re-transmit an RTB message until the CTB message is received by one-hop neighbours successfully. With the help of the broadcast vehicle's information contained in the *Propagation Direction* fields of an RTB frame, any vehicle that overhears the RTB frame but not moving in the desired propagation direction of the encoded message will not respond with a CTB message but rather suspend its on-going transmissions and update their Network Allocation Vector (NAV), accordingly.

On the other hand, if a vehicle receives an RTB frame, it will use the designed LAA to check if it is qualified to reply the CTB message with the help of the position information contained in the received RTB frame. This is possible since each vehicle broadcasts its periodic status message which contains its IP address, position, moving speed, and direction of movement. Hence, using the LAA after receiving an RTB frame, a node is able to know if there are other nodes within the radio transmission range of the source node ahead of itself. However, if the node's position is between the source vehicle and other vehicles in one-hop radio coverage of the sender vehicle, the vehicle will suspend replying with a CTB packet since no significant distance is gained along the encoded message desired propagation direction. Hence, the node's NAV will be updated in accordance with the *duration* field contained in the RTB packet, else, a back-off counter will be started so as to reply with a CTB packet, after which the node keeps sensing the channel in the meantime to receive the encoded message for a rebroadcast. For instance, in Fig. 3.1, node *B* will not reply with a CTB frame after learning that there are other vehicles with higher distance gain using the LAA algorithm but rather updates its NAV. Likewise, vehicle *C* will also update its NAV after receiving the RTB since the direction information contained in the *direction* field of the RTB frame shows a different intended propagation direction.

If there exist only node *i* with the highest distance gain within the transmission coverage and in the desired propagation direction of the source vehicle, then node *i* becomes the eligible candidate and will start a back-off timer upon receiving an RTB frame for replying with a CTB frame to the source node. However, if there exist more than one eligible station as is the case in Fig. 3.1 (see node *D* and *E*), each eligible node will start a back-off counter in order to reply with a CTB packet with the help of the following metrics: a) the distance gain Δd between node *i* and the sender; b) the received signal-to-noise-ratio (SNR) and packet error rate (PER), which is usually estimated using the received RTB short message, and c) the relative velocity between node i and the source node. Depending on these criteria, the rebroadcasting metric η is evaluated and used to determine and select the most suitably qualified candidate for rebroadcasting the encoded packets to enable the nodes outside the radio coverage of the source node to receive the encoded packets. Mathematically, this metric is given by

$$\eta = \frac{e}{E_{max}} + \left[\frac{\Delta v}{V_P} + \left(1 - \frac{\Delta d}{R_T}\right)\right] \tag{3.13}$$

where Δd is the encoded packet transmission distance which is given by the difference between the location of the source vehicle and the recipient (i.e. node i), R_T is the maximum IEEE 802.11p radio signal transmission range defined in [195], which is an IEEE standard enhanced to support WAVE [75], e is the PER of the encoded packet which is determined based on the calculated SNR, E_{max} denotes the highest acceptable PER as specified in [77], V_P and Δv denotes the maximum and relative velocity, respectively.

CARER protocol requires the selected vehicle to reply the source vehicle with a CTB frame within the DIFS interval in order to prevent interruption of an RTB/CTB handshake mechanism between itself and the selected node from other transmission flows. Finally, the station with the minimum value of η will reply the source node with a CTB frame first and, then becomes the chosen node to rebroadcast the encoded message. In general, a mobile station with the longest distance gain, small relative velocity, and better channel conditions is always the most suitably qualified candidate for rebroadcasting the encoded message. Eventually, other vehicles will end up updating their NAVs, accordingly, whenever they receive or overhear other RTB/CTB frames.

By applying the concept of mini-slot [31, 15, 129, 133], the DIFS interval is further divide into a number of mini-slots. Hence, in the proposed CARER scheme, vehicles start a timer in terms of mini-slots to enable them to contend for medium access. The total number of mini-slots MS_n can be calculated as

$$MS_n = \left|\frac{T_{DIFS}}{\Gamma}\right| \tag{3.14}$$

and Γ denotes the length of a mini-slot which is given by

$$\Gamma = T_{\Delta} + 2 \cdot \ell \qquad (3.15)$$

where T_{Δ} represents the total time duration it takes a transceiver to switch between the two modes (i.e., receiving and transmitting mode), and ℓ denotes the average propagation delay of the channel within the transmission range, T_r. The rebroadcasting metric η is then mapped to MS_n by dividing η into MS_n different segments, and each partition is given by

$$\mathcal{P}_0 = \left\lfloor \frac{\eta}{MS_n} \right\rfloor \qquad (3.16)$$

Upon successful evaluation of rebroadcasting metric η, each eligible rebroadcasting vehicle sets its back-off timer to k mini-slots provided its η falls within $\{\eta_{min} + ((\mathrm{k}-1) \cdot \mathcal{P}_0), (\eta_{min} + (\mathrm{k} \cdot \mathcal{P}_0))\}$, where k falls between the range of 1 to MS_n (i.e., $\mathrm{k} \in [1, MS_n]$). Finally, the vehicle that has the minimum value of η (i.e., η_{min}) will eventually reply the source node first with a CTB packet, and therefore, selected as the current rebroadcasting station, accordingly. Currently, to the best of our knowledge, there has not been a harmonized agreement on fading and shadowing models so far for vehicular communication systems [135]. In order to determine the received signal power, the Friis free-space model [154] is adopted in the theoretical analysis. In line with the work of Proakis, the bit error rate (BER) of the encoded messages over an additive white Gaussian noise (AWGN) channel with binary phase-shift keying modulation is taken as $X\left(\sqrt{(2\mathcal{E}_b/N_0)}\right) = X\left(\sqrt{(2P_r/r_b N_0)}\right)$, where $X(n) = \left(1/\sqrt{2\pi}\right) \int_n^{\infty} e^{-t^2/2dt}$, N_0 denotes the noise power spectral density, $\mathcal{E}_b$ represents the received energy per bit, r_b is the basic rate and P_r is the received power [43]. In [41], it is given that $e = 1 - \left(1 - X\left(\sqrt{(2P_r/r_b N_0)}\right)\right)^L = 1 - \left(1 - X(I/\Delta d)\right)^L$, with

$I = \sqrt{(2P_t G_t G_r (c/f_c)^2)/(r_b N_0 (4\pi)^2)}$, G_t is the transmitter antenna gain, P_t is the transmission power, G_r is the receiver antenna gain, c is the measured speed of light, and

f_c is the carrier frequency. Using the definition of PER e as given above, the rebroadcasting node selection metric (1) can be rewritten as

$$\eta = \left[1 - \left(1 - X\left(\frac{I}{\Delta d}\right)\right)\right]^{L} (E_{max})^{-1} + \left[\frac{\Delta v}{V_P} + \left(1 - \frac{\Delta d}{R}\right)\right] \qquad (3.17)$$

Therefore, η is a function of Δv, V_P, and Δd once the values of the parameters such as I, L and R are obtained. The minimum and maximum values of the rebroadcasting metric η are denoted by η_{min} and η_{max}, respectively. Consequently, it shows that the selection of mini-slots for network channel access contention solely depends on difference in distance as well as relative velocity to the source vehicle.

3.2.4 Ensuring Safety Message Priority

Safety-related messages from emerging vehicular safety applications normally require direct communication owing to their stringent delay requirement. For instance, in the case of a sudden hard breaking or accident, the vehicles following those ones involved in accident as well as those in opposite direction will be sent a notification message [170]. The proposed CARER protocol uses a multi-channel concept which accommodates both safety-related and infotainment messages. It provides support for the priority of different messages by the application of different ACs using different channel access settings, which in turn, enables highly relevant safety messages to be transmitted timely and reliably even when operating in a dense vehicular network scenario. Therefore, to ensure provision of guaranteed acceptable minimum delay to safety-related messages for inter-vehicle communications in the proposed vehicular communication protocol, the widely-used priority-based Enhanced Distribution Channel Access 802.11e (EDCA) scheme is adopted and refined for service differentiation. With the addition of the safety-related services, all the services are sub-divided into five (5) different classes (see Fig. 3.3).

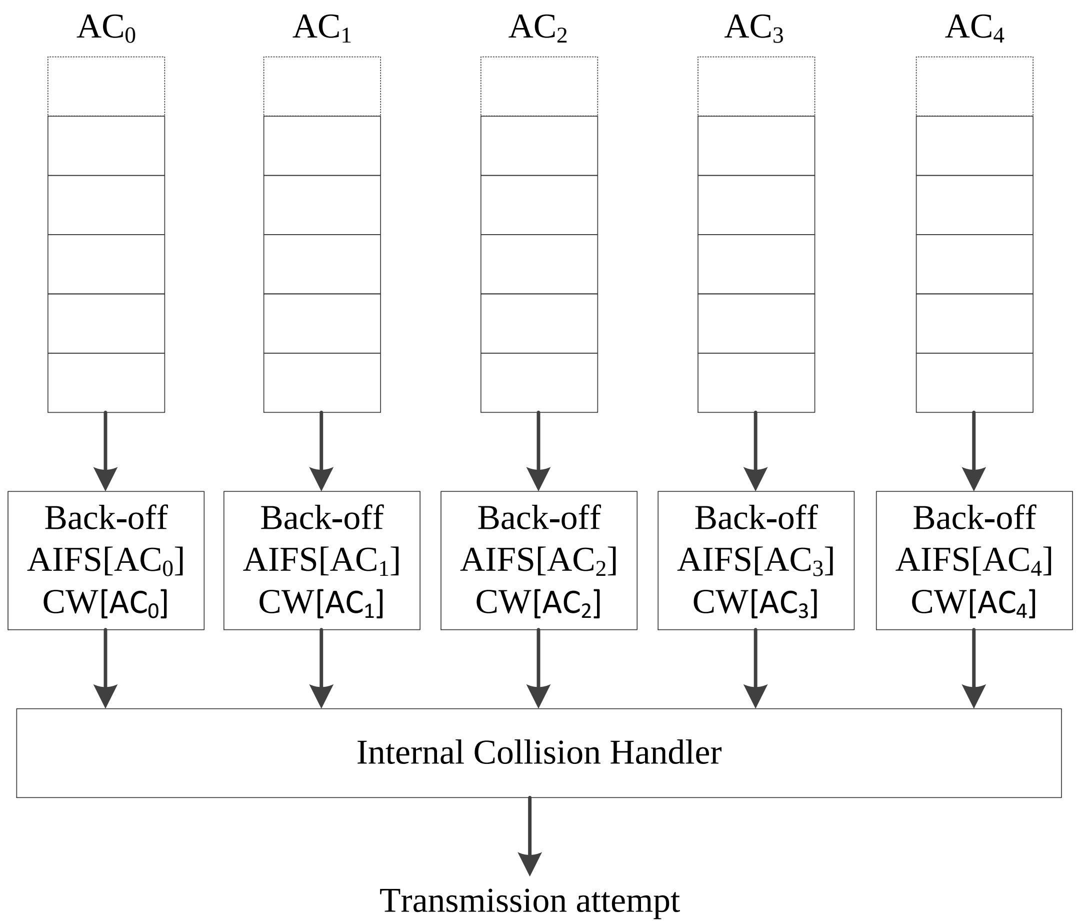


Fig. 3.3: The refined 802.11e MAC with five ACs

The refined EDCA is designed to enhance performance and provide differentiated QoS. Vehicular traffics of different classes are assigned to one of the five ACs as shown in Table 3.1 which is associated with a separate encoded message transmission queue and acts independently of others in each node. The QoS demands of the different ACs are differentiated by assigning different parameters such as AIFS values, Contention Window (CW) sizes, and TXOP limits. In order to guarantee the QoS requirements of Safety encoded messages, smaller values of AIFS/CW are assigned to increase the chances of winning the channel access contention. In the same manner, assigning larger TXOP limit elongates the channel holding periods of the vehicle that won the channel access contention. In other words, each of the five service classes maintain different level of priorities for accessing the shared media based on their individual ACs (see Table 3.1), (note that they are also referred to as Access Categories (ACs), where each AC maintains a different Arbitration Inter-Frame Space Number (AIFSN) to ensure that high priority class has less wait time for channel utilization. CARER protocol channel access method

Table 3.1: Value of the Parameters for Different AC Services

AC	CWmin	CWmax	AIFSN	PF	Wait-time
0	aCW_{min}	aCW_{max}	9	2	264 µs
1	aCW_{min}	aCW_{min}	6	2	152 µs
2	$[aCW_{min} + 1/2] - 1$	$[aCW_{min} + 1/2] - 1$	3	2	72µs
3	$[aCW_{min} + 1/4] - 1$	$[aCW_{min} + 1/2] - 1$	2	2	56µs
4	$[aCW_{min} + 1/4] - 1$	$[aCW_{min} + 1/2] - 1$	2	1	56µs

uses random access scheme based on carrier sense multiple access with collision avoidance (CSMA/CA) which adopts the same settings of AIFS and CW according to the specification of IEEE 802.11e as shown in Eq. (3.18) and (3.19) below;

$$AIFS[AC] = AIFSN[AC] \cdot aSlotTime + T_{SIFS} \tag{3.18}$$

$$CW[AC] = min\{(CW[AC] + 1)PF[AC], CW_{max}[AC]\} \tag{3.19}$$

where $AIFSN$ (i.e. $AIFSN_{[AC]} \geq 2$) is a positive integer, $aSlotTime$ and PF denote the duration of a timeslot and persistence factor (that is set to 1 and 2 for encoded safety and non-safety message, respectively). In line with the fundamental access mechanism of the legacy IEEE 802.11, vehicle i must sense the medium before initiating the transmission of the encoded messages. If the medium is sensed idle for a time interval greater than an AIFS, then vehicle i transmits the encoded messages. Otherwise, the transmission is deferred and a back-off process is initiated where vehicle i initializes and begins decreasing the back-off timer denoted as back-off counter. From Eq. (3.18) and Eq. (3.19), it can be noticed that as the values of the minimum CW and *AIFSN* decrease, the priority of the corresponding class increases, accordingly. In other words, vehicle i usually selects

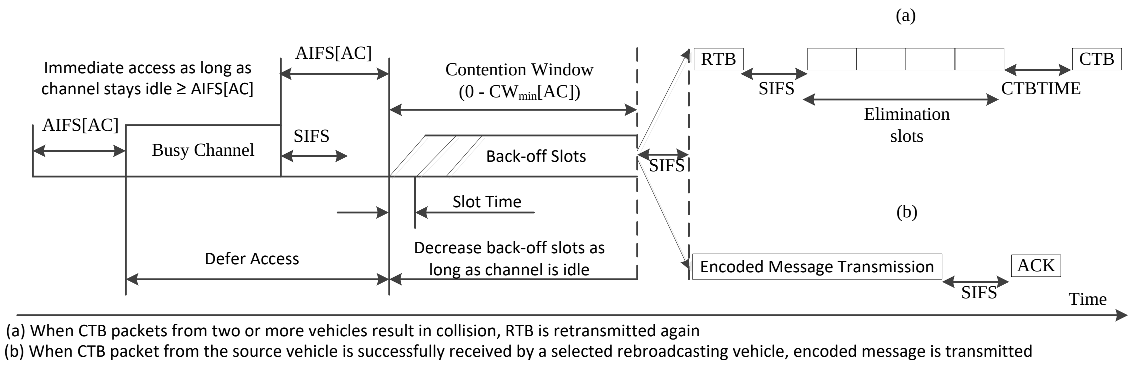


Fig. 3.4: Transmission sequence of packets. (a) Repeat of RTB and CTB packets. (b) Encoded messages and ACK packets.

a backoff timer from the minimum contention window for encoded safety message transmission, and doubles the CW after each unsuccessful retransmission attempt of the encoded safety message up to a maximum value referred to as maximum CW (CW_{max}). Hence, this process guarantees that encoded safety messages will always have the highest service priority.

3.2.5 CTB Packets Collision(s) Resolution

When there is more than one vehicle with the furthest possible equal distance gain from the source vehicle, all of them may find the channel empty after receiving RTB packet and continue to send CTB packets since other vehicles with less distance gain will certainly keep from replying with CTB frame. Additionally, other vehicles that have not replied with CTB packet will sense the shared media occupied and terminate their own back-off counters, even though they have initiated their back-off counters, accordingly. Unfortunately, since all vehicles start sending the CTB packets at the same time, their CTB packets will eventually result in collision. As a result, when the source vehicle overhears a transmission but unable to decode the CTB frame, it automatically detects the resultant collision and retransmits the RTB frame after SIFS time duration, as shown in Fig. 3.4 (a).

However, only the eligible rebroadcasting vehicles that have sent CTB frames which lead to collision will join the collision resolution. When an eligible rebroadcasting node that has formerly replied with a CTB packet to the source vehicle receives a retransmitted RTB packet, it will sub-divide $\mathcal{P}_0$ into MS_n segments. Hence, each of the sub-segments will be $\mathcal{P}_1 = \mathcal{P}_0/MS_n$. The vehicle now selects a random mini-slot, starts the back-off stage and divides their η between $[\lfloor \eta_{min} + (\eta - \eta_{min})/\mathcal{P}_1 \rfloor \cdot \mathcal{P}_0, \eta_{min} + (\lfloor \eta - \eta_{min})/\mathcal{P}_1 \rfloor + 1) \cdot \mathcal{P}_0]$ into MS_n sub-segments. The vehicle then waits for a total of k mini-slots (where $k \in \lfloor 1, MS_n \rfloor$) to reply the source vehicle with a CTB packet again, only if $[\eta_{min} + \lfloor(\eta - \eta_{min})/\mathcal{P}_1 \rfloor \cdot \mathcal{P}_0 + (k-1)\mathcal{P}_1] \leq \eta < [\eta_{min} + \lfloor(\eta - \eta_{min})/\mathcal{P}_1 \rfloor \cdot \mathcal{P}_0 + (k \cdot \mathcal{P}_1)]$. This process continues iteratively until a successful CTB frame is received by the source vehicle and a rebroadcasting vehicle is finally successfully selected or until retransmissions due to CTB packet collisions reach W_{max} times. The rebroadcasting metric developed for the proposed CARER protocol uses three unique variables such as distance gain (Δd), PER (e) and SNR, that is usually obtained with the aid the RTB packet received, and the relative velocity between vehicle i and the source vehicle. Hence, with these three variables, it is extremely unlikely that two vehicles will end up having exactly the same η. In other words, the designed collision resolution algorithm is highly effective for the selection of a unique rebroadcasting vehicle. Below, in Algorithm 1, is the pseudo-code of the rebroadcasting vehicle selection procedures.

Algorithm 1: Rebroadcasting Vehicle Selection Algorithm

```
Start the process…
Vehicle i received an RTB short frame
If Transmitter_address = Initial_address Then
  If vehicle i received the RTB short frame for the first time Then
     confirm Propagation_direction.
    If vehicle i's movement is in the intended packet dissemination direction
      Then
      Goto 1.
     Else
       update the network allocation vector
     End if
    Else
      Goto 1
```

13: **End if**

14: **Else**

15: **If** vehicle i received the RTB short packet for the first time **Then**

16: **If** vehicle i maintains a gain in distance in the intended packet dissemination direction **Then**

17: Goto 1.

18: **Else**

19: update the *network allocation vector*

20: **End if**

21: **Else**

22: **Goto** 1

23: **End if**

24: **End if**

25: Compute the PER, η_{min}, $\mathcal{P}_0$, velocity and distance gain

26: $\eta \leftarrow$ vehicle i to mini-slots

27: Initialise the back-off timer

28: **Goto** 1.

29: **If** $0 < repeat\_limit < W_{max}$ **Then**

30: Calculate $\mathcal{P}_{repeat\_limit} = \mathcal{P}_0 / [MS_n]^{repeat\_limit}$

31: $\eta \leftarrow$ vehicle i to mini-slots

32: Initialise the back-off timer

33: **Goto** 1

34: **Else**

35: Arbitrarily select a mini-slot MS_n.

[159]: Initialise the back-off timer

37: **Goto** 1

38: **End if**

While back-off counter $\neq 0$ **Do**

  If vehicle i receives the CTB short frame, a response from the RTB packet **Then**

    Stop the back-off counter

    update the *network allocation vector*

    Break

  End if

End while

If backoff counter $= 0$ **Then**

  Respond with a CTB packet

End if

Return

3.2.6 Dissemination of Encoded Message and ACK Packets

Upon successful reception of a CTB packet from the successfully selected rebroadcasting station, the source vehicle now transmits its encoded message, as is diagrammatically expressed in Fig. 3.4 (b). The source vehicle also includes in the broadcasted encoded packet the IP address of the successfully selected rebroadcasting vehicle which had replied with a CTB short frame. Though, other vehicles within the transmission coverage of the source vehicle can overhear and receive the broadcasted encoded packet because it is a broadcast transmission and not unicast, each of the recipients checks the rebroadcasting vehicle IP address field and will not reply with ACK packet if the IP address is not its own. Consequently, only the selected rebroadcasting vehicle whose IP address is contained in the broadcasted encoded message is responsible for sending an ACK packet to the source vehicle. Then, the same vehicle rebroadcasts (i.e., forwards) the received encoded message. Thus, ensuring a greater transmission coverage to enable vehicles outside the radio communication range of the source vehicle to receive the encoded message so as to make informed decisions with respect to the content of the encoded message.

Additionally, other vehicles between the source vehicle and the selected rebroadcasting vehicle that receive the broadcasted encoded packet cannot rebroadcast it just as they cannot acknowledge it. The ACK short frame when received by the source vehicle from the selected rebroadcasting vehicle guarantees the reliability of the encoded message dissemination and delivery in the desired propagation direction. If the source vehicle does not receive the ACK packet from the selected rebroadcasting vehicle before the set ACK time-out, then the back-off procedure explained in Section 3.2.4 will be followed until an ACK frame is successfully received by the sender. The steps adhered to in this back-off process are the same as those of legacy 802.11 standards family when an ACK frame does not reach the sender before a time-out.

3.2.7 Encoded Message Redundancy Control

When vehicle i has successfully received a CTB short frame, then i automatically becomes the current broadcast vehicle to broadcast the encoded packets after waiting one Short Inter-Frame Space (SIFS) time interval. Using the rebroadcast station selection metric η, the selected rebroadcasting vehicle acknowledges reception of the encoded packets once a successful transmission is done. Each vehicle maintains a list that contains the records of the recently received encoded packets in the last T ms. The entries in the list include the source vehicle address (*S_Addr*) and sequence number (*Seq_Num*) of the encoded packets. When vehicle i receives an encoded message, it checks the list and drops the encoded message if that exact *Seq_Num* and *S_Addr* of i have already been recorded before in the list. Consequently, the proposed CARER protocol controls and prevents packets redundancy by automatically deleting duplicates of already received encoded messages. Otherwise, the entries of the list are update with the successfully received encoded message. After the receiver, say vehicle j has successfully replied vehicle i with an ACK packet upon successful reception of the encoded packet, j automatically becomes the next broadcast station (i.e. the selected rebroadcasting node that will rebroadcast (or relay) the encoded messages to guarantee wider transmission coverage) and repeats the RTB/CTB handshake in the MAC layer. The transmission of the ACK frame is initiated at a time interval equal to one *SIFS* after the end of the reception of the transmitted encoded message(s).

3.3 Media Access Delay

The delay T_r caused by the process of choosing a vehicle to rebroadcast the encoded messages is the function of the time interval between the transmission of an RTB frame by the source node and successful selection of a vehicle that will rebroadcast the encoded messages. Hence, this delay T_r is computed as the addition of the two delays experienced due to an RTB/CTB handshake, and mathematically expressed as

$$T_r = AIFS[4] + T_{RTB} + T_{CTB} \qquad (3.20)$$

If w is denoted as the average time interval it took the back-off counter of the broadcast vehicle to reach 0, then

$$T_{RTB} = \sum_{i=0}^{\infty} 4p^i(1-4p)\left[i\left(w + t_{rtb\_r}\right) + (w + t_{rtb})\right] \qquad (3.21)$$

where $4p^i(1-4p)$ represents the probability that the sender successfully transmitted an RTB short packet at back-off period i with average corresponding delay of $i\left(w + t_{rtb\_r}\right) + (w + t_{rtb})$. Since the proposed protocol enables nodes to start a timer in terms of mini-slots to enable them to contend for channel access, if the i^{th} time slot is selected then w can be represented with $w|i\ \left(i \in \left[0, CW[4]\right]\right)$ which then allows the source node to uniformly select a time slot from $\left[0, CW[4]\right]$ so that

$$w = \sum_{i=0}^{CW[4]} \left(\frac{1}{1 + CW[4]}\right).(w|i) \qquad (3.22)$$

and,

$$w|i = \begin{cases} \sum_{d=1}^{i} \bar{X}_t, & i \in [0, CW[4]] \\ 0, & i = 0 \end{cases} \quad (3.23)$$

where X_t represents the average time delay in the i^{th} time slot of $CW[4]$ and $\bar{X}_t$ denotes the mean of the average time delay. This time delay may have been caused by the frozen time owing to a successful message transmission, collisions or simply an idle time slot.

The total access delay T of the encoded message is a function of the time interval between the arrival of the message at the head of the queue and its acknowledgement. This time interval consists of: 1) an arbitration inter-frame space (AIFS); 2) the delay T_{RTB} due to backoff procedure, the frozen time as a result of other ongoing broadcasts, the rebroadcasting (i.e., the retransmission) duration owing to an RTB collisions and the successful RTB broadcast time; 3) delay T_{CTB} due to retransmission as a result of a CTB collision and its successful transmission; and 4) the delay T_{XOR} due to the encoded message collision, successful transmission and acknowledgement. Accordingly, the overall encoded message access delay T becomes

$$T = AIFS[4] + T_{RTB} + T_{CTB} + T_{XOR} \quad (3.24)$$

Let X_{ic} represent the incidence that a station's encoded message transmission ended in collision in the i^{th} time slot while X_{is} represents the incidence of a successful transmission in the i^{th} time slot and X_{ij} represents the event that there is no transmission in the i^{th} time slot. Therefore, the probability that there is no attempt of transmitting the encoded message in the i^{th} time slot can be shown as

$$p_{(X_{ij})} = \prod_{i=0}^{4} (1 - p_i)^{(n_i)(x_j),i} \quad (3.25)$$

while the probability of successful transmission of the encoded message in the i^{th} time slot can be shown as

$$p_{(X_{is})} = \prod_{i\in[0,4]}^{4} (1-p_i)^{n_i} . \sum_{j=0}^{4} x_{j,}i . p_i . \binom{n_i}{1} . (1-p_i)^{(n_i-1)} \tag{3.26}$$

where

$$x_j, i = \begin{cases} 1, & \text{if } AIFS[i] \leq AIFS[4] + k \\ 0, & \text{otherwise} \end{cases}$$

and x_j, i cross-checks whether the nearby stations of AC[i] will be contending with the source node for the channel access in the i^{th} time slot of CW[4], and n_i represents the total number of neighbouring stations belonging to AC[i] which are contending for channel access. Consequently, the probability of collision at the attempt of transmission of the encoded message in the i^{th} time slot can be shown as

$$p_{(X_{ic})} = 1 - p_{(X_{is})} - p_{(X_{ij})}$$

$$= 1 - \left[\left(\prod_{i\in[0,4]}^{4} (1-p_i)^{n_i} . \sum_{j=0}^{4} x_{j,}i . p_i . \binom{n_i}{1} . (1-p_i)^{(n_i-1)} \right) - \left(\prod_{i=0}^{4} (1-p_i)^{(n_i)(x_j),i} \right) \right]$$

(3.27)

Thus, the overall average frozen period experienced by the transmitting vehicle per one successful encoded message transmission and one successful broadcast duration of AC[i] is denoted as $\bar{F}$. From Eq. (3.26), the successful broadcast probability of AC[i] can be obtained as $\prod_{i\in[0,4]}^{4}(1-p_i)^{n_i} . \sum_{j=0}^{4} x_{j,}i . p_i . \binom{n_i}{1}. \ (1-p_i)^{(n_i-1)}$, hence, the average frozen time due to one successful transmission of encoded message by the source broadcasting vehicle can be expressed as

$$\bar{F} = \prod_{i \in [0,4]}^{4} (1 - p_i)^{n_i} . \sum_{j=0}^{4} x_{j,} i . p_i . \binom{n_i}{1} . (1 - p_i)^{(n_i - 1)} . \mathbb{S}_{AC[i]} \qquad (3.28)$$

Let the total frozen time experienced by the source broadcasting vehicle as a result of one packet collision be denoted as $\bar{\mathbb{C}}$, which is approximately equal to $T_{RTB} + AIFS[4]$. Accordingly, the mean of the average delay in the i^{th} timeslot can be linearly expressed as

$$\bar{X}_t = \left(\bar{\mathbb{C}} \cdot p_{(X_{ic})}\right) + \left(\bar{F} \cdot p_{(X_{is})}\right) + \left(\varphi \cdot p_{(X_{ij})}\right) \qquad (3.29)$$

The total period of time between the successful reception of an RTB packet by the selected rebroadcasting vehicle and the successful reception of a CTB packet by the encoded message source vehicle, T_{CTB}, varies depending on the duration it takes the source vehicle to receive a CTB packet successfully from the selected rebroadcasting vehicle. With the proposed CARER protocol, the selected rebroadcasting vehicle initiates its back-off counter in order to reply with a CTB packet for the RTB packet received from the encoded message source node. A three state space $i, j,$ and k is used to illustrate the back-off processes which accurately represent the activities of the successfully selected rebroadcasting vehicle's back-off timer with back-off stage denoted by $i | i \in [0, W_{max}]$, the initial value of the back-off counter denoted by $j | j \in [1, MS_n]$, and the total number of elapsed mini-slots since the beginning of the back-off timer denoted by $k | k \in [0, MS_n]$. The wireless radio channel is hypothetically assumed to be in one of three possible states, such as success, collision, or idle state, which takes into consideration the cases of one transmission at a time, multiple simultaneous transmissions, and no transmission attempt, respectively, over the wireless radio channel. Let us define T_{suc} and T_{col} as the duration of a successful transmission, and collision duration of encoded packet, respectively. Hence, T_{suc} and T_{col} can be expressed, respectively as

$$T_{suc} = \left[\frac{L}{R}\right] + (AIFS + T_{PHY}) \qquad (3.30)$$

and

$$T_{col} = \left[\frac{L}{R}\right] + (EIFS + T_{PHY}) \qquad (3.31)$$

where L, R, and T_{PHY} represent the encoded packet length, the data rate, and the time duration of the physical layer convergence protocol (PLCP) preamble and header, respectively. Following the illustrated state transition through back-off slots in different contention zones, T_{CTB} becomes

$$T_{CTB} = \sum_{i=0}^{W_{max}} \left(\prod_{j=0}^{i-1} X_{t(j)} \right) [T_{col} + (T_{suc} \cdot T_i)] \qquad (3.32)$$

where T_{col} and T_{suc} represent the probability of collision and successful transmission of CTB packet, respectively, and T_i denotes the total period of time taken for the selected rebroadcasting vehicle to successfully reply the source node with a CTB packet, all at back-off stage i. Finally, the average period of time taken to successfully transmit the encoded packet can be given by

$$T_{XOR} = \sum_{i=0}^{\infty} p^i (1-p) \left[i \left(w + T_{RTB\_r} + T_{SIFS} + T_{ACK} + \right) + (T_{RTB} + T_{CTB}) \right] \qquad (3.33)$$

where $p^i(1-p)$ represents the probability of encoded packet successful transmission after i total number of attempts, and $\left[i \left(w + T_{RTB\_r} + T_{SIFS} + T_{ACK} + \right) + (T_{RTB} + T_{CTB}) \right]$ represents the average time taken to complete the i retransmission process.

3.4 Location-Aware Algorithm (LAA)

In VANETs, nodes are aware of their location (or coordinates) with the help of the embedded global positioning system (GPS). Vehicles also discover the location of their neighbouring vehicles from the status messages broadcasted periodically by each node which contains vehicle direction, velocity, position and MAC information. Given that the coordinates of the destination vehicle are known, the direction and distance from the source to the destination nodes is calculated by using vector formulae where the magnitude

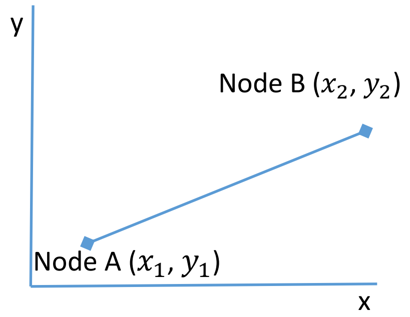


Fig. 3.5: Graphical representation of Vector $\overline{AB}$

of vector $\overline{AB}$ is the distance between station A, and B as depicted in Fig. 3.5. Mathematically, the transmitting vehicle calculates the distance to its destination nodes using

$$\overline{AB} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \qquad (3.34)$$

where (x_1, y_1) and (x_2, y_2) stands for initial and final coordinates of the vehicles, respectively. In the same manner, the direction of the vector $\overline{AB}$ is given by θ which is the formation of horizontal angle between point A and B.

$$\theta = tan^{-1}\left\{\frac{y_2 - y_1}{x_2 - x_1}\right\} \qquad (3.35)$$

3.5 Performance Evaluation Measurement

The following performance evaluation measurements are used in conjunction with the performance metrics used in [170] to evaluate the results of the analysis and the simulation experiments:

- *Data delivery rate* DD_{rate}, which is the rate of data packets that are successfully delivered to the selected rebroadcasting vehicle for the purposes of relaying to cover wider transmission range. It reflects the degree of reliability of the proposed scheme. The encoded data delivery rate is given as

$$DD_{rate} \stackrel{\text{m}}{=} \frac{N_{pRB}}{N_{pGEN}} \qquad (3.[159])$$

  where N_{pRB} and N_{pGEN} represent the total number of encoded messages successfully received from the source vehicle by the selected rebroadcasting vehicle and the overall number of encoded messages generated by the sender, respectively.

- *Average delivery delay* Δ_d, which is the average period it takes a data message to successfully arrive at the destination. Δ_d also encompasses the delay due to route discovery process, and the queue in data message broadcast. Thus, the average encoded packet delivery delay is given by

$$\Delta_d \stackrel{\text{m}}{=} \left(\sum_{k=1}^{N_{pRB}} \left[T_{N_{pRB_k}} - T_{N_{pGEN_k}} \right] \right) \Big/ N_{pGEN} \qquad (3.37)$$

  where $T_{N_{pRB_k}}$ and $T_{N_{pGEN_k}}$ denote the duration taken before the k^{th} encoded packet is successfully received by the selected rebroadcasting vehicle, and the exact time it was generated at the source vehicle, respectively.

- *System Throughput* $\mathcal{T}$, which is the aggregate of data rate delivered to all vehicles in the network that are beyond the radio transmission range of the original source node, as a result of the rebroadcast transmission of the selected relay vehicle. This throughput can also be referred to as aggregate throughput of the network. According to [170], the steady-state system throughput $\mathcal{T}$ of random access, and data packet broadcast network can be expressed as

$$\mathcal{T} = e^{-\lambda T} \sum_{i=1}^{\infty} i P_w(m) \frac{(\lambda T)^i}{i!} \tag{3.38}$$

where λ denotes the data packets arrival rate, T represents the average duration per time slot, λT denotes the average number of data packet attempted transmissions per time slot (i.e. the average offered load), and $P_w(m)$ is the probability of the selected rebroadcasting vehicle receiving an encoded packet without errors when m simultaneous transmissions are on the wireless channel. It is expressed as $P_w(m) = [1 - BER(m)]^L$ with L representing the length of the encoded packet in bits.

3.6 Simulation Setup

In this section, a comparison of CARER and reference protocol (SR scheme) is demonstrated using simulation experiments, focusing on a highway scenario with 200 vehicles.

3.6.1 Simulation Settings and Assumptions

Given that both wireless communication protocols as well as vehicular mobility significantly affect the overall performance, their joint effect has been considered by using

Table 3.2: Value of parameters used in the simulations

Parameter	**Value**	**Parameter**	**Value**
Frequency	5.9GHz	Data rate	3Mbps
Bandwidth	10 MHz	DIFS time	64μs
Modulation	BPSK	TX power	2mW
Packet size	512 byte	AR	37 byte

$\boldsymbol{E_{max}}$	8%	AG	17 byte
$\boldsymbol{f_c}$	2.4G	V_P	50 m/s
$\boldsymbol{G_t}$	1	P_t	15 dBm
$\boldsymbol{CW_{min}}$	15	G_r	1
$\boldsymbol{CW_{max}}$	1023	R	300m
$\boldsymbol{L}$	1024 byte	r_b	1M

a simulation tool which integrates both wireless network simulator, NS-2 [50] and a vehicular traffic generator, NS traffic trace generation tools which is presented in [59]. Specifically, NS traffic trace generation tool is a microscopic vehicular traffic generator used to reproduce the movement patterns of vehicles on the road. It allows for the consideration of realistic origins and destinations of the traffics, and movements restrained by the three-dimensional structure of mobile vehicles as well as by road rules and regulations. NS-2 is a well-used simulator in analysing vehicular networks [116] [41] [69] and was used to validate the analytical model. In the NS-2 simulation, an overhauled 802.11 model [21] is modified in order to ensure a higher level of simulation accuracy, and support preamble and PLCP header processing and capture, cumulative SINR computation, and frame body capture.

The publicly available highway patterns and NS-2 traffic trace generation tools were used in order to obtain an appropriate vehicular movement pattern for the simulation, as well as to achieve a realistic vehicular movement scenario with a dynamic network topology. The unique vehicular movement patterns were generated by means of microscopic traffic simulation and validated against real-life data collected on the motor highways. Specifically, a 3km long motor highway is considered, having 4 lanes comprising of 2 lanes in opposite direction with high vehicular traffic density. In these simulation experiments, mobile stations are arbitrarily distributed in the two opposite directions along the two-lane road pattern with a minimum average of 30m space between any given pair of adjacent vehicles that are in the same lane. In order to achieve accurate, close to real-life results, vehicular network simulations should be carried out with radio propagation models that include typical real-world effects, such as shadowing and fading [174]. The probabilistic Nakagami model with a fading intensity $\mathrm{m} = 3$ is used with the vehicles velocity randomly distributed in the range of the discrete set $V =$

$\{(30 + 10 * k)m/s,\ \forall k \in [0,3]\}$ for the simulation of channel fading effect. Additionally, both the PHY and MAC layer parameters configuration are in accordance with the IEEE 802.11p protocols [195]. The simulation experiments are based on the assumptions that the antenna gain at the receiver is 3dB, effective radiated power (ERP) is 23dBm, the receiver sensitivity is -85dBm (as recommended in [169]), the attenuation $PL(d) = 47.9 + 27.5\log_{10}(d)$, with d representing the distance in meters [23], and the threshold for the SINR is 10dB. Using the above assumed parameters configuration, the maximum radio communication distance in the absence of obstacles and interferers is 300m.

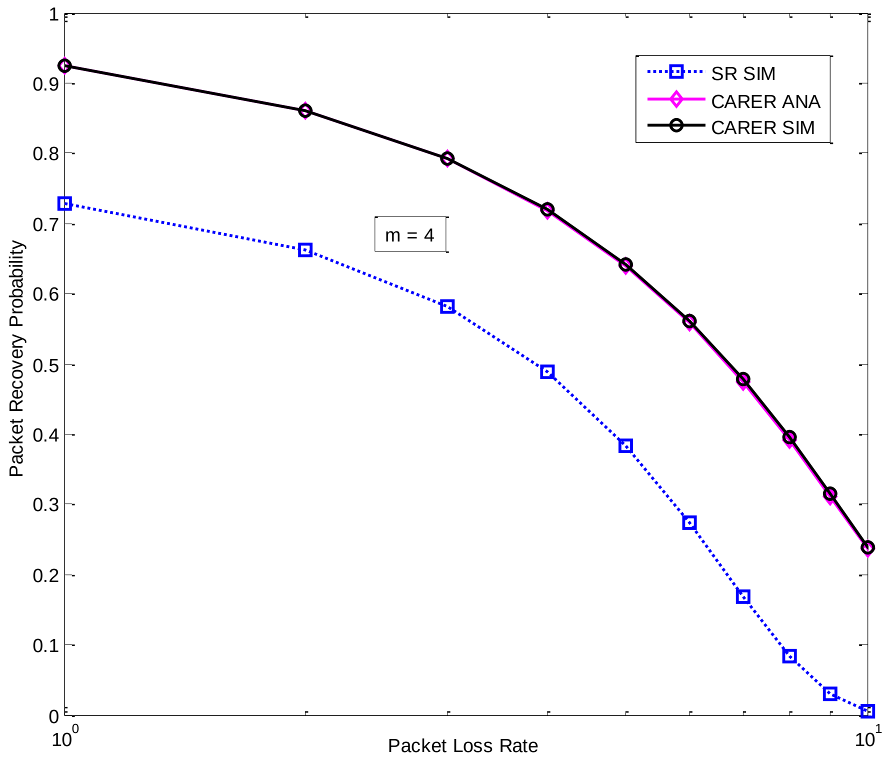


Fig. 3.6 (a): $m = 4$

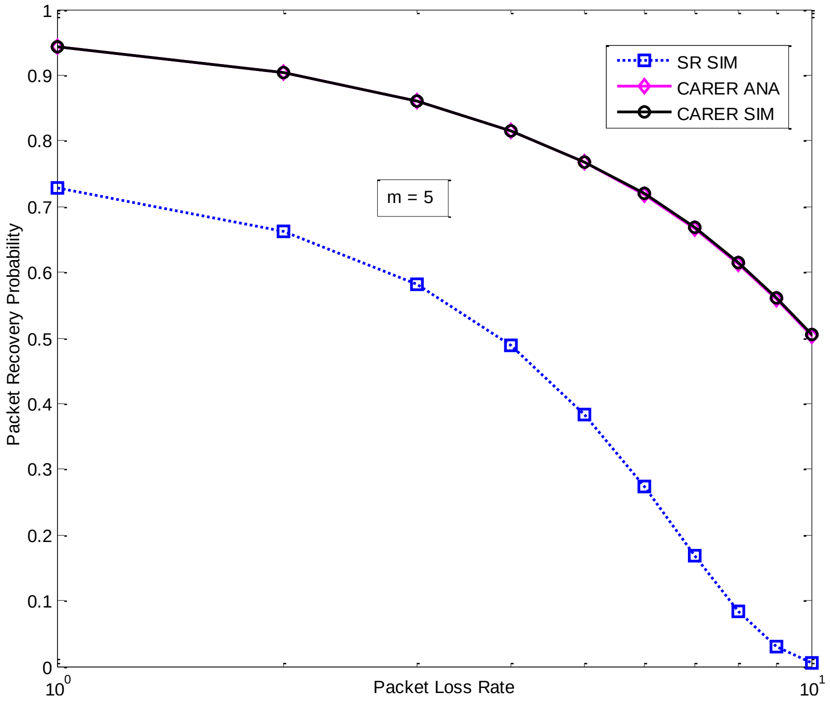


Fig. 3.6 (b): $m = 5$

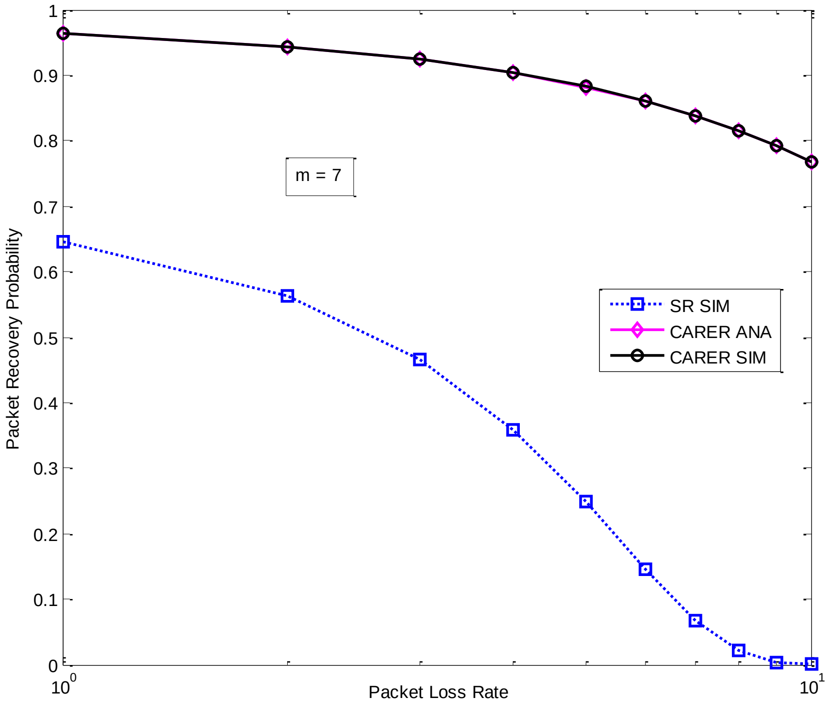


Fig. 3.6 (c): $m = 7$

Fig. 3.6 (a-c): Performance comparison between the CARER and the SR scheme using packet recovery probability as a function of packet loss rate.

3.6.2 Results and Discussion

The packet recovery probability and the percentage of collision probability as a function of the packet loss rate and generation probability, respectively, were analysed and calculated. The *x*-axis of the graphs shown in Fig. 3.6 (a) – (c) and Fig. 3.7 (a) – (c) indicate packet loss rate and generation probability obtainable in the network. The performance metrics used in the evaluation were measured in a saturated vehicular network[5]. Both the analytical and simulation results of the proposed CARER are compared with the simulation results of a Simple Repetition-based (SR) error recovery scheme that does not apply the network coding technology. Different results of packet recovery probability obtained from the simulations and the analytical model are shown in Figs. 3.6 (a) – (c) for the values of the numbers of retransmissions, $m = 4$, 5 and 7 respectively. Packet recovery probability is defined as the ratio of the total number of lost packets recovered through m number of retransmissions to the total number of packets lost. Figs. 3.6 (a) – (c) show both the analytical and simulation results of the recovery probability for both CARER and SR when the value of $m = 4$, 5 and 7 respectively.

The recovery probability of both CARER and SR starts to reduce significantly when data loss rate increases towards 10^1 (see Fig. 3.6 (a) – (c)). This rapid degradation in loss recovery probability (LRP) caused by increased change of data loss rate from 10^0 to 10^1 is due to the fact that fast retransmission of both the raw and encoded packets tends to congest the channel thereby resulting to excessive network overhead and the consequent QoS deterioration. Generally, UDP which resides at the transport layer shows increasing poor performance across the network whenever the overall data loss rate exceeds 10^0 towards 10^1. Therefore, as the rate of packet loss increases, more data transmissions are lost and even their retransmissions tend to be lost as well either due to channel congestion, increased network overhead or distance between the sender and the receivers. In Figs. 3.6 (a), there is a significant improvement (over 20% in maximum) in packet loss recovery ability of CARER over SR scheme. This can be explained by the fact that conventional error recovery techniques based on retransmission of packets repeat each transmission separately thereby congesting the channel excessively as opposed to CARER which combines two or more packets into one, without increasing the size of the packet through

[5] Saturated network is a standard in network performance evaluation and analysis [213], and it provides a practical estimation of the optimal performance achievable.

the assistance of network coding technology. In Fig. 3.6 (b), the performance gap between CARER and SR gets even wider due to increase number of retransmission from m = 4 to m = 5. This increased performance gap is expected considering that every retransmission of the encoded message by CARER provides higher chances of data loss recovery given the increased data content of the encoded message as opposed to SR which retransmits every packet separately.

More interesting result is witnessed in Fig. 3.6 (c) where there is a clear significant improvement (over 50% in maximum) in loss recovery probability of CARER over SR scheme. What is noteworthy in Fig. 3.6 (c) is not only the fact that the performance of CARER (both analytical and simulation results) increased, accordingly, with the increase in number of transmission from $m = 5$ to 7, but the packet loss probability of SR scheme decreased from 0.74 to 0.63 (over 10% decline in performance). This significant decline of packet recovery probability of SR can be explained by the fact that, though, retransmission-based loss recovery techniques increase the chances of recovering packets not received or correctly received in the previous transmission, the repeated packets increase network overhead. Thus, after a given number of consecutive repeats may lead to excessive channel congestion and consumption of a substantial amount of the channel bandwidth thereby giving rise to excessive increase of network overhead and further loss of data transmissions due to QoS deterioration. In other words, indiscriminate retransmissions proofs counter-productive in most cases.

Fig. 3.7 (a) – (c) shows the results of packet collision probability for both CARER and SR schemes for different values of m. The percentage of packets transmission collisions probabilities obtained from the simulations and the analytical model for varying numbers of retransmissions ($m = 2$, 5, and 7) were measured and the results shown in Fig. 3.7 (a) – (c). In general, CARER shows a performance gain (10% improvement) over SR as is evident in Fig. 3.7 (a) – (c) in terms of reduced data transmission collision probability. This can be explained by the fact that the defined parameter set for the EDCA used in WAVE standard is capable of prioritizing messages. Hence, under heavy network density (increased packet generation rate) with increasing number of nodes sending AC_3 packets especially, the collision probability tends to increase significantly. Therefore, the reduction in the percentage of packet collision probability that exist between the CARER and SR is expected given that an increased traffic density will undeniably lead to increased channel load especially for SR scheme when the total number of packet retransmission increases as opposed to CARER which uses network coding technology to combine several packets without necessarily increasing the encoded packet size. In other words, the total number of individual packets contention is reduced using CARER as a result of the coding technology applied in contrast to SR protocol.

The percentage of data collision probability of both CARER and SR starts to increase considerably as packet generation probability increases towards 1.0 (see Fig. 3.7 (a) – (c)). This rapid increase in the percentage of collision rate is caused by increased contention for access to the medium caused by high network saturation as the rate of packet generation increases under heavy network density. In the same manner, Fig. 3.7 (b) – (c) shows a gradual increase in the percentage of packet collision probability across the results of both the simulations and analytical model for the CARER and the SR protocol as the number of data retransmission increases from m = 2 (see Fig. 3.7 (a)) to m = 5 (see Fig. 3.7 (b)) and when m = 7 (see Fig. 3.7 (c)). This observed increase in percentage of collision rates for both schemes is as a result of increased channel congestion and contention due to high number of packets retransmissions to ensure high level of lost packet recoverability.

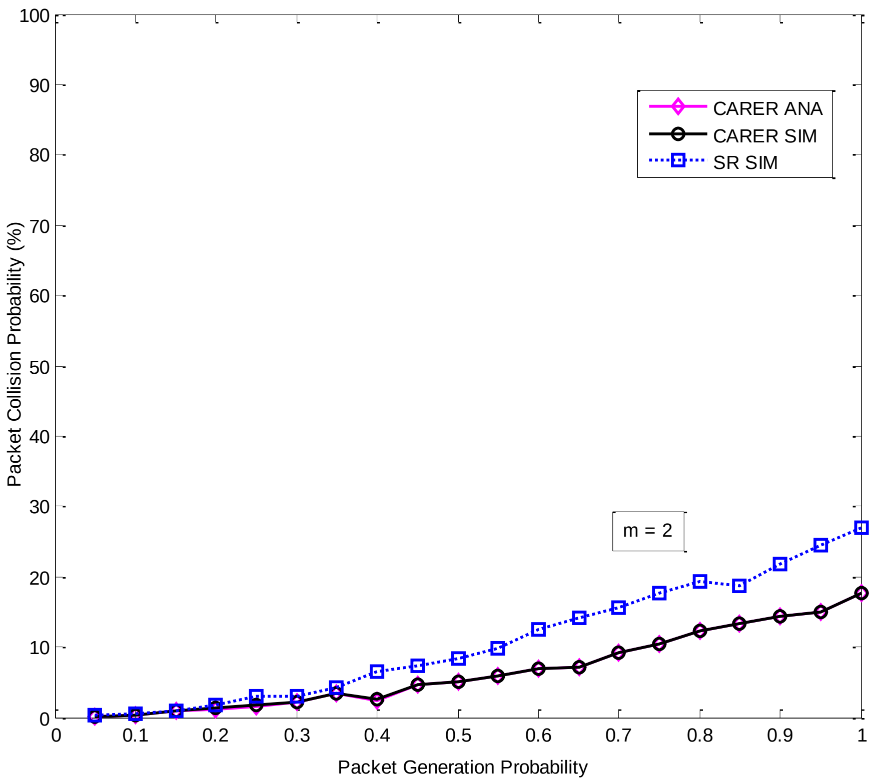


Fig. 3.7 (a): $m = 2$

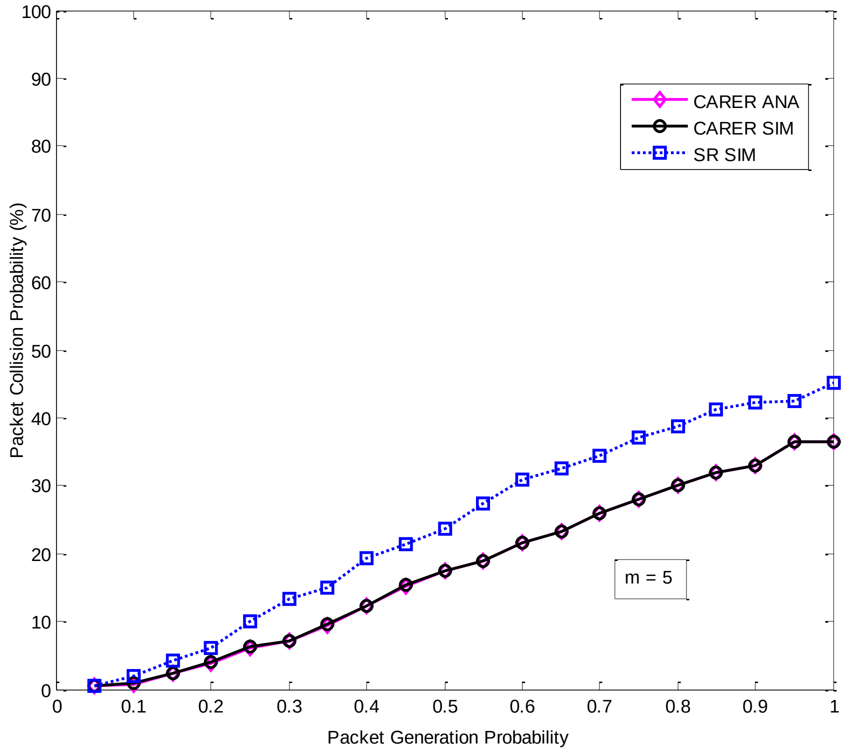


Fig. 3.7 (b): $m = 5$

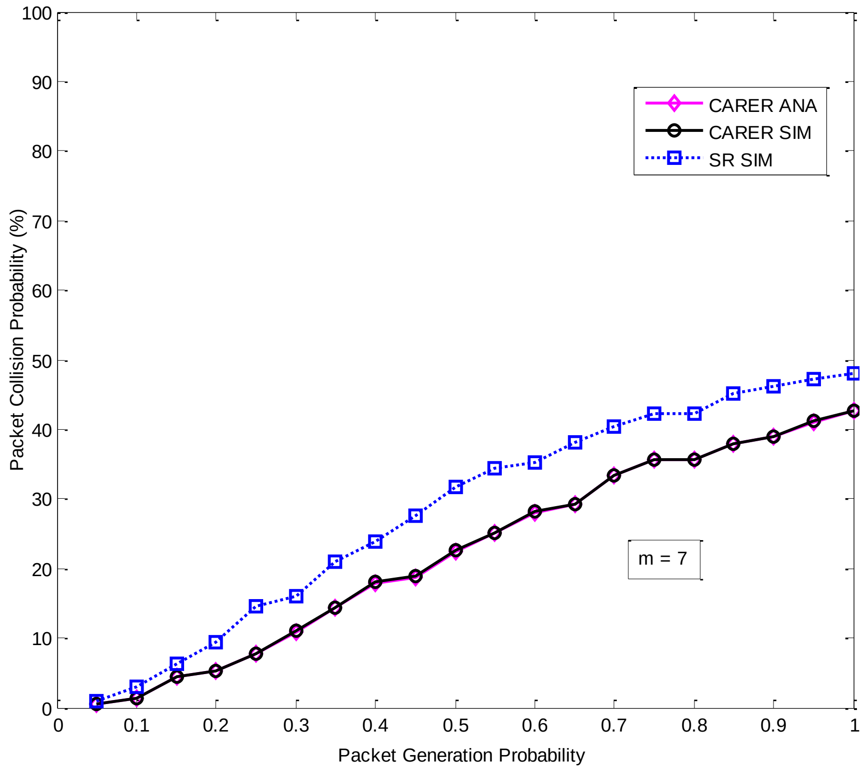


Fig. 3.7 (c): $m = 7$

Fig. 3.7 (a-c): Performance comparison between the CARER and the SR scheme using percentage of packet collision probability as a function of packet generation probability.

However, the increased collision rate can be minimized with proper adjustment of CW according to ACs. In other words, adjustment mechanism for CW and AIFSN should be finely tuned when traffic load increase with its associated high packet collision probability. Hence, dynamically adjusting the CW minimizes the internal and external collision of IEEE 802.11e [177].

The encoded packet delivery rate in Fig. 3.8 (a) – (c) as a function of the packet generation rate (packets/s) is analysed and calculated. The *x*-axis of the graphs shown in Fig. 3.8 (a) – (c) indicate packet loss rate and generation probability obtainable in the network. The results of encoded packet delivery rate achieved from the simulations and the analytical model are shown in Figs. 3.8 (a) – (c) for $m = 2$, 5, and 7, respectively.

The average delivery rate of both CARER and SR/ELR protocols starts to decline significantly as packet generation rate increases towards 10^1 (see Fig. 3.8 (a) – (c)). The resultant steep degradation in data delivery rate is due to the increased change of data generation rate (i.e. increase in the total number of packets) towards 10^1. The steep increment of packets generated per second coupled with fast retransmissions of data packets tends to congest the channel thereby resulting to excessive network overhead and the consequent deterioration of overall network QoS. From the results depicted in Fig. 3.8 (a) – (c), it is observed that, for both low and high rate of packet generation, CARER protocol can offer a performance advantage of multiple orders of magnitude. In Fig. 3.8 (a), the performance level of both protocols seems to tally with each other, though CARER shows a minimal edge over SR (up to 4% data delivery performance advantage). Similarly, this little gap in performance can be explained by the fact that SR/ELR protocol transmits each packet separately as opposed to CARER which combines two or more packets into one, without increasing the size of the packet through the use of network coding concept. In Fig. 3.8 (b), the performance improvement gap between CARER and SR/ELR gets even wider due to increased number of retransmission from m = 2 to m = 5. This increased performance advantage is expected considering that every retransmission of the encoded message by CARER provides higher chances of data packets delivery given the increased data content of the encoded message as opposed to SR which retransmits every packet separately.

In Fig. 3.8 (c), a clear significant improvement (over 30% in maximum) of data packets delivery rate of CARER over SR/ELR protocol as the value of m increases from 5 to 7. It is observed in both Fig. 3.8 (b) and (c) that not only did the performance of

CARER (both analytical and simulation results) exhibit an improved performance in terms of the number of data packets delivery with an increase in number of m from 5 to 7, but the performance of both protocols shows a decline as the number of retransmission attempts climaxed at 7. However, the degree of performance degradation is more conspicuous in SR/ELR protocol compared to CARER protocol. This development can be explained by the fact that retransmission proofs counter-productive after a certain number of attempts. As for the explanation regarding the observed significant decline in data packet delivery rate of SR protocol from 0.9 to 0.7 in Fig. 3.8 (c), the repeated packets resulted to increase network overhead because every one of the packets are transmitted separately as opposed to CARER which uses network coding to combine N independent packets into one.

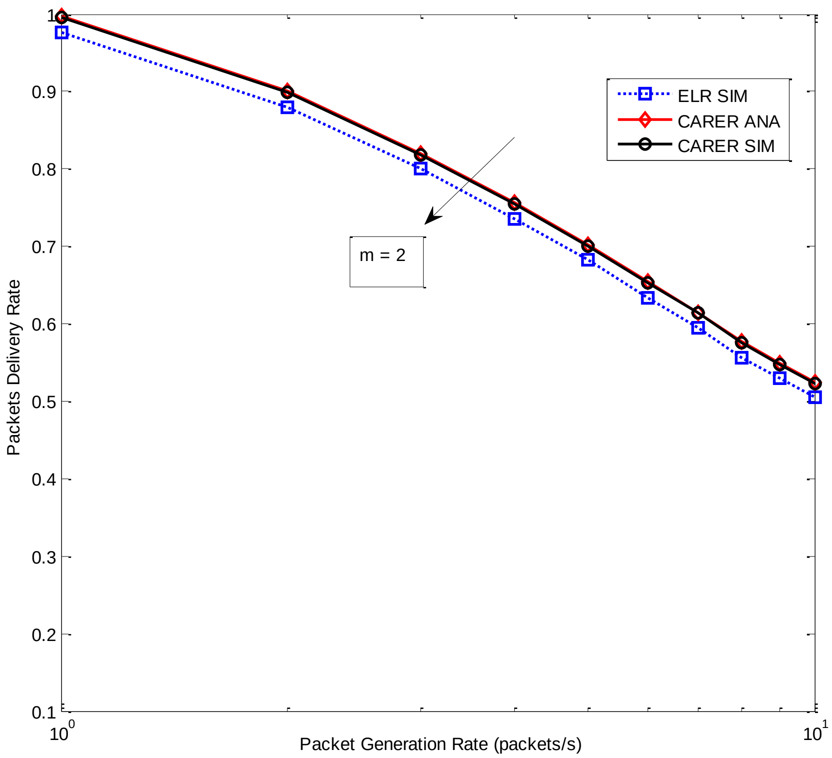


Fig. 3.8 (a): $m = 2$

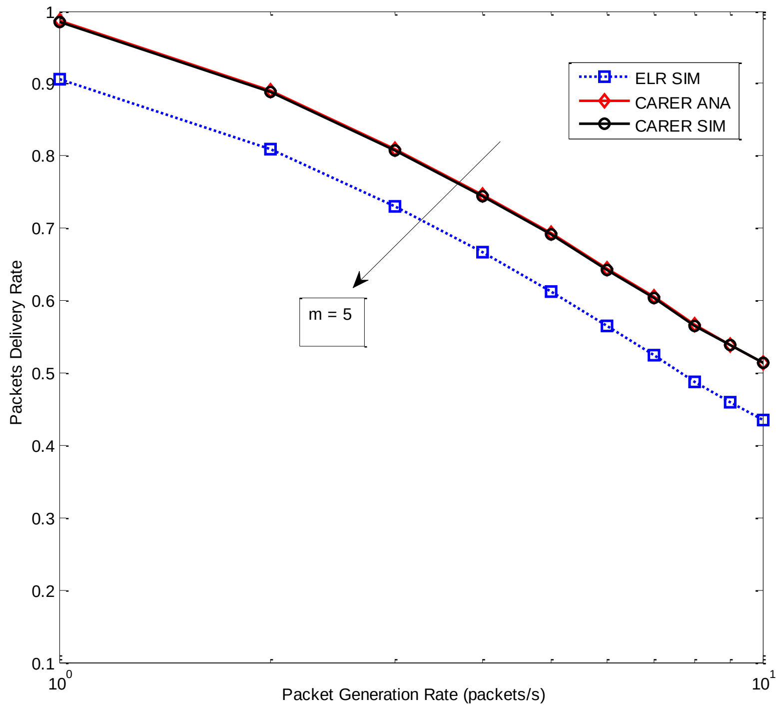


Fig. 3.8 (b): $m = 5$

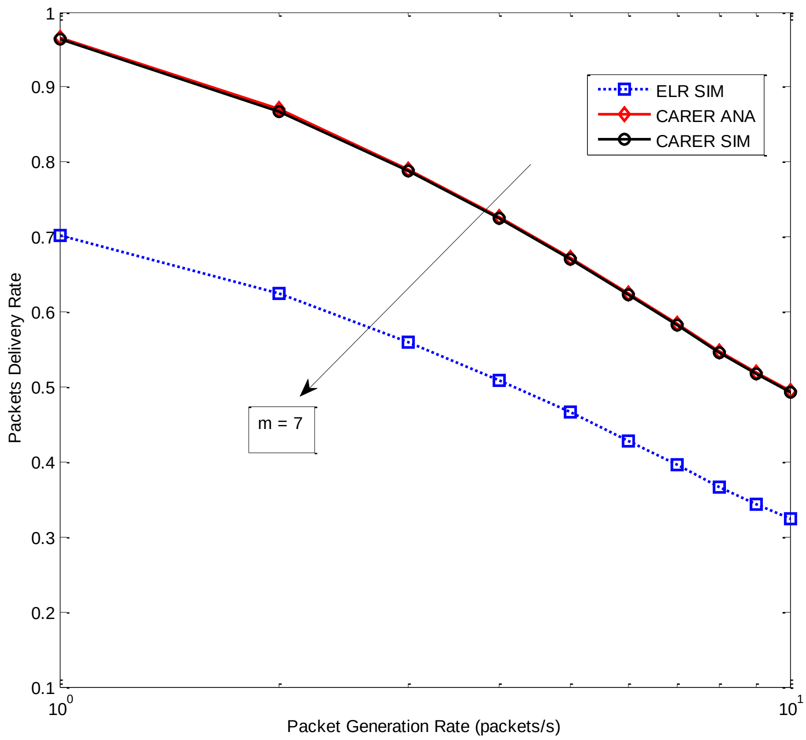


Fig. 3.8 (c): $m = 7$

Fig. 3.8 (a-c): Performance comparison between the CARER and the ELR scheme using packet delivery rate as a function of packet generation rate (packets/s)

Hence, after a given number of consecutive repeats (m = 7), the communication channel becomes excessively congested and a substantial amount of the channel bandwidth is also consumed, thereby giving rise to significant QoS deterioration, which in turn, affected the delivery rate (as is evident in Fig. 3.8 (c)).

In general, it can be seen from Fig. 3.8 (a) – (c) that the analytical results practically coincide with the simulation experiment results (95% confidence interval). It is clearly demonstrated from Fig. 3.8 (a) – (c) that data packets delivery rates (which represent the probability that all vehicles within the evaluated area receive the broadcasted packets successfully) decrease dramatically with an increase in the packets generation rates. In other words, it shows that the data delivery rates get smaller as the traffic density becomes heavier.

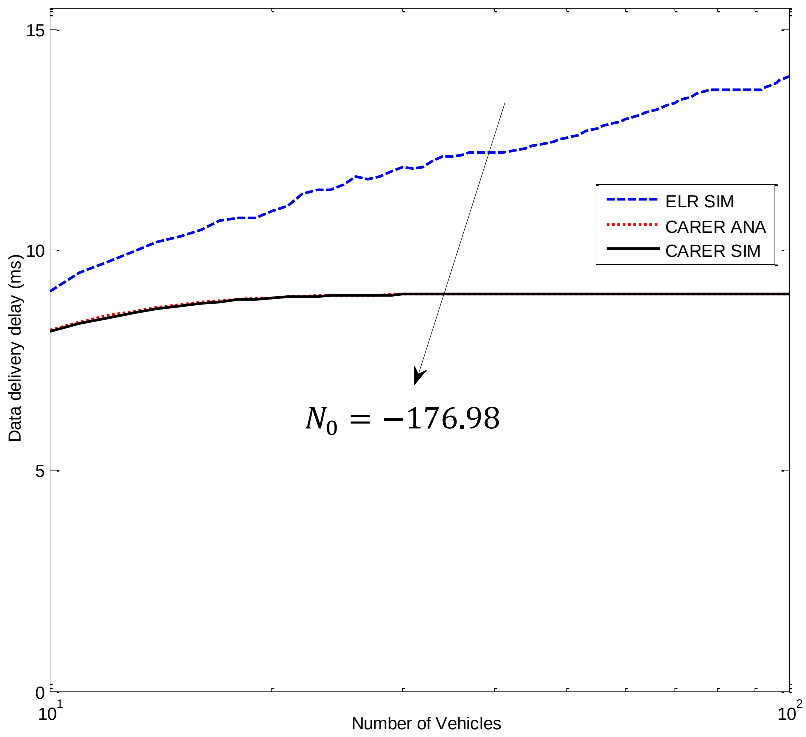


Fig. 3.9 (a): $N_0 = -176.98$

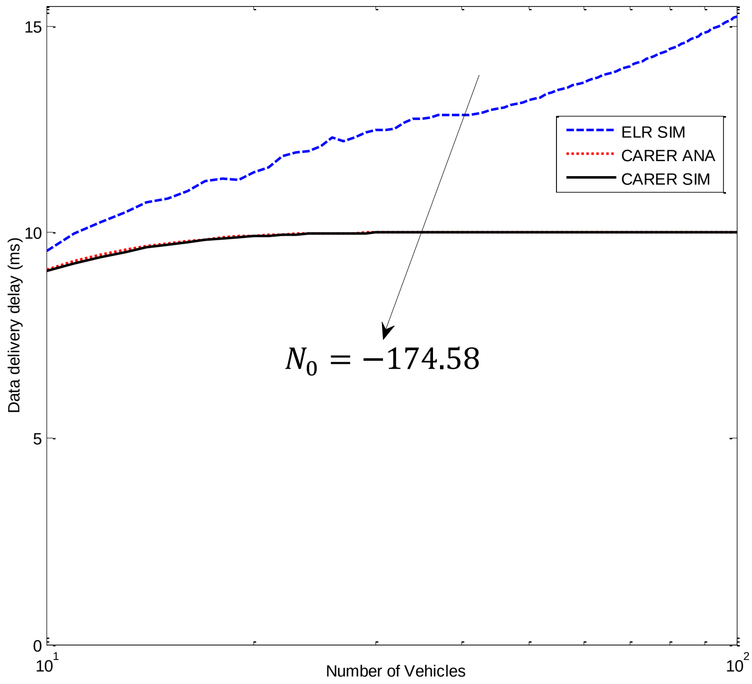


Fig. 3.9 (b): $N_0 = -174.58$

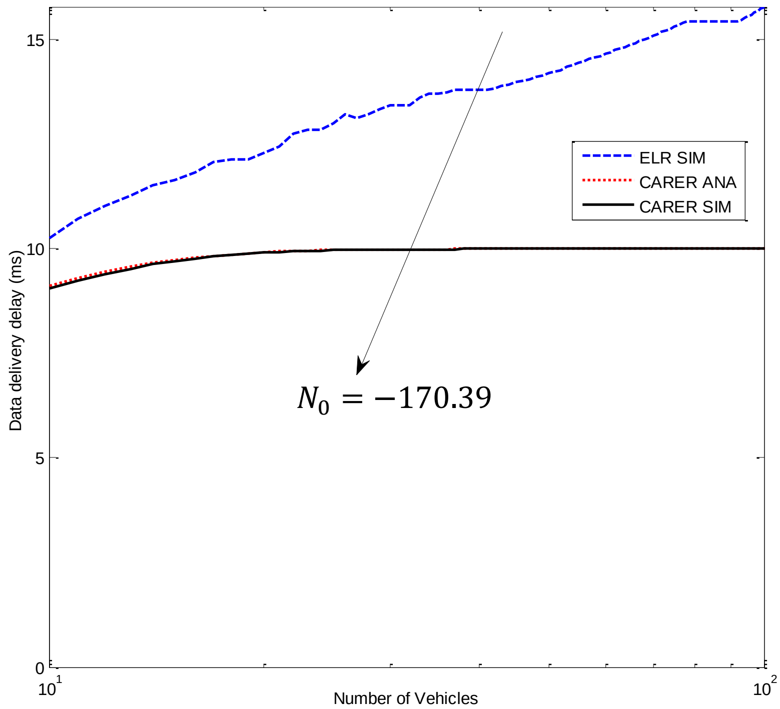


Fig. 3.9 (c): $N_0 = -170.39$

Fig. 3.9 (a-c): Performance comparison between the CARER and ELR scheme using data delivery delay as a function of number of vehicles (i.e., vehicular traffic density).

In Fig. 3.9 (a) – (c), the results of the average data delivery delay were measured as a function of both vehicular density and background noise N_0 levels. It is clearly seen that the average data access delays of the SR protocol are far higher in multiple orders of magnitude compared to those of the CARER protocol, and the performance gap steeply increases with the increase of number of vehicles and background noise levels (see Fig. 3.9 (a) through Fig. 3.9 (c)). The observed performance improvement in terms of average data access delay of CARER over SR protocol is possible due to several features associated with CARER protocol: 1) the CARER protocol uses the adjustment of performance parameters such as CWmin, CWmax, AIFSN, and PF which makes it possible for packets with higher QoS requirements (i.e. safety-related packets) to be accorded highest priority thereby resulting in a smaller access delay, as opposed to SR protocol, where safety-related packets have to contend with other non-safety-related packets with the same priority; and 2) with the CARER protocol, a rebroadcasting metric η, is used to successfully select the most suitable vehicle, which in turn, enables the selected node to only wait a minimum number of mini-slots to reply an RTB short packet with a CTB packet, as opposed to SR protocol.

Similarly, Fig. 3.10 (a) – (c) show the end-to-end system throughput measured as a function of number of vehicles (i.e. traffic density). Compared to SR protocol, CARER improves the end-to-end system throughput by multiple orders of magnitude. As expected, CARER protocol outperforms SR scheme under all workloads (i.e. vehicular density) as a result of: 1) application of network coding technology to increase the content of every single transmission (by XORing n packets into one encoded packet), 2) using a cross-layer approach empowered with a selection metric η to choose only one rebroadcasting station at each hop, which not only can eliminate the inherent problem of broadcast storm associated with broadcast transmission but can alleviate the hidden station problem and increase the packets transmission reliability.

With m = 7 in Fig. 3.10 (c), there is not only a clear significant improvement in terms of average end-to-end system throughput shown by CARER over SR protocol, but the system throughput of SR protocol got lowered almost by half compared to the result in Fig. 3.9 (a).

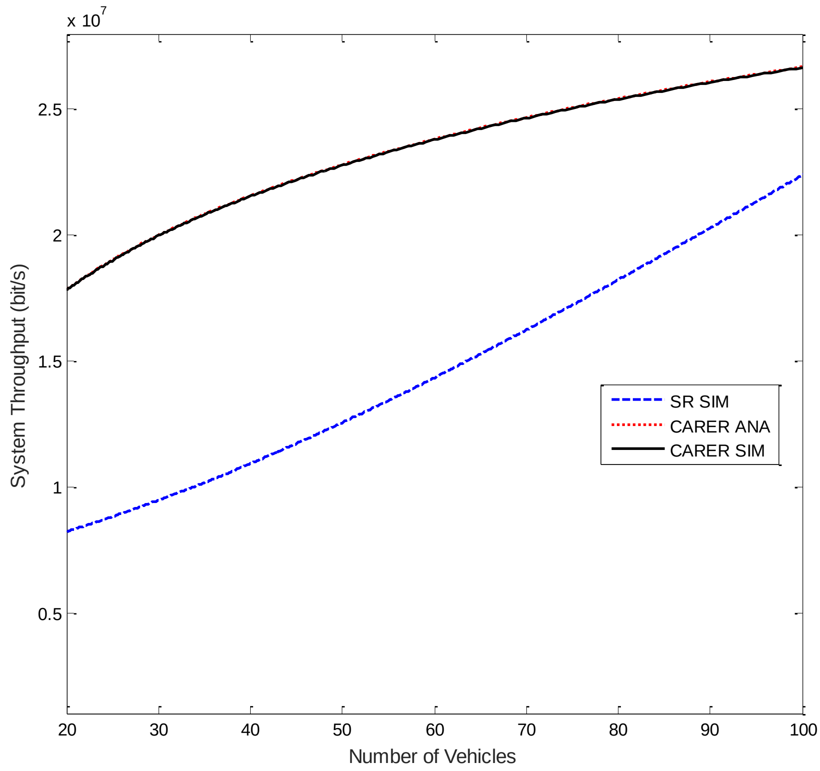


Fig. 3.10 (a): $m = 2$

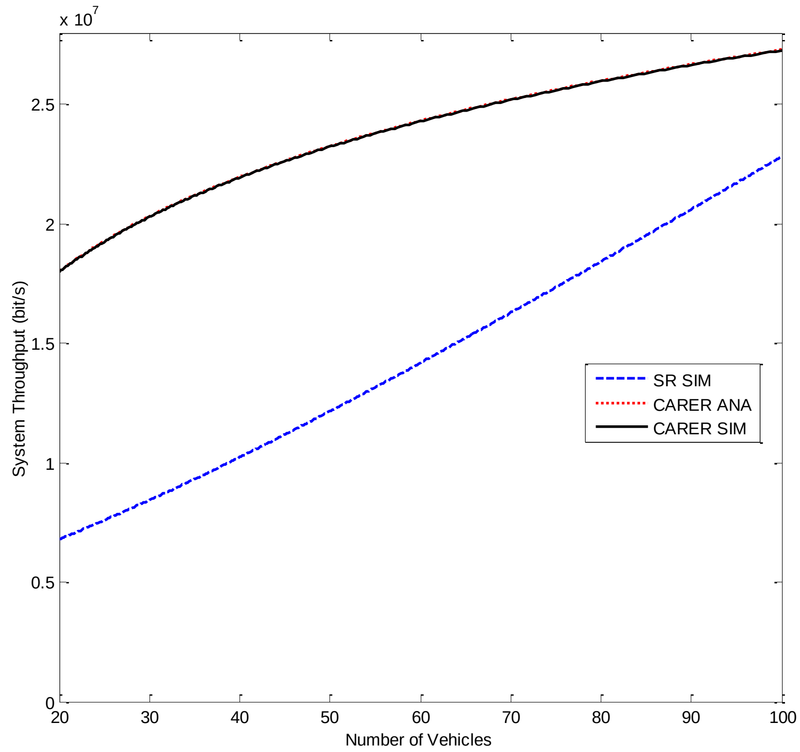


Fig. 3.10 (b): $m = 5$

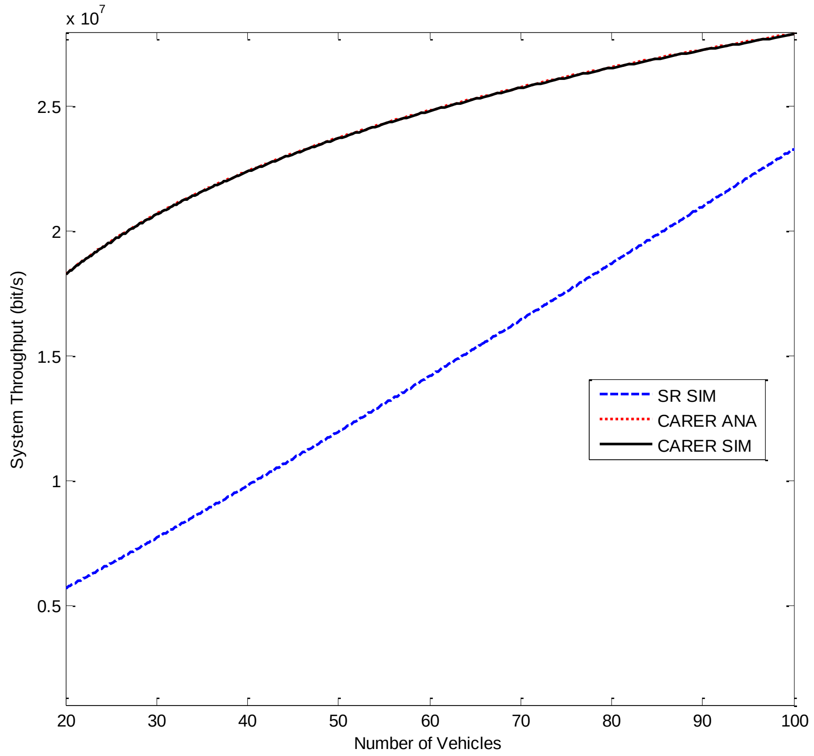


Fig. 3.10 (c): $m = 7$

Fig. 3.10 (a) – (c): Performance comparison between the CARER and the SR scheme using average system throughput as a function of number of vehicles (i.e., vehicular traffic density).

This can be explained by the fact that high number of packets retransmissions can lead to excessive network overhead and congestion. Thus, resulting to packet collision, which counters performance in terms of achievable end-to-end system throughput for SR scheme, whereas CARER protocol which combines *n* packets into one without increasing the size of the packet through the use of network coding technology provides higher chances of data delivery given the increased data content of the encoded message.

Chapter Four

Broadcast Reliability through Random Network Coding (RNC) and Cooperative Cross-layer MAC Communication*

4.1 Introduction

The study presented in this chapter investigates how to apply the combination of RNC and vehicle clustering technique with the aid of cooperative packet dissemination so as to achieve improved transmission reliability, maximize the achievable network throughput, and enhance bandwidth efficiency. Several studies have shown that RNC can asymptotically achieve both unicast and multicast capacity in wireless networks, which are characterized by known error-prone wireless channels. Although the proposed CARER protocol discussed in the previous chapter demonstrates an overall impressive performance in terms of successful packet recovery probability, high data delivery rate, minimum delivery delay, and high system throughput across the vehicular networks; the level of incurred network overhead cannot be overlooked. The high level of overhead can be partly due to the use of a high complex rebroadcasting node selection metric, which is applied by CARER scheme to determine and select the most suitably qualified candidate (i.e. vehicle) for rebroadcasting the encoded packets, and the processes involved in selection procedure. Furthermore, this chapter considers the benefits of combining RNC concept with vehicle clustering technique, since vehicle clustering is known to sub-divide the whole vehicular network into separate manageable group (or sub-networks) primarily for boosting the overall network performance.

Hence, in this chapter, by combining the potentials of RNC, vehicle clustering technique, and cooperative cross-layer MAC vehicular communication method, a cluster based vehicular communication scheme, named Reliable and Enhanced cooperative Cross-layer MAC (RECMAC) scheme is proposed. This vehicular communication

* Part of this chapter has been peer reviewed and published in [P.3], [P.11] and [P.13] as shown in list of publications.

scheme based on RNC, vehicle clustering, and cooperative communication technique aims to improve encoded message broadcast transmission reliability and maximise optimal achievable throughput with low algorithmic complexity so as to guarantee low network overhead, which in turn, results to improved overall network QoS. Thus, in order to resolve the challenge of heavy network overhead, which is associated with the proposed CARER protocol in Chapter 3, the proposed RECMAC scheme, through vehicle clustering technique minimises the adverse effect of unhealthy contention for channel utilization by sub-dividing the entire vehicular network into separate manageable clusters. Each cluster has its own Cluster Heads (CH). The CHs control both intra-cluster and inter-cluster communication in order to avoid heavy communication overhead, especially in a saturated vehicular network environment. A refined Cluster Member (CM) to CH (CM-to-CH) handshake is also developed, which helps to prevent heavy communication overhead as a result of increased channel congestion and contention for utilization. Additionally, as oppose to the use of a high algorithmic complex rebroadcasting node selection metric which is applied in CARER scheme to determine and select the most suitably qualified encoded packets rebroadcasting vehicle, the proposed RECMAC scheme in this chapter simply allows the next-hop CHs to re-encode and rebroadcast (or relay) the coded messages to enable the clusters beyond the transmission coverage of the source vehicle to receive the encoded messages.

4.2 Theoretical Basis of Random Network Code based Retransmission

4.2.1 Proposed RECMAC System Model

With the algorithm of the proposed RECMAC protocol, packets transmission is cluster-based, where each cluster is composed of N mobile stations as is demonstrated in Fig. 4.1. The model is built on the assumption that the network is saturated with the source mobile station having packets to broadcast to destination vehicle with the intention that other members of the source cluster will overhear the broadcasted messages. In other words, if Cluster B needs to inform the vehicles in Cluster E about an emergency ahead, the communication must be propagated through Cluster C, since Cluster C is the intermediate cluster between B and E.

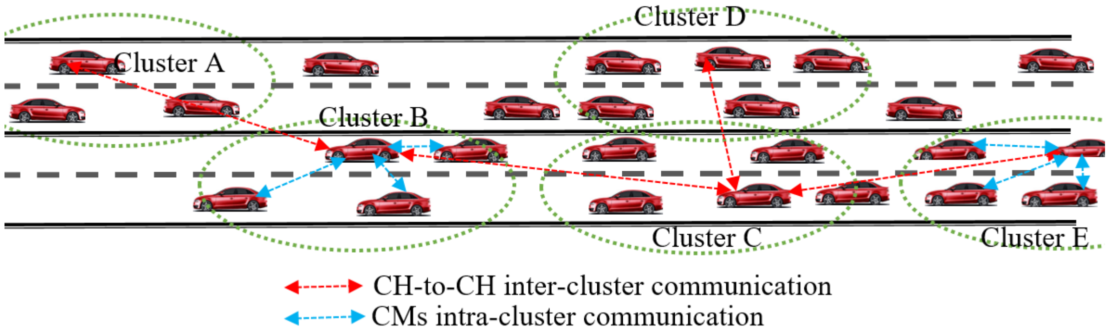


Fig. 4.1: A typical vehicular clustering system model

4.2.2 RECMAC Scheme Algorithm

The proposed RECMAC Scheme algorithm consists of two stages such as packets encoding (see Fig. 4.2 for detailed packets encoding opportunities and processes) at the CH of the source cluster, and packets decoding (see Fig. 4.3) at the destination node. It is noteworthy to mention that all vehicles maintain a virtual packet pool Ƥ (or a virtual buffer), $(Ƥ \in \mathbb{N}) = (P_1, P_2, P_3, \cdots, P_{\mathbb{M}})^{\mathbb{T}}$, where $\mathbb{N}$ and $\mathbb{M}$ denote a set of natural numbers, and the total number of self-generated and received packets from other vehicles within the last $\mathbb{T}$ (ms), respectively. Prior to packets coding, the source vehicle generates a matrix of $1{\times}\mathbb{M}$ encoding vector $\mathbb{V}$, which is randomly computed over the Galois Field $(GF(q)$. Then, random network coding is used to encode both the native and received packets Ƥ contained in the virtual buffer as

$$\mathbb{C} = (P_1, P_2, P_3, \cdots, P_{\mathbb{M}})^{\mathbb{T}} \cdot \mathbb{V} \tag{4.1}$$

Firstly, the source vehicle makes single-hop broadcast of the coded data packets $\mathbb{C}$ to the Cluster Members (CMs). The encapsulation formation of the encoded data packets $\mathbb{C}$, and encoding vector $\mathbb{V}$ into one frame is depicted in the diagram shown in Fig. 4.4. Since all the nodes within the source cluster (i.e., the CMs) are all in radio communication range of one another, it is guaranteed that all the vehicles around the immediate zone of interest (ZoI) (i.e. the area where a traffic emergency has ensued) will receive the broadcast transmission from the source vehicle provided that the pre-set threshold SNR_0 is less than the received Signal-to-Noise-Ratio (SNR). In order to avoid transmission collision, only the CH has the privilege of replying the source vehicle with a CTB and an

ACK frame to acknowledge the successful reception of the broadcasted encoded data packets $\mathbb{C}$ by the source vehicle.

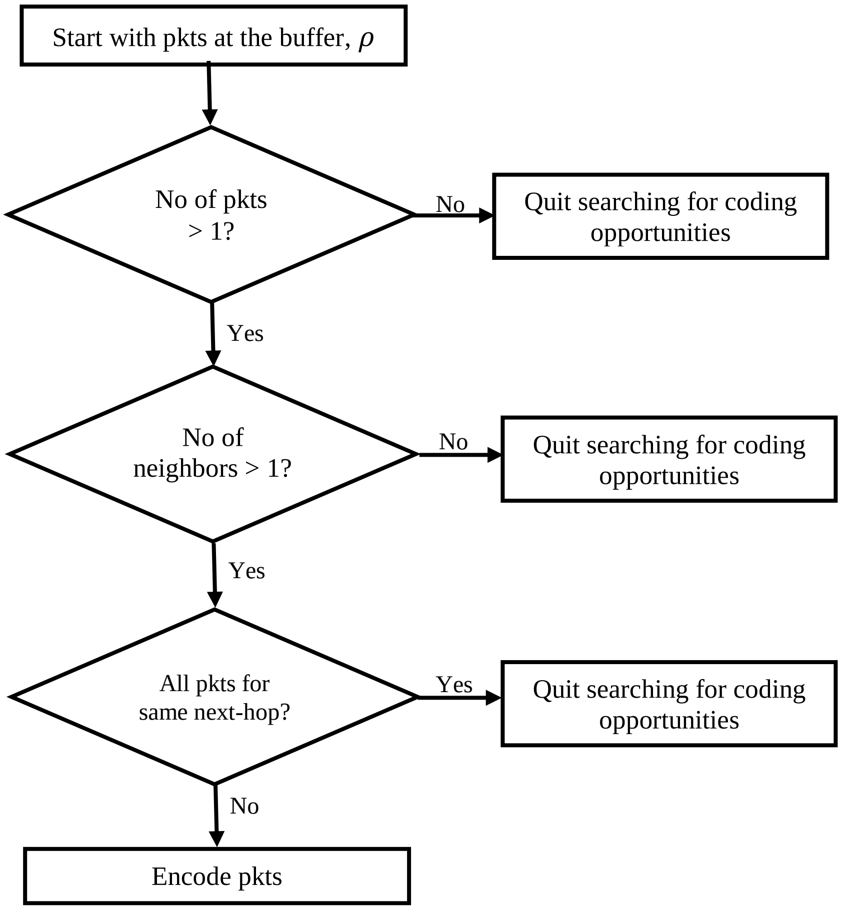


Fig. 4.2: Flowchart for packets encoding opportunity and processes.

Where $\rho \in \aleph = \{P_1, P_2, P_3, \dots, P_n\}$ denotes the possible set of packets (pkts) to be coded, which is the set of packets contained in the buffer (i.e., packet pool) as heard in the last T seconds.

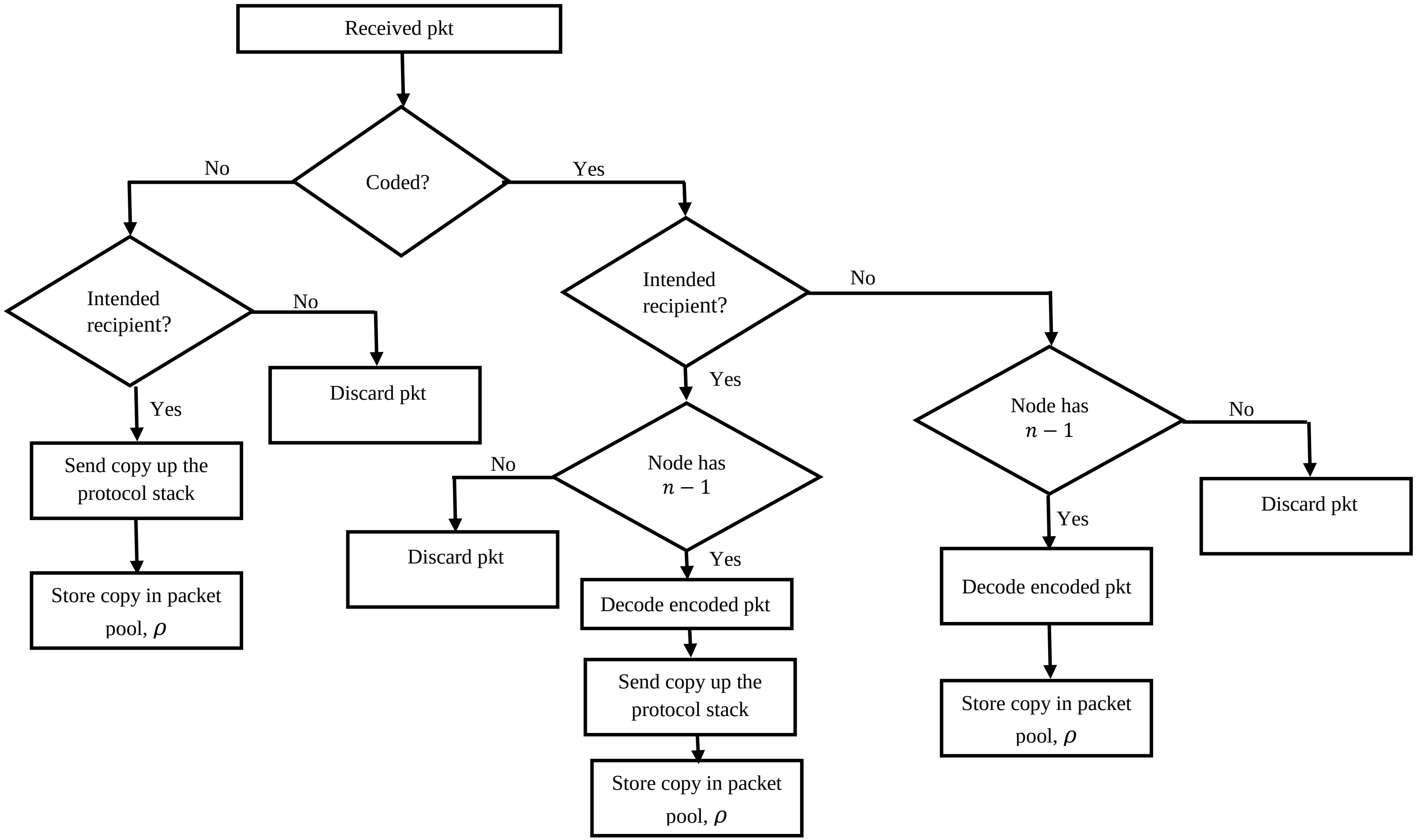


Fig. 4.3: Packets Decoding Opportunity and Processes

Secondly, the CH of the source cluster employs the same concept of RNC to increase the capacity of the broadcasted encoded emergency messages' retransmission through re-encoding the received encoded emergency messages with its own self-generated native packet and the packets received from other vehicles within the last $\mathbb{T}$ (ms) in order to widen the transmission coverage of the safety messages. In essence, the retransmission concept allows the vehicles beyond single-hop broadcast transmission of the source vehicle to receive the emergency messages and take action necessary action. This procedure continues with the rest of the intermediate CHs in the same manner, until the broadcasted encoded emergency messages are delivered to the clusters with n-hop broadcast transmission from the ZoI (where $n \ngtr 4$). Now, let $\mathcal{P}_{\mathbb{C}} = \left(P_{\mathbb{C}_1}, P_{\mathbb{C}_2}, P_{\mathbb{C}_3}, \mathbb{C} \cdots, P_{\mathbb{C}_N}\right)^{\mathbb{T}}$ denote the total number of packets from the last single-hop broadcast transmission, so that $\mathbb{C}_{R_k}$ and $\mathbb{V}_{R_k}$ are the resultant encoded data packets and encoding vector, respectively, which are contained in $\mathcal{P}_{\mathbb{C}_k} | \, k = 1, 2, 3, \cdots, N$. Hence, each CH embarking on retransmission of the broadcasted emergency messages will randomly generate $\alpha_1, \alpha_2, \alpha_3, \cdots, \alpha_N$ encoding coefficients over $GF(q)$ to be able to re-encode the received packets with its own self-generated raw packets as

$$\mathbb{C}_i = \sum_{k=1}^{n} \mathbb{C}_{R_k} \cdot \alpha_k \qquad (4.2)$$

$$\mathbb{V}_i = \sum_{k=1}^{n} \mathbb{V}_{R_k} \cdot \alpha_k \qquad (4.3)$$

where $\mathbb{C}_i$ is the new re-encoded data (i.e. the combination of originally broadcasted encoded emergency messages $\mathbb{C}$ from the source vehicle and the new packets contained in

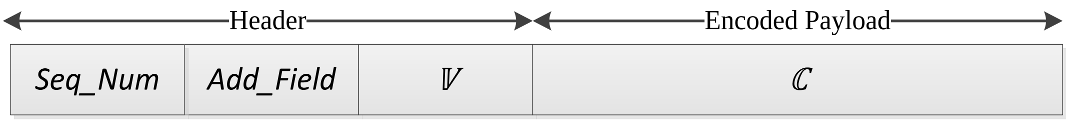


Fig. 4.4: Encoded packet frame structure

the virtual buffer of the CH), and $\mathbb{V}_i$ denotes the corresponding re-encoding vector. The processes involved in the re-encapsulation and re-encoding of $\mathbb{C}$ and the new packets is shown in Fig. 4.5.

Since the RECMAC scheme uses broadcast transmission technique, high rate of both the encoded $\mathbb{C}$ and re-encoded $\mathbb{C}_i$ data packets redundancy across the clusters will definitely be inevitable. In order to resolve this high rate of data packets redundancy, each $\mathbb{C}$ and $\mathbb{C}_i$ are given unique sequence number, *SeqNum*. Hence, with the aid of *SeqNum*, duplicates of $\mathbb{C}$ and $\mathbb{C}_i$ are automatically detected and deleted by the receiving vehicles before the process of decoding is initialised.

Decoding at the receiving vehicle: Upon achieving the data packets redundancy control through the use of each encoded and re-encoded messages' sequence number (*SeqNum*), the recipient vehicles eventually initiate data decoding. Let us assume that N number of re-encoded data packets (i.e. $\mathbb{C}_i = \left(\mathbb{C}_{i_1}, \mathbb{C}_{i_2}, \mathbb{C}_{i_3}, \cdots, \mathbb{C}_{i_N}\right)$ has been received; then, the corresponding re-encoding matrix can be expressed as

$$\mathbb{V}_i = \left(\mathbb{V}_{i_1}, \mathbb{V}_{i_2}, \mathbb{V}_{i_3}, \cdots, \mathbb{V}_{i_N}\right)^T$$

$$= \begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} & \cdots & \alpha_{1\mathbb{M}} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} & \cdots & \alpha_{2\mathbb{M}} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \cdots & \alpha_{3\mathbb{M}} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \alpha_{N1} & \alpha_{N2} & \alpha_{N3} & \cdots & \alpha_{N\mathbb{M}} \end{bmatrix} \quad (4.4)$$

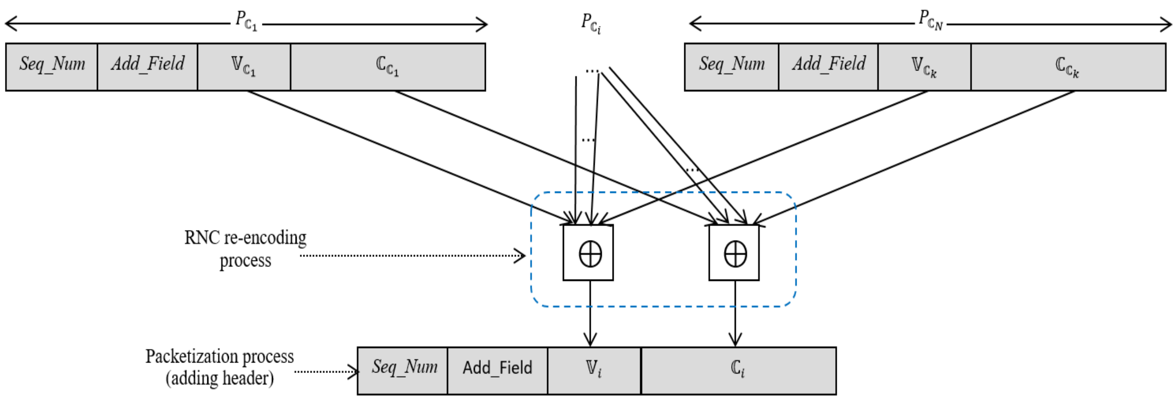


Fig. 4.5: Packets encoding and re-encoding process

Hence, from Eq. (4.1), it follows that the correlation between the original blocks of individual packets and the received encoded packets could be expressed as

$$\mathbb{C}_i = \text{Ƥ} \cdot \mathbb{V}_i \qquad (4.5)$$

Thus, the original packets $\text{Ƥ} = (P_1, P_2, P_3, \cdots, P_{\mathbb{M}})$ can be successfully decoded and recovered through the application of Guassian elimination method if $rank(\mathbb{V}_i) = \mathbb{M}$.

4.2.3 Vehicular Cluster Formation

Vehicular clustering is the process of subdividing the vehicular network into small manageable, coordinated groups to improve transmission reliability (i.e. boost overall network performance) and minimise unhealthy network overhead. Some algorithms have been proposed for vehicular clustering, which takes into consideration the special characteristics of vehicular networks [91, 111, 132, 187]. In this chapter, an algorithm for efficient vehicular cluster formation based on the vehicles' location as well as the direction of movement is also developed. The developed algorithm uses the Euclidean distance to segment the network into smaller groups of vehicles (i.e. clusters). In order to maintain stability in the life cycle of the vehicular clusters, the algorithm considers each vehicles' direction of movement. In order words, the proposed vehicular cluster formation algorithm only allows vehicles that are sharing common direction (i.e., same direction) of movement to belong to same cluster. Contrarily, if vehicles that are moving in opposite direction (in a highway road with 4 lanes, say) are allowed to become members of the same cluster, the life span of the cluster will certainly be very short [8]. Considering the specified IEEE 802.11p standard (DSRC radio) transmission range of 1km for a freeway [48] such as highway road scenario without buildings and with the aid of the Euclidean distance, the algorithm decides amongst requesting vehicles the ones that can be grouped and accepted as members of the same cluster. Each vehicle broadcasts its current kinematics information such as location, speed and direction of movement to create awareness of its presence to every neighbouring vehicle within its one-hop transmission. Finally, the cluster formation algorithm uses these kinematics details to segment the whole vehicular network into separate manageable clusters.

4.2.4 Cluster Head (CH) Selection

With the aid of the received kinematics information broadcasted by different vehicles, each node builds its own one-hop neighbouring vehicle list. Vehicle j can be successfully selected as the CH, if and only if, vehicle j has the maximum number of one-hop neighbouring vehicle list, closest relative speed with respect to the average speed, and minimum average distance to the other vehicles in one-hop neighbouring list. Finally, based on these three conditions, the most suitably qualified candidate will be selected to be the CH based on the following cluster leader selection metric.

$$\mathcal{F}(j) = a\left(\sum_{k\in\mathbb{N}(j)} d\left(D_j, D_k\right)\right)\Big/ N_j + b\left(\sum_{k\in\mathbb{N}(j)} |\Delta\mathcal{V}|\right)\Big/ N_j - \left(c \cdot N_j\right) \qquad (4.6)$$

where

$$d\left(D_j, D_k\right) = d\left(D_k, D_j\right)$$

$$= \sqrt{\left(D_{k1} - D_{j1}\right)^2 + \left(D_{k2} - D_{j2}\right)^2 + \left(D_{k3} - D_{j3}\right)^2 + \cdots + \left(D_{kn} - D_{jn}\right)^2}$$

$$= \sqrt{\sum_{k=1,j=1}^{n} \left(D_k - D_j\right)^2} \qquad (4.7)$$

where $d\left(D_k, D_j\right)$ denotes the Euclidean distance between vehicles k and j; N_j represents the total number of vehicles within one-hop transmission range of vehicle j; $|\Delta\mathcal{V}| = \left|\mathcal{V}_k - \mathcal{V}_j\right|$ is the vehicular velocity difference between vehicles k and j; a, b, c are weight factors, with $a + b + c = 1$; and $\mathbb{N}(j)$ represents the set of one-hop neighbouring vehicles to vehicle j.

Based on Eq. (4.6), the vehicle with the minimum value of the CH selection metric $\mathcal{F}$ will eventually be selected as the CH, and every other vehicle within one-hop transmission range of the selected CH automatically becomes CMs. Consequently, these CMs are not allowed to participate in or initiate any further CH selection process unless the currently selected CH leaves the cluster or becomes unresponsive (i.e. dead node). In other words, the CMs and CH are different from one another as shown in Eq. (4.8) below

$$\begin{cases} CM = \langle k, \forall k \in \mathbb{N}(j) \; and \; k \neq j \, \rangle \\ CH = \langle j | \mathcal{F}(j) = Min\big(\mathcal{F}(k), \forall k \in \mathbb{N}(j)\big) \rangle \end{cases} \tag{4.8}$$

4.2.5 Cluster Management

In order to accept a new CM into the cluster, a three-way handshake is initiated and completed between the new vehicle and the CH. The successfully selected CH periodically broadcast short beacons called *invite-to-join* (ITJ) packets to all the neighbouring vehicles within one-hop transmission range. The short ITJ beacons contain the CH direction of movement information to enable the receiving vehicle decide whether it is allowed to join or not. This is highly imperative since vehicles moving in opposite direction are not permitted by the developed algorithm to join clusters moving in a different direction so as to ensure cluster stability and durability. When a vehicle that is not currently a member of the cluster receive the ITJ beacon, it will check the direction of movement of the cluster (i.e. CH) and if it tallies with its own direction of movement, then the vehicle will respond with a similar short packet called *request-to-join* (RTJ) packet. Finally, the CH upon receiving an RTJ message will reply with an acceptance (or ACK) message to the vehicle if actually their direction of movement is the same. Consequently, the vehicle then becomes an active member to the cluster.

On the other hand, one of the special characteristics of vehicular network is that vehicles negotiate bends at road intersections and change lanes. This means that vehicles can leave or join clusters at any point in time. The operations of vehicles leaving or joining a cluster only exhibit local impacts on the cluster's network topology if the node is a CM. In contrast, when a CH is departing from a cluster, it first relinquishes the cluster leader responsibility to the most closely positioned vehicle to itself. The handing over of leadership responsibility to another CM to automatically become the CH serves to: 1) keep the cluster coordinated as a one-hop transmission range network under a new CH without re-initiating the procedure of CH selection, since the closest node to the current CH will definitely have the minimum value of $\mathcal{F}$ which is required to be successfully selected as a CH; 2) avoid incurring an extra network overhead which arises from the use of the CH re-selection algorithm when the CH leaves the cluster and a new CH is re-selected with the aid of the cluster leader selection procedure discussed in Section 4.2.4. When two clusters merge for the possible reasons of proximity or lack of CMs while moving in the same direction, the new CH selection procedure is performed in accordance with the selection metric defined in Section 4.2.4.

4.3 Performance Analysis

In this Section, the efficiency of the proposed RECMAC scheme is investigated through performance analysis carried out in terms of network throughput, algorithmic complexity, and data broadcast reliability.

4.3.1 Network Throughput Analysis

In Fig. 4.1, there are two distinct stages of message disseminations. Firstly, within the source cluster, the source vehicle broadcasts the encoded message to the CMs. Secondly, as discussed in Section 4.2.5, only the CH acknowledges the receipt of the broadcast from the source vehicle with an ACK frame. Then, the CH re-encodes the coded message $\mathbb{C}$ with its own self-generated raw packets as well as the received packets from other vehicles within the last $\mathbb{T}$ (ms), if any, and rebroadcasts the re-encoded message to CHs of the neighbouring clusters. Hence, let the probability of successful transmission of the encoded and re-encoded messages be denoted with P_s. The proposed RECMAC scheme's probability of successful transmission analysis is derived under a narrowband Rayleigh block fading channel based on theorem 1 below.

Theorem 1: *In a narrowband Rayleigh block fading vehicular communication link, with vehicles broadcasting packets at probability p using equal power levels, the probability of successful packet transmission assuming a desired source cluster sender-receiver CMs distance d_0 and k number of other CHs belonging to neighbouring clusters at distances $d_i|i = 1, 2, \cdots, k, i \neq (k/2)$ can be expressed as*

$$P_s(SNIR \geq \Theta) = exp\left(-\frac{2N_0\Theta}{P_0 d_0^{-\alpha}}\right) \cdot \prod_{i=1, i\neq(k/2)}^{k} \left(1 - \frac{2\Theta p}{R_i^{\alpha} + 2\Theta}\right) \qquad (4.9)$$

where Θ denotes a given SINR threshold which is based on the communication device and the adopted coding and modulation scheme, N_0 represents noise power, P_0 denotes the transmit power, d_0 is the distance between the source vehicle and its destination vehicles,

α denotes the path loss exponent, and $R_i = d_i/d_0$. The proof of **theorem 1** is shown below.

*Proof of **Theorem 1**: Derivation of the probability of successful transmission* $(N_0 \neq 0)$

Let $\mathbb{Q}_0$ represent the total received power from the source vehicle, with $\mathbb{Q}_i$, such that $i = 1, 2, \cdots, k, i \neq (k/2)$ represents the received power as an exponential random variable with mean $\widetilde{\mathbb{Q}}_i$ from k potential interferers. It is noteworthy to mention that all the received powers are exponentially distributed, such that

$$p\mathbb{Q}_i(r_i) = \frac{1}{\widetilde{\mathbb{Q}}_i \cdot e^{(-r_i/\widetilde{\mathbb{Q}}_i)}}$$

where $\widetilde{\mathbb{Q}}_i = P_i d_i^{-\alpha}$ represents the mean received power. Consequently, the aggregate interference I (i.e., the sum average of the received power from each undesired transmitters) affecting the transmission at the recipient vehicle is given by

$$I = \sum_{i=1}^{k} \mathbb{Q}_i \cdot \mathbb{S}_i$$

where $\mathbb{S}_i$ denotes a sequence of independent and identically distributed (i.i.d.) Bernoulli random variables with $P(\mathbb{S}_i = 0) = (1 - p)$, and $P(\mathbb{S}_i = 1) = p$. Thus, both encoded and re-encoded messages are guaranteed successful delivery when both destinations have higher SNIR than the target threshold SNIR Θ. Therefore, the probability of successful transmission is expressed as

$$P_{st}(SNIR \geq \Theta) = E_I[P(\mathbb{Q}_0 \geq \Theta(N_0 + I) \mid I)^2]$$

$$= E_{\mathbb{Q},\mathbb{S}}\left[exp\left(-\frac{2\left[\Theta\left(\sum_{i=1,i\neq(k/2)}^{k} N_0 + \mathbb{Q}_i\,\mathbb{S}_i\right)\right]}{2\widetilde{\mathbb{Q}}_0}\right)\right]$$

$$= exp\left(-\frac{2N_0\Theta}{\widetilde{\mathbb{Q}}_0}\right)E_{\mathbb{Q},\mathbb{S}}\left[\prod_{i=1,i\neq(k/2)}^{k} exp\left(-\frac{2\Theta(\mathbb{Q}_i\mathbb{S}_i)}{\widetilde{\mathbb{Q}}_0}\right)\right]$$

$$= exp\left(-\frac{2N_0\Theta}{P_0 d_0^{-\alpha}}\right)\times\prod_{i=1,i\neq(k/2)}^{k}\left[P(\mathbb{S}_i = 1)\cdot\int_0^{\infty} exp\left(-\frac{2\Theta q_i}{\widetilde{\mathbb{Q}}_0}\right)\times p2\mathbb{Q}_i(q_i)dq_i + P(\mathbb{S}_i = 0)\right]$$

$$= exp\left(-\frac{2N_0\Theta}{P_0 d_0^{-\alpha}}\right)\cdot\prod_{i=1,i\neq(k/2)}^{k}\frac{p}{1+2\Theta\left({}^{d_i}/_{d_0}\right)^{\alpha}} + (1-p)$$

$$= exp\left(-\frac{2N_0\Theta}{P_0 d_0^{-\alpha}}\right)\cdot\prod_{i=1,i\neq(k/2)}^{k}\left(1-\frac{2\Theta p}{R^{\alpha}+2\Theta}\right)$$

■

Obviously, the overall achievable throughput in a large, saturated wireless network is generally constrained by the level of interference experienced across the network. Therefore, focussing on the interference part under the assumption that $N_0 = 0$, the bounds that are basic is determined, such that the stipulated signal-to-interference-ratio threshold Θ will not be exceeded even with an unconstrained transmit power using the following corollary.

Corollary 1: *With unit transmit power $P_i = 1$ and $N_0 = 0$ and under similar assumptions as in Theorem 1, the probability of successful packet transmission under a desired communication channel of a normalized distance, $R_0 = d_0/d_0 = 1$, and k number of other CHs belonging to neighbouring clusters at normalized distances $R_i = d_i/d_0 \,|i = 1,2,\cdots,k, i \neq (k/2)$ can be expressed as*

$$P_S(SIR \geq \Theta) = \prod_{i=1,i\neq(k/2)}^{k}\left(1-\frac{p}{\left(\frac{R_i^{\alpha}}{\Theta}+1\right)}\right) = L_I(\Theta) \qquad (4.10)$$

where $L_I(\Theta)$ represents the interference level I's Laplace transform, which is estimated at the stipulated signal-to-interference-ratio threshold Θ. The proof of corollary 1 is shown below.

Proof of Corollary 1: *Derivation of the probability of successful transmission* $(N_0 = 0)$

The mean power from the i^{th} interferer with unit transmit power at distance $R_i | i = 1, 2, \cdots, k; i \neq (k/2)$ is $1/R_i^{\alpha}$. According to Mathar and Mattfeldt [136], the Laplace transform of an exponential distribution with mean $1/\lambda$ is $\lambda/(\lambda + l)$, $l \geq 0$. Hence, the Laplace transform of I as is the case in [136] becomes

$$L_I(l) = \prod_{i=1, i \neq (k/2)}^{k} \left(\frac{pR_i^{\alpha}}{R_i^{\alpha} + l} + (1 - p) \right)$$

$$= \prod_{i=1, i \neq (k/2)}^{k} \left(1 - \frac{p}{\left(\frac{R_i^{\alpha}}{l}\right) + 1} \right)$$

From (4.9) and with $N_0 = 0$, $R_i = d_i/d_0$ (that is, normalized distances), the probability of successful transmission now becomes

$$P_{st}(SIR \geq \Theta) = \prod_{i=1, i \neq (k/2)}^{k} \left(1 - \frac{p}{\left(\frac{R_i^{\alpha}}{\Theta} + 1\right)} \right)$$

■

In this research, the overall network throughput is defined as the average amount of received data by both the CMs of the source cluster and other destination clusters in a unit time slot. This is the end result of multiplying the total number of received packets by the CMs of the source cluster and other destination clusters with the amount of information contained in a single encoded packet. With the use of a high target SNIR, the amount of information contained in a single encoded data can be increased. Unfortunately, at the same time, the use of high target SNIR reduces the probability of successful transmission and the average number of received encoded packets at the destination nodes.

In this section, the maximum network throughput under a saturated vehicular traffic condition is obtained. The saturated vehicular traffic condition means that the source node and CHs always have enough data packets for network coding exercise. Consequently, a saturated vehicular traffic condition makes it possible to obtain a network throughput upper bound, unlike unsaturated traffic scenario.

The analysis is based on the assumption that the locations of the vehicles represent a Poisson point process[7] (PPP), with the distance between the source vehicle, CMs of the source cluster and other destination clusters fixed and there are k other vehicles constituting the 2-dimensional PPP. Although Eq. (4.10) gives the probability of successful transmission based on normalized vehicle distances $R_0 = d_0/d_0 = 1$ and k other CHs belonging to neighbouring clusters at normalized distances $R_i = d_i/d_0$, here, the joint density of $d_1, d_2, d_3, \cdots, d_k$, that is, normalized distances is established. Apparently, for one-dimensional PPP with density γ, the normalised distance from vehicles to their intended receivers creates the arrival times of a PPP [136]. Therefore, the inter-arrival intervals are independent and identically distributed (i.i.d.) exponential with density γ as:

$$f_{d_i - d_{(i-1)}}\left(\beta_i - \beta_{(i-1)}\right) = \gamma e^{-\gamma\left(\beta_i - \beta_{(i-1)}\right)}. \tag{4.11}$$

Accordingly, in the case of normalised distance $0 \le d_1 \le d_2 \le d_3 \le \cdots \le d_k$, the composite density function of the inter-arrival intervals becomes

$$\begin{aligned} f_{d_1,d_2,d_3,\cdots,d_k}(\beta_1,\beta_2,\beta_3,\cdots,\beta_k) &= f_{d_1,d_2,d_3,\cdots,d_k - d_{(k-1)}}\left(\beta_1,\beta_2,\beta_3,\cdots,\beta_k - \beta_{(k-1)}\right) \\ &= \left(\gamma e^{-\gamma\beta_1}\right)\left(\gamma e^{-\gamma(\beta_2-\beta_1)}\right)\cdots\left(\gamma e^{-\gamma\left(\beta_k-\beta_{(k-1)}\right)}\right) \\ &= \gamma^k e^{-\gamma\beta_k}, \quad 0 \le \beta_1 \le \beta_2 \le \beta_3 \le \cdots \le \beta_k. \end{aligned} \tag{4.12}$$

[7] For large vehicular networks, Poisson point process is the same as a homogeneously arbitrary distribution for general practical purposes.

On the other hand, when vehicles are randomly distributed in accordance with a 2-dimentional PPP with density γ, the squared normalized distances from the intended receivers, according to [136], maintain the same distribution as the arrival periods of a PPP with density $\gamma\pi$. Similarly, from [217], the outcome becomes

$$f_{d_i^2-d_{(i-1)}^2}\left(\beta_i-\beta_{(i-1)}\right)=\gamma\pi e^{-\gamma\pi\left(\beta_i-\beta_{(i-1)}\right)}, \tag{4.13}$$

Consequently, the squared normalized distances have a composite distribution with density

$$f_{d_1^2,d_2^2,d_3^2,\cdots,d_k^2}(\beta_1,\beta_2,\beta_3,\cdots,\beta_k)=(\gamma\pi)^k e^{-\gamma\pi\beta_k}, \tag{4.14}$$

$$0\leq\beta_1\leq\beta_2\leq\beta_3\leq\cdots\leq\beta_k.$$

Finally, from Eq. (4.10), the conditional success probability can be re-written as

$$P_s(SIR\geq\Theta)=\prod_{i=1,i\neq(k/2)}^{k}\frac{\Theta d_0^\alpha(1-p)+(d_i^2)^{\alpha/2}}{\Theta d_0^\alpha+(d_i^2)^{\alpha/2}} \tag{4.15}$$

Thus, by integrating Eq. (4.15) w.r.t. the composite density in Eq. (4.14) with $\alpha=3$, gives us

$$P_s(SIR\geq\Theta)=\int_0^\infty\left((\gamma\pi)^k e^{-\gamma\pi\beta_k}\right)$$

$$\cdot\int_0^{\beta_k}\cdots\int_0^{\beta_2}\prod_{i=1,i\neq(k/2)}^{k}\frac{\Theta d_0^3(1-p)+\beta_i^2}{\Theta d_0^3+\beta_i^2}\,d\beta_1\cdots d\beta_{(k-1)} \tag{4.16}$$

Through the application of a related inductive technique as was used by Mathar and Mattfeldt [136], it can be shown that

$$\int_0^{\beta_k} \cdots \int_0^{\beta_2} \prod_{i=1, i\neq(k/2)}^{k} \frac{\Theta d_0^3(1-p)+\beta_i^2}{\Theta d_0^3+\beta_i^2} d\beta_1 \cdots d\beta_{(k-1)}$$

$$= \frac{1}{(k-1)!}\left[\beta_k - atan\left(\frac{\beta_k}{\sqrt{\Theta d_0^3}}\right) p\sqrt{\Theta d_0^3}\right]^{(k-1)} \quad (4.17)$$

Therefore, putting Eq. (4.17) into Eq. (4.16) gives us

$$P_s(SIR \geq \Theta) = \int_0^{\infty} \left[\left(\beta - atan\left(\frac{\beta}{\sqrt{\Theta d_0^3}}\right) p\sqrt{\Theta d_0^3}\right)^{(k-1)} \cdot \frac{(1-p)\Theta d_0^3+\beta^2}{\Theta d_0^3+\beta^2} e^{-\gamma\pi\beta_k} \frac{(\gamma\pi)^k}{(k-1)!}\right] d\beta \quad (4.18)$$

4.3.2 Analysis of the Complexity of RECMAC Scheme Algorithm

Given the known limited computation, storage, and bandwidth resources in vehicular networks [91], complex algorithms may not be the best option to implement in vehicular networks. This must always be considered, especially when maintaining optimal reliability of safety-related messages is the major objective. Hence, one of the intrinsic goal of this thesis in addition to guaranteeing transmission reliability with a sustained increasing rate in overall network throughput by applying RNC performed over a Galois Field $GF(k^n)$ is to design a vehicular communication scheme with a light-weight, low complexity algorithm that will be easily implemented in vehicular network environments. So, in this sub-section, the level of algorithmic complexity of RECMAC scheme is investigated. Likewise, the feasibility of the proposed RECMAC algorithm and its applicability over VANETs were concisely illustrated by investigating the computational complexity associated with the encoding, re-encoding, and decoding processes.

Firstly, unlike conventional wireless networks, mobile vehicles in vehicular networks maintain a periodic status messages, which are broadcasted at regular intervals to inform neighbouring vehicles of their speed, direction of movement, and other kinematic information. These periodic messages, though, very small packets, can lead to an overwhelming network signalling complexity especially in a saturated communication scenarios. Although, RECMAC scheme is designed to work in a saturated vehicular traffic, it sub-divides the network into separate small manageable clusters to maintain a low signalling complexity and minimise network overhead. Therefore, there are a total of k broadcasted packets for $k|k \leq \mathbb{N}$ number of CMs in a given cluster, since the broadcasting is usually constrained within the source clusters. Apparently, it shows that the complexity of the network signalling can be regarded as linear $O(\mathbb{N})$, given that signalling overhead is constrained through manageable clusters.

Secondly, the level of overhead complexity incurred as a result of the processes of packets encoding, re-encoding and decoding were also considered. In the process of packets coding, the source vehicle randomly generates an $\mathbb{M}$ encoding co-efficients, such that $\mathbb{M} \leq \mathbb{N}$, over the Galois field ($GF(q)$), which is used to generate a linear combination of P raw packet blocks. In the same way, the re-encoding processes also involves random generation of $p|p \leq \mathbb{N}$ coding co-efficients over the Galois field ($GF(q)$) in order to generate a linear combination of the initial coded messages $\mathbb{C}$ with any available P raw data packet blocks. Thus, it follows that the computational complexity associated with both raw packets encoding and the coded packets re-encoding processes could be considered as linear, (i.e., $O(\mathbb{N})$), and very low given that total number of vehicles belonging to a particular cluster is usually small, especially in a highway scenario. In the same manner, given that each vehicle decodes the encoded data through Gaussian elimination technique, it follows that its complexity can be regarded as cubic $O(\mathbb{N}^3)$ and computationally lead to low complexity.

4.3.3 Broadcast Reliability Analysis

In order to estimate message transmission reliability of vehicular networks using RECMAC scheme, a new reliability estimation metric called Packet Delivery Failure (PDF) ratio is defined so as to evaluate the performance reliability of the proposed vehicular communication protocol. PDF ratio is defined as the ratio of the total number of packets that are not correctly received or recovered at the destination vehicles to the total number of packets transmitted from the transmitter.

Generally, in wireless communication, the total power consumptions are categorized into: 1) power consumptions due to power amplifier P_A, and 2) power consumptions due to other functioning circuits. As a result, when an energy is lost with a path loss exponent $\mathcal{L}$ which is determined empirically over AWGN due to fading channel, then, the received signal power P_r can be expressed as

$$P_r = h^2 P_{d_0} \left(\frac{d_0}{d}\right)^{\mathcal{L}}, \quad 2 \leq \mathcal{L} \leq 8 \qquad (4.19)$$

where h denotes the channel gain, $\mathcal{L}$ is the path loss exponent, d_0 represents the transmitter-receiver close-ranged reference distance, d represents the packet transmission distance between the transmitter and the receiver, and $P_{d_0}$is the reference received signal power at the transmitter-receiver close-ranged reference distance, d_0. Hence, the overall reference received signal power P_{d_0}can be computed approximately as in [29]

$$P_{d_0} = \frac{G_r G_t f^2 P_A}{M_l N_f [(4\pi d_0)^2 (1+\alpha)]}$$

$$= \frac{R_b E_b G_r G_t f^2}{M_l N_f [(4\pi d_0)^2 (1+\alpha)]} \qquad (4.20)$$

where G_r and G_t denote the receiver and transmitter antenna gain, respectively, f denotes the carrier frequency, N_f and M_l represent the receiver noise figure and link margin, respectively, R_b and E_b represent the basic transmission bit rate and the received energy due to amplifier per one bit of data that is transmitted, respectively, and $\alpha = (\zeta/\beta) - 1$ with ζ representing peak to average ratio that largely depends on the type of modulation scheme adopted and the corresponding size of constellation, while β denotes the drain efficiency of the Radio Frequency (RF) power amplifier. Since ζ largely depends on type of modulation scheme that is used and its corresponding size of constellation, adopting Multiple Quadrature Amplitude Modulation (MQAM) scheme makes $\zeta =$

$3\left[\left(\sqrt{M}-1\right)/\left(\sqrt{M}+1\right)\right]$. The received signal to noise ratio, SNR_r can be obtained by putting Eq. (4.20) into Eq. (4.19) as

$$SNR_r = \frac{P_r}{N_0 R_b}$$

$$= h^2 \left(\frac{G_r G_t f^2 d_0^{\gamma-2}}{M_l N_f d^{\gamma}[(4\pi)^2(1+\alpha)]}\right)\left(\frac{E_b}{N_0}\right) \quad (4.21)$$

where N_0 denotes the single side thermal noise power spectral density. This is built on the assumption that the channel gain complies with the narrowband Rayleigh block fading distribution, so that its probability density function can be expressed as

$$f(x;\sigma) = \frac{x}{\sigma^2} e^{-\left(\frac{x^2}{2\sigma^2}\right)}, \ \ for\ x \geq 0 \qquad (4.22)$$

with the Cumulative Distribution Function (CDF) given as

$$F(x) = 1 - e^{-\left(\frac{x^2}{2\sigma^2}\right)}, \ \ for\ x \in [0, \infty) \qquad (4.23)$$

where σ denote the scale parameter of the Rayleigh distribution. Therefore, the wireless vehicular communication link's packet loss probability, P_{loss} will be given by

$$P_{loss} = P_r(SNR_r \leq SNR_0)$$

$$= P_r\left[h \leq \sqrt{\frac{cN_0 d^{\gamma}}{E_b}}\right]$$

$$= 1 - e^{-\left(\frac{cN_0 d^{\gamma}}{E_b}\right)} \qquad (4.24)$$

where

$$c = \frac{SNR_0 M_l N_f \left[(4\pi)^2\left((1+\alpha)\right)\right]}{G_r G_t f^2 d_0^{\gamma-2}} \qquad (4.25)$$

As discussed in the previous chapter, suppose that there is j vehicles which are members of the cluster, then, each encoded packet broadcasted from the last hop is guaranteed to be successfully received by the participating stations in that cluster so far that it can be received by at least one of these j vehicles. Therefore, the probability of successfully receiving a broadcasted packet equal to $1-(P_{loss})^{j}$. Suppose that there is a total of k number of encoded messages amongst the N generated native and received packets to be broadcasted from the last hop, then, the probability of successfully receiving both the j and k of N can be computed approximately as

$$P(j,k)=\left[\binom{N}{k}\left(1-(P_{loss})^{(j+k)}\right)\right]^{(N-k)} \quad (4.26)$$

Note that in introduction of the proposed CARER protocol in Chapter three, it is stated that the payload, C in each encoded message is the linear combination through bitwise exclusive OR (XOR operation) of the A original generated native and received packets. It follows that C can only be recovered if the rank of the encoding matrix that makes up the encoding vectors v which is attached with the received encoded messages is not greater than A. That is, $rank(v_r)\leq A$, then, the original packets P_i (where $i=1,2,\dots n$) can be recovered with Gaussian elimination. However, the coded packets decoding conditions may not always be satisfied by the k^{th} packets received by the destination vehicle, given that the encoding vectors v_r are randomly generated over $GF(k^n)$.

Hence, a new defining parameter p_A is introduced, which denotes the probability that the rank of $\mathcal{B}$, which is an $m\times n$ coding matrix that is randomly generated over $GF(k^n)$ is equal to $min(m,n)$. Apparently, $p_A=1$ when $rank(\mathcal{B})\leq min(m,n)$. In other words, the rank of $\mathcal{B}$ is a non-negative integer and cannot be greater than either m or n. That is to say that p_A expresses the probability that the decoding conditions are not satisfied by the m randomly generated $1\times n$ encoding vectors. Consequently, over a $GF(k^n)$, the exact value of p_A can be obtained as in [185]:

$$p_A=\begin{cases}1-\prod_{q=0}^{m-1}\left(1-\frac{1}{k^{n-q}}\right), & for\ rank(\mathcal{B})\geq min(m,n)\\ 1, & for\ rank(\mathcal{B})<min(m,n)\end{cases} \quad (4.27)$$

From Eq. (4.27), the chances of recovering original packets, A decreases as the resulting values of the probability p_A get relatively very small for $rank(\mathcal{B}) > min(m,n)$. As a result, PDF in one hop broadcast (i.e., except the last hop broadcast) can be computed approximately as

$$PDF_0 = \sum_{j=0}^{N}\sum_{k=0}^{N}\binom{N}{j}\left[\left(1-(P_f)^{(j)}\right)(P_f)^{N-j}\right].\binom{N}{k}\left[\left(1 - (P_{loss})^{(j)}\right)^k (P_{loss})^{j(N-k)}\right].p_A \quad (4.28)$$

where P_f denotes the probability that a transmitted encoded packet is not successfully received. Thus, the PDF_l can be computed approximately for the encoded packet's last-hop transmission as

$$PDF_l = \sum_{j=0}^{N-1}\sum_{k=0}^{N}\binom{N-1}{j}\left[\left(1-(P_f)^{(j)}\right)(P_f)^{N-1-j}\right].\binom{N}{k}\left[\left(1-(P_{loss})^{(j+1)}\right)^k \cdot (P_{loss})^{(j+1)(N-k)}\right].p_A \quad (4.29)$$

Finally, from Eq. (4.28) and (4.29), the total packet delivery failure ratio, PDF_t becomes

$$PDF_t = 1 - [(1 - PDF_0)\cdot(1 - PDF_l)] \quad (4.30)$$

4.4 Simulation Setup

In this section, a comparison of RECMAC and the reference protocol (CARER) [43] is shown using simulation experiments, focusing on a highway scenario with 100 vehicles, 200 vehicles, and 300 vehicles.

4.4.1 Simulation Settings and Assumptions

In this section, a close to real-life vehicular network simulation scenario based on Nakagami model for the V2V communication link is presented. MATLAB® tool [137] is used to implement the simulator based on the assumed system model and channel in Section 4.2.1. Around 100 to 300 smart vehicles are spaced horizontally along a two-lane highway of opposite direction with an intra-vehicle spacing of 30m in a 1km highway road segment. Each vehicle broadcasts with a 12 Mbps channel rate. The results of the simulation experiments are averaged over 500 runs. Given that the erasure probability is a basic performance factor for evaluating the transmission reliability, a realistic V2V communication channel is considered, with the erasure probability given as a function of distance in a typical vehicular network environment. The pdf of the signal amplitude X based on this assumed channel model is

$$fX(x) = \frac{2m^m x^{(2m-1)}}{m(P_r)^2} exp\left(-\frac{mx^2}{2P_r}\right)$$
$$m \geq \frac{1}{2},\ P_r > 0$$

where m is the Nakagami-m channel fading figure, and P_r denotes the total received power. Molisch *et al.* [141] reported a path loss component (i.e., 1.8 – 1.9) for a typical free highway vehicular communication environment. In this simulation, it is assumed that the path loss component is 2 for freeway highways. In [21], Chen *et al.* estimated the fading figure m on empirical measurement for a free highway V2V communication link as

$$n = \begin{cases} 0.75, & d > 80 \\ 1.5, & d < 80 \end{cases}$$

The physical and MAC layer parameters used are shown in Table 4.1 and the estimated values of m in the simulation. Additionally, the specified transmission power of 20dBm according to [48], message size of 200bytes, and the transmission and reception antenna gain of 2 were assumed.

To further estimate the performance of RECMAC scheme using a closer to real-life network model, further implementation of RECMAC in the Network Simulator II (ns-2) [50] is also performed with the realistic mobility pattern of the vehicles generated using Simulation of Urban MObility (SUMO) [165]. SUMO, which is designed by the German Aerospace Center (GAC), is an open-source, discrete-time traffic, and space-continuous mobility pattern simulator that is capable of modelling the behaviour of individual drivers. Both the acceleration, and overtaking decision of the mobile nodes are determined through the use of the traveling speed of the leading vehicle, distance and dimension of vehicles, as well as the profile of acceleration and deceleration. The same Nakagami model for the V2V communication channel is set in the simulator. The transmission power is set for all the vehicles as 760mw in accordance with IEEE 802.11p/DSRC standard specification, while the transmitter and reception antenna gain is set to 2. Likewise, all other parameters such as radio frequency, reception, and carrier threshold, etc, are also configured according to the specification of IEEE 802.11p/DSRC standard. The vehicles are introduced into the highway road according to a Poisson process as discussed in Section IV.A with a rate equal to two vehicles per second. The total simulation time is 500 seconds. The vehicle cluster formation process begins at the 43rd second after all the mobile vehicles have entered the highway. The network performance evaluation metrics used in this study (i.e. throughput rate (Mbps) and packet delivery failure PDF_t ratio) are evaluated for the remaining 457 seconds.

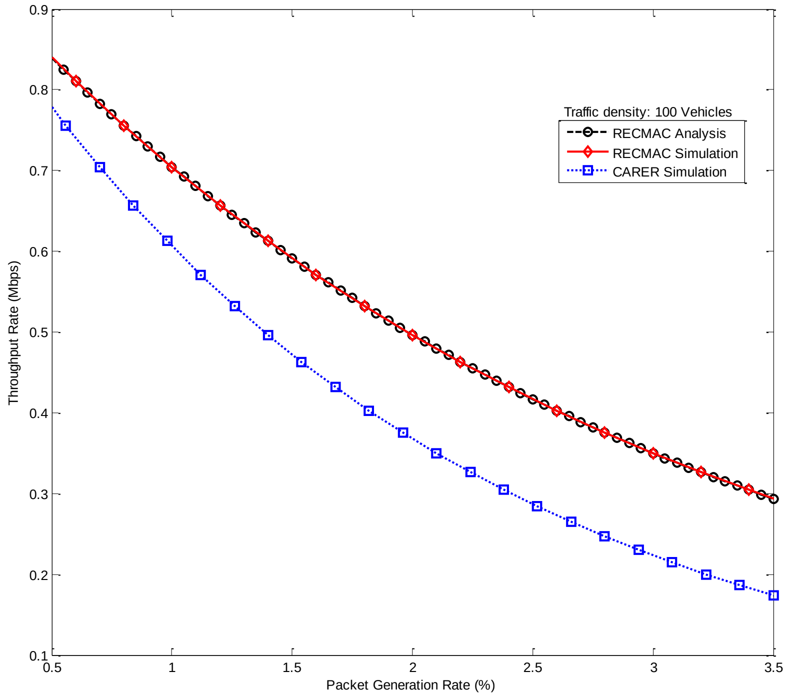
4.4.2 Results and Discussion

Both the analytical and simulation results of RECMAC scheme against CARER scheme [43] were plotted so as to get insight into the gain of random network coding especially in achieving improved reliability with minimum complexity and optimal achievable network throughput. For the simulation, a Bernoulli random variable and an exponential random variable are generated to represent the packet transmission event of each mobile vehicle and Rayleigh fading channel, respectively. Some of the dimensionless network parameters were also set, such as the path loss attenuation factor $\alpha = 3$, transmission power $P_0 = 1$, and radius of the cluster r$= 2$. The coefficients of the random network coding are randomly generated over a $\mathbb{G}(2^8)$ Galois Field. The wireless channel between the broadcasting vehicle and the receiving vehicles is modelled by joint log-distance path loss model and Rayleigh fading.

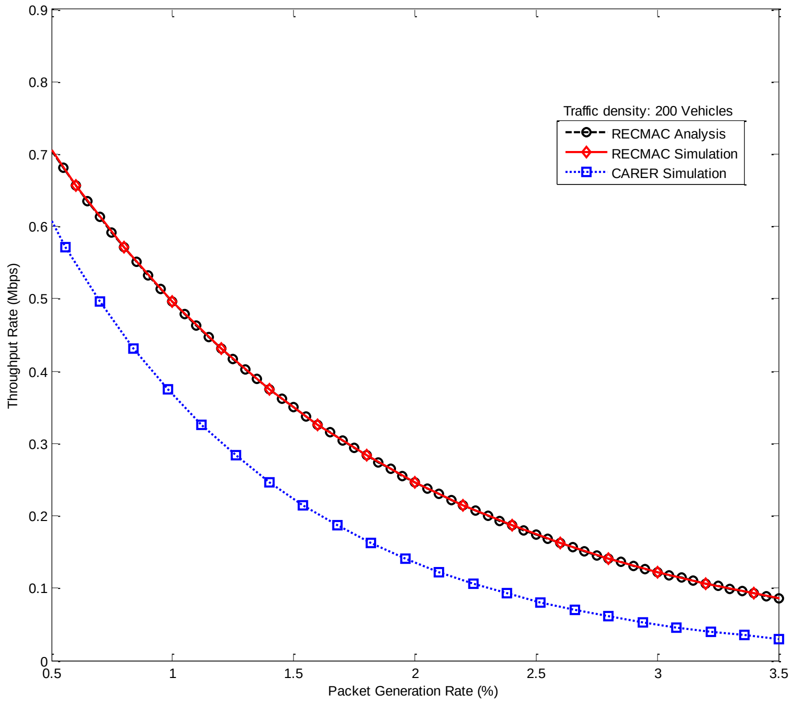
Fig. 4.6 (a) – (c) present report on the effects of packet generation rate on the overall network throughput performance, and show that as the percentage of packet generation rate increases, as anticipated, the channel utilization decreases greatly. It is noteworthy to notice that as the percentage of packet generation rate rapidly increases, the resultant diminishing effect becomes more and more acute. This can be explained by the fact that the increased percentage of packet generation rate obviously resulted to increased contention for channel utilization both with intra-cluster by the participating CMs and inter-cluster by CHs in control of cluster to cluster message exchange. Furthermore, this is also partly due to the fact that the defined parameter set for the EDCA used in IEEE 802.11p standard is capable of prioritizing messages; hence, under heavy network density (i.e., increased percentage of packet generation rate) with increasing number of vehicles sending high priority (safety) messages, the collision probability tends to increase significantly. In other words, the resulting significant increase of collision probability adversely affects the overall network performance, especially in terms of throughput deterioration.

The overall network throughput performance of both RECMAC and CARER schemes start to decrease significantly as the percentage of packet generation rapidly increases towards 3.5 (see Fig. 4.6 (a) – (c)). This rapid decrease in terms of network throughput across both protocols became worse from Fig. 4.6 (a), 4.6 (b) to 4.6 (c) due to increased contention for channel access caused by high network saturation as the rate of packet generation increases under heavy network density (from traffic density of 100 vehicles to 300 vehicles). This observed rapid decrease in the overall network throughput performance for both schemes are caused by increased, heavy network overhead as a result of increased channel congestion and contention due to high percentage of packets generation rate across the entire network. In other words, the increased heavy network overhead created by increased percentage of packets generation rate practically exhibits an over bearing effect on the overall network performance.

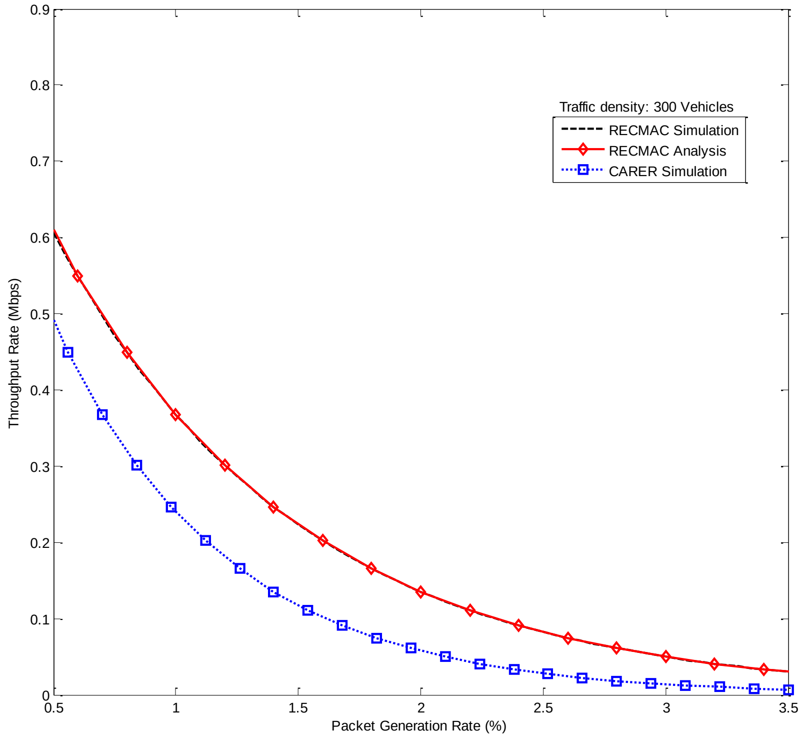
However, this effect of increased network overhead is more adverse on CARER scheme compared to RECMAC as can be seen in Fig. 4.6 (a), 4.6 (b) and 4.6 (c). It is observed that RECMAC scheme offers a performance advantage of multiple orders of magnitude against CARER scheme in terms of network throughput. This can be partly due to: 1) the fact that the RECMAC minimises the effect of contention for channel utilization by sub-dividing the entire network into separate manageable clusters with CHs that control both intra-cluster and inter-cluster communication (including the developed and enhanced CM-to-CH handshake), which undeniably avoids heavy network overhead as a result of increased channel congestion and contention; and 2) the complex rebroadcasting node selection metric [43] used by CARER scheme to determine and select the most suitably qualified candidate (i.e. vehicle) for rebroadcasting the encoded packets to enable the vehicles outside the radio coverage of the source vehicle to receive and decode the encoded messages.


Traffic density: 100 Vehicles
RECMAC Analysis
RECMAC Simulation
CARER Simulation
Throughput Rate (Mbps)
Packet Generation Rate (%)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.5
1
1.5
2
2.5
3
3.5

(a)


Traffic density: 200 Vehicles
RECMAC Analysis
RECMAC Simulation
CARER Simulation
Throughput Rate (Mbps)
Packet Generation Rate (%)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5
1
1.5
2
2.5
3
3.5

(b)

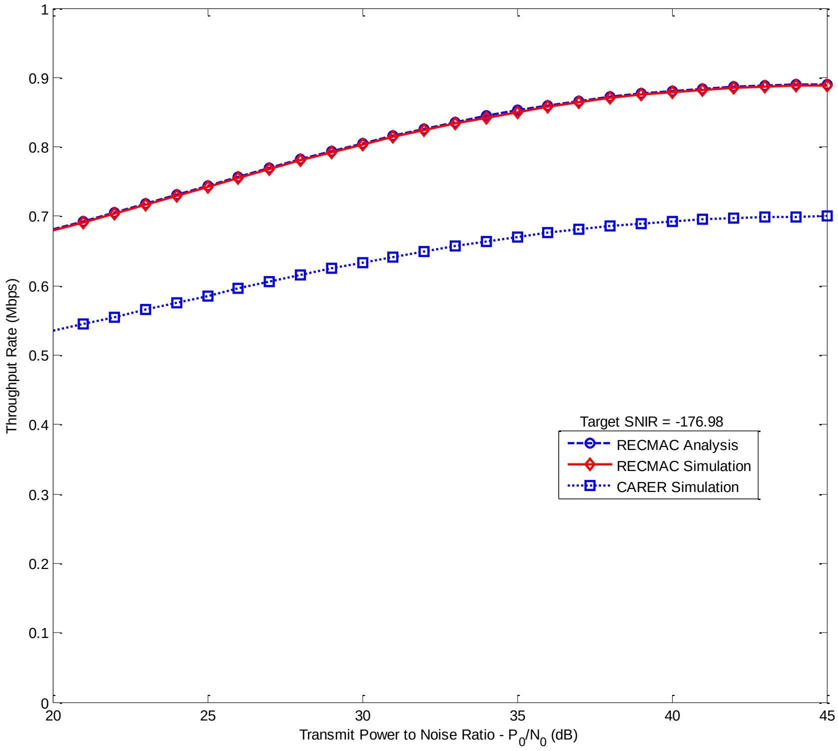


(c)

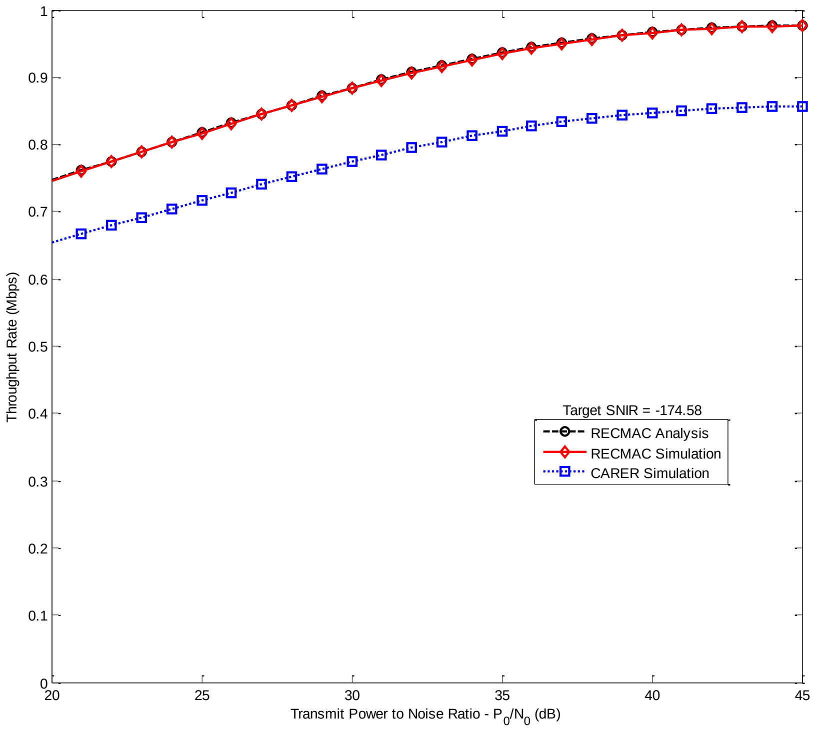
Fig. 4.6 (a) – (c): Performance comparison between the RECMAC and CARER scheme using throughput rate (Mbps) as a function of percentage of packet generation rate with increasing vehicular traffic density from 100 to 300 vehicles.

Therefore, as opposed to RECMAC, which simply allows the CHs to re-encode and rebroadcast the coded messages to enable the clusters beyond the transmission coverage of the source vehicle to receive the encoded messages, CARER scheme incurs additional network overhead due to the high complexity of the rebroadcasting node selection metric and the processes involved in selecting a vehicle that will rebroadcast the encoded messages. In other words, this extra network overhead which the use of this selection metric incurs leads to the deterioration of CARER scheme network performance in terms of the achievable network throughput compared to RECMAC scheme.

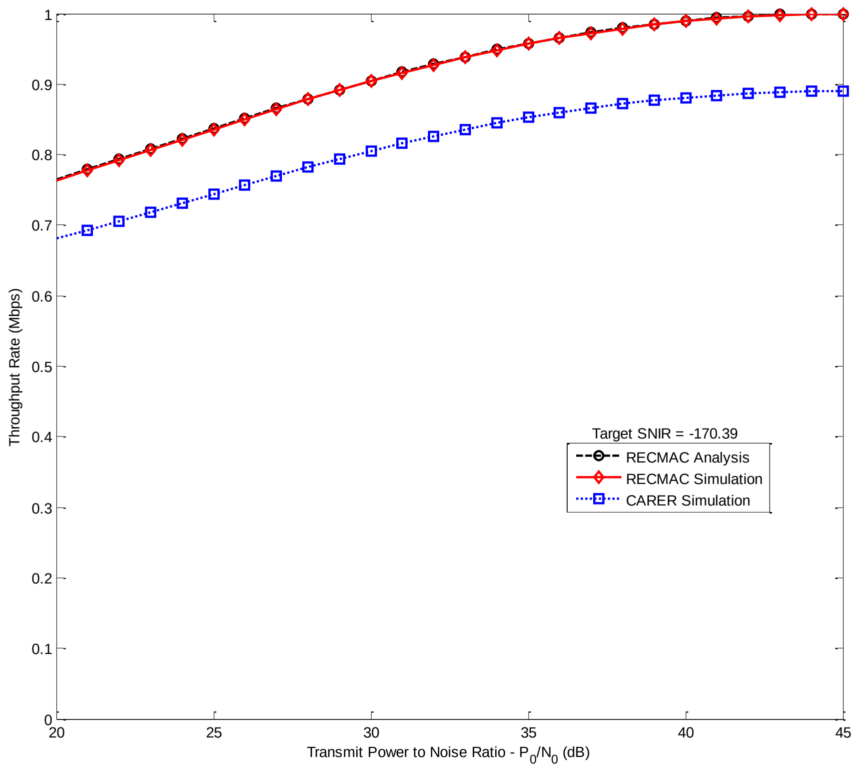
Fig. 4.7 (a) – (c) show the effect of selecting an optimal target SNIR Θ on the overall network performance, especially the network throughput. It can be clearly seen that the overall network throughput performance can be increased by selecting an optimal target SNIR Θ at the PHY layer as is evident in Fig. 4.7 (a) through Fig. 4.7 (c). It shows that with a high target SNIR Θ, the encoded packets can be broadcasted with high spectral efficiency.


Throughput Rate (Mbps)
Transmit Power to Noise Ratio - P_0/N_0 (dB)
Target SNIR = -176.98
RECMAC Analysis
RECMAC Simulation
CARER Simulation

(a)


Throughput Rate (Mbps)
Transmit Power to Noise Ratio - P_0/N_0 (dB)
Target SNIR = -174.58
RECMAC Analysis
RECMAC Simulation
CARER Simulation

(b)

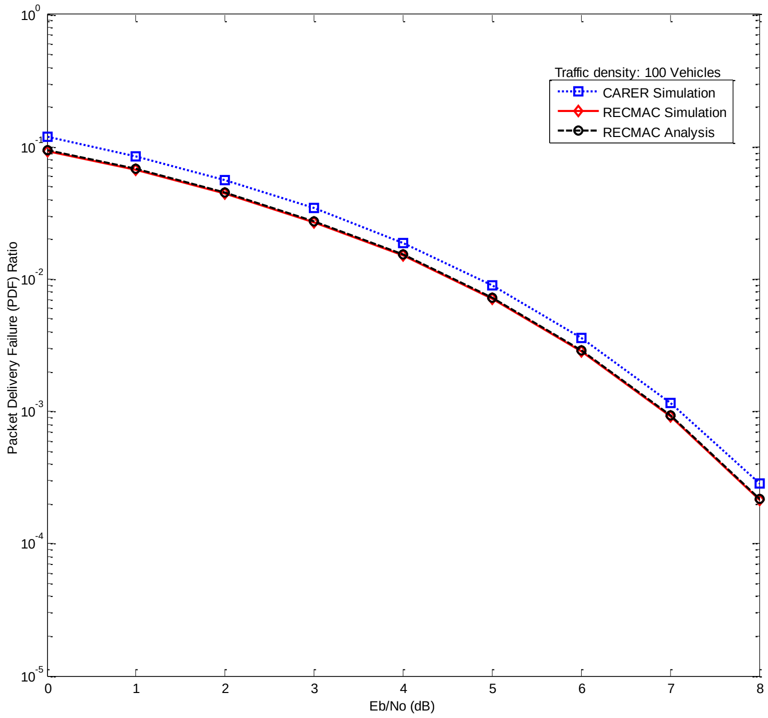


(c)

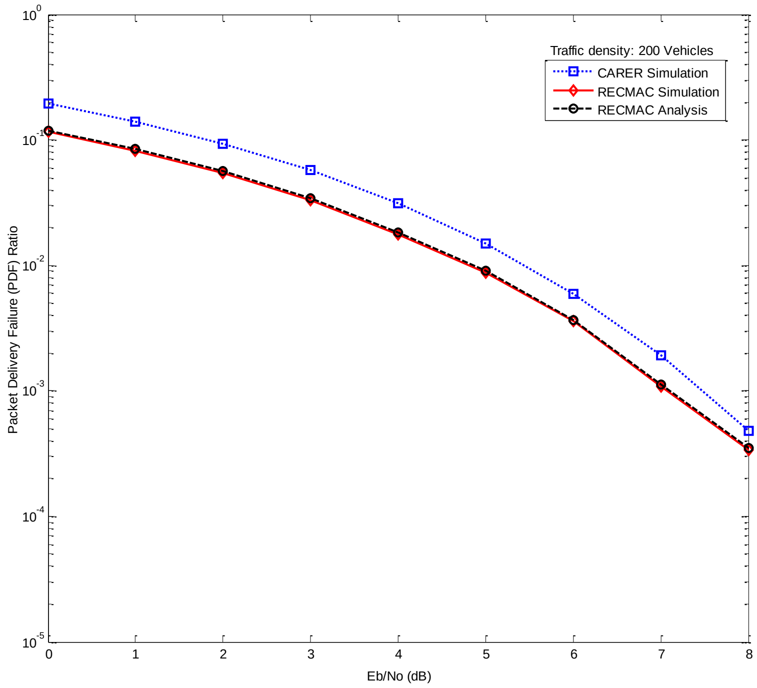
Fig. 4.7 (a) – (c): Performance comparison between the RECMAC and CARER scheme using throughput rate (Mbps) as a function of throughput rate (Mbps) as a function of transmit power to noise ratio - P_0/N_0 (dB) with increasing target SNIR Θ from -174.98 to -170.39.

However, the probability of successful transmission of the encoded and re-encoded packets P_s becomes very low. On the other hand, using a low target SNIR Θ, many encoded and re-encoded packets that contain little information can be successfully transmitted. As can be seen from both the analytical and simulation results in Fig. 4.7 (c), the optimal target SNIR Θ that maximizes the overall network throughput performance is -170.39 dB when transmit power to noise ratio $P_0/N_0 = 43$ dB. It is noteworthy to mention that the selected optimal target SNIR $\Theta = -170.39$ dB can be reduced if the noise level increases so as to minimise the channel error. Remarkably, the RECMAC scheme also demonstrated better performance compared to the CARER protocol as can be witnessed in Fig. 4.7 (a) through Fig. 4.7 (c). Similarly, this can be as a result of the fact that the RECMAC scheme minimises unhealthy contention for channel utilization, which in turn, reduces the network overhead and its associated adverse effect of performance deterioration by using effective network segmentation through clustering approach. Hence, with the RECMAC protocol, the clustering concept helps to sub-divide the whole vehicular network into separate manageable sub-networks with low network overhead as opposed to CARER protocol, which incurs heavy network overhead with adverse effect over the overall network performance due to the use of constant periodic status messages that are broadcasted at regular intervals in vehicular communication networks. The advantages of applying network clustering concept by RECMAC protocol includes primarily for boosting overall network performance as well as improving network security. More so, the use of use of high complex algorithm oriented rebroadcasting node selection metric by the CARER protocol to search for a rebroadcasting node for the encoded messages as opposed to RECMAC scheme also leads to increased network overhead and spectral inefficiency, which at the long run, results to poor overall network performance especially in terms of network throughput.

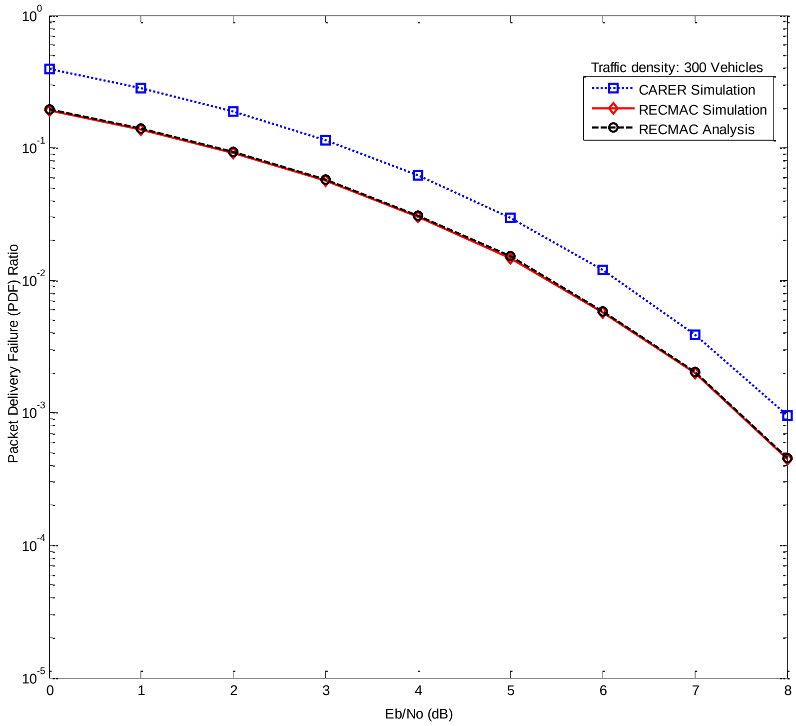
The performance of the proposed RECMAC scheme against existing CARER protocol was also verified in terms of transmission reliability using the developed PDF_t ratio performance metric discussed in Section 4.3.3. The outcome of PDF_t ratio over varying transmit E_b/N_0 (dB) and vehicular traffic density changing from 100 vehicles to 300 vehicles with other parameters unchanged is measured in Fig. 4.8 (a) through Fig. 4.8 (c). As can be clearly seen in Fig. 4.8 (a) through Fig. 4.8 (c), RECMAC achieved better network performance in terms of transmission reliability than the CARER scheme with lower packet delivery failure ratio. Fig. 4.8 (a) through Fig. 4.8 (c) show that under the same condition of transmit E_b/N_0 (dB), the RECMAC scheme can offer a performance advantage of multiple orders of magnitude of lower PDF_t ratio than CARER protocol. As the rate of E_b/N_0 increases, the PDF_t ratio of both schemes drastically drops, accordingly, which means that the network transmission reliability performance is improved. Interestingly, across Fig. 4.8 (a) – ((b), the PDF_t ratio of the proposed RECMAC did not only remain much lower than that of CARER scheme, but the performance gap between the two protocols widens as the traffic density increases from 100 vehicles in Fig. 4.8 (a), and 200 vehicles in Fig. 4.8 (b) to 300 vehicles in Fig. 4.8 (c) with the largest PDF_t ratio performance gap. This can be explained by the fact that RECMAC applies vehicles clustering concept, which was discussed above, as opposed to CARER as well as due to the use of high complex rebroadcasting node selection metric by the CARER protocol to search for the most suitably qualified vehicle that will rebroadcast the encoded messages to ensure wider coverage beyond the transmission radio range of the source vehicle.



(a)



(b)



(c)

Fig. 4.8 (a) – (c): Performance comparison between the RECMAC and CARER scheme using PDF_t ratio as a function of increasing rate of E_b/N_0 (dB) and vehicular traffic density from (a) 100 vehicles, (b) 200 vehicles to (c) 300 vehicles.

However, Fig. 4.8 (a) – (c) also show that both the RECMAC and CARER schemes exhibit gradual but steady increment in network performance deterioration in terms of transmission reliability as the traffic density increases as can be seen in Fig. 4.8 (b) and Fig. 4.8 (c) with 200 vehicles and 300 vehicles, respectively. This can be attributed to the fact that an increment in vehicular traffic density comes with an associated increase in percentage of packet generation rate with a corresponding increase in contention for channel utilization, which in turn, leads to increased overall network overhead. Unfortunately, heavy network overhead generally impacts the overall network performance adversely.

Chapter Five

Radio Spectrum Requirement for Timely and Reliable Vehicular Safety Communication Support

5.1 Introduction

Although both Chapter 3 and 4 of this thesis have dwelled on different approaches of guaranteeing data packets transmission in vehicular networks with the minimum tolerable latency, this Chapter focusses on the actual amount of radio spectrum required for reliable and timely road traffic safety communication as the key part of the emerging ITS applications hugely depends on real-time, delay-sensitive V2V and V2I communications. Communication experts expect that at the end of 2020, vehicles will be manufactured and fully equipped with wireless electronic communication devices and multi-sensors that will enable them to prevent any vehicle collision that may occur with the help of timely and reliable vehicular information exchange/communication [57]. This exchange of road traffic safety messages is meant to provide vehicle drivers with safety alerts so as to warn them of impending traffic situations that may lead to road accidents. Thus, in VANETs, road traffic safety is accomplished with the help of two categories of messages, namely; 1) Cooperative Awareness Message (CAM) [84], and 2) Decentralized Environment Notification Message (DENM) [85]. The CAM is a periodically generated and broadcasted short message, which notifies the neighbouring vehicles within one-hop transmission range of the sender's status information such as direction of movement, velocity, location, etc. The DENM, on the other hand, is used to alert nearby vehicles about an emergency like a situation that may lead to vehicle collision or an actual occurrence of accident along the road. Therefore, the efficiency of any road traffic safety application wholly relies on reliable and timely dissemination of these messages with the minimum latency to ensure that the neighbouring vehicles receive the broadcasted packets and on time, to enable them to take appropriate actions that can prevent the imminent road accident.

With reference to the considerable existing and on-going research and standardization efforts by academia, industries, and government agencies as discussed in

Section 1.1 of Chapter 1, the development of the DSRC/WAVE standard and the European standard ITS-G5 has been seen as the most current significant efforts to actualize the long anticipated vehicular network. However, both DSRC/WAVE and the European standard ITS-G5 are based on recently approved IEEE 802.11p specification, which uses a simplified version of CSMA/CA as MAC protocol that is usually characterized by unbounded media access delay and best-effort quality. In order to provide an alternative delay-sensitive MAC protocol for future vehicular network, ITS-G5 system, European Telecommunications Standards Institute (ETSI) recently proposed an STDMA MAC [130].

As revealed in the discussion in Chapter 2, recent studies conducted to investigate the performance of IEEE 802.11p-based vehicular safety communication systems have identified its reliability and scalability challenges especially in high density vehicular networks such as urban or multi-lane highway vehicular network scenarios [23, 154, 6]. One of the possible explanations responsible for these reliability and scalability issues is inadequate and insufficient allocation of radio spectrum to V2V communication systems. In the US, the FCC has allocated 75MHz bandwidth to WAVE-based ITS services within the 5.850GHz – 5.925GHz band where only 10MHz radio spectrum is dedicated to critical road safety application. In Europe, the situation is similar where radio spectrum of 10MHz CCH is allocated to life-saving safety messages out of the 30MHz bandwidth available in the allotted 5.875GHz – 5.905GHz band for vehicular communication systems [17]. Generally, there are no well-established literatures yet on this issue to ascertain whether this allocated 10MHz bandwidth would be sufficient for critical safety messages in CCH except an initial study conducted by CEPT [61]. Hence, in this chapter, an in-depth study of the required amount of radio spectrum sufficient to guarantee reliable and minimum latency requirement of critical road safety messages is carried out. Furthermore, a feasibility analysis of radio spectrum requirement for scalable and reliable vehicular safety communication is carried out. In the feasibility analysis, the synchronized STDMA MAC protocol is compared with the DSRC/WAVE and European standard ITS-G5, which are based on IEEE 802.11p specification generally known for its unbounded media access delay and best-effort quality, as well as scalability and reliability issues. Additionally, the Message Reception Failure (MRF) is used as a performance metric to investigate and ascertain the minimum spectrum requirement for efficient, scalable, and reliable road traffic safety communication system. A highly saturated vehicular communication scenario of eight (8) lane highway road segment with four (4) lane opposite vehicular movement is considered.

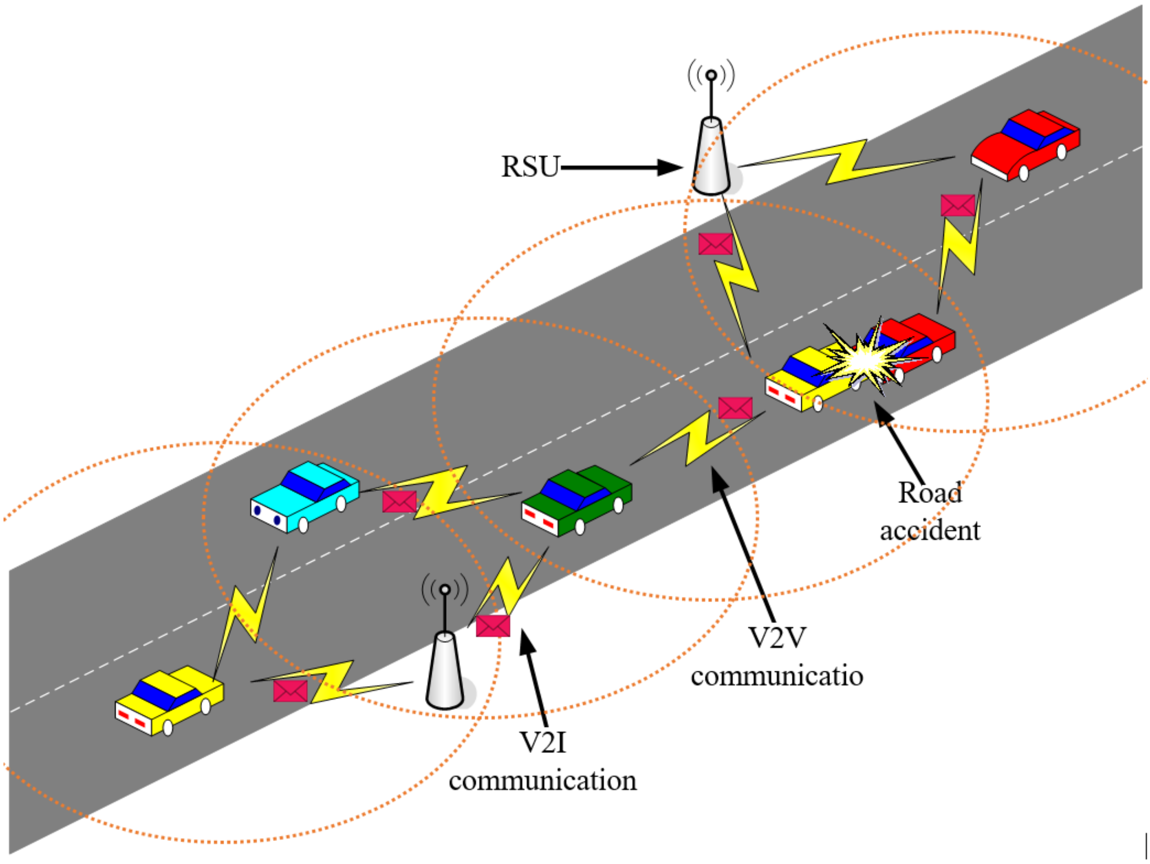


Fig. 5.1: System model of safety vehicular communication for mobile vehicle traffic.

5.2 Theoretical Basis for Investigating Spectrum Requirement for Timely and Reliable Vehicular Safety Communication Support

5.2.1 System Model

In this study, it is assumed that the mobile vehicles are fully equipped with multi-sensors and radio transceivers specifically dedicated for road traffic safety communication systems. Fig. 5.1 illustrates how DENMs are automatically generated at the event of an emergency like a road accident and broadcasted to neighbouring vehicles within several hundred meters (i.e., one-hop) range with the minimum latency. Additionally, all the mobile vehicles constantly check and monitor the advertisements/other activities on the

CCH when those vehicles are not broadcasting either periodic CAMs or even-driven DENMs. If the intended neighbouring receivers fail to receive or correctly receive the broadcasted message with an acceptable minimum delay due to obvious reasons, the transmission will be considered lost and result in decreased probability of MRF (P_{MRF}), accordingly. The performance metric P_f, as a measure for both CAMs and DENMs broadcast reliability, is given as the relationship of the number of transmitted messages that meet the acceptable minimum delay N_{MinDel} to the total number of transmitted messages N_{Total} over the vehicular communication network. Mathematically, the probability of MRF can be expressed as

$$P_{MRF} = \frac{N_{MinDel}}{N_{Total}} \tag{5.1}$$

5.2.1.1 MAC Layer Models

Two different types of access protocols, namely STDMA and CSMA/CA based MAC schemes, were implemented so as to effectively provide balanced assessment of the minimum spectrum requirement necessary for reliable road safety vehicular communication with a guaranteed acceptable minimum latency. It is noteworthy to mention that both STDMA and CSMA/CA based MAC protocols are usually applied to control the shared medium access contention over the single medium specifically dedicated for road traffic safety application.

5.2.1.1.1 CSMA/CA based MAC Algorithm

The recently approved 802.11p specification MAC algorithm employs the same exponential back-off procedure that is implemented by legacy IEEE 802.11 family. Hence, in accordance with the carrier sensing mechanism, each transmitter must first sense the channel to ensure that it is at least idle for a stipulated AIFS period of time prior to actually accessing the shared channel for packets transmission. Fig. 5.2 shows a typical CSMA/CA based MAC algorithm. In the case where the shared medium becomes busy or occupied within the stipulated AIFS period of time, the transmitting vehicle must defer its shared medium access for another randomized time period specified by the CW. Unfortunately, under a saturated vehicular network environment with increasing contention for channel access due to high channel load, a typical vehicular network, which uses CSMA/CA based MAC scheme for shared channel access will certainly experience an unpredictable and exponentially increasing media access delay.

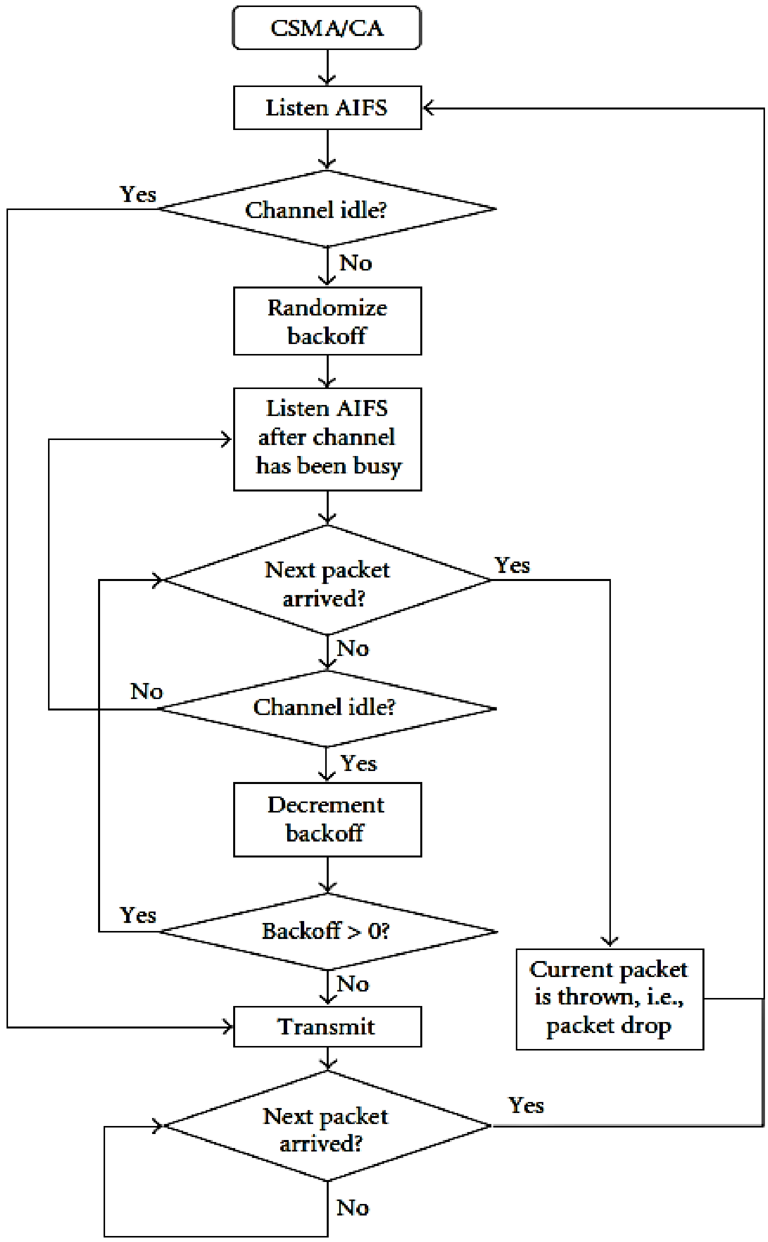


Fig. 5.2: CSMA/CA based MAC procedure in accordance with IEEE 802.11p/DSRC using a vehicular traffic model with broadcasted time-driven packets at pre-determined rates (i.e., at every 100ms)

Although the issue of high shared media access delay in vehicular networks has been partially resolved in Section 3.2.4 (Safety Message Priority Satisfaction) of Chapter 3 of this thesis by ensuring the provision of the acceptable minimum delay to safety-related messages for inter-vehicle communications in the proposed CARER protocol. In CARER protocol, the widely-used priority-based IEEE 802.11e EDCA scheme is adopted and enhanced for service differentiation. However, in a highly-saturated network scenario in a busy traffic which is generally the case in urban or city areas, especially during the rush hours in the morning and evening times, it is obvious that the media access delay may become unpredictable given the increased amount of communication load and overhead due to saturation in the channel. Consequently, there is a dire need to propose and implement a MAC scheme capable of guaranteeing reliable delivery of road traffic safety-related packets within the minimum acceptable delay in vehicular networks.

5.2.1.1.2 STDMA based MAC Algorithms

Unlike CSMA/CA based MAC schemes, whose shared media access delay becomes unpredictable and exponentially increases with increase in network/channel load, the STDMA based MAC schemes use a synchronized time-slot structure to guarantee reliable data packet transmission with a bounded media access latency even in highly saturated and congested network scenarios. Originally, this type of MAC scheme was first proposed and implemented for efficient coordination of maritime traffic [179]. With STDMA, each vehicle in a vehicular communication network begins by first listening to the activities in the channel for a period of one-time frame in order to discover which timeslots are currently busy with the broadcasting of data packets from other vehicles. As a result, some nominal transmission slots (NTSs) will eventually be selected for the transmission of each data packet during one frame. Each of the few selected NTSs is usually picked from the available group of empty time-slots, which is called selection interval (SI). Then, where there are no available unoccupied timeslots within the SI, the timeslot occupied by the most furthest away mobile node will be re-used, otherwise one slot will be randomly selected from the available group of empty slots. Hence, until another NTS is chosen by the use of the same procedure as described above, the originally selected NTS will continually be made use of, at least for a few successive frames. Consequently, the above illustrated mechanism helps to guarantee that the shared media access delay associated with STDMA based MAC schemes is reduced to the acceptable minimum level by ensuring that the shared media access delay is upper-bound by the length of the interval (i.e., the SI).

5.2.1.2 PHY Layer Model

In accordance with IEEE 802.11a specification, the study adopted a PHY layer model based on OFDM technique. Furthermore, in order to ensure the tractability of the simulation experiments while highlighting the correlation that exists between channel bandwidth and data packet transmission reliability, a simplification was made by assuming that a dynamic modulation scheme with a minimum SINR threshold, θ and a constant data rate is adopted to guarantee that the received packets will be successfully decoded. The minimum SINR θ can be expressed as

$$SINR = P_s \Big/ \left(\sum_{n=0}^{N} P_{i,n} + N_0 \right) \geq \theta \qquad (5.2)$$

where P_s denotes the strength of the received signal, $P_{i,n}$ represents the interference effect received from the n^{th} current active transmitter, and N_0 is the single side thermal noise power spectral density. Additionally, the study is also based on the assumption that link data rate in a typical wireless network increases proportionally with respect to the amount of available channel bandwidth. As an example, a QPSK modulation scheme can achieve a link data rate of 6Mbps in a 10MHz channel and the increment in data rate can double up to 12Mbps in a 20MHz channel, accordingly.

Nevertheless, the assumption is rather optimistic given that the effect of Doppler fading as well as root mean square delay spread in vehicular communication network media can impact the spectrum efficiency negatively with an increasing channel bandwidth [171]. Thus, representing the power delay profile (PDP) of the vehicular network channel also called the multi-path intensity profile by $A_c(\tau)$, which signifies the average power inherent in a given multi-path delay, it would be easily computed empirically. Hence, both the average delay of the channel and the RMS delay spread can be easily expressed in terms of the PDP $A_c(\tau)$ as

$$T_{Av} = \frac{\int_0^\infty \tau A_c(\tau) d\tau}{\int_0^\infty A_c(\tau) d\tau} \quad (5.3)$$

and

$$T_{RMS} = \sqrt{\frac{\int_0^\infty (\tau - T_{Av})^2 A_c(\tau) d\tau}{\int_0^\infty A_c(\tau) d\tau}} \quad (5.4)$$

It is noteworthy to mention that the probability density function (PDF) pT_r of the random delay spread T_r is expressed in terms of $A_c(\tau)$ as

$$pT_r(\tau) = p(T_r = \tau) = \frac{A_c(\tau)}{\int_0^\infty A_c(\tau) d\tau} \quad (5.5)$$

Thus, relative to the PDF, T_{Av} and T_{RMS} denote the average and RMS values of the random delay spread T_r, respectively. Consequently, defining the average and RMS delay spread using Eq. (5.3) and Eq. (5.4), respectively, or equivalently, evaluating the PDF of T_r using Eq. (5.5) measures the overall latency associated with a particular multi-path component by its relative power, in order to ensure that weak multi-path components do not greatly increase the associated delay spread as opposed to strong multi-path components. In other words, the multi-path components that are below the stipulated noise threshold (i.e., noise floor) like the weak multi-path components will certainly not be able to significantly affect these characterisations of the delay spread.

Similarly, the delay spread associated with a vehicular communication channel can be roughly characterized using the random time delay T_r with $A_c(\tau)$ asymptotically equal to zero for $\tau \geq T_r$. Typically, the approximated value is mostly assumed to be the achievable RMS delay spread, that is, $T_r = T_{RMS}$. Note that a linearly modulated transmission signal with symbol duration D_s using the above assumed approximation can suffer a significant Inter Symbol Interference (ISI), especially if D_s is much less than T_r. On the contrary, a linearly modulated transmission signal with symbol duration D_s under a similar condition can suffer a negligible ISI when D_s is much greater than T_r. Obviously, it can be assumed that $D_s \ll T_r$ implies that $D_s < T_r/10$, and in the same manner, $D_s \gg T_r$ automatically implies that $D_s > 10T_r$. Accordingly, depending on the details of the channel, when D_s does not exceed a relatively acceptable minimum order of magnitude of

T_r, it means that the system will likely experience a degree of ISI that may or may not lead to significant performance degradation.

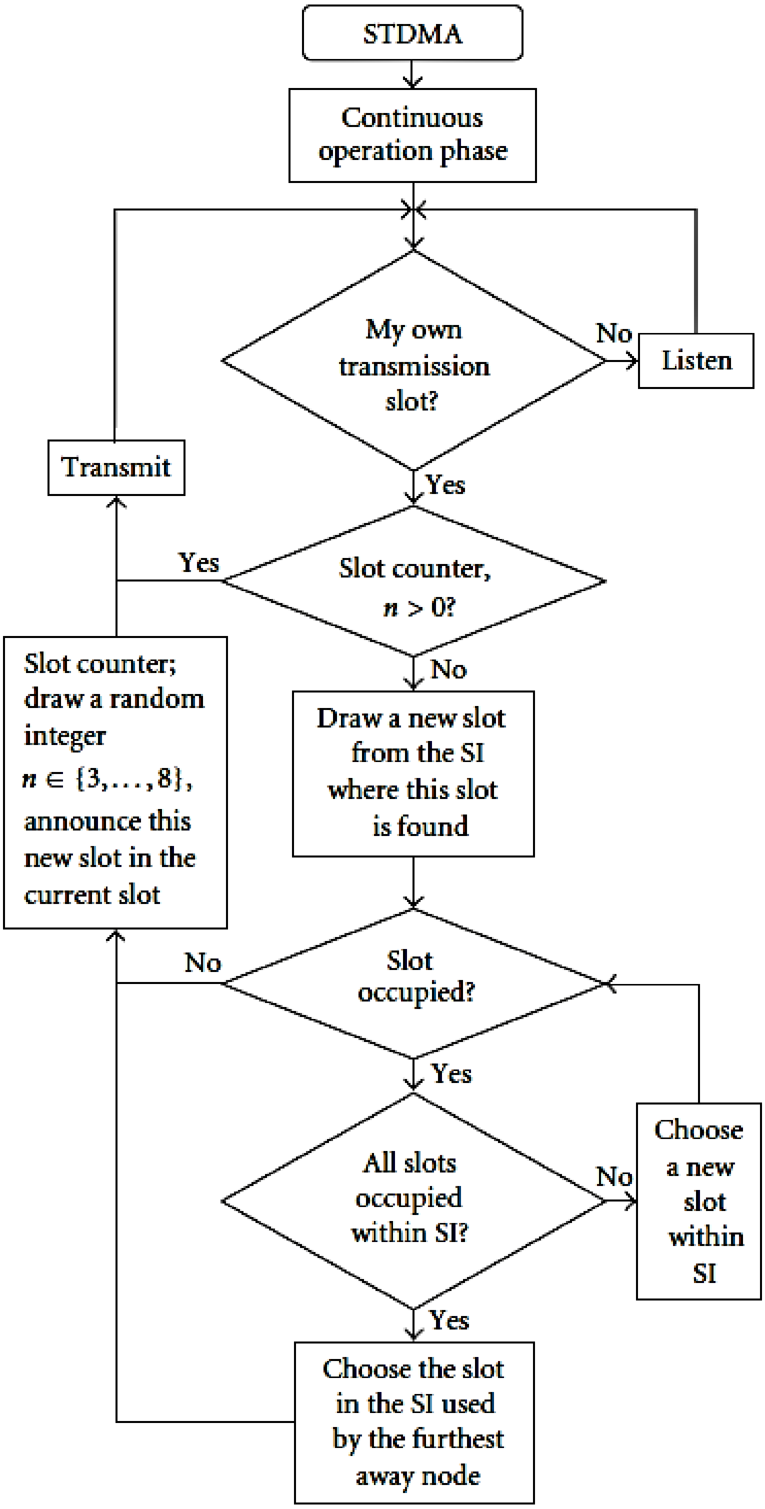


Fig. 5.3: STDMA based MAC procedure using a vehicular traffic model with broadcasted time-driven packets at pre-determined rates (i.e., at every 100ms).

Therefore, the significance of delay spread depends on how it impacts on the ISI. In other words, if the symbol period D_s is long enough in contrast to the delay spread, then an equivalent ISI-free vehicular communication channel can be expected. On average, a symbol period that is 10 times as big in contrast to the achievable delay spread would be good enough to obtain an equivalent ISI-free vehicular communication channel. Similarly, the correlation between the delay spread and the frequency domain is the concept of Coherence Bandwidth (CB), which is the available bandwidth over which the communication channel can be presumed to be flat. In other words, the CB is directly related to the inverse of the obtainable delay spread. Thus, the larger the CB, the shorter the delay spread.

5.3 Performance Analysis

In this Section, the efficiency of both CSMA/CA and STDMA based MAC algorithms is investigated through performance analysis carried out as a measure of the probability of message reception failure, and RMS delay spread.

5.3.1 Safety Message Transmission (MAC-to-MAC) Delay

Providing channel access while ensuring the guarantee of QoS provision in terms reliability and delay is a challenging but crucial task of the MAC layer. In a typical safety vehicular communication, not only is guaranteed transmission reliability highly required, but a predictable and acceptable minimum MAC-to-MAC delay [166], which contributes to timely transmission and reception of safety packets, is equally highly required. Road traffic safety related packets must be transmitted and received within a minimum attainable delay T_{dl}, which means that such high priority, delay-sensitive, time-critical packets must be delivered on time to the vehicles within the ZoI, i.e. the zone (or area) where a traffic emergency has occurred or is about to occur. Thus, in this contribution, MAC-to-MAC delay T_{mm} as a performance metric is adopted for measuring the performance and efficiency of the MAC solutions (i.e. CSMA/CA and STDMA based MAC algorithms) investigated in the study. Hence, in both MAC algorithms, safety related packet transmission and reception deadline τ_{dl} can only be satisfied if and only if the deadline is bigger than MAC-to-MAC delay, T_{mm}. That is, $T_{dl} > T_{mm}$. In other words,

T_{mm} can be given as the total aggregate of the shared media access delay T_{ca}, packet propagation delay T_{pp}, and packet decoding delay T_{pd}. In Fig. 5.4, a shared medium access request at the source vehicle (Tx) occurs at t_0, and the length of period from t_0 to t_d represents the total MAC-to-MAC delay, since the message is successfully decoded at t_d. Thus, the following delays make up the total safety message transmission delay:

- **Channel (or Media) access delay**, T_{ca} represents the length of duration taken by a transmitter starting from media access request up to the time of actual packet transmission. For road traffic safety vehicular communication, a safety packet will be dropped if the deadline is lesser that the channel access delay, that is, $T_{dl} < T_{ca}$. This is as a result of the fact that when the media access delay of a particular safety message tends to infinity, i.e. $T_{ca} \rightarrow \infty$, its deadline expires and it gets dropped at the source vehicle given that another new packet with updated kinematic details is generated periodically at least every 100ms. Thus, once a new packet is generated, the old one is no longer relevant since the vehicle most have changed location due to mobility.
- **Packet propagation delay**, T_{pp} denotes the actual length of duration it takes the transmitted signal (i.e., packet) to travel from the source vehicle (i.e., the transmitter) to the receiver. Therefore, depending on the routing approach applied, if the routing is not successful due to intermediate node break-down, then $T_{pp} \rightarrow \infty$.
- **Packet decoding delay**, T_{pd} denotes the actual length of duration taken to convey a successfully decoded message to the upper layers of the recipient vehicle. It follows that $T_{pd} \rightarrow \infty$ if the decoding is not successful as a result of fading effect, interference or noise.

Finally, total MAC-to-MAC delay T_{tdl} is given as

$$T_{tdl} = T_{ca} + T_{pp} + T_{pd} \qquad (5.6)$$

It is noteworthy to mention that the critical safety/emergency alert is generally very short. Thus, its transmission time is omitted here. Hence, reliable and timely safety vehicular communication is said to be achieved if transmitted safety-related packet meets a hard deadline since missing the hard deadline could result in fatal costs or penalties such as vehicle collisions on the road, which mostly leads to loss of lives and properties. Specifically, in this study, it is said that a particular MAC (either CSMA/CA or STDMA based MAC) performed well if and only if at least 90 percent of all the received packets maintain media access delay that is less or equal to the deadline (i.e., 100ms), otherwise such MAC performance is adjudged poor, and does not meet the hard deadline.

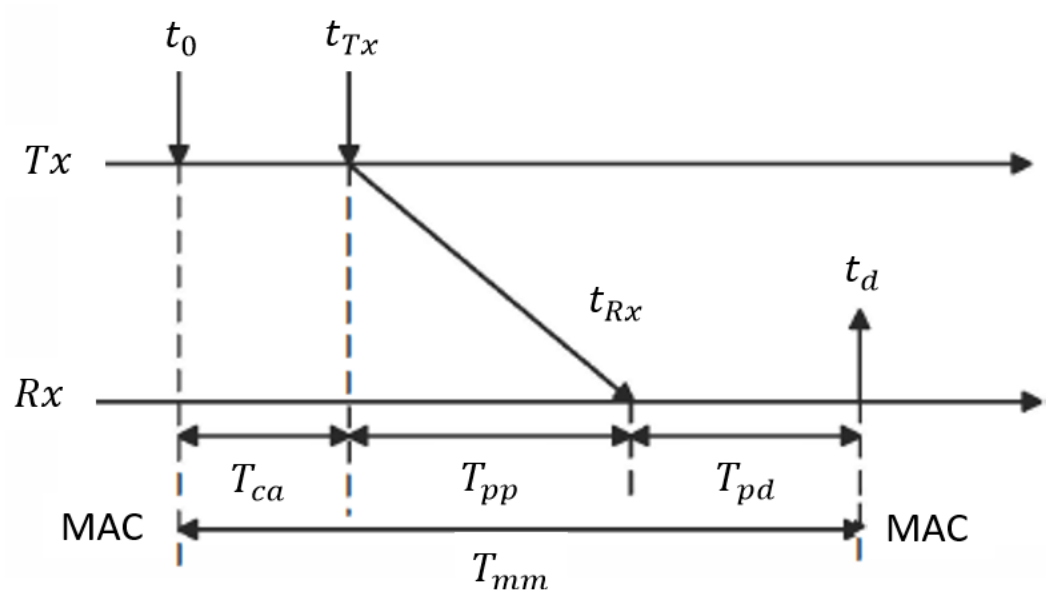


Fig. 5.4: Safety Message Transmission (MAC-to-MAC) Delay

5.4 Simulation Setup

In this section, a comparison of the implemented CSMA/CA and STDMA based MAC approaches for vehicular communication is shown using simulation experiments, focusing on urban-highway scenarios with 150 vehicles, 300 vehicles, and 500 vehicles.

5.4.1 Simulation Settings and Assumptions

In this section, CSMA/CA and STDMA based MAC approaches for vehicular communication were implemented in order to investigate the spectrum requirement of the two MACs and to evaluate their performance in terms of transmission reliability and the minimum achievable delay spread using MATLAB® [137]. Similarly, a close to real-life urban-highway vehicular network scenario is simulated using sets of realistic parameter settings, which are commonly applied in the literature. For the purpose of the minimum spectrum requirement for reliable vehicular communication and other obvious reasons, a typical urban-highway is used, which has been considered [48] as the worst-case scenario in terms of high spectrum requirement and need for the minimum acceptable delay for efficient road traffic safety communication as a result of high vehicle density, mobility and rapid topology changes [6]. The urban-highway vehicular road considered in this simulation experiments is a 5x5 Manhattan grid road network, as depicted in Fig. 5.5, with 2000m edge length and BonnMotion tool [148] to generate suitable node mobility model. The roads consist of eight (8) lanes of 5m width with four (4) lanes on opposite direction.

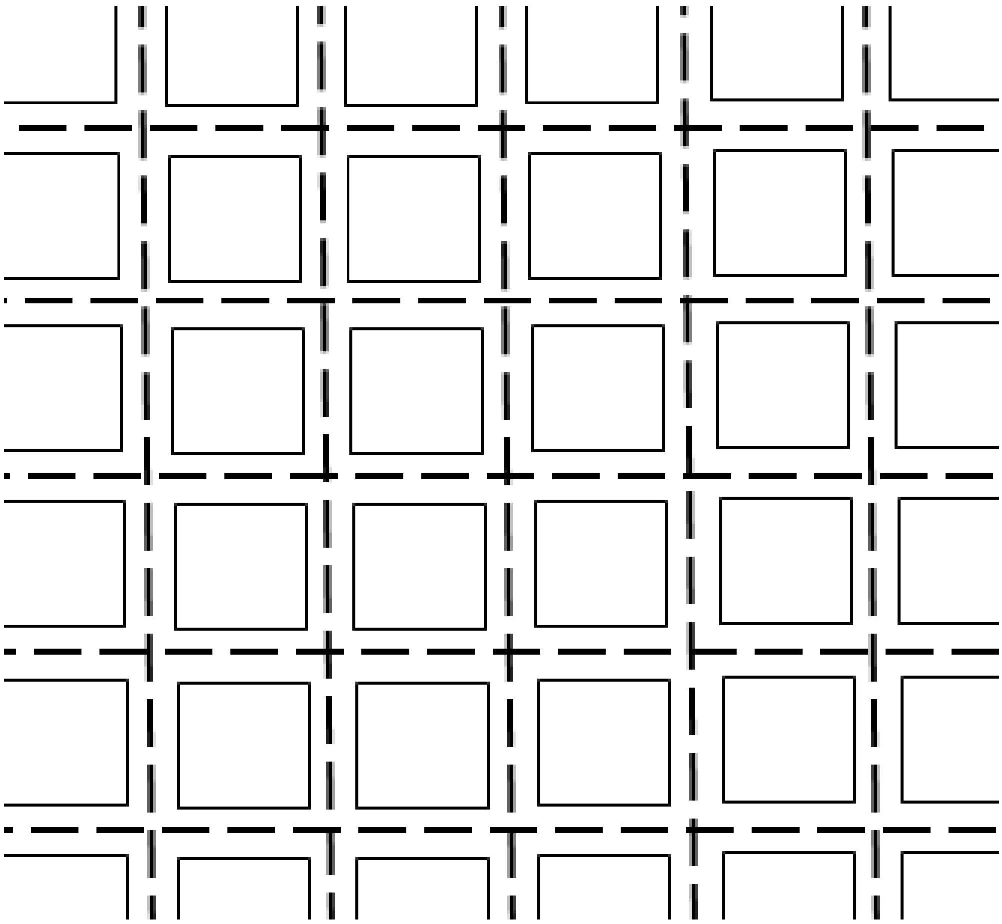


Fig. 5.5: A typical 5x5 Manhattan grid road network

The arrival of vehicles is modelled as a Poisson process on each of the lanes with arrival interval of three (3) seconds[8].

In this simulation experiment, each of the lanes was assigned a different average speed in order to ensure that the dynamics associated with road safety vehicular communication is reflected in the simulated scenarios. Similarly, the velocity of the mobile nodes on each of the lanes obeys a normal distribution with the assigned velocity and a standard deviation of 1m/s. The velocity of the outer most lane is set at 90km/h, the three inner most lanes are assigned an average speed of 130km/h, and the velocity of the middle lane is 108km/h. Thus, for this evaluation, the chosen set is the most critical especially for road traffic safety communication, that is, high dense vehicular traffic with fast moving vehicles. The vehicular traffic density, on average, is approximately eleven (11) mobile vehicles per kilometre on each of the lanes.

The safety-related data packets that each vehicle generates are periodic CAM for vehicles status information awareness creation, and event-triggered DENM to inform other neighbouring vehicles of an accident or impending vehicle accident. With either of these safety-related data packet traffic, each mobile node's initial broadcasting duration is random and independent. For the size of a safety packet, the FCC standard recommended a 300byte message size as specified in IEEE 802.11p/DSRC specification with a repetition rate of 10Hz, while the ETSI suggested that safety related packets be broadcast in a packet size of 800 bytes using a repetition rate of mere 2Hz. The US standard IEEE 802.11p/DSRC specification is adopted in this simulation experiment since virtually all the use-cases that are based on either DENM or CAM demand a maximum delay of 100ms with minimum periodic update frequency of 10Hz [57], [86].

Similarly, a combination of Nakagami-m [199] and dual-slope piecewise-linear model for fading effects [24] and distance dependent path-loss [182], respectively, are used as the channel propagation model in the simulator. The parameters for the Nakagami radio propagation model were fine-tuned according to the reported actual measurements contained in [174]. Furthermore, the piecewise-linear model uses a path-loss exponent γ_1 as well as standard deviation φ_1 within a critical safe distance d_c. Then, beyond this

[8] According to road traffic safety regulation, each vehicle must maintain a safe following distance of three (3) seconds from the vehicle in front.

critical safe distance, the signal strength weakens with another path-loss exponent γ_2 and standard deviation φ_2. In a typical urban-highway vehicular environment, this dual-slope piecewise-linear model for a distance dependent path-loss is presented through a widely-adopted log-normal model and expressed as follows:

$$P(d) = \begin{cases} P(d_0) - 10\gamma_1 \log_{10}\dfrac{d}{d_0} + Y_{\varphi_1}, & d_0 \leq d \leq d_c \\ P(d_0) - 10\gamma_1 \log_{10}\dfrac{d_c}{d_0} - 10\gamma_2 \log_{10}\dfrac{d}{d_c} + Y_{\varphi_2}, & d > d_c \end{cases} \quad (5.7)$$

where $P(d)$ denotes the received signal strength at distance d; $P(d_0)$ represents its counterpart at reference distance d_0; and $(Y_{\varphi_1}, Y_{\varphi_2}) \in Y_\varphi$ denotes a zero-mean, which is usually a randomly distributed variable characterized by a standard deviation φ. The path-loss exponents γ_1 and γ_2 are 2.1 and 3.8, respectively, while the critical safe distance d_c is 100m. Moreover, it is noteworthy to mention that the fading effect of Nakagami-m is only averaged over a close proximity of the mobile node, while slow-fading, usually represented by a widely-adopted log-normal model, can be summed and integrated for any distance over the piecewise-linear slope path-loss model that is beyond a certain wavelength [31]. Thus, the results discussed in Section 5.4.2 exclude the effect of fading so as to emphasize only on the adverse effect of heavy network congestion as a result of insufficient allocation of channel bandwidth.

In the simulation, it is assumed that all the mobile nodes have the same output power, i.e., 33dBm per 10MHz, which is the acceptable maximum output power allowed over the control channel according to ITS-G5A specification. Similarly, the noise and clear channel assessment (CCA) thresholds are -99dBm and -93dBm per 10MHz, respectively, which approximately corresponds to a 1km sensing range. Lastly, in order to ensure successful packet reception with the minimum latency, SINR threshold of 6dB is needed. On the other hand, the MAC parameter settings for CSMA/CA such as CW and AIFS are set at 3 and $58\mu s$, respectively, in conformity with the highest priority accorded to safety messages in vehicular networks. The total number of timeslots in the case of STDMA based MAC per frame grows in line with the improvement of the data rate, while the length of the frame is presumed to be 1 second (i.e., a constant). In other words, one timeslot duration tallies with the duration taken to transmit a packet of 300bytes size.

Unless otherwise stated, in all the three different scenarios used in this simulation experiment, the time parameters applied are chosen from the IEEE 802.11p PHY specification.

Furthermore, in order to investigate the effect of available spectral resource on the reliability of safety packet transmission, the channel bandwidth of the CCH is varied from 10MHz up to 40MHz. The simulated urban-highway scenarios are filled up with the generated vehicular traffic. Finally, the broadcast message reception was recorded over 60,000ms (i.e., 1 minute) period.

Table 5.1: Values of parameters used in this simulation

Parameter	**Value**
Data rate	3Mbps
Packet size	300bytes
Sensing range	1000m
CW_{min} (CSMA/CA)	3
CW_{max} (CSMA/CA)	Not used due to broadcast nature of VANETs
Latency requirement	100ms
SINR threshold	6dB
Frame length (STDMA)	1s
AIFS (CSMA/CA)	$58\mu s$
Slot time	$9\mu s$
SIFS	$16\mu s$
Back-off time	$58\mu s$
Number of lanes	5 x 2

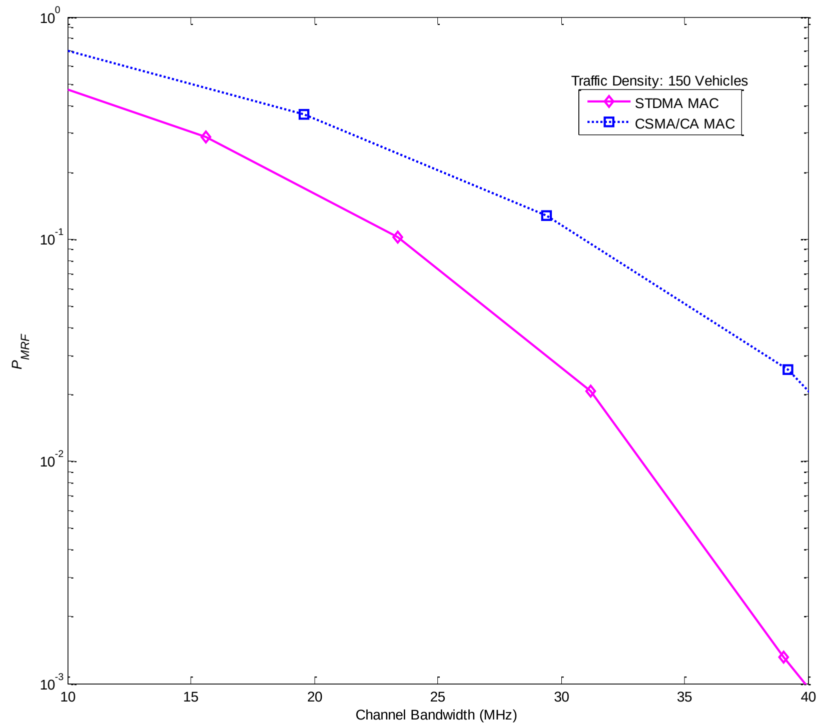
From the definition of Eq. (5.1), the probability of message reception failure is calculated. The rest of the parameters with their settings as used in the simulation are shown in Table 5.1.

5.4.2 Results and Discussion

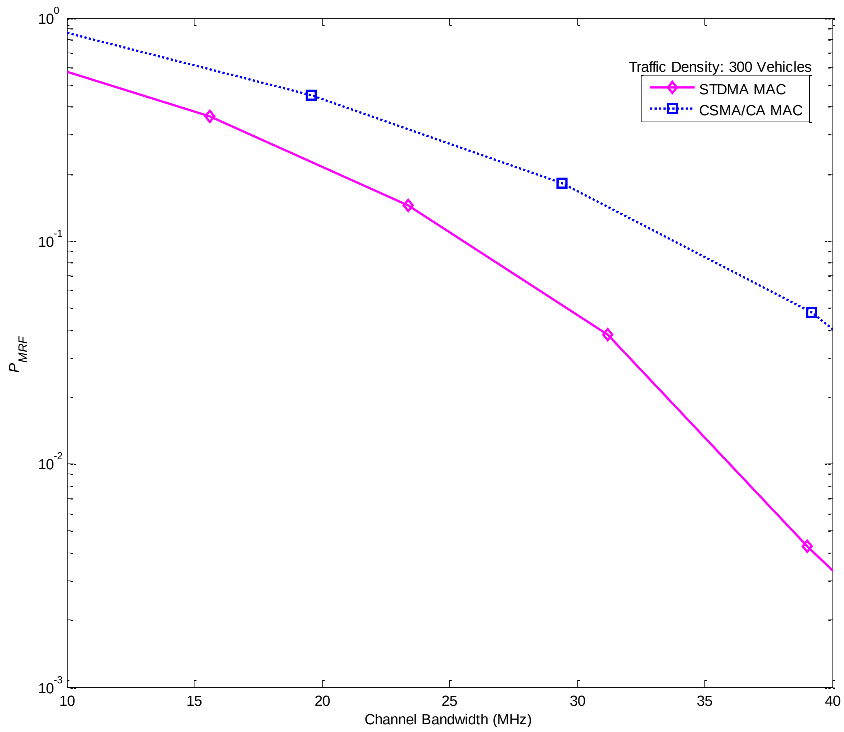
5.4.2.1 Probability of Message Reception Failure

As shown below, message transmission delay and probability of message reception failure (P_{MRF}) as performance metrics are used to evaluate the efficiency and degree of performance gain between CSMA/CA and STDMA based MACs in road traffic safety vehicular communication. Firstly, safety packet transmission reliability over CSMA/CA and STDMA based MACs were measured in comparison between different spectral resource allocations, i.e., from 10MHz up to 40MHz. In order to demonstrate the effect of allocated spectral resource on vehicular message broadcast reliability as well as on the overall vehicular network performance, the resultant message transmission reliability of STDMA and CSMA/CA based MACs was measured as a function of the allocated spectral resource and the amount of traffic (i.e., vehicular traffic density) across the entire vehicular network. Additionally, the channel bandwidth is varied from the US FCC officially allocated 10MHz to 40MHz, which effectively allows an increased the number of packets generated (or network traffic load) from low to high. The simulated vehicular network urban-highway road segments are filled up with generated vehicular traffic during the initialization phase.

Fig. 5.6 (a) – (c) demonstrate that the wider the available spectral resource, the higher the QoS and the overall performance of the entire vehicular network will improve. From the results contained in Fig. 5.6 (a) to Fig. 5.6 (c), it is evident that the performance of both STDMA and CSMA/CA based MACs in terms of transmission reliability shows remarkable improvement with less probability of data packets transmission and reception failure at the receivers as the available spectral resource increases from 10MHz to 40MHz. Additionally, the result goes a long way to prove that high (at least more than 10MHz) spectrum is required for a high density urban or sub-urban vehicular environment with a maximum reliability demand. The performance demonstrated in the results makes it clear that over 40MHz bandwidth is required in order to guarantee the maximum (i.e., 99%) transmission reliability in certain cases. However, the overall improvement in transmission reliability is a lot higher with STDMA based MAC compared to CSMA/CA based MAC as can be witnessed in Fig. 5.6 (a), 5.5 (b) and 5.5 (c).



(a)



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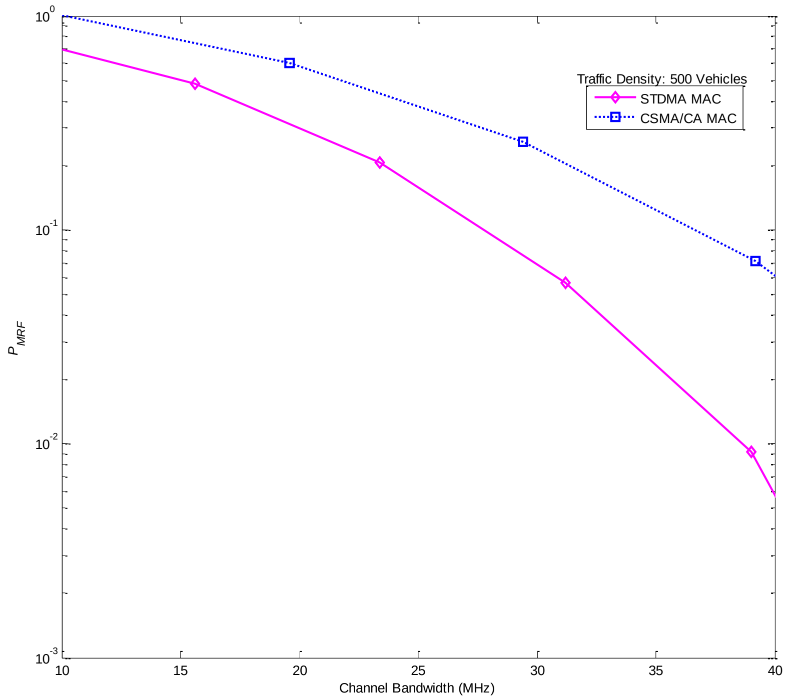


(c)

Fig. 5.6 (a) – (c): Performance comparison between the STDMA and CSMA/CA based MAC algorithms using Probability of message reception failure (P_{MRF}) as a function of the available channel bandwidth (measured in MHz) with increasing vehicular traffic density from 150 vehicles up to 500 vehicles.

It is observed that STDMA based MAC offers a performance advantage of multiple orders of magnitude (i.e., over 10% performance gap) against CSMA/CA based MAC in terms of the minimum obtainable probability of data message reception failure at the receivers as the available spectral resource increases from 10MHz to 40MHz. Obviously, from Fig. 5.6 (a), Fig. 5.6 (b), and Fig. 5.6 (c), it is clear that the probability of data message reception failure is well beyond 20% with allocation of 10MHz channel bandwidth but steeply reduces as the available channel bandwidth (i.e., spectrum allocation) increases from 10MHz up to 40MHz.

Notwithstanding the impressive performance of both CSMA/CA and STDMA based MACs in terms of P_{MRF} by improving safety data packets transmission reliability, a more important striking difference is seen between the two considered MACs. It is shown in Fig. 5.6 (a) – (c) that even at the same allocation of 10MHz channel bandwidth, STDMA out performs the CSMA/CA based MACs due to the fact that CSMA/CA MAC algorithm is strictly based on rigorous contention for shared channel access which leads to increased network overhead, whereas STDMA based MACs provide a structured shared medium access and prevent the negative impact of unhealthy contention for shared channel access even when the communication channel is fully loaded and saturated. In other words, the vehicles are synchronized by time slots. This means that each time that new vehicles enter the shared medium, they first give a listening to the activity of the shared channel for one frame duration, and have the frame divided into several groups according to the number of messages they need to send per frame. Finally, as discussed in Section 5.2.2, each vehicle selects one NTS from each group for transmission of its own data packets and then starts to transmit continuously. Similarly, a reuse factor is assigned to each NTS so as to allow for adapting to the changes occurring in the shared channel, which represents a given number of the following frames where the transmission timeslot is utilized by the mobile node. Then, successively, another NTS will be carefully selected when the current counter (i.e., the pre-assigned reuse factor) expires, out of the available NTSs within its SI. In other words, unlike CSMA/CA, STDMA based MACs always provide media access even when all the time-slots of the SI are occupied by selecting as another NTS the one utilized by the furthest vehicle, as discussed in Section 5.2.2 above. Thus, this approach prevents the unhealthy shared channel congestion and increased overhead caused by heavy contention for channel utilization in the case of CSMA/CA based MAC algorithms, which in turn, leads to poor data packet transmission reliability, as is the case in Fig. 5.6 (a), Fig. 5.6 (b), and Fig. 5.6 (c).

More interestingly, it can be seen from Fig. 5.6 (b) and Fig. 5.6 (c) that the volume of vehicular traffic density also has direct impact on the transmission reliability of safety related data packets. The reason for this may be due to the fact that increased channel load and congestion due to excessive network saturation sometimes result in deterioration of the overall network QoS and may even lead to transmission collision. Thus, the end result becomes an overall increased probability of safety packets transmission and reception failure, which is noticed in both Fig. 5.6 (b) and Fig. 5.6 (c) with increased traffic density from 300 vehicles (see Fig. 5.6 (b)) to 500 vehicles (see Fig. 5.6 (c)). However, in either case, STDMA based MAC algorithm always out performs the CSMA/CA, again, due to the same reasons discussed above. Most importantly, this negative impact of increased vehicular traffic density is very conspicuous in Fig. 5.6 (c) especially on CSMA/CA based

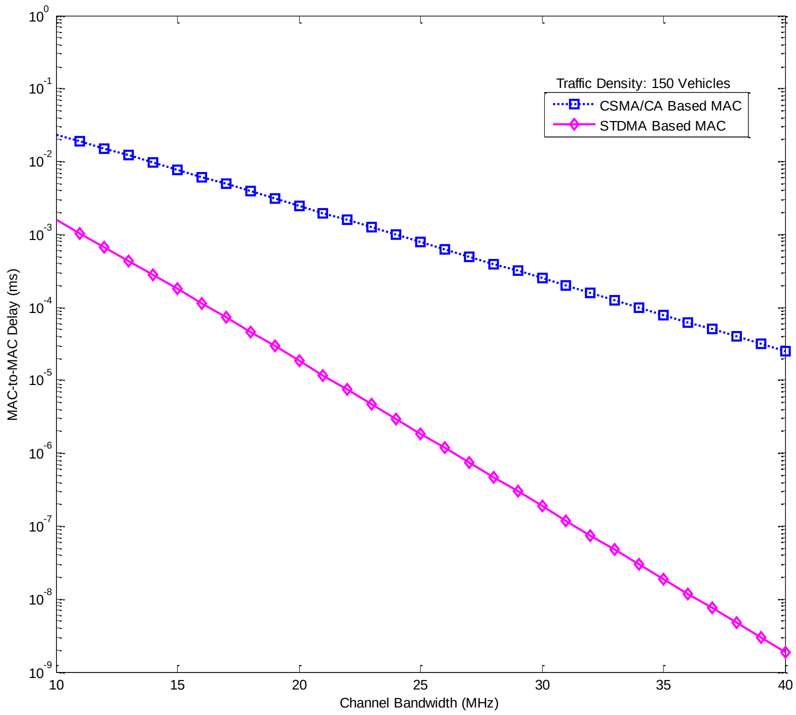
MAC algorithm performance. The figure shows that, at exactly 10MHz bandwidth allocation, the probability of safety data message reception failure is 100%. This simply means that no transmission is correctly received and decoded at the destination due to poor network QoS. Similarly, it can be clearly seen that as the available channel bandwidth increases from 10MHz up to 40MHz, that the probability of safety data message reception failure reduces drastically and significantly in Fig. 5.6 (a) towards 0%, which means that virtually all the transmitted safety data packets are correctly received and decoded at the intended receivers. However, the increase in vehicular traffic density from 150 vehicles (see Fig. 5.6 (a)) to 500 vehicles (see Fig. 5.6 (c)) categorically shows that more than 10MHz bandwidth (i.e., at least 50MHz channel bandwidth) is required for efficient and reliable transmission of safety related packets as opposed to the existing official 10MHz bandwidth allocation for road traffic safety communication in VANETs. In other words, the performance depicted in Fig. 5.6 (a) through Fig. 5.6 (c) opposes in every sense the existing official regulatory resolution of allocating a meagre 10MHz channel bandwidth over 5.9GHz band for exchange of safety packets by FCC in 1999. The result further suggests that a significant modification would be required in either the overall design of IVC system or the amount of spectrum allocation required to achieve an efficient vehicular communication system, especially for safety traffic exchange in VANETs.

5.4.2.2 Safety Message Transmission Delay

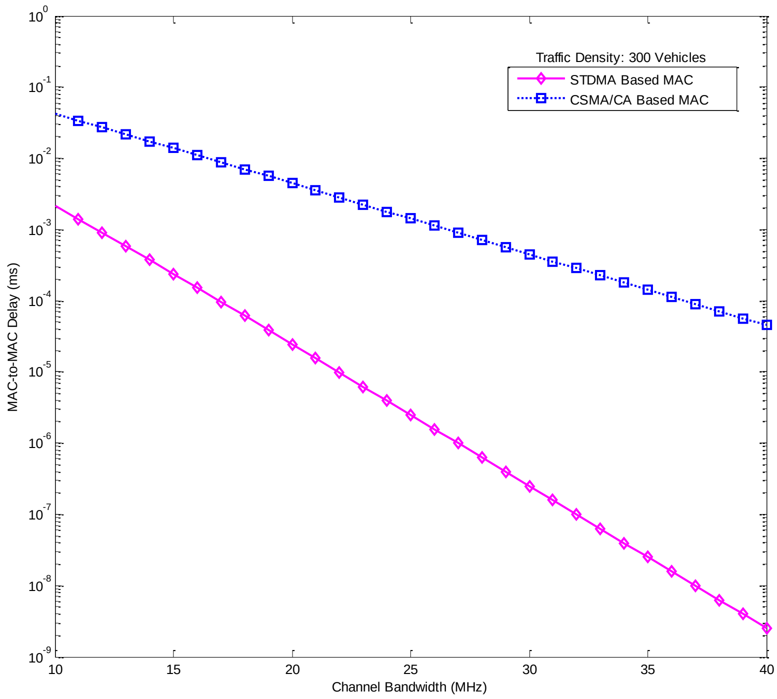
As shown below, message transmission delay performance of both STDMA and CSMA/CA based MAC algorithms were measured in comparison between different spectral resource allocations (i.e., from 10MHz up to 40MHz). In order to demonstrate the impact of available spectrum on the latency of vehicular communication as well as on the overall vehicular network performance, the resultant message transmission delay of both CSMA/CA and STDMA based MAC algorithms were measured as a function of the allocated spectral resource and the amount of vehicular traffic density across the simulated vehicular network scenarios. Additionally, the channel bandwidth is varied from the US FCC officially allocated 10MHz up to 40MHz in order to clearly obverse the impact on the two shared media access algorithms. In Fig. 5.7 (a), Fig. 5.7 (b), and Fig. 5.7 (c), it can be observed that the safety related message transmission delay significantly reduces both in a low and in a high vehicular traffic density as the available spectrum (i.e., channel bandwidth) increases from 10MHz up to 40MHz. The results depicted in Fig. 5.7 (a), Fig.

5.7(b), and Fig. 5.7(c) also demonstrate that the wider the available spectral resource, the lower the overall delay (i.e., the total Safety Message Transmission Delay) performance of both the CSMA/CA and STDMA based MAC algorithms. The results also indicate that more than 40MHz bandwidth is required to guarantee the minimum acceptable latency as well as 99% reliability in certain cases. Once more, as discussed in the case of providing reliability for safety related message transmission, the performance depicted in Fig. 5.7(a), Fig. 5.7 (b), and Fig. 5.7 (c) glaringly contrasts the existing official regulatory resolution of allocating a meagre 10MHz bandwidth for safety related message exchange in vehicular networks both in US by US FCC in 1999.

Similarly, the results presented in Fig. 5.7 (a), Fig. 5.7 (b), and Fig. 5.7 (c) likewise indicate that the shared media load shows different impacts on the safety message transmission delay, depending on the particular shared channel access approach adopted in each MAC algorithm.



(a)



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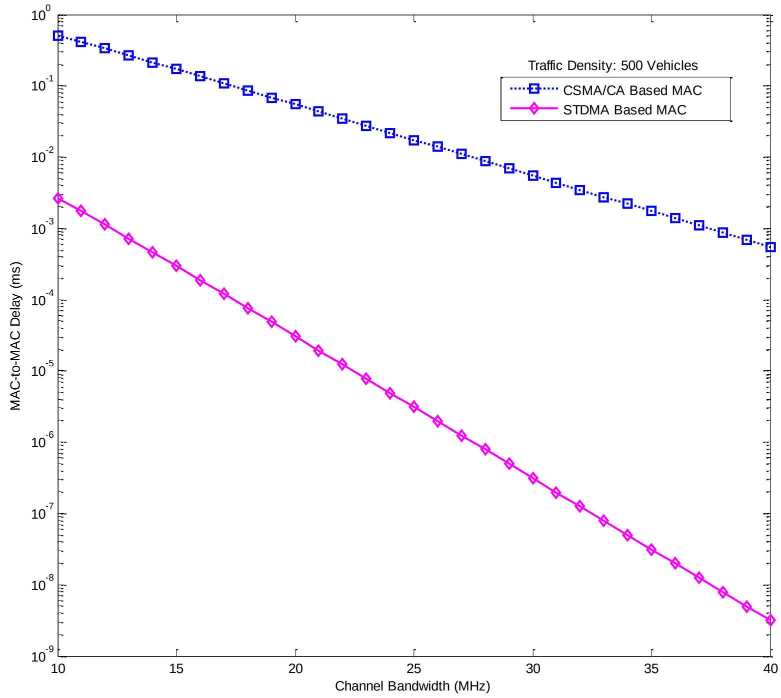

(c)

Fig. 5.7 (a) – (c): Performance comparison between STDMA and CSMA/CA based MAC algorithms using total safety message transmission delay (T_{tdl}) as a function of the available channel bandwidth (measured in MHz) with increasing vehicular traffic density from 150 vehicles up to 500 vehicles.

Consequently, from the obtained results as contained in Fig. 5.7 (a), Fig. 5.7 (b), and Fig. 5.7 (c), it is evidently clear that the STDMA based MAC algorithm out performs the CSMA/CA based MAC algorithm in terms of safety message transmission delay when measured as a function of the available spectrum resource as well as the amount of vehicular traffic density. The results show that the STDMA based MAC algorithm has a performance gap of multiple orders of magnitude as opposed to the CSMA/CA based MAC algorithm in terms of the minimum acceptable latency that can be tolerated in order to guarantee fast and timely transmission and reception of safety related packets in vehicular networks so as to avoid road accident occurrence. Obviously, from Fig. 5.7 (a), Fig. 5.7 (b), and Fig. 5.7 (c), it is clear that the transmission delay experienced by the CSMA/CA based MAC algorithm is well above 15% compared to the STDMA based MAC algorithm even with the same allocation of 10MHz channel bandwidth. Furthermore, the overall transmission delay resulting from using the CSMA/CA based MAC algorithm drastically increases even as the available channel bandwidth (i.e., spectrum allocation) increases from 10MHz up to 40MHz in contrast to the STDMA based MAC algorithm, whose delay reduces sharply to less than 1% as the available channel bandwidth increases from 10MHz up to 40MHz. The poor performance of the CSMA/CA based MAC approach as against the STDMA based MAC approach in terms of transmission delay of safety packets is as a result of the fact that safety data traffic in VANETs applies high priority queues in contrast to non-safety related data traffic as provided by the EDCA mechanism, which is adopted by IEEE 802.11p. The high priority access accorded to safety related data traffic implies short sensing durations but also few back-off values from which to select from after sensing the channel to be occupied by another vehicle. Note that IEEE 802.11p MAC algorithm uses an exponential back-off scheduler. Hence, for a very low shared channel load (as is the case in Fig. 5.7 (a) with only 150 vehicles), low shared media access delay is provided after the channel sensing duration. However, when the channel load increases (as is the case in Fig. 5.7 (b) and Fig. 5.7 (c) with 300 vehicles and 500 vehicles, respectively), the shared channel access delay increases exponentially. In other words, the channel access delay becomes unpredictable with the CSMA/CA based MAC approach as the traffic density increases, leading to increase in channel loads. On the other hand, the STDMA based MAC approach uses a structured channel access mechanism to guarantee a predictable safety message transmission delay even in worst case vehicular network scenarios with high traffic density and high channel loads, which is the case in Fig. 5.7 (c) with an increased number of participating vehicles. Thus, since the shared channel access delay of the STDMA based MAC approach is predictable even in a high traffic density as opposed to IEEE 802.11p MAC algorithm that is based on the CSMA/CA approach, the total safety message transmission delay of the STDMA based MAC approach is upper-bounded by the length of the selection interval (SI) as discussed in Section 5.2.2.

Chapter Six

Conclusions and Future Work

6.1 Conclusions

Many pioneering efforts are well under-way in different auto-mobile industries, academia, and communication companies to manufacture smart vehicles (e.g., Google cars). The smart vehicles are expected to be properly equipped with wireless communication technologies and sensors, which will enable them to communicate wirelessly on the move in order to provide safety on the road. This thesis presents an intensive research on how to identify ways of enhancing the communication reliability of the smart vehicles. In the existing literature today, which are related to our research topic, as is comprehensively reviewed and presented in Chapter 2, several studies have been carried out on the issue of communication reliability over vehicular networks. However, due to the identified limitations of these existing solutions/schemes, which are presented in the literature review of this dissertation, new practical approaches were introduced in this research to ensure reliable and enhanced message broadcast efficiency in vehicular networks for road traffic safety by proposing new novel algorithms and wireless communication protocols. The contributions achieved in this research through detailed analytical study of the concept of network coding, which led to the proposal of CARER protocol and RECMAC scheme, have shown clearly that road traffic safety through vehicular networks is attainable. Additionally, the results of the theoretical analysis presented in Chapters 3, 4, and 5 are further validated through extensive simulation experiments. Both the theoretical and simulation results show that the analytical models are accurate in calculating the recovery of lost packet(s), and packet collision probability, high data delivery rate, the minimum delivery delay, and high system throughput for both periodic status and emergency (safety) packets. With the findings in this dissertation, it is obvious that the proposed protocols (CARER and RECMAC) can be adopted by auto-mobile industries and communication companies such as Google for deployment with their emerging smart vehicles, after due consideration of the future work itemized in Section 6.2.1 through Section 6.2.4 below.

With the proposed CARER protocol in this thesis as is evident in Figs. 3.6 (a) and (b), there is a significant improvement (over 20% in maximum) in packet loss recovery ability compared to the existing SR protocol. This can be explained by the fact that conventional error recovery techniques based on retransmission of packets repeat each transmission separately thereby congesting the channel excessively as opposed to CARER which combines two or more packets into one, without increasing the size of the packet through the assistance of network coding technology. Additionally, more interesting result is witnessed in Fig. 3.6 (c) where there is a clear significant improvement (over 50% in maximum) in loss recovery probability of CARER over the SR scheme. What is noteworthy in Fig. 3.6 (c) is not only the fact that the performance of CARER (both analytical and simulation results) increases accordingly with the increase in number of transmission from m = 5 to 7, but the packet loss probability of SR scheme decreases from 0.74 to 0.63 (over 10% decline in performance).

Furthermore, the findings from the results of the analysis and simulation experiments of this research suggest that the existing FCC official regulatory resolution of allocating a meagre 10MHz bandwidth for safety message communication over 5.9GHz band is insufficient. The results further show that a significant modification would be required in either the overall design of V2V communication systems or the amount of spectrum allocation required to achieve efficient vehicular communication system, especially for safety traffic exchange in VANETs. The results presented in Fig. 5.6 (a), Fig. 5.6 (b), and Fig. 5.6 (c) clearly show that over 40MHz bandwidth as opposed to the officially allocated 10MHz is required in order to achieve maximum (i.e., 99%) vehicular network communication reliability in certain cases. Lastly, it is obvious from the experimental results shown in Fig. 5.6(a), Fig. 5.6(b), and Fig. 5.6(c) that the probability of data message reception failure is well beyond 20% with allocation of 10MHz channel bandwidth but steeply reduces as the available channel bandwidth (i.e., spectrum allocation) increases from 10MHz up to 40MHz.

6.2 Future Work

In this section, various possible ways towards future studies, which are related to the work presented in this thesis are suggested as shown below. The various studies carried out in this dissertation prompt the following concerns (or challenges) to be further studied and explored as interesting future work. In other words, though much research work remains to be carried out, it is our expectation that the various solutions proposed and presented in this thesis would form a step for future practical implementation and adoption of efficient and reliable vehicular communication systems.

6.2.1 Practical Implementation of the Proposed Protocols/Schemes in Real-life Vehicular Testbeds

One of the next crucial requirements towards empirical implementation as well as detailed evaluation of these proposed protocols and schemes in this thesis is the actual carrying out of their implementation and intensive evaluation over real-world vehicular hardware platforms so as to further identify their strengths and weaknesses for the purposes of future improvement. Although the studies reported in this thesis have been carefully implemented and evaluated by way of extensive simulation experiments under a software based realistic vehicular network scenarios, the limitations and constraints of simulation based implementation and evaluation cannot be overlooked. Hence, the benefits of further evaluation of the different proposed solutions in Chapters 3, 4 and 5 of this dissertation over real-world testbeds cannot as well be over-emphasized, and will surely form an interesting future study to embark on.

6.2.2 Improving Receiver Feedback

The work presented in Chapter 3 of this thesis (just like other related studies reported in the literature) is based on the assumption of a total receiver feedback-free network communication environment. In other words, a feedback-free network communication environment entails that vehicles do not send or receive the feedback such as ACK or NACK as a means of ensuring transmission reliability. Although, as part of the contributions in this thesis, unlike the existing solutions reported in the literature, where acknowledgement is not expected from any of the receivers, a rebroadcasting vehicle selection metric is designed to determine and select the most suitably located vehicle to rebroadcast the encoded packets to enable the vehicles outside the radio range of the source node to receive the encoded packets. As a result, only the selected vehicle is required to send acknowledgement to the source vehicle on behalf of the other receivers within one-hop range before rebroadcasting the received encoded packet to widen the penetration coverage of the coded message. However, using the reception status of one mobile node to presume the reception status of every other nodes in one-hop range remains vague. Hence, an interesting challenge worthy of thorough investigation may include how to find ways of receiving ACK or NACK from all the neighbouring vehicles, which will go a long way to guarantee absolute transmission reliability. Thus, leaving no room for guessing and unnecessary assumption, especially in a road traffic safety (i.e., emergency) message communication.

6.2.3 Theoretical Bound on the Performance of NC based Error Recovery

Both the contributions presented in this thesis and some of the solutions reported in the literature have demonstrated that NC is capable of improving the performance of classical error recovery techniques such as repetition and relay based packet transmission far beyond the possible error recovery limits of basic (or non-coded) repetition or relay based data transmission. However, the need to know and establish (if any) the theoretical error recovery bound (i.e., limit) of NC based error recovery techniques deserves to be researched upon as a promising future work to extend the work presented in Chapter 3 and 4 of this thesis. In other words, knowing and establishing the error recovery limit beyond which the performance diminishes will go a long way to enable future work in this direction to focus more on developing novel NC based data loss recovery algorithms that will overcome such performance bound(s).

6.2.4 Experimental Evaluation of CSMA/CA for Minimum Tolerable Delay in Safety Vehicular Communication Networks

Both DSRC/WAVE and the European standard ITS-G5 are based on the recently approved IEEE 802.11p specifications for the support of network communication in VANETs. However, like other legacy IEEE 802.11 family members, IEEE 802.11p applies a simplified version of CSMA/CA as MAC protocol, which is usually characterized by unbounded media access delay and best-effort quality. Thus, with CSMA/CA MAC approach, the state of the shared channel at the source node is used to assume the probability of message reception rate at the intended receivers [89]. Unfortunately, no experimental study (or analytical work) has been carried out to investigate whether there is actually any such assumed correlation. As a result, Jamieson *et al*. [89] opined that the actual lack of such assumed correlation between the sender and the receivers' channel measurement may be the reason for challenges like the exposed terminal problem, and capture effect. Notwithstanding, CSMA/CA is widely known for improving transmission reliability by avoiding collision, but on the other hand, the use of carrier sensing in wireless communication introduces delay in packet transmission, which is not a luxury in vehicular networks, especially with the transmission of emergency (i.e., safety) packets. Consequently, for efficient and reliable safety message communication in VANETs, the use of IEEE 802.11p, which is based on CSMA/CA, under extremely dense vehicular network scenarios could lead to unacceptable MAC-to-MAC delay. Thus, extensive experimental evaluation of CSMA/CA for a guaranteed and predictable minimum acceptable delay in safety vehicular communication networks would form an interesting future work in furtherance of the study presented in Chapter 5 of this thesis.

Appendix A

Part of the MATLAB® Simulation Source Code

```
%Vehicle to RSU (V2I) Communications

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

axis([0 1000 0 1000]);                    % To set the window size to 1000

DELAY=0.5;

DELAY1=0.45;

[a,b]=ginput(5);                          % Take input from user

line(a,b,'color','black'); hold on;       % Draw a line connecting the points taken as input from user

rnd_speed=randi([10,20],1,1);             % Random speed between 10-20 m/s is given to the vehicle

dist_whole=sqrt((a(2)-a(1))^2+(b(2)-b(1))^2);   % Distance between 2 points is calculated

speed_new=round(dist_whole/rnd_speed);

x=linspace(a(1),a(2),speed_new);          % Random speed is given by taking speed_new points in linspace

y=linspace(b(1),b(2),speed_new);

u=linspace(a(2),a(3),speed_new);

v=linspace(b(2),b(3),speed_new);

w=linspace(a(3),a(4),speed_new);

z=linspace(b(3),b(4),speed_new);

q=linspace(a(4),a(5),speed_new);

r=linspace(b(4),b(5),speed_new);

arr1=[x u w q];                           % Array of all 'x' co-ordinates of 4 lines

arr2=[y v z r];                           % Array of all 'y' co-ordinates of 4 lines
```

```
[xcord1,ycord1]=ginput(1);                    % Select a point for RSU 1

text(xcord1,ycord1,'RSU 1 ','HorizontalAlignment','right');

[xcord2,ycord2]=ginput(1);                    % Select a point for RSU 2

text(xcord2,ycord2,'RSU 2 ','HorizontalAlignment','right');

plot(xcord1,ycord1,'o','MarkerFaceColor','blue'); % RSU 1 plotted on the figure window

plot(xcord2,ycord2,'o','MarkerFaceColor','blue'); % RSU 2 plotted on the figure window

p=plot(x,y,'square','MarkerFaceColor','green','MarkerSize',5);     % Vehicle moving along the road

title('V2I connectivity');                    % Title is given to the figure

for i=1:1000

   for j=1:length(arr1)-1


        p.XData = arr1(j);             % X co-ordinate for that particular road segment

        p.YData = arr2(j);             % Y co-ordinate for that particular road segment

        first_dist=[xcord1,ycord1;arr1(j),arr2(j)]; % Take euclidian distance between vehicle's position on the road and RSU 1

        distance1=pdist(first_dist,'euclidean');

        second_dist=[xcord2,ycord2;arr1(j),arr2(j)]; % Take euclidian distance between vehicle's position on the road and RSU 2

        distance2=pdist(second_dist,'euclidean');


        pause(DELAY1);

        if distance1<=100                    % if distance between RSU 1 and vehicle's position < 100 m

             line1=plot([xcord1,arr1(j)],[ycord1,arr2(j)],'--','color','green'); % Show connectivity to RSU 1

             range1=plot([arr1(j),arr1(j+1)],[arr2(j),arr2(j+1)],'color','green');          % plot the points for given line space. Hence moving vehicle effect
```

```
            pause(0.3);
            set(line1,'Visible','off');              % Visibility property is set to ='off'
            set(range1,'Visible','on');              % Visibility property is set to ='off'

        elseif distance2<=100
            line2=plot([xcord2,arr1(j)],[ycord2,arr2(j)],'--','color','green');
            range1=plot([arr1(j),arr1(j+1)],[arr2(j),arr2(j+1)],'color','green');            %
plot the points for given line space. Hence moving vehicle effect
            pause(0.3);
            set(line2,'Visible','off');              % Visibility property is set to ='off'
            set(range1,'Visible','on');              % Visibility property is set to ='off'

        else
              first=plot([arr1(j),arr1(j+1)],[arr2(j),arr2(j+1)],'color','red');
              set(first,'Visible','on');
        end
  end
end
hold off;

%Vehicle to Vehicle (V2V) Communications
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%
axis([0 1000 0 1000]);          % To set the window size to 1000
DELAY=0.5;
DELAY1=0.45;
[x1,y1] = ginput(2);            % To take input from user for line 1
line(x1,y1,'color','black');    % draw the line (Road 1)
```

```
hold on ;

[x2,y2] = ginput(2);              % To take input from user for line 2

line(x2,y2,'color','black');      % draw the line (Road 2)

rnd_speed1=randi([10,20],1,1);

dist_first_line=sqrt((x1(2)-x1(1))^2+(y1(2)-y1(1))^2);       % Distance between two
points is calculated

speed_new1=round(dist_first_line/rnd_speed1);              % This is the new speed for
1st vehicle

rnd_speed2=randi([10,20],1,1);

dist_second_line=sqrt((x2(2)-x2(1))^2+(y2(2)-y2(1))^2);       % Distance between 2
points is calculated

speed_new2=round(dist_first_line/rnd_speed1);              % This is the new speed for
2nd vehicle

point1=linspace(x1(1),x1(2),speed_new1);  % Random speed is given by taking new
speed number of points in a linspace

point2=linspace(y1(1),y1(2),speed_new1);

point3=linspace(x2(1),x2(2),speed_new2);

point4=linspace(y2(1),y2(2),speed_new2);

first_vehicle=plot(point1,point2,'s','MarkerFaceColor','red');    % Plot first vehicle on
road 1

second_vehicle=plot(point3,point4,'o','MarkerFaceColor','blue');    %    Plot    second
vehicle on road 2

title('V2V connectivity simulation');                        % Title is given to the figure

for i=1:1000


   for k = 1:speed_new1                  % for all the values in linspace

       first_vehicle.XData = point1(k);  %first vehicle's x co-ordinate

       first_vehicle.YData = point2(k);  %first vehicle's y co-ordinate

       second_vehicle.XData = point3(k); %second vehicle's x co-ordinate

       second_vehicle.YData = point4(k); %second vehicle's y co-ordinate
```

```
plot(point1(k),point2(k),point3(k),point4(k));

vehicle_dist=[point1(k),point2(k);point3(k),point4(k)];    % Calculate the Euclidian distance between two vehicle's positions

distance1= pdist(vehicle_dist,'euclidean');

if distance1<=100            % If the distance is within 200 m

line1=plot([point1(k),point3(k)],[point2(k),point4(k)],'--','color','green');    % Show connectivity between two vehicles

pause(0.3);              % Delay of 0.45

set(line1,'Visible','off');    % Visibility property of line is set to 'off'

end

pause(DELAY1);              % Delay of 0.5


end

set(first_vehicle,'Visible','off'); % Visibility property of first vehicle's position is set to 'off'

set(second_vehicle,'Visible','off'); %Visibility property of second vehicle's position is set to 'off'

end

hold off;


%SIMULATION OF VANET MOBILITY AND V2V SIMULATION

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

entry=[1500 2500 4000]; %ycoordinates of entry ramps

exit=[1550 2550 4050];  %ycoordinates of exit ramps

trafficdensity=[100 150 200 250 300 350 400 450 500];

v2v=[0 0 0 0 0 0 0 0 0]; %list having the connectivity entries for different traffice densities

target=41; %car numbered 41 is taken as target
```

```
neighbours=[];

duration=[0 0 0 0 0 0 0 0 0];

avg_cont_neighbours=[0 0 0 0 0 0 0 0 0];

for cars=100:50:500

    connectivity=[0 0 0 0 0];

    times=[];

    same_neighbours=[];

    ycoord1=transpose(randperm(5000,cars)); %the array has ycoordinate positions of cars on lane 1

    ycoord2=transpose(randperm(5000,cars)); %the array has ycoordinate positions of cars on lane 2

    ycoord3=transpose(randperm(5000,cars)); %the array has ycoordinate positions of cars on lane 3

    ycoord4=transpose(randperm(5000,cars)); %the array has ycoordinate positions of cars on lane 4

    ycoord1=sort(ycoord1,1); %sorting to get cars in increasing order of positions

    ycoord2=sort(ycoord2,1);

    ycoord3=sort(ycoord3,1);

    ycoord4=sort(ycoord4,1);

    positions=zeros(5000,4);

    speed=zeros(5000,4);

    oldcoord=0;

    %placing cars numbered uniquely in increasing in a 5000x4 matrix named

    %positions and their respective speeds in a mtrix called speed (wherever no car is present, positions and speed value is zero)

    for j=1:cars

        index=ycoord1(j);

        positions(index,1)=j;   %place car at the position pointed by the ycoord1 array
```

```
        speed(index,1)=(31-22).*rand(1,1) + 22; %speed values (50 & 70 miles /hour) converted to m/s
    end
    %for cars in lane 2:
    maximum=max(max(positions));    %for car labels to be in continuity
    for j=1:cars
        index=ycoord2(j);
        positions(index,2)=maximum+j;   %for car labels to be in continuity
        speed(index,2)=(31-22).*rand(1,1) + 22; %speed values (50 & 70 miles /hour) converted to m/s
    end
    %for cars in lane 3:
    maximum=max(max(positions));
    for j=1:cars
        index=ycoord3(j);
        positions(index,3)=maximum+j;
        speed(index,3)=(31-22).*rand(1,1) + 22; %speed values (50 & 70 miles /hour) converted to m/s
    end
    maximum=max(max(positions));
    %for cars in lane 4:
    for j=1:cars
        index=ycoord4(j);
        positions(index,4)=maximum+j;
        speed(index,4)=(31-22).*rand(1,1) + 22; %speed values (50 & 70 miles /hour) converted to m/s
    end
    for i=1:5 %five iterations for computing average 5
```

```
timeflag=0;
neighbours=[];
for j=1:22 %10 minutes in all=600 secs, value of j is the seconds value

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % For Lane 1:
    %safety application messages will be exchanged here (every 1 sec)
    rand1=rand(1,1);
    rand2=rand(1,1);
    if rand1>0.833
        entryramp=randi(3,[1,1]);   %to chose an entry ramp randomly
        if ~(ismember(entry(entryramp),ycoord1)) %checking if no vehicle is already present there
            %add a vehicle here
            ycoord1(length(ycoord1)+1)=entry(entryramp);
            positions(entry(entryramp),1)=max(max(positions))+1;    %label the new car
            speed(entry(entryramp),1)=(31-22).*rand(1,1) + 22;  %assign it a random speed
        end
    end
    if rand2>0.833
        exitramp=randi(3,[1,1]);    %to chose an exit ramp randomly
        if ismember(exit(exitramp),ycoord1) %remove if there is car at that exit ramp that can exit
            if positions(exit(exitramp),1)~=target %target car should not be removed
                ycoord1=ycoord1(find(ycoord1~=exit(exitramp)));    %car location removed from ycoord array
                positions(exit(exitramp),1)=0;  %car removed
```

```
            speed(exit(exitramp),1)=0;  %corresponding speed entry cleared
         end
      end
   end
   ycoord1=sort(ycoord1,1); %sort the vehicles in increasing order of positions
   for k=1:1    %1 loop assumed to be of 100ms for required granularity
      for l=1:length(ycoord1) % for each car in the lane
         if(l<=length(ycoord1))  %to avoid indexing error when no. of cars reduce during lane changing, in short recalculating the length
            acc=-5+10*rand(1,1);    %random acceleration value within -5 and +5 m/s^2
            r=speed(ycoord1(l),1);
            newspeed=abs(r+acc);
            if(l~=length(ycoord1))
               if(ycoord1(l+1)-ycoord1(l)<=10)
                  flag=1;
                  %look if lane change is poosible :-
                  m=ycoord1(l);
                  for g=m-10:m+10 %checking if any car is present in the parallel lane near that position
                     if  ismember(g,ycoord2)
                        flag=0; %if so,lane change is not possible in lane2
                     end
                  end
                  if flag==1  %if there is space for changing lanes
                     %change lane here:
                     ycoord2(length(ycoord2)+1)=m;
                     positions(m,2)=positions(m,1);  %move the car to next lane
```

```
                positions(m,1)=0;   %clear the car label from current lane
                speed(m,2)=speed(m,1);  %move the corresponding speed entry to adjacent lane
                speed(m,1)=0;   %clear the speed entry from current lane
                ycoord1(l)=0;   %remove the position entry from ycoord1 array
                ycoord2=sort(ycoord2,1);     %sort the array pointing to next lane to get them back in increasing order after adding car
            elseif flag==0 %if lane change was not possible
                dist=ycoord1(l+1)-ycoord1(l);
                factor=(-0.75+sqrt(0.5625+0.02804*dist))/0.01408;
                newspeed=min(factor,speed(ycoord1(l+1),1));   %reduce the speed as given in the project desciption
            end
        end
    end
    if(ycoord1(l)~=0)
        oldcoord=ycoord1(l);
        ycoord1(l)=round(ycoord1(l)+newspeed*0.01);  %position update per 100ms
        ycoord1(l)=mod(ycoord1(l),5000)+1;  %rollback position
        if(positions(ycoord1(l),1)==0)
            positions(ycoord1(l),1)=positions(oldcoord,1);   %move the car forward
            positions(oldcoord,1)=0;    %clear previous position
            speed(ycoord1(l),1)=newspeed;   %similarly with speed matrix
            speed(oldcoord,1)=0;
        end
    end
end
```

```
        end
        ycoord1=ycoord1(find(ycoord1~=0));   %remove the cleared entries from ycoord1 array, car is no more present there as it changed lanes
    end



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  %similar computation for each lanes(refer to detailed comments above). Lane 2:
    %entry and exit here
    rand1=rand(1,1);
    rand2=rand(1,1);
    if rand1>0.833
        entryramp=randi(3,[1,1]);
        if ~(ismember(entry(entryramp),ycoord2)) %checking if no vehicle is already present there
            %add a vehicle here
            ycoord2(length(ycoord2)+1)=entry(entryramp);
            positions(entry(entryramp),2)=max(max(positions))+1;
            speed(entry(entryramp),2)=(31-22).*rand(1,1) + 22;
        end
    end
    if rand2>0.833
        exitramp=randi(3,[1,1]);
        if ismember(exit(exitramp),ycoord2)
            if positions(exit(exitramp),2)~=target
                ycoord2=ycoord2(find(ycoord2~=exit(exitramp)));
                positions(exit(exitramp),2)=0;
```

```
            speed(exit(exitramp),2)=0;
        end
    end
end
ycoord2=sort(ycoord2,1);
for k=1:1
    for l=1:length(ycoord2) % for each car in a lane
        if(l<=length(ycoord2))
            acc=-5+10*rand(1,1);
            newspeed=abs(speed(ycoord2(l),2)+acc);
            if(l~=length(ycoord2))
                if(ycoord2(l+1)-ycoord2(l)<=10)
                    flag=1;
                    %look if lane change is poosible in lane 1:-
                    m=ycoord2(l);
                    for g=m-10:m+10
                        if  ismember(g,ycoord1)
                            flag=0; %lane change not possible in lane 1
                        end
                    end
                    if flag==1
                        %change lane here to lane 1:
                        ycoord1(length(ycoord1)+1)=m;
                        positions(m,1)=positions(m,2);
                        positions(m,2)=0;
                        speed(m,1)=speed(m,2);
                        speed(m,2)=0;
```

```
            ycoord2(l)=0;
            ycoord1=sort(ycoord1,1);
        elseif flag==0
            %look if lane change is poosible in lane 3:-
            for g=m-10:m+10
                if  ismember(g,ycoord3)
                    flag=0; %lane change not possible in lane 3
                end
            end
            if flag==1
                %change lane here to lane 3:
                ycoord3(length(ycoord3)+1)=m;
                positions(m,3)=positions(m,2);
                positions(m,2)=0;
                speed(m,3)=speed(m,2);
                speed(m,2)=0;
                ycoord2(l)=0;
                ycoord3=sort(ycoord3,1);
            elseif flag==0 %if lane change was not possible at all
                dist=ycoord2(l+1)-ycoord2(l);
                factor=(-0.75+sqrt(0.5625+0.02804*dist))/0.01408;
                newspeed=min(factor,speed(ycoord2(l+1),2));
            end
        end
    end
end
if(ycoord2(l)~=0)
```

```
                oldcoord=ycoord2(l);
                ycoord2(l)=round(ycoord2(l)+newspeed*0.01); %position update per 100ms
                ycoord2(l)=mod(ycoord2(l),5000)+1;%rollback position
                if(positions(ycoord2(l),2)==0)
                    positions(ycoord2(l),2)=positions(oldcoord,2);
                    positions(oldcoord,2)=0;
                    speed(ycoord2(l),2)=newspeed;
                    speed(oldcoord,2)=0;
                end
            end
        end
    end
    ycoord2=ycoord2(find(ycoord2~=0));
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
%Lane 3:
%entry and exit here
rand1=rand(1,1);
rand2=rand(1,1);
if rand1>0.833
    entryramp=randi(3,[1,1]);
    if ~(ismember(entry(entryramp),ycoord3)) %checking if no vehicle is already present there
        %add a vehicle here
        ycoord3(length(ycoord3)+1)=entry(entryramp);
```

```
        positions(entry(entryramp),3)=max(max(positions));
        speed(entry(entryramp),3)=(31-22).*rand(1,1) + 22;
    end
end
if rand2>0.833
    exitramp=randi(3,[1,1]);
    if ismember(exit(exitramp),ycoord3)
        if positions(exit(exitramp),3)~=target
            ycoord3=ycoord3(find(ycoord3~=exit(exitramp)));
            positions(exit(exitramp),3)=0;
            speed(exit(exitramp),3)=0;
        end
    end
end
ycoord3=sort(ycoord3,1);
for k=1:1
    for l=1:length(ycoord3) % for each car in the lane
        if(l<=length(ycoord3))
            acc=-5+10*rand(1,1);
            newspeed=abs(speed(ycoord3(l),3)+acc);
            if(l~=length(ycoord3))
                if(ycoord3(l+1)-ycoord3(l)<=10)
                    flag=1;
                    %look if lane change is poosible in lane 2:-
                    m=ycoord3(l);
                    for g=m-10:m+10
                        if  ismember(g,ycoord2)
```

```
        flag=0; %lane change not possible in lane 2
    end
end
if flag==1
    %change lane here to lane 2:
    ycoord2(length(ycoord2)+1)=m;
    positions(m,2)=positions(m,3);
    positions(m,3)=0;
    speed(m,2)=speed(m,3);
    speed(m,3)=0;
    ycoord3(l)=0;
    ycoord2=sort(ycoord2,1);
elseif flag==0
    %look if lane change is poosible in lane 4:-
    for g=m-10:m+10
        if  ismember(g,ycoord4)
            flag=0; %lane change not possible in lane 4
        end
    end
    if flag==1
        %change lane here to lane 4:
        ycoord4(length(ycoord4)+1)=m;
        positions(m,4)=positions(m,3);
        positions(m,3)=0;
        speed(m,4)=speed(m,3);
        speed(m,3)=0;
        ycoord3(l)=0;
```

```
                ycoord4=sort(ycoord4,1);
              elseif flag==0 %if lane change was not possible at all
                dist=ycoord3(l+1)-ycoord3(l);
                factor=(-0.75+sqrt(0.5625+0.02804*dist))/0.01408;
                newspeed=min(factor,speed(ycoord3(l+1),3));
              end
            end
          end
        end
        if(ycoord3(l)~=0)
          oldcoord=ycoord3(l);
          ycoord3(l)=round(ycoord3(l)+newspeed*0.01);   %position   update
per 100ms
          ycoord3(l)=mod(ycoord3(l),5000)+1;%rollback position
          if(positions(ycoord3(l),3)==0)
            positions(ycoord3(l),3)=positions(oldcoord,3);
            positions(oldcoord,3)=0;
            speed(oldcoord,3)=0;
            speed(ycoord3(l),3)=newspeed;
          end
        end
      end
    end
    ycoord3=ycoord3(find(ycoord3~=0));
  end
```

%%

```
%for lane 4:
%entry and exit here
rand1=rand(1,1);
rand2=rand(1,1);
if rand1>0.833
   entryramp=randi(3,[1,1]);%3 or 4???
   if ~(ismember(entry(entryramp),ycoord4)) %checking if no vehicle is already present there
      %add a vehicle here
      ycoord4(length(ycoord4)+1)=entry(entryramp);
      positions(entry(entryramp),4)=max(max(positions));
      speed(entry(entryramp),4)=(31-22).*rand(1,1) + 22;
   end
end
if rand2>0.833
   exitramp=randi(3,[1,1]);%3 or 4???
   if ismember(exit(exitramp),ycoord4)
      if positions(exit(exitramp),4)~=target
         ycoord4=ycoord4(find(ycoord4~=exit(exitramp)));
         positions(exit(exitramp),4)=0;
         speed(exit(exitramp),4)=0;
      end
   end
end
ycoord4=sort(ycoord4,1);
```

```
for k=1:1
    for l=1:length(ycoord4) % for each car in a lane
        if(l<=length(ycoord4))
            acc=-5+10*rand(1,1);
            newspeed=abs(speed(ycoord4(l),4)+acc);
            if(l~=length(ycoord4))
                if(ycoord4(l+1)-ycoord4(l)<=10)
                    flag=1;
                    %look if lane change is poosible in lane 3:-
                    m=ycoord4(l);
                    for g=m-10:m+10
                        if  ismember(g,ycoord3)
                            flag=0; %lane change not possible
                        end
                    end
                    if flag==1
                        %change to lane 3 here:
                        ycoord3(length(ycoord3)+1)=m;
                        positions(m,3)=positions(m,4);
                        positions(m,4)=0;
                        speed(m,3)=speed(m,4);
                        speed(m,4)=0;
                        ycoord4(l)=0;
                        ycoord3=sort(ycoord3,1);
                    elseif flag==0 %if lane change was not possible
                        dist=ycoord4(l+1)-ycoord4(l);
                        factor=(-0.75+sqrt(0.5625+0.02804*dist))/0.01408;
```

```
                newspeed=min(factor,speed(ycoord4(l+1),4));
              end
            end
          end
          if(ycoord4(l)~=0)
            oldcoord=ycoord4(l);
            ycoord4(l)=round(ycoord4(l)+(newspeed)); %position update per 100ms
            ycoord4(l)=mod(ycoord4(l),5000)+1;%rollback position
            if(positions(ycoord4(l),4)==0)
              positions(ycoord4(l),4)=positions(oldcoord,4);
              positions(oldcoord,4)=0;
              speed(oldcoord,4)=0;
              speed(ycoord4(l),4)=newspeed;
            end
          end
        end
      end
      ycoord4=ycoord4(find(ycoord4~=0));
    end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    %answering the questions:
    new=[];
    [row,col]=find(positions==target);  %store the coordinates of target car by finding it using its label in the positions matrix
    for o=1:4
```

```
        for p=1:5000
            X=[p,500+(o-1)*3;row,500+(col-1)*3];    %factor of 3 multiplied to take into account the 3m lane separation
            if positions(p,o)~=0
                if pdist(X,'euclidean')<50   %communication range=50, has to be change to run for a different range
                    if j==1
                        neighbours(length(neighbours)+1)=positions(p,o);    %add all communication neighbors to an array for the 1st second
                    end
                    new(length(new)+1)=positions(p,o);  %similar array for every other second which will be overwritten every seconds iteration
                end
            end
        end
    end
    if j==1
        common=intersect(neighbours,new);
        common_cont=intersect(neighbours,new);
    else
        common_cont=intersect(common,new);    %this array will store the continuos neighbours every second
        common=intersect(neighbours,new);   %recalculate common neighbours for consecutive seconds iteration
    end
    if timeflag==0
        if length(common)>=3
            times(i)=j;
        elseif length(common)<3
```

```
            timeflag=1; %set if less than 3 cars are common to avoid further iteration
         end
      end
      if j==20 %continuous duration of time for question 3
         same_neighbours(i)=length(common_cont); %number of continuos neighbors after 10 seconds
      end
      %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
   end
   [row,col]=find(positions==target);
   for o=1:4
      for p=1:5000
         X=[p,500+(o-1)*3;row,500+(col-1)*3]; %factor of 3 multiplied to take into account the 3m lane separation
         if positions(p,o)~=0
            if pdist(X,'euclidean')<50  %communication range has to be changed here to get outputs for a different range
               connectivity(i)=connectivity(i)+1; %increment for every neighbor in communication range
            end
         end
      end
   end
 end
 avg_cont_neighbours(cars/50-1)=mean(same_neighbours);
 duration(cars/50-1)=mean(times);
 v2v(cars/50-1)=mean(connectivity);
end
```

```
%Question 1:

figure(1);

plot(trafficdensity,v2v);

title('Connectivity Plot for communication range = 50 meters');

xlabel('Traffic Density');

ylabel('Average number of nodes');

%Question 2:

figure(2);

plot(trafficdensity,duration);

title('Connectivity Duration Plot (3 neighbours) for communication range = 50 meters');

xlabel('Traffic Density');

ylabel('Average duration');

%Question 3

figure(3);

plot(trafficdensity,avg_cont_neighbours);

title('Average number of same neighboursfor a continuous period of 10s, range = 50 meters');

xlabel('Traffic Density');

ylabel('Average no. of same neighbours');
```

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