Title: A Model to Offer Reliable Data Transmissions in Vehicular Ad hoc Network

Name: MEHARAJ THEEN JAMEEL

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A Model to Offer Reliable Data Transmissions in Vehicular Ad hoc Network

By

MEHARAJ THEEN JAMEEL

1218451

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University of Bedfordshire

Supervisors

Dr. Sijing Zhang

Dr. Enjie Liu
Abstract

Vehicular Ad-hoc Network (VANET) is one of the widely used networks across various intelligent transport applications in order to support the autonomous driving, reduce network congestion and overcome any kind of the accidents occurring on the road. This report involves in focusing on the safety applications where the vehicles involve in broadcasting the safety messages that are highly time critical and reliability sensitive. The importance of delivering the broadcasted safety messages of VANET in highly timely and reliable manner has resulted in undertaking this research work. In order to support the reliable delivery of the broadcasted safety messages, this research has developed a model called Reliable Vector Clustering (RVC) which involves in neighbour node identification, vehicle cluster formation and broadcasting the coded data using the network coding method. In order to evaluate this developed model, analytical model developed and simulation studies have been carried out in this report. The analytical model has developed a criterion that helps in choosing the best vehicle as the cluster head node and the simulation studies have compared the effectiveness of the developed method. These simulation studies have revealed the effectiveness of proposed RVC method in improving the packet error recovery probability and packet delivery ratio when compared to the existing methods.
Acknowledgment

The support from a number of people greatly helped in completing this research and in reaching the current position in my MSc research program. Firstly, I am grateful for the almighty in supporting me all through the research and giving me the required strength for undertaking the research work despite many hurdles. Secondly, I would like to extend my sincere thanks to my first supervisor Dr. Sijing Zhang and my second supervisor Dr. Enjie Liu for their consistent support and guidance they have provided all through the research work. Despite their very busy schedules, both the supervisors were highly patient in offering their valuable feedback and in explaining the research ideas.

Thirdly, I am thankful to Research Graduate School (RGS) committee for their support they offered whenever all through the research needed work. Last but not least, I am also thankful to my friends and family members without whom the completion of this research would not be possible.
Dedication

I would like to dedicate this research work to my wife and my daughter
**Table of Contents**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>2</td>
</tr>
<tr>
<td>Acknowledge</td>
<td>3</td>
</tr>
<tr>
<td>Dedication</td>
<td>4</td>
</tr>
<tr>
<td>Chapter 1: Introduction</td>
<td>7</td>
</tr>
<tr>
<td>1.1. Research Rationale</td>
<td>7</td>
</tr>
<tr>
<td>1.2. Aim and Objectives</td>
<td>8</td>
</tr>
<tr>
<td>1.3 Choice of Simulator</td>
<td>9</td>
</tr>
<tr>
<td>1.4 Thesis Contents</td>
<td>10</td>
</tr>
<tr>
<td>Chapter 2: Literature Review</td>
<td>12</td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>12</td>
</tr>
<tr>
<td>2.2 Clustering in VANET</td>
<td>12</td>
</tr>
<tr>
<td>2.3 Existing clustering methods in VANET</td>
<td>13</td>
</tr>
<tr>
<td>2.4 MAC Layer Reliability</td>
<td>16</td>
</tr>
<tr>
<td>2.5 Error Recovery Approaches</td>
<td>17</td>
</tr>
<tr>
<td>2.6 Network Coding</td>
<td>20</td>
</tr>
<tr>
<td>2.7 Network coding methods for error recovery in VANET</td>
<td>21</td>
</tr>
<tr>
<td>2.8 Summary</td>
<td>23</td>
</tr>
<tr>
<td>Chapter 3: Methodology and Methods</td>
<td>24</td>
</tr>
<tr>
<td>3.1 Introduction</td>
<td>24</td>
</tr>
<tr>
<td>3.2 Key research questions</td>
<td>24</td>
</tr>
<tr>
<td>3.3 Proposed Model</td>
<td>25</td>
</tr>
<tr>
<td>A. Clustering method</td>
<td>25</td>
</tr>
<tr>
<td>B. Network Coding</td>
<td>27</td>
</tr>
</tbody>
</table>
Chapter 1: Introduction

1.1. Research Rationale

Vehicular Ad Hoc Network (VANET), a type of Mobile Ad Hoc Network (MANET) gained high attention among practitioners and researchers due to its wider benefits to the working of Intelligent Transport Systems (ITS). VANET is similar to MANET in which several vehicles are interconnected to each other in order to communicate and exchange useful information. The communication in VANET is provided in two schemes namely Vehicle–to-Vehicle (V2V) communications and Vehicle-to-Infrastructure (V2I) communications (Lu et al, 2014). Taking these two types of the communications that are offered by VANETs, they help the moving vehicles either to access the internet, other kind of services or to communicate with other vehicles while on road. Therefore, the main applications of VANET are of two types namely (1) safety applications and (2) comfort applications. The safety applications involve in mobile vehicles sharing information about the road accidents, traffic congestion, about the road conditions and the comfort applications involve in allowing mobile vehicles to access web browsing (Cunha et al, 2016; Eze et al, 2016). Among these two applications, the safety applications of VANET gained high importance due to the ability of these applications in saving people from road accidents, improving the driver experience and enhancing the level of road safety. Proper working of these safety applications of VANET requires reliable delivery of the packets from source to destination (Dixit et al, 2016). In other words, the main benefits of VANET safety applications can be obtained only when the packets sent from the source reach the destination accurately without any kind of errors.

Ensuring reliable transmission of data even though is considered very important for VANET safety applications; it is also considered highly challenging issue. The unique characteristics of VANET such as high and random mobility of vehicles, wireless communication, channel contention, geographical constraints, and dynamic network topology due to frequent changes
in node positions make reliable data transmission highly complex in the VANETs. The wireless communication medium among the vehicles causes channel interference due to shared radio interferences and the low channel strength results in the increase of Bit Error Rate (BER) (Eze et al, 2016). All these aspects increase the chance of packet losses during transmission, thereby affecting reliability of data transmitting over these VANETs. The biggest obstacle to the provision of QoS and to support reliable transmission in VANET is presence of high node mobility with random node movements making the wireless links in the network unreliable (Cunha et al, 2016; Dixit et al, 2016). On the other hand, VANET when using contention-based IEEE 802.11 protocol, offering delay-bound QoS becomes highly challenging issue. In this situation, the number of vehicles that are contending for the same wireless channel increases and thereby increases the level of packet-delay and also data-congestion.

The rationale behind undertaking the current research is the great need of ensuring reliable transmission of the data over the VANETs that are used for safety and critical applications. This research is intended in reviewing the state-of-art techniques available to offer reliable delivery of data over the VANETs used in safety and critical applications. Considering the presence of different reliability requirements for the different types of the safety applications that are supported by VANETs, in this research a model is developed. This model is designed to have two techniques namely the clustering technique and the network coding method. The clustering technique is designed to reduce the congestion level in the VANET and network coding is considered in order ensure reliable transmission and reduced congestion in VANET.

1.2. Aim and Objectives
The main aim of this research lies in developing a practical model based on clustering concept to assure reliable delivery of the broadcast packets in VANETs used for safety and critical applications.

The main objectives of this research are,

1. To critically review the state of art mechanisms that are currently available to offer reliable communications and QoS in VANET through extensive literature review.
2. To reduce the extent of data congestion in a contention-based VANET by using clustering mechanism as part of this research.
3. To increase the probability of reliable data delivery over VANETs by considering the concepts of retransmissions and network coding.

4. To develop a model using both clustering and network coding techniques in order to assure reliable delivery with congestion avoidance on VANETs.

5. To evaluate the proposed model using a combination of analytical models and simulation studies.

The primary aim of Mini Progression Point (MiPP) is to critically review the existing literature works on QoS and reliable communication in VANETs. In this MiPP report, various routing protocols and frameworks that are developed to offer QoS in VANET are specified. Based on the theoretical foundation provided by this literature review, the proposed method and its details are given in the methodology section of this MiPP report.

1.3 Choice of Simulator

The evaluation of the proposed model is done in this research using the simulation studies that will be carried out using a network simulation tool that is based on C++ and Object-oriented tool Command Language (OTcl). The simulator that is chosen to carry out the simulation studies in this research is the Network Simulator 2.22 (NS 2.33). The object-oriented architecture of NS2 simulator helps in discretely scheduling each step that is present in the proposed clustering method and the network coding method. In the process of using the NS 2.33 software in order to simulate and evaluate the proposed model, the following steps are being adopted,

1. Creation of virtual environment using the software VMware Workstation 11.0
2. Install Fedora Linux in this virtual machine through the creation of a separate Linux virtual environment.
3. Download and install the NS 2.33 version of the network simulator software in this virtualised Linux environment.
4. Create and simulate a VANET network environment in NS 2.33 by relying on IEEE 802.11p standard and the network animator tool of NS 2.33.
5. Using BRUTE traffic generator in NS 2.33 in order to generate the packets at constant rate by each vehicle present in the simulated VANET. According to Bonelli et al (2005),
this BRUTE traffic generator helps in generating different types of traffic packets such as Poisson traffic, Poisson Arrival Burst (PAB) traffic and the Constant Bit Rate (CBR) traffic.

6. Using XGraph tool, which is a part of the network simulator software in order to present the simulation results through graphical representations.

1.4 Thesis Contents

The organisation of this report is carried out into four main chapters with the main intention of meeting the aim and objectives of this research work.

Chapter 1: Introduction

In this chapter, the research rationale of this research work is specified. Besides this research rationale, the aim and objectives of this research work along with the choice of the network simulation made are also given in this chapter.

Chapter 2: Literature Review

In this chapter, the main background of this project is presented. The existing works on VANET reliability are critically reviewed and the various methods that are related to this are presented and analysed in this chapter.

Chapter 3: Methodology and Methods

In this chapter, the details of the Reliable Vehicle Cluster (RVC) model are details. The details of the analytical model that is developed to support the developed model is presented in this chapter.
Chapter 4: Simulation Studies

In this chapter, the details of the simulation studies carried out in this research are presented. Details of the simulation parameters and the obtained simulation results are clearly presented in this report.

Chapter 5: Conclusion and future work

The key findings of this research are summarised in the conclusion section are presented in this chapter. The scope of future work of this research is also given in this chapter.
Chapter 2: Literature Review

2.1 Introduction
In the context of VANET involving in broadcasting the packets, reliability is specified as ability of a network to ensure that all the required vehicles received broadcast messages accurately without any loss or error. According to Ma et al (2011), the existing techniques that are proposed to improve reliability of the broadcasting packets over IEEE802.11 networks come under either one of the following three mechanisms. The first one is acknowledgement in which source node collects the acknowledgements from the receiver in order to improve broadcast reliability. The second mechanism is continuous push in which source node involves in repeatedly transmitting data till total coverage is reduced for improving broadcast reliability and the third mechanism is continuous pull in which receivers continuously request the data from source node till the complete data is being received. According to Cunha et al (2016), reliability provision in VANET is addressed by the existing works either using a dedicated routing protocol, MAC scheme or clustering method. Taking the finding of critical review of existing literature works that the extent of clustering methods designed to ensure VANET reliability is less (Mu'azu et al, 2013; Cooper et al, 2017), this research focuses on developing a clustering base reliability scheme for VANET. For this purpose, some of the existing clustering schemes that are proposed to address reliability issue in VANET are critically reviewed in this section.

2.2 Clustering in VANET
VANET possess unique characteristics such as dynamic connectivity, high vehicle mobility, and frequent changes in the topology and self-organizing in nature. In VANET, this clustering is defined as the process of arranging the vehicles into various groups depending on specific rules or specific criteria. Each cluster also known as a virtual group is characterized with the presence of cluster head, cluster members and cluster gateways. Therefore, any vehicle in a VANET cluster plays the role of cluster gateway, cluster head and cluster member. According
to Cooper et al (2017), the formation of VANET clusters works in such a way that each cluster consists of only one cluster head that is chosen based on specific criteria as shown in Figure 1.

![Cluster formation in VANET (Hande & Muddana, 2016)](image)

**Figure 1: Cluster formation in VANET (Hande & Muddana, 2016)**

As the vehicles in a VANET are highly mobile with unique mobility patterns, the vehicles move randomly from one cluster to another cluster. Many studies in the literature (Garai & Boudriga, 2013; Hande & Muddana, 2016) that focused on VANET clustering indicated that clustering offers several benefits like proper bandwidth utilization, optimization of bandwidth usage, reducing overhead in communication efficient allocation of the resources and higher ratio of packet delivery.

### 2.3 Existing clustering methods in VANET

Cooper et al (2017) carried out a comparative survey on the various clustering methods proposed for VANET. This survey has reviewed a large number of clustering methods that were proposed for VANET. Also, this study identified that all these existing VANET clustering methods were proposed based on specific requirements such as topology discovery, channel access management, security, traffic safety and QoS assurance. The clustering methods such as cluster configuration protocol (CCP), Multichannel Corporative Base Clustering Map Protocol (MCC-MAC) and Stability Based Clustering Algorithm (SBCA) are specified by Cooper et al (2017) as the clustering methods that are designed to ensure quality of service and reliability for VANET packets. Kuklinski & Wolny (2009) developed a clustering method called DBC (Density Based Clustering) for vehicle ad-hoc networks. This density-based clustering method is a multi-level clustering technique that is aimed at forming highly stable and also
long-lasting clusters in order to ensure reliability communication. This density-based clustering method is designed in such a way that formation of cluster is done based on the metric called complex clustering in which node density, link quality, traffic conditions along with the connection graph are considered. This density-based clustering method works in three different phases where first phase involves in estimating connectivity level in terms of network density. Second phase involves in selecting the stable links among all existing links and last phase involves in determining reputation of the node before becoming member of a particular cluster.

Fekair et al (2016) proposed a routing protocol to ensure quality of service and specifically reliability in VANET using clustering-based scheme. The QoS clustering algorithm involves in selecting cluster head based on QoS value that is obtained using hello messages. To increase reliability of the network, the cluster head and cluster members give more attention to the link expiration time for each node. In this method QoS value is calculated using parameters like bandwidth, jitter, link expiration time and the delay. This clustering method in order to ensure higher quality of service also consists of multipoint relay nodes. In every cluster one or more relay vehicle are chosen that has the responsibility of relaying the information among various clusters. Based on this clustering method, CBQOS – Vanet is a routing protocol that is proposed and found to exhibit higher quality of service with higher reliability assurance. Yang and Tang (2014) proposed a corporative clustering method to improve reliability of broadcasting packets over vehicular ad-hoc networks. Specifically, this cooperative clustering MAC protocol is designed to improve reliability of the safety messages which are transmitted over the VANET. The main concept of this cooperative clustering method is that there exist particular helper nodes that relay safety messages to the vehicles which have not received the broadcasted packets accurately. In this clustering method corporation is performed among the vehicles during the ideal slots so that packets lost in failed transmission or sent to the receiver. Also, this corporation occurring within a cluster is aimed at not disturbing the normal broadcasting process. This corporative clustering method is designed to have three main stages namely cluster formation, safety message delivery and the corporation in the cluster. Initially the cluster formation stage involves in forming the cluster and safety message delivery takes place using broadcasting packets. Using acknowledgement field in the packet header, the lost packets are identified, and corporation nodes are required for
retransmission. The selection of corporation vehicles or helpers is done on voluntary basis that sends the request of corporation message when it is ready to act as the helper. Su and Zhang (2007) developed clustering base MAC protocol for improving quality of service in vehicular ad-hoc networks. This protocol is abbreviated as Cah-mac which uses ideal slots that are present in particular frame for packet relaying. This clustering method works in such a way that selection of helper and corporation slot is done dynamically. However this clustering method is criticized for considering idealistic model in which patterns of vehicle mobility are not taken into account. Rathore et al (2010) develop a clustering base MAC protocol called CMAC (Cluster MAC) to ensure reliable message delivery with low levels of delay. This CMAC protocol uses centralized approach by considering the concept of road side units besides the highly mobile vehicles. The clustering method is based on road side unit and hence each region of road side unit is divided into various predefined clusters having the ability of frequency reuse among the non-adjacent clusters. Due to the formation of clusters that are close to each other, there arises the hand off region among inter-clusters. The ability of roadside unit in maintaining a particular table storing information about nodes that are communicating over a particular channel helps in solving hidden node problem by this clustering method. Even though this scheme is identified to provide higher reliability levels through increase in the packet delivery ratio, study carried out by AlMheiri & AlQamzi (2015), specified that this cluster MAC protocol of MANET suffers from the limitation that it cannot work when road side unit is not present and works based on predefine the clusters which cannot be true in all the situations. El mouna Zhiouaet et al (2012) developed a QoS method for cluster base VANET. The QoS balancing method is developed to select appropriate gateway in each cluster so that higher packet delivery ratio is obtained, and network reliability is improved. In a VANET that is organized in the form of clusters with each cluster having a cluster head and various cluster nodes, cluster gateways. This proposed QoS balancing method ensures in selecting the appropriate gateway. The decision on gateway selection is based on various factors such as load present in the cluster, duration of like connectivity between cluster head and gateway candidates, strength of received signal.

Hande and Muddana (2016) carried out a survey on existing clustering algorithms that is designed for VANET in order to assure proper delivery of the data over VANET. This study indicated that clustering algorithms proposed for VANET come under several types such as
density based, direction based, stable based, beacon based, multichannel based algorithms. Among all these clustering methods only a few clustering methods such as density-based clustering algorithm specifically focused on assuring reliable packet delivery.

2.4 MAC Layer Reliability

The IEEE802.11p standard of wireless local area network (WLAN) that stands for wireless access in vehicular environment (WAVE) is one of the most widely implemented VANET standards. Besides IEEE802.11p, IEEE802.1609 standard is also used to support vehicular communication and depends on upper layer specifications in protocol suite. The protocol suite of this wireless vehicular communication family is given in Figure 2. The MAC layer of IEEE802.11p suffers from various packet losses because of packet collisions, access delays that are due to various challenging issues caused by the MAC protocols that are highly contention based. IEEE802.11 standard of MAC layer adopts random access method which is based on CSMA/CA mechanism (Carrier Sense Multiple Access/ Collision Avoidance) in order to avoid the packet collisions in MAC layer (Cooper et al, 2017). For majority of MAC protocols in IEEE802.11P, Distribution Coordination Function (DCF) is the fundamental mechanism. Broadcasting is adopted by MAC schemes based on DCF using three main functions such as acknowledgement, CTS/RTS (Clear to Send/ Request to Send) and the retransmissions (Rathore et al, 2010; Cunha et al, 2016).

![Diagram of Protocol suite of vehicular standard family](image)

Figure 2: Protocol suite of vehicular standard family (Muazuet al, 2013)

The contention based MAC protocols make reliability assurance by MAC layer highly challenging issue, which resulted in the development of contention free techniques such as Time Division Technique (TDMA), According to Muazu et al (2015), adoption of TDMA scheme helps in allocating particular time slots to access the channels through packet collisions can be avoided and reliable packet delivery can be assured. In the content of VANET IEEE802.11p
standard, use of TDMA helps in improving transmission range of access point present in road size unit through which sensitiveness of acknowledgement messages can be greatly improved. Muazh et al (2013) developed a clustering method for based on TDMA. In this clustering method, TDMA slots are implemented without having centralized control and selection of route containing source, destination and cluster head is based on the QOS metrics.

Shanhin and Kim (2016) developed clustering-based MAC method for vehicular networks in order to improve reliable delivery of the packets. This clustering technique is based on time division multi access through which each vehicle is allocated with two mini-slots in each of the synchronous time intervals. The allocation of mini slots using enhanced TDMA decreases the chance of packet collision and thereby helps in assuring reliable delivery of safety messages over the VANET.

### 2.5 Error Recovery Approaches

The IEEE802.11p standard of wireless networks used for vehicular ad-hoc network suffers from packet errors and packet losses due to the presence of wireless channels that are highly prone to packet losses because of channel interference, network congestion and access delays. According to Eze et al (2016), the rate of packet loss in a wireless network greatly depends on effect of noise and channel interference present in the environment, existing distance between receiver and sender and extent of packet collisions caused due to network congestion. Two error control approaches that are traditionally used to control the packet loss rate and maximize error recovery in a wireless network are forward error correction (FEC) and Automatic Repeat Request (ARQ). FEC is one of the commonly used error recovery techniques for providing reliable transmission of data by correcting the errors at receiver. The FEC techniques involves in receiver identifying and correcting the errors without contacting the source. This is possible when the sending packet is incorporated with some redundant information that helps the receiver to identify the errors in the received packet and correct them. Dharmaraja et al (2016) specified some of the commonly utilized coding methods for generating redundant data in FEC such as low-density parity check (LDPC), Reed Solomon (RS) and Hamming Code.
Gholibeigi et al (2016) has developed FEC based interleaving optimization method for improving communication quality and transmission reliability. This optimization method has been developed by combining FEC method, dynamically updating inter-arrival frequency at receiver and interleaving through which the rate of packet loss and access delay can be minimized. Zaidi et al (2017) developed an FEC method called Enhanced Random Early Detection FEC (ERED-FEC) that helps in carrying out forward error functionalities at access point. This method takes the current traffic load present in the network along with the condition of wireless channel in order to select the redundancy packets through which the probability of error recovery at the receiver can be maximized. Forward looking FEC (FL-FEC) is another FEC mechanism proposed by Aliyu et al (2017) that involves in selecting non continuous level of source packets existing in the previous blocks of FEC for generating the required redundancy information. This way of using previous FEC blocks is intended to minimize and avoid burst packet loss during data transmission.

In the context of vehicular networks, FEC technique is adopted extensively to correct the errors that occur over the wireless networks. For example, WAVE amended in IEEE802.11P standard users bit level FEC coding method for processing received signals. In a typical VANET having broadcasting environment, there exists the situation where huge chunks of bits being corrupted in continuous manner during the occurrence of transmission collision. As bit level FEC mainly involves in recovering data errors and data losses that are dispersed evenly, the burst loss of bits occurred in VANET cannot be recovered by these bit level FEC methods. To overcome the limitations of bit level FEC, packet level FEC methods have been introduced (Xie et al, 2016). Since the messages that are broadcasted in vehicular communications are highly delay sensitive, time constraint, the packet level FEC methods (Wu et al, 2015) cannot be directly applied as they are developed for communication scenarios in which data streams will be available readily for transmission.

ARQ is another commonly used error recovery method which involves in receiver detecting the packet error/packet loss and requesting the source for retransmission. In this ARQ error recovery mechanism, packet retransmissions are indicated using two methods namely (1) retransmission request from receiver, (2) time out of the timer that is set at the sender.
packets are retransmitted when transmission failure is detected by the receiver when it receives negative acknowledgment packet (NACK) when it does not receive any acknowledgement packet from the receiver within the set time period (Wang et al, 2015). Here, acknowledgement (ACK) is specified as short message that is being sent by the receiver for informing the appropriateness of receiver receiving the transmitted message. This ARQ method has one of the widely adopted error recovery methods in designing the various communication protocols like transmission control protocol (TCP) (Duke et al, 2015), IEEE802.11 MAC protocol (Rademacher, 2015) to support one to one communication in highly reliable manner.

In the literature, many studies have been carried out to provide reliable communication solutions for wireless networks using ARQ method. Study conducted by Nakamura et al (2015) developed an ARQ based reliable method where time slot is assigned for the receiver for checking the received frame and sending ACK frame before time slot. Another study by Dugganet al (2016) developed ARQ based reliable solution in which both sender and receiver uses time slots that are synchronised with each other in order to determine packet losses and there by requesting the retransmission. Despite all these existing solutions based on ARQ improving transmission reliability of broadcast messages over WLAN, MANETs, neither of them has been developed specifically for vehicular networks. In other words, conventional ARQ error recovery method and other reliable solutions developed based on ARQ don’t consider the unique features of VANET which there by makes them not suitable for supporting reliable broadcasting on VANET.

Hybrid ARQ (HARQ) is an error recovery method that is known for using the features of both FEC and ARQ in order to control the errors. HARQ outperforms FEC and ARQ methods as it can perform both error correction and also error detection to deal with packet errors and packet loss. The idea behind HARQ error recovery method is to use FEC redundancy bits to recover the errors to recover the errors and also ARQ to request for retransmissions. Different HARQ methods have been developed (Fong et al, 2017) based on the different CODEC methods for generating FEC redundancy bits and different ways to initiate retransmission in ARQ method. However, this hybrid approach to error recovery (HARQ) is effective when data transmission is carried out in the form of data streams to make sender add the FEC
redundancy bits and when receiver can send acknowledgement packets to initiate the retransmissions (Jiang, 2018). In case of vehicular networks neither of these conditions hold true because of the need of broadcasting safety information related to road traffic over the vehicular networks. On the other hand, HARQ error recovery methods suffer from two limitations (1) HARQ methods unable to retransmit packets with in a particular time if FEC redundancy bits are not sufficient to recover the errors, (2) Inability of HARQ techniques to adjust the FEC redundancy bits in a dynamic manner based on the existing network conditions (Graumannl, 2016). This critical discussion clearly reveals the unsuitability of conventional error recovery methods for supporting reliable broadcasting of road safety messages in VANET.

2.6 Network Coding

Network coding is one of the widely used error recovery methods on wireless channels more specifically when broadcasting the packets. Network coding technique effectively uses the network band width to transmit the data during the packets in broadcasting fashion. Error recovery is done by network coding by reducing number of retransmissions as relay will be used for packet forwarding and also for carrying out certain logic operation. Working of network coding method is given in figure 2 where the three nodes present in a network are represented as X, Y and Z. In this example, node X tend to send P0 packet to Z and node Z intends in sending P1 packet to X. When network coding method is used, the packets transmitted from X to Z and Z to X will be relayed by Y. When traditional routing is considered, relaying by Y will be done by transmitting each packet separately. In case of network coding Y node performs exclusive OR operation (xOR) on the packets and send the resulted encoded packet to X and Z.

XOR-ing this encoded packet by X and Z with previously existing packets helps in obtaining the packet that is intended to be sent by the other node in the network. The initial work on network coding has been carried out by Ahlswede et al (2000) followed by theoretical study by Li et al (2003) on linear network coding (LNC). Linear network coding method helps in guaranteeing maximum level of capacity bound for the multicast communications as each router encodes certain number of packets to form a single packet so that band width efficiency of the wireless links can be improved. This linear combination will be received by
every station which is later required to decode the mixed packets to obtain the required ones (Thomos et al, 2011). This linear network coding method has been extended in the form of random network coding (RNC) to make each station select linear coefficients in a random and also non centralized manner (Fong et al, 2017). Many studies in the literature adopted this random network coding method for obtaining the required broadcasting process efficiently over the wireless networks.

Opportunistic coding method is a network coding developed by Koetter & Kschischang (2008) in which “exclusive or” operation is carried out by for coding the packets. In this opportunistic coding-based network coding method, every relaying node uses shared wireless medium nature for obtaining the information about the data present with the neighbouring nodes. Receiver can decode the received packet by performing XOR operation on the encoded packet. This XOR based network coding method has been applied by different studies (Chachulski et al, 2007) over wireless networks to support one hop, multi hop and broadcasting communications. XOR based network coding method have many advantages over the linear network coding method as packet decoding can be done by every receiver immediately without the requirement for having other linear combination (Matsuda et al, 2011). This helps in minimizing the latency level, which is one of the key requirements to support broadcasting of road safety messages that are time sensitive with less delay over vehicular networks.

2.7 Network coding methods for error recovery in VANET

The ability of network coding methods in obtaining low latency level of transmission of the messages over wireless channels made this method to be applied extensively by several studies that focused on vehicular networks. Antonopoulos et al (2013) developed network coding method based on ARQ for error recovery in vehicular ad-hoc network. This network coding method was developed in the form of MAC protocol that coordinates channel access among various relays that use network coding methods. This way of coordinating the channel access for different relays helped in minimizing the number of retransmissions that were required for error recovery and also increasing network performance levels in terms of quality of service parameters. Liu et al (2016) proposed network coding method for improving band
width utilization of vehicular ad-hoc networks that are used for broadcasting the road safety messages. This network coding method is developed for the scenario in which there exist two data sources for data broadcasting at same time in same area. In such a situation, network coding method will be used by the relay node for decreasing the number of retransmissions, rebroadcasting events along with amount of band width that is consumed. This work has also addressed the problem faced by relay node whether to wait for coding opportunity when it has received the packet to minimize the extent of delay.

This problem is addressed by introducing two versions of this network coding method such as Buffer size control method and the time control method. Both these methods are part of introduced network coding method with the main aim of minimizing the delay experienced by packet at each hop during data transmission. Jauregui & Malaina (2016) developed another transmission control method to improve reliability of data transmission by using network coding method. This study has proposed a dynamic network coding method that selects several sources to be existing at the same time in the network. The decisions regarding packet forwarding will be taken by using network coding method at each relay node so that the redundancy level is reduced and at the same time performance level of the packet transmission is maximized. This way of using network coding method helped in improving transmission reliability when compared to other methods on vehicular networks. Error recovery method for VANET has been developed by a study that was carried out by Xie et al (2015). This study has introduced physical layer base network coding method in which two ways-based relay channels is used to support reliable transmission of data in the above layers of the network.

Yang et al (2014) carried out a study in which a reliable error recovery method has been developed for vehicular networks. This error recovery method is based on network coding method such that a handshake signal (request to broadcast/clear to broadcast) has been developed to support reliable broadcasting of data over wireless ad-hoc network. Evaluation of this network coding-based error recovery method identified the ability of handshake signal invoke on the problem of hidden node in the wireless networks in the vehicular network and there by minimize the rate of packet collision and packet error. Li et al (2003) have applied network coding method to improve content distribution through CodeOn method. In this method broadcasting of the message contents will be carried out actively between roadside access points and the vehicles using corporate vehicular ad-hoc
communication. In this CodeOn method, network coding method has been applied for dealing with wireless transmission and thereby improving reliability of the content transmission. Study carried out by Zaidiet al (2016) has investigated the concept of distributing content between the vehicles that are present within a cluster present in network coding method. In this study two types of network coding methods have been considered such as random linear network coding method and random XOR network coding method. Considering the unique properties of each of these network coding methods CSMA based MAC protocol has been adopt for delivery of safety messages successfully in a reliable manner.

2.8 Summary
In this literature review chapter, the critical review of some of the existing methods offering MAC reliability for vehicular ad-hoc networks has been carried out. Some of the clustering methods developed to support reliability transmission in VANET have been critical reviewed and identified that lack of proper guarantee provided by these methods to support reliable transmission of the safety messages. Critical review of conventional error-control and error-recovery methods such as FEC, ARQ and HARQ revealed their unsuitability for vehicle ad-hoc networks used in safety applications in which time-critical and safety messages are required to be broadcasted in a reliable manner. This critical review of the other error-control methods has also identified the ability of network coding method to support reliable broadcasting of the safety messages due to the provision of low latency and in minimising the data redundancy levels.
Chapter 3: Methodology and Methods

3.1 Introduction

The vehicular ad-hoc networks that are widely deployed in the intelligent transportation and the safety applications require assuring reliable delivery of the packets. The unique characteristics of VANET when compared to MANET, requires the need of developing a specific method that can assure reliable delivery of the broadcasted packets over VANETs used for the high safety applications. Some of the previous works on reliability assurance in VANET have targeted on clustering methods in order to assure that packets are delivered with high assurance. However, neither of the existing clustering methods consider the concept of incorporating network coding in order to improve the reliability of broadcast packet delivery. Some of the existing clustering methods developed for VANET such as cluster MAC (Rathore et al, 2010) and cooperative clustering method (Yang and Tang, 2017) have relied on using relay nodes or cooperative nodes to retransmit the packets that have been lost. However, there is no guarantee that these cooperative nodes or the relay nodes will be able to transmit all the broadcasted packets that have been lost during the data transmission.

Taking this research gap that is identified in the literature into account, this section presents the methodology section of the current research work. This methodology and methods section are mainly aimed at detailing the proposed solution to offer reliability assurance for the broadcasted packets over VANET. Initially, in this chapter the research questions that will be answered by this research are given and later the clear details of the proposed clustering method for reliability assurance in VANET are provided. In describing the proposed solution, the different techniques that are adopted such as the clustering methods and the network coding method are briefly described. Finally, a brief idea of the simulation tools that are chosen to evaluate the proposed scheme is given in this methodology section.

3.2 Key research questions

The main questions that will be answered by this research are,
1. How can VANETs used in safety and critical applications assure reliable delivery of the broadcasted packets?
2. How can VANETs overcome the problem of packet errors that commonly occur over the wireless communication channels?

3.3 Proposed Model

This research is involved in proposing a clustering method for VANET that ensures reliable delivery of the broadcasting packets to each node in the network used for safety applications. To deal with the issue of packet errors that can occur over wireless communications, clustering method is combined with the network coding method. Therefore, the proposed model to assure QoS and reliable packet delivery consists of two techniques: Clustering and Network coding that are detailed below.

A. Clustering method

The clustering method of this model intends in organising the vehicular ad-hoc network in the form of clusters. Each cluster that is formed in VANET consists of a cluster head and the cluster nodes. In the process of forming clusters in VANET, the proposed clustering method adopts several steps such as neighbouring node identification, cluster head selection and packet broadcasting. Sequential execution of these steps takes place and the list of activities adopted in each step is given below,

1. Neighbour node identification

The first step involved in this clustering method is the neighbour node identification, which aims at each node gaining location awareness of it and its neighbouring nodes. Considering the low-cost availability of the Geographical Position Service (GPS), this clustering method assumes that each vehicle consists of GPS in order to identify its location relative to other vehicles in the network. This neighbour node identification stage involves in broadcasting the “Hello Request” packets consistently to all the neighbouring nodes.

The main purpose of these ‘Hello Request’ is to broadcast the location of each vehicle in the network to its neighbouring vehicles and to identify the location of the neighbouring vehicles. Location of the neighbouring vehicle is identified by making each neighbouring node respond to these ‘Hello Request’ packets with the ‘Hello Reply’ packets. These ‘Hello Reply’ packets
possess the same format as that of the ‘Hello Request’ packets but consist of the address location of the neighbouring vehicle in the network. This broadcasting of the ‘Hello Request’ and ‘Hello Reply’ packets will be done with a communication range of each vehicle present in the VANET and this communication range is specified as ‘R’ with diameter ‘d’. Therefore, by the completion of this neighbour node identification stage, all the vehicles present in a VANET will be able to identify their position in the VANET and also the neighbouring vehicles that are present in VANET. The main reason of carrying out this neighbour node identification step is that a VANET is generally formed by vehicles having random mobility patterns, where each vehicle might not be aware of the location of other vehicles present in the network. In order to deal with this issue, neighbour node identification stage is introduced in this proposed clustering method.

2. Cluster head selection

The second step involved in the proposed clustering algorithm is the cluster head selection, which is mainly aimed at choosing the cluster head node within the communication range of each vehicle. In this step, each vehicle that has gained clear information of its changing location and its neighbouring vehicles, checks for the presence of cluster head in the nearby vicinity. This checking of the presence of cluster head vehicle is done using the packet broadcasting process. Considering that each vehicle in VANET possesses a communication range of R, each vehicle in VANET can check for the presence of cluster head within this communication range. In this process of searching, if the vehicle has identified the presence of cluster head vehicle within its communication range R, then the vehicle sends ‘cluster joining request’ to the cluster head vehicle. Based on the result of this cluster joining request, the request vehicle can join the cluster.

However, in the process of searching for the cluster head vehicle, there is a chance for identifying no cluster head within its communication range R. In this situation, when a vehicle has not identified the presence of any cluster head vehicle within its communication range, this proposed method allows that vehicle to be declared itself as the cluster head. This vehicle is formed as the cluster head for the cluster that is formed within the communication range of the chosen cluster head node. The formed cluster head broadcasts its presence as the cluster head to all the vehicles that are present within the communication range of the cluster head.
head. The main responsibility of the cluster head in this proposed method is to control the overall cluster in terms of data transmission and also to deal with any kind of the packet losses or packet errors occurring in the cluster. By the end of this stage, each vehicle present in the VANET will become either a cluster member by joining the exiting cluster or become a cluster head by forming a new cluster.

3. Packet broadcasting

The third step that is involved in the proposed clustering method is the packet broadcasting. The main purpose of this packet broadcasting step is to start the broadcasting of the packets related to any emergency or safety application that has been occurred. All the above two steps of the proposed clustering method namely the neighbour node identification and the cluster head selection are carried out when the network is idle state without disturbing the on-going data transmission over the VANET. As soon as the emergency event or a traffic safety event has occurred, each vehicle present in the VANET will be involved in generating its packets and broadcasting them to the neighbouring nodes. This packet broadcasting stage of the proposed clustering method is slightly different in the sense that each vehicle present in the cluster broadcasts the packets to all its neighbouring nodes and also cluster head node. This transmission of data from each vehicle in the cluster to the cluster head is feasible due to the presence of a direct communication link with the cluster head node that is present within its communication range. In this way, the cluster head node will be able to get the data from all the cluster member vehicles that are present in the cluster.

In spite of the cluster head node receiving the data from all the vehicles present in the cluster, this cluster head node involves in adopting the steps of data aggregation. The main purpose of this data aggregation is to collect all the data, identify the redundant data that is present and remove this redundant data from the aggregated data. By the end of this stage, the cluster head node will be having data that is sent from all the nodes present in the cluster.

B. Network Coding

The second most crucial technique that is present in the proposed model is the network coding. The main purpose of this network coding is to improve the reliability of the data transmitted over VANET by maintaining high efficiency and network performance of the VANET. Among the various mathematical operations that can be applied in this network
coding, this research involves the adoption of Exclusive-Or (XOR) operation. In spite of the cluster head playing the major role in each dynamically formed cluster, this cluster head is responsible for implementing the network coding part. That is, the cluster head vehicle of each cluster intends in adopting XOR operation as part of network coding, which involves in performing XOR operation on the data that is received from all the vehicles present in the cluster.

The main purpose of using this network coding approach at the cluster head is to provide higher flexibility to each vehicle present in the cluster to request the lost packets from cluster head node itself, instead of requesting from the source vehicle of the lost packets. As the proposed clustering method intends in having a direct link between the cluster head vehicle and all the vehicles that are present in that cluster, packet retransmissions from the cluster head vehicle becomes easier and quicker than packet retransmissions from the source vehicle. The main purpose of choosing XOR operation among the different methods available in network coding is that this XOR operation helps in effectively removing the duplicates and in aggregating the data obtained from different sources as indicated in Fragouli & Soljanin (2007); Fragouli et al (2016). This way of relying on the cluster head vehicle to retransmit the error packets or lost packets reduces the number of retransmissions as cluster head retransmits only the aggregated packets after XOR and the source nodes retransmits the individual packets. The working of this network coding method using XOR operation is shown in the below Figure 3.
In the VANET shown above, two clusters are formed with cluster heads CH1 and CH2 respectively. The CH1 of cluster 1 receives the packets ($P_a$) from cluster vehicle A, packets ($P_b$) from cluster vehicle B and packets ($P_c$) from cluster vehicle C. By taking all these broadcasted packets; CH1 performs network coding by XOR and produces output as $P_a \oplus P_b \oplus P_c$. Here, $\oplus$ specifies XOR operation.

If cluster vehicle C has faced an error in the broadcasted packets or lost the packets due to the highly error prone wireless channel, retransmission requests are used to notify the cluster head vehicle CH1 about the packet loss or packet error. Based on this retransmission request, the CH1 retransmits $P_a \oplus P_b \oplus P_c$, which helps in reducing the number of retransmissions. The cluster vehicle C will be able to decide the packets from vehicle A ($P_a$) as it already possess the packets that are generated by itself ($P_c$) and the packets obtained from vehicle B ($P_b$). This way of retransmitting the lost or error packets occur between the cluster head vehicles and the other vehicles, till all the broadcasted packets reach the receiver in highly reliable manner. Therefore, the use of network coding using XOR operation in the proposed model offers two
advantages such as (1) minimising the network congestion level in VANET by reducing the number of retransmissions and (2) increasing the network reliability level by relying on cluster heads to retransmit the XoRed packets.

One of the key features of this proposed model is the consideration of the workload that is carried out by the cluster head node with the main intention of reducing this workload. Besides relaying the packet transmission between the vehicle and the base station, the cluster head vehicle in the proposed model is also involved in adopting the network coding method. Reliability is ensured by this proposed model through packet retransmissions only instead of using error correction. In other words, practical application of the proposed model helps in assuring reliability by retransmitting the packets when they are either lost or consists of error. For instance, if the broadcasted packets from source vehicle to cluster head vehicle consists of error, then error recovery is carried out by sending the retransmission requests and getting the retransmitted packets. The main reason behind relying on only packet retransmission rather than packet error correction is the criteria used in the proposed model in selecting the cluster head such that each cluster head consists of a direct link with the cluster vehicles in the cluster. As each cluster head consists of a direct link with the cluster vehicle node, packet retransmissions become an easier way to assure reliable transmission when compared to packet error correction. However, this requires the need of cluster head vehicle detect when there are errors in the transmitted packets or when the packets are lost. For this purpose, the proposed model intends in using the Cyclic Redundancy Check (CRC) code for each packet that is transmitted. When the source vehicle transmits the messages in broadcasting format, it calculates CRC value for every packet and amends it at the end of the packet. The cluster head vehicle which receives this packet calculates CRC code before performing the data aggregation and network coding. This calculated CRC code will be checked against the CRC code that is already present in the received packet. If both CRC codes (obtained and calculated) match with each other, it intends that the received packet doesn’t contain any errors. If these CRC codes do not match with each other, it intends that received packet consists of errors and therefore requests for retransmissions. As this proposed model uses CRC code that is calculated individually for each packet, the cluster head vehicle will be able to identify even if two consecutive packets contain errors or when they are being lost. This is because, the CRC code that is calculated for one packet is unique and is different from the
one calculated for another packet as indicated. In this way of the proposed model making cluster head vehicle use CRC code checker and source vehicle calculating the CRC code helps in addressing the case of error recovery when errors occur between the source node and the cluster head vehicle. On the other hand, the property of this CRC code to be unique for each packet helps in addressing the second cases of error recovery when two or more packets are erroneous or lost.

3.4 Flowchart of the proposed method

The flowchart showing the working process of the proposed model is given in this section. This flowchart completely details all the steps that are involved at the source and also at the destination in order to assure reliable delivery of the packets.
Figure 4: Flow chart of the proposed system
3.5 Analytical Model

For the analytical model, a VANET is considered with multiple lanes in which the clusters are formed autonomously depending in the mobility patterns of the vehicles. Each vehicle in this VANET becomes either a cluster head or a cluster member. The formation of the cluster, selection of cluster head and the identification of the neighbouring nodes that is carried out in the first two steps of the clustering method are detailed below,

Consider two vehicles A and B with their geographical positions in the VANET as A \((x_a, y_a)\) and B \((x_b, y_b)\). These two vehicles A and B can become neighbouring nodes when,

\[
R \geq d(A, B) \quad (1)
\]

In the above Equation (1), \(R\) specifies the communication range of each vehicle A and B and \(d_{AB}\) specifies the distance between these two vehicles A and B. Based on the coordinates of A and B, \(d_{AB}\) is calculated as,

\[
d_{AB} = \sqrt{(x_b - x_a)^2 + (y_b - y_a)^2} \quad (2)
\]

In the same way, vehicle A with communication range \(R_A\) in the VANET can become a part of a cluster with cluster head vehicle CH1 of, if Equation (3) is satisfied.

\[
R_A \geq d(A, CH1) \quad (3)
\]

In Equation (3), \(d_{ACH1}\) represents the distance between the vehicles A and cluster head vehicle CH1, which can be calculated using the formula in Equation (2).

3.5.1 Assumptions

In the process of developing the analytical model for the developed model, some key assumptions have been made. The first assumption is that the vehicles forming the vehicular ad-hoc network do not have any hardware and software problems, which thereby make them, work effectively throughout the simulation without any failures. The second assumption is that at any point of time, there exists at least one cluster head in the vehicular
ad-hoc network that is intended in carrying out the network coding method. The third assumption is that all the vehicles including the cluster head node is equipped with GPS in order to continuously track its location relative to its neighbouring vehicles present in the network.

3.5.2 Clustering Method

One of the important steps involved in the proposed model is the vehicle clustering method, which mainly aims at dividing the vehicular ad-hoc network into a number of clusters. The proper execution of this vehicle clustering method requires the selection of particular vehicles as the cluster head. The analytical model developed for the proposed model intends in developing a criterion to select the cluster head node in a vehicle cluster instead of randomly choosing a vehicle as the cluster head. There exist three main reasons behind developing specific criteria for selecting the cluster head in the developed model. These reasons are (1) cluster head vehicle in the proposed model consists of several functionalities such as performing network coding, packet retransmission to support error recovery, (2) high role of cluster head in supporting the reliable broadcasting of the safety messages on the vehicular network, (3) need of maintaining direct link between the cluster head node and the other nodes in the cluster. All these reasons reveal the need of selecting clustering head node that performs all these activities through long lasting operation in the vehicular network. For this purpose, Euclidean distance between the vehicles, direction of vehicle travelling, vehicle speed is considered in order to decide the vehicle that must be the cluster head of a particular vehicle cluster existing in the vehicular ad-hoc network.

In the process of developing the cluster head selection criteria, the neighbouring node identification step of the proposed model is also used. Despite developing this analytical highly specific to this proposed model, some of the existing works by Ma et al (2011); Xie et al (2016); Muazu et al (2013); Shahin and Kim (2016) have been used for better idea. From execution of this neighbouring node identification step, every vehicle identifies its location, its one-hop neighbouring nodes. In this process every vehicle i in the network will have a list of one-hop neighbours called L_i and the total number of the vehicles present in this list L_i is represented as N_i. The criteria that help in selecting a vehicle i as cluster head by comparing with other vehicle j is given as C(i) and is given in Equation 1.
\[ C(i) = \frac{\sum_{x=1}^{L_i} ED(V_i, V_x)}{N_i} + \frac{\sum_{x=1}^{L_i} (S_x - S_i)}{N_i} \]  

(1)

Where,

X is a variable

\( L_i \) is the total set of one-hop neighbours of vehicle i

\( N_i \) is the total number of vehicles in \( L_i \)

\( ED(V_i, V_j) \) is the Euclidean distance between the vehicles \( V_i \) and \( V_j \)

\( S_i \) is the travelling speed of vehicle i

\( S_i - S_j \) is the difference between the travelling speeds of two vehicles i and j

The Euclidean distance between any two vehicles in the network is calculated as,

\[ ED(V_i, V_j) = ED(V_j, V_i) = \sqrt{(V_{i1} - V_{j1})^2 + (V_{i2} - V_{j2})^2 + (V_{i3} - V_{j3})^2 + \ldots + (V_{iz} - V_{jz})^2} \]  

(2)

\[ = \sqrt{\sum_{x=1}^{L_i} (V_{ix} - V_{jx})^2} \]  

(3)

Substituting the formula for Euclidean distance in equation (1), the cluster head selection criteria for each vehicle cluster can be obtained as,

\[ C(i) = \frac{\sum_{x=1}^{L_i} (V_{ix} - V_{jx})^2}{N_i} + \frac{\sum_{x=1}^{L_i} |S_x - S_i|}{N_i} \]  

(4)

The value of \( C(i) \) is calculated for every vehicle in a cluster and the vehicle having the least value of \( C(i) \) will be chosen as the cluster head node of that particular vehicle cluster. All the other vehicles will become the members of the cluster. Therefore, from the execution of two steps: neighbour node identification and cluster head selection, every vehicle becomes either a cluster member (CM) or cluster head (CH) based on the criteria below,
\[ V_i = \begin{cases} \text{CH when } C(i) = \text{Min } (C(i)) \text{ where } i = 1 \text{ to } N_i \\ \text{CM when } i \text{ belongs to } L_i \text{ where } i = 1 \text{ to } N_i \end{cases} \] (5)


As part of the analytical model, the plan for the formation of the vehicle cluster is made such that the vehicles travelling in one direction will be selected to form a cluster instead of selecting the vehicles travelling in different directions. This way of selecting only the vehicles travelling in one direction to form the cluster helps in maximising the lifetime of the each vehicle cluster that is formed in the network.

### 3.6 Analysis of broadcast reliability

The reliability of the broadcasted safety messages on a vehicular ad-hoc network is analysed as part of the developed analytical model through calculation of a reliability estimation metrics. The reliability estimation metric that is calculated in the developed analytical model is Packet Delivery Failure (PDF).

#### 3.6.1 Packet delivery failure

The packet delivery failure is a reliability metric that calculates the ratio of total packet number which have not been delivered or recovered successfully at the receiver to total packet number that has been sent by the sender. In the process of developing analytical model for this broadcast reliability some of the existing works by Wang et al (2015); Zhang and Liu (2015); Benrhaiem et al (2016); Zhu et al (2016) have been referred. In the context of the VANET, delivery failure of a broadcasted safety packet occurs during two situations (1) when there is loss in the transmitted packet and (2) when the received error packets cannot be recovered successfully by the receiver vehicle. If \( P_{\text{fail}} \) specifies the probability of a broadcasted packet by vehicle \( V_i \) facing a loss during transmission, then probability that broadcasted packet reaches the receiver successful is given as,

\[ P_{\text{success}} = 1 - (P_{\text{fail}})^k \] (6)

In the above equation, \( k \) represents the total number of vehicles present in a particular cluster \( k \). When all the \( k \) vehicles present in the cluster have generated \( N \) packets with each packet having \( x \) number of the encoded messages by application of random network coding method,
then the probability that all these encoded packets reach the destination successful is calculated as,

\[ P(k, x) = \left[ \binom{N}{x} \left( 1 - \left( P_{\text{fail}} \right)^{(k+x)} \right) \right]^{(N-x)} \] (7)

In the proposed model, in order to assure the reliable delivery of the broadcasting messages with low level of redundancy, random based network coding method is utilised. In this process, each packet that is broadcasted as the safety message is being encoded by the cluster head. This received encoded message will be able to be decoded by the one-hop receiver based on the encoding matrix consisting of the encoding vectors. Based on this aspect, the packet delivery failure for one-hop broadcasted packets is calculated as,

\[ PDF_1 = \sum_{x=0}^{N} \sum_{k=0}^{N} \left[ \binom{N}{x} \left( 1 - \left( P_{\text{fail}} \right)^{(k+x)} \right) \left( P_{\text{fail}} \right)^{(k)(N-x)} \right]^{1} \left[ \binom{N}{k} \left( 1 - \left( P_f \right)^{(k)} \left( P_f \right)^{(N-k)} \right) \right] \] (8)

In equation (8), \( P_f \) specifies the probability at which an encoded packet transmitted does not reach the receiver vehicle in a successful manner. Based on the calculation of packet delivery failure of one-hop transmission, the packet delivery failure for the final hop transmission of the encoded packets can be calculated as,

\[ PDF_{\text{last}} = \sum_{k=0}^{N} \sum_{x=0}^{N-1} \left[ \binom{N}{x} \left( 1 - \left( P_{\text{fail}} \right)^{(k+1+x)} \right) \left( P_{\text{fail}} \right)^{(k+1)(N-x)} \right]^{1} \left[ \binom{N-1}{k} \left( 1 - \left( P_f \right)^{(k)} \left( P_f \right)^{(N-1-k)} \right) \right] \] (9)

Taking the values of \( PDF_1 \) and \( PDF_{\text{last}} \), the total packet delivery failure of the cluster with \( k \) number of the vehicles in it is calculated as,

\[ PDF_{\text{total}} = 1 - \left[ 1 - PDF_1 \right] \cdot \left[ 1 - PDF_{\text{last}} \right] \] (10)

Xie, H., Boukerche, A., & Loureiro, A. A. (2016)

Substituting the equation (8) and (9) in equation (10) obtains the total packet delivery failure probability of each vehicle cluster present in the vehicular ad-hoc network.
3.7 Summary

In this chapter an analytical model for the developed model is presented in this chapter. In this analytical model the criteria for selecting the cluster head vehicle is specified and the packet delivery failure rate is calculated.

Chapter 4: Simulation Results

4.1 Introduction

The evaluation of developed analytical model is carried out in this research using simulation studies. In this chapter, the details of the simulation setup in network simulator and the obtained simulation results are presented.

4.2 Simulation Setup

In this research, simulation studies are carried out in order to test and evaluated the developed analytical model for the proposed model using the three techniques like neighbour node identification, cluster head selection and message broadcasting. In order to carry out the simulation studies, Network Simulator (NS 2.3) is the simulation software that is used in this project. According to Issariyakul & Hossain (2011), network simulator also known as the real simulator is one of the widely used network simulation software for the research projects in networking. Some of the key features of network simulation software that has resulted in selecting this software for this project are event based simulation, ability to simulation IEEE 802.11 p standard of the wireless network and ability to present the end results using both text based output and also graphic based output (Henderson et al, 2008). Network simulator consists of an event-based scheduler that helps in scheduling the various activities that are involved in the simulation process such as network initialisation, deployment of the nodes, initialisation of the node, initiation of the transmission and so on.

In this project, a vehicular ad-hoc network is simulated by simulating IEEE 802.11 p standard with mobile nodes, such that these mobile nodes act as the vehicles of the network. The simulation of these mobile nodes is carried out on a wireless environment such that the
vehicles can communicate over the wireless channels. The other simulation parameters that were used in order to carry out the simulation part refer to table:

<table>
<thead>
<tr>
<th>Simulation Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of vehicle nodes</td>
<td>45</td>
</tr>
<tr>
<td>Type of nodes</td>
<td>Mobile nodes</td>
</tr>
<tr>
<td>Type of channel</td>
<td>Wireless communication channel</td>
</tr>
<tr>
<td>Packet type</td>
<td>Safety messages</td>
</tr>
<tr>
<td>Channel model</td>
<td>Two Ray Ground channel</td>
</tr>
<tr>
<td>Wireless standard</td>
<td>IEEE 802.11p</td>
</tr>
<tr>
<td>Frequency band</td>
<td>5.9 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Size of Packet</td>
<td>512 bytes</td>
</tr>
<tr>
<td>Data rate</td>
<td>2 Mbps</td>
</tr>
<tr>
<td>CW$_{min}$</td>
<td>15</td>
</tr>
<tr>
<td>CW$_{max}$</td>
<td>1023</td>
</tr>
<tr>
<td>SIFS time</td>
<td>16 $\mu$s</td>
</tr>
<tr>
<td>DIFS time</td>
<td>64 $\mu$s</td>
</tr>
<tr>
<td>Simulation time</td>
<td>400 sec</td>
</tr>
</tbody>
</table>

Table 1: Simulation Parameters

By simulating IEEE 802.11p standard of the wireless network, a vehicular ad-hoc network is created with 250 number of vehicles. The design of the vehicular ad-hoc network is done such that the network is organised in the form of four vehicles such that few vehicles travel in one direction and the other few travels in other direction. These vehicles communicate with each
other by broadcasting the safety message packets which are the size of 512 bytes. In the simulated vehicular ad-hoc network, Markov Error Model is simulated in order to cause any kind of the errors such that these errors can be controlled by the developed Reliable Vehicle Cluster (RVC) method. The implementation process is carried out in such a way that all the three techniques present in the developed model are being implemented in which the identification of the neighbouring vehicles, formation of the clusters and broadcasting the safety messages will be carried out in the network.

4.2 Simulation details

The simulation of the proposed model in the vehicular ad-hoc network is carried out in this study using Network Simulator NS 2.3. Using the TCL (Tool Command Language) and OTCL (Object oriented Tool Command Language) code, the simulation parameters given in Table 1 are simulated. As part of the simulation, a vehicular ad-hoc network is simulated in this study. For this purpose, the existing directory for vehicular ad-hoc network in NS 2.3 such as IEEE 802.11p is called as shown in code snippet given in Figure 5.

```
set val(chan) Channel/WirelessChannel ;# Channel Type
set val(prop) Propagation/TwoRayGround ;# radio-propagation model
set val(mac) IEEE802.11p
set val(ifq) Queue/DropTail/PriQueue ;# interface queue type
set val(ll) LL
set val(ant) Antenna/OmniAntenna ;# antenna type
set val(ifqlen) 50 ;# max packet in ifq
set val(nn) 45 ;# number of mobilenodes
set val(rp) AODV
set val(x) 50
set val(y) 50
set val(nam) GRM. nam
set val(traffic) ftp ;# cbr/poisson/ftp
```

Figure 5: Shows code snippet
The formation of the vehicular ad-hoc network is later done by randomly deploying the vehicles in the considered network area. The initialisation of the vehicles in the form of nodes and initialisation of the simulation parameters is done in OTCL code as given in Figure 6.

![Initialisation of the vehicles in the form of nodes](image)

*Figure 6: Initialisation of the vehicles in the form of nodes*

The proposed model is implemented in the simulated vehicular ad-hoc network through formation of the clusters, when cluster head for each cluster is selected based on the chosen criteria. The finally simulated vehicular ad-hoc network with the formation of clusters where each cluster head vehicle is represented in blue colour is given in Figure 7.
Figure 7: Simulated vehicular ad-hoc network with the formation of clusters

In the process of simulating the proposed model, the errors in the vehicular ad-hoc network are also simulated. Figure 8 shows the way in which packets are lost from vehicular ad-hoc network due to the error prone channel present in the network.
4.4 Evaluation Parameters

The simulation of IEEE 802.11p and the proposed model will be carried out in order to evaluate the proposed model in terms of the following three evaluation parameters.

1. **Average throughput**

This evaluation parameter is defined as the total number of the packets that are broadcasted by the vehicles in VANET in a unit time period. Calculation of this average throughput is done using the formula in Equation (4)

$$\text{Average throughput} = \frac{\text{Number of packets sent}}{\text{Unit time period}} \quad (4)$$

This evaluation parameter helps in assessing if the proposed model is able to improve the average throughput and efficiency of the total VANET.

2. **Packet delivery ratio**

The packet delivery ratio specifies the number of packets that are delivered to the receiver successfully to the total number of packets that have been sent by the source node. The packet delivery ratio of the proposed model is calculated using the formula in Equation 5.
Packet delivery ratio = \[
\frac{\text{Number of packets successfully reached to the receiver}}{\text{Total number of packets sent}}
\] (5)

Issariyakul, T., & Hossain, E. (2011)

This packet delivery ratio helps in assessing the error prone nature of wireless channel used for communication in VANET.

4.5 Analysis of the simulation results

The results obtained from the simulation of the vehicular ad-hoc network and the implementation of the reliable vehicle cluster method are critically analysed and presented in this section. Running the simulation for 400 seconds has resulted in obtaining the graphical outputs regarding the packet delivery rate, packet error recovery probability and the throughput rate. Initially recording the total number of packets that have been sent by generating from the source’s vehicles and the total number of packets that have been received by the intended receiver node are done. Based on this, calculation of the packet delivery rate is done. This calculation of the packet delivery rate is done by taking the ratio of the total number of packets that have been sent from the source vehicle to the number of the packets that have been received at the receiver.

We compare the RVC cluster with Cooperative MAC and cluster MAC. First, we see the cooperative MAC, cooperative MAC communication is a reliable method to improve the transmission performance in VANET. In VANET the fast movement of vehicle leads to changes in the network topology. To reduces the probability of successful data transmissions in the Medium Access Control (MAC). The Cooperative MAC uses multi cooperative nodes to forward data and it will improve the successful data transmission. The cooperative MAC will select the cooperative nodes according to the direct successful transmission in the communication range between the source node to the destination node, if the time slot is available. In cooperative MAC the excessive transmission redundancy caused by multiple cooperative forwarding in one time. Reliable cooperative communication in VANET is depend on the status of the surrounding vehicles. The cooperative node is obtained by probabilistic model, so it will avoid the redundant data transmission overhead caused by excessive cooperative forwarding. Cooperative MAC uses the Time Division Multiple Access (TDMA) based MAC protocol to improve the successful transmission rate in VANET.
Hongjing Zhou 1 and Jiawei Huang 4, (June 2019). It uses the probabilistic model for cooperative communication. Cooperative MAC is possible only if the destination node is in the communication range. It must have one available time slot to transmit the data from cooperative node. When compared to RVC the delivery rate for cooperative MAC is low.

Second, we compare the RVC with the Cluster MAC using Carrier Sense Multiple Access (CSMA). Due to the characteristic of VANET such as high speed, unstable communication link and network partitioning, data transmission is becoming challenging. The design of MAC protocol for VANET is to achieve reliable delivery of messages within the limit even the density of vehicles varies rapidly in the network. Cluster MAC protocols can avoid limits channel contention, provide fairness to channel access, increase radio capacity by the spatial rescue of the network resources. It will effectively control the topology of the network. Due to the high mobility characteristic of VANET, vehicles are frequently joining and leave the clusters. It will affect the connectivity in the network. Cluster based MAC protocol depend on the carrier sense multiple access (CSMA) and collision free time division multiple access (TDMA). MAC protocol is mainly affected by several factors such as number of one hop neighbour node in the communication link, time period, direction of travelling and vehicles position (abooobeker.sidhik,unai.hernandez,nekane.sainz@deusto.es). In the high scenarios, data congestion and packet delivery increase by an enormous rate, due to lack of network resources. Using CSMA there will be a long contention period among vehicles for using network resources and therefore the use of MAC protocol is not scalable. The packet data delivery rate is also low when compared to RVC.

Figure 9 shows the graphical output that is plotted between the packet generation rate and the packet delivery rate. As the simulated vehicular ad-hoc network consists of the wireless channels, there is a great chance of packet losses which can have a great negative impact on the rate of packets that are delivered to the receiver. In this simulation, the number of retransmissions (rt) that are permitted for a vehicle in the vehicular ad-hoc network are varied to identify its impact on the rate of packet delivered to the receiver vehicle in the network. Figure 9 shows the variation in packet delivery rate to the receiver vehicle with the increase in the packet generation rate. Here the number of retransmissions that are allowed for each vehicle in the network and the cluster head are rt= 5. In Figure 9, the packet generation rate indicated in x-axis and the packet delivery rate specified in y-axis are of the similar parameters.
which is number of packets/unit time. The packet delivery rate of the network when the proposed reliable vehicle clustering method is applied is compared with the other two existing methods cluster-MAC and cooperative-MAC methods that are referred in the literature. Critical analysis of this graph reveals that the packet delivery rate of the proposed RVC method is certainly higher than the two existing clustering methods developed for vehicular ad-hoc network. With the increase in the rate at which packets are generated by each vehicle in the network, the rate at which these packets are delivered to the receiver has also increased. However, comparative analysis has revealed the ability of proposed RVC method in recording slightly high level of the packet delivery rate than the existing methods. One main reason behind this is the presence of neighbour node identification step in which each vehicle consists of the list of the one-hop neighbouring node that helps in selecting the most suitable cluster head by RVC through which the probability of reliability transmission increased and thereby the rate of delivery of the packets also increases for RVC method. The other reason is the criteria used to select the cluster head vehicle such that it consists of a direct link with the cluster member vehicles. This helps in maximising the delivery of transmitted packets, thereby increasing the packet delivery rate as shown in Figure 9.

![Packet generation Vs Delivery rate](image)

**Figure 9: Packet delivery rate of proposed RVC model when retransmissions =5.**

The number of retransmissions that are supported by the proposed reliable vehicle clustering method are increased from 5 to 8 where rt= 8. The packet delivery rate that is obtained for the vehicular ad-hoc network when the number of retransmissions is increased is shown in
Figure 9. When compared to previous graph, here the rate of packet delivery is slightly higher for the proposed RVC method despite keeping the packet generation rates the same. Even with the increase in the number of retransmissions, the packet delivery rate of proposed RVC method is recorded to be higher than the other two existing methods cluster and cooperative MAC as shown in Figure 10. The main reason for this is the ability of cluster head node supporting a greater number of retransmissions in RVC method through which the chance of the packet getting delivered successfully to the receiver increased, thereby increasing its packet delivery rate. The use of cyclic redundancy check code for each packet sent from the source vehicle has also become another key reason for this proposed RVC method in recording high packet delivery rate as given in Figure. From this analysis, it is evident that as the number of the retransmissions are increased, the rate of packet delivery also increases despite keeping the same packet generation rate. This is due to the number of increased retransmissions supporting the reliable communication at a greater extent on the vehicular ad-hoc networks.

![Packet generation Vs Delivery rate](image)

**Figure 10: Packet delivery rate of proposed RVC model when retransmissions =8**

The packet recovery probability of the vehicular ad-hoc network when the proposed RVC method is implemented is also calculated and plotted in the graph shown in figure. Here, the packet recovery probability is specified the probability at which the receiver will be able to recover any kind of errors or losses present in the received packets. The graph plotted in
The figure reveals the packet recovery probability of RVC analytical model, simulation model and the existing cluster-MAC method. On the x-axis, the packet delivery failure rate is specified and on y-axis the packet recovery probability levels are indicated. Critical analysis of this graph reveals that with the increase in the packet delivery failure rate, the packet recovery probability level has declined for both the proposed RVC method and the existing cluster-MAC method. This decline is mainly because of the increase in the rate of failure in packet delivery when the rate at which the packets are generated has increased. Comparative analysis of this graph has revealed that the packet recovery probability value of both analytical model and the simulation studies is the same with increase in the rate of packet delivery failure. This probability of the packet recovery is higher for RVC method when compared to that of the cluster-MAC method as given in the graph presented in Figure 11. The main reason for this can be explained due to the ability of cluster head in the proposed RVC method using the CRC checker to verify if the received packets consist of any errors. And due to cluster head node consisting of random network coding method through which the redundancy level of broadcasting messages decreases and the probability of recovering the lost packets from the encoding packets increases. In this way of effectively selecting the cluster head node to perform the network coding and data retransmission activities helped in increasing the probability of error recovery at the receiver vehicle when the proposed RVC method is applied.

![Packet recovery probability Vs Delivery failure rate](image)

Figure 11: Packet recovery probability
RVC analytical model is developed to evacuate three parameters which are namely packet delivery ratio, throughput and delay. The main reason for RVC analytical is to compare the cluster VANET with the non-clustered to find out its superiority. In RVC analytical a mathematical model to calculate the packet delivery ratio for non-clustered VANETs which are present in Raghavendra Pal, Arun Prakash, Rajeev Tripathi, Dhananjay Singh. Analytical model for cluster vehicular Ad hoc Network. The difference in analytical and simulation are mainly due to the inclusion of propagation model in Mohamed A. Abd El-Gawad1,2, Mahmoud Elsharief1,3 and HyungWon Kim1. The channel noise and other physical layer properties in simulation. These properties are not considered in analytical model.

Another evaluation parameter that is being considered in this project for the simulation is the throughput rate. The graph plotted and given in Figure 12 is between the throughput rate and the packet generation rate. Here, the x-axis is mentioned with packet generation rate that is expressed with the parameters number of packets per second. The throughput rate is the other parameter plotted on y-axis with the units Mbps. The variation in the network throughput level when the proposed RVC method is applied is plotted against the change in packet generation rate. From the critical analysis of the graph, it is evident that the increase in the packet generation rate resulted in the fall of the throughput rate for the proposed RVC method and the two existing methods cluster-MAC and cooperative-MAC.

![Figure 12: The throughput rate and the packet generation rate](image-url)
From the critical analysis it is evident that throughput rate of proposed RVC method is higher when compared to the existing methods cluster-MAC and cooperative-MAC. The higher throughput value of RVC method can be better justified based on the fact that the proposed reliable vehicle cluster method can select the cluster head appropriateness through which the lifetime of the cluster is increased and at the same time, the number of retransmission are reduced to support the reliable data delivery. This way of supporting formation of clusters that are of huge lifetime and supporting the reliable data delivery helps in increasing the throughput rate of the network.

4.6 Summary
The critical analysis of the simulation results has helped in evaluating the developed reliable vehicle cluster method to support the reliable communication of the safety messages over the vehicular ad-hoc network. Evaluation using simulation results revealed the existence of the great similarity between the analytical and the simulation studies. The ability of the reliable vehicle clustering method in improving the reliability of the safety messages that are broadcasted over the vehicular ad-hoc networks has been identified.
Chapter 5: Conclusion and Future Work

5.1 Conclusion

This research is involved in identifying the need of providing reliable delivery of safety messages over the vehicular ad-hoc network. The IEEE 802.11P standard of vehicular ad-hoc network suffers from the medium access delay due to the channel interference and the presence of the error-prone wireless channel. Over the past few years, the evolution of intelligent transport systems resulted in the usage of vehicular ad-hoc networks across various safety applications. The use of vehicular ad-hoc networks in these safety applications require the need of delivering safety messages in timely manner and without any errors to the intended receivers. The need of broadcasting safety messages has been identified in the vehicular ad-hoc networks that are used for that are used for the safety applications. As many vehicles intended in broadcasting the safety messages regarding the accidents or any traffic situations at the same time, assuring reliable delivery of the broadcasted safety messages is more critical for the use of wireless ad-hoc networks. Identifying the importance of reliable broadcasting of safety messages and the need of minimizing the redundancy levels, this research has involved in proposed a method called reliable vehicular clustering method which involves in using a set of techniques in order to support reliable delivery of broad casted safety messages to the intended receiver in a wireless ad-hoc network. The clustering method involves in adopting three main steps namely identification of neighbouring nodes, formation of cluster and then packets broadcasting the data. Random network coding is used in the proposed model to encode the broadcasted packets by cluster head in order to improve error recovery capability and minimize the extent of data reduced that might occur during broadcasting the data.

This research is unique because of proposing a novel model that intends in assuring reliable delivery of the broadcasted packets over a VANET. The high application of VANETs in the
safety and critical applications requires reliable delivery of the broadcasted packets to each vehicle in the VANET in order to make them aware of the emergency situations or any safety situations that have occurred while on road. Despite this importance of assuring reliable data delivery, the unique properties of the VANETs make this reliability assurance a great challenging issue for these networks. In this research, a novel model is proposed to assure reliable data delivery. This proposed model consists of two main techniques namely the clustering method and the network coding method. The purpose of each of these techniques and the steps adopted in each of these techniques as part of the proposed model is,

1. Clustering method intends in organising the VANET into various clusters and is implemented using three steps namely neighbour node identification, cluster head selection and the packet broadcasting.

2. Network coding method is implemented in each cluster head where the packets received from each vehicle in the cluster are XORed. This network coding is used to retransmit the XORed packets to any cluster vehicle that has faced either packet error or packet loss. This network coding is used to reduce the congestion levels on the network and improve the reliability levels of the network.

The effectiveness of these techniques in the proposed model is evaluated in this research using a combination of the mathematical analysis and the simulation modelling. Effectiveness of this proposed model with several methods has been identified in this report using both development of analytical model and the simulation studies. Initially an analytical model has been developed for selecting the cluster head node in a particular cluster and in calculating the packet delivery failure rate in a network. The criteria for selecting a cluster head vehicle among several vehicles present in the cluster has been developed with great care such that the most suitable cluster head that performs network coding and error recovery techniques can be chosen. In order to maximize the lifetime of the clusters form, the proposed model has planned to form the clusters with the vehicles travelling in one particular direction. As part of the analytical model, the packet delivery failure rate has also been calculated for each vehicle cluster by identified the probability for one hop transmission and final hop transmission. Network simulator software has been used in this research in order to test the developed analytical model. The simulation results that were obtained revealed the effectiveness of the proposed method in terms of the packet delivery rate, packet error
recovery probability and the throughput rate. This evaluation identified the effectiveness of developed reliable vehicle cluster method in outperforming the existing cluster methods developed for reliable communication in MANET.

5.2 Future Work

Huge developments in the wireless technologies resulted in the development of autonomous driving systems that uses intelligent transport application system in order to travel from one distance to other without the need of a driver. The use of wireless ad-hoc networks at a greater extent is indicated to increase the number of vehicles that are connected to form a wireless ad-hoc network (Cooper et al, 2017). With the increase in the number of vehicles that are connected over vehicular ad-hoc network, there exists several issues in the network such as the hidden-node problem. Aliyu et al (2017) defined the hidden node problem as the situation in which a mobile node will be visible for the access point but will not be visible for other node in the network. In the context of the vehicular ad-hoc network, the hidden node problem specifies the situation where a vehicle will be visible to the access point or the roadside unit but will not be visible to the next vehicle. In this way of the presence of the hidden node problem, there is a great chance for the occurrence for the packet collisions due to broadcasting of the packets. Considering the huge existence of this hidden node problem in VANET as indicated in Gholibeigi et al (2016), there is a great need to deal with this problem in order to support the reliable communication of the broadcasted data. The future work of this project is intended in developing a novel method like the handshake signal in order to identify the hidden node, reduce the packet collisions and thereby enhance the level of reliability of the broadcasted data when used for the safety applications.

5.3 Research study plan

I started my MSc Research program in March 2017, which lasts for 15-month time period. Based on the time available to complete my research work, the following Gant Chat is prepared for 15-month time period from March 2017 and June 2018.
Great care is taken to adhere with this time plan presented in the form of Gantt Chart in order to complete the research work and all the other interim submissions within the deadline. Considering the availability of very short time period, some of the activities like literature and mathematical analysis are carried out in simultaneous manner.
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Mohamed A. Abd El-Gawad1,2, Mahmoud Elsharief1,3 and HyungWon Kim1*

A cooperative V2X MAC protocol for vehicular networks


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Appendix – Code
# Reliable data transmission in vehicular ad-hoc networks

```python
proc getCmdArgu {argc argv} {
    global val
    for {set i 0} {$i < $argc} {incr i} {
        set arg [lindex $argv $i]
        if {([string range $arg 0 0] != "-" )} continue
        set name [string range $arg 1 end]
        set val($name) [lindex $argv [expr $i+1]]
    }
}

getCmdArgu $argc $argv
```

# nodes: 16, pause: 10.00, max speed: 20.60, max x: 1000.60, max y: 1000.60

```plaintext
$node_0 set X_ 230.87349631721
$node_0 set Y_ 932.379089746357
$node_0 set Z_ 0.000000000000000
$node_1 set X_ 106.219082626879
$node_1 set Y_ 272.17898782115
$node_1 set Z_ 0.000000000000000
$node_2 set X_ 651.314596522934
$node_2 set Y_ 881.10817299346
$node_2 set Z_ 0.000000000000000

$node_3 set Y_ 222.385881993981
$node_3 set Z_ 0.000000000000000
$node_4 set X_ 432.34692149499
$node_4 set Y_ 598.450129497244
$node_4 set Z_ 0.000000000000000
$node_5 set X_ 989.648305775330
$node_5 set Y_ 612.648718625659
$node_5 set Z_ 0.000000000000000
$node_6 set X_ 481.099119891556
$node_6 set Y_ 11.249551395864
$node_6 set Z_ 0.000000000000000

```

n -t * -s 0 -x 230.87834963172699 -y 932.37908974635695 -z 0 -z 38 -v circle -c black
n -t * -s 1 -x 106.219082626879 -y 272.1789878211499 -z 0 -z 30 -v circle -c black
n -t * -s 2 -x 651.314596522934 -y 881.1081729934604 -z 0 -z 38 -v circle -c black
n -t * -s 3 -x 252.031977154 -y 222.385881993981 -z 0 -z 38 -v circle -c black
n -t * -s 4 -x 432.3469214949988 -y 598.45012949724481 -z 0 -z 38 -v circle -c black
n -t * -s 5 -x 989.6483057753396 -y 612.64871862565962 -z 0 -z 38 -v circle -c black
n -t * -s 6 -x 481.09911989155597 -y 11.249551395864 -z 0 -z 30 -v circle -c black
n -t * -s 7 -x 514.53630417202396 -y 572.38097862695395 -z 0 -z 38 -v circle -c black
n -t * -s 8 -x 318.77837484478969 -y 911.25668948898999 -z 0 -z 38 -v circle -c black
n -t * -s 9 -x 499.99819720191497 -y 801.45983693740584 -z 0 -z 38 -v circle -c black
```
# Initialize Global Variables in Vehicular ad-hoc Network
set ns_ [new Simulator]
set tracefd [open ./GRRM.tr w]
$ns_trace-all $tracefd
if { "$val(nam)" == "GRRM.nam" } {
  set namtrace [open ./$val(nam) w]
  $ns_namtrace-all-wireless $namtrace $val(x) $val(y)
}

n -t * -a 4 -s 4 -S UP -v circle -c black -i black
n -t * -a 6 -s 6 -S UP -v circle -c black -i black
n -t * -a 1 -s 1 -S UP -v circle -c black -i black
n -t * -a 6 -s 6 -S UP -v circle -c black -i black
n -t * -a 2 -s 2 -S UP -v circle -c black -i black
n -t * -a 2 -s 2 -S UP -v circle -c black -i black
n -t * -a 3 -s 3 -S UP -v circle -c black -i black
l -t * -s 0 -d 1 -S UP -r 15000000 -D 0.01 -c black
l -t * -s 0 -d 2 -S UP -r 10000000 -D 0.002 -c black
l -t * -s 1 -d 3 -S UP -r 10000000 -D 0.002 -c black
l -t * -s 1 -d 7 -S UP -r 10000000 -D 0.002 -c black
l -t * -s 3 -d 2 -S UP -r 10000000 -D 0.002 -c black

# defines the node size in nam
for {set i 0} {$i < $val(nn)} {incr i} {
  $ns_initial_node_pos $node_(i) 2
}

# Tell nodes when the simulation ends
for {set i 0} {$i < $val(nn)} {incr i} {
  $ns_ at $stopTime "$node_(i) reset"
}

$ns_ at $stopTime "stop"
$ns_ at $stopTime "puts "\nNS EXITING..."
$ns_ at $stopTime "$ns_halt"
$ns_ at 123.283242884454 "$god_set-dist 2 9 2"
$ns_ at 123.283242884454 "$god_set-dist 5 5 4"
$ns_ at 123.283242884454 "$god_set-dist 5 9 3"
$ns_ at 123.283242884454 "$god_set-dist 6 8 2"
$ns_ at 123.283242884454 "$god_set-dist 8 9 1"
$ns_ at 126.507824127765 "$god_set-dist 0 5 4"
$ns_ at 126.507824127765 "$god_set-dist 5 6 3"
$ns_ at 126.507824127765 "$god_set-dist 5 8 1"
$ns_ at 126.507824127765 "$god_set-dist 5 9 2"
Appendix code for the RVC Analytical

BEGIN {
    seqno = -1;
droppedPackets = 0;
receivedPackets = 0;
count = 0;
}

#packet delivery ratio
if($4 == "AGT" && $1 == "s" && seqno < $6) {
    seqno = $6;
} else if(($4 == "AGT") && ($1 == "r")) {
    receivedPackets++;
} else if ($1 == "D" && $7 == "tcp" && $8 > 512){
droppedPackets++;
}

#end-to-end delay
if($4 == "AGT" && $1 == "s") {
    start_time[$6] = $2;
} else if(($7 == "tcp") && ($1 == "r")) {
    end_time[$6] = $2;
} else if($1 == "D" && $7 == "tcp") {
    end_time[$6] = -1;
}

END {
for(i=0; i<=seqno; i++) {
    if(end_time[i] > 0) {
        delay[i] = end_time[i] - start_time[i];
        count++;
    }
    else {
        delay[i] = -1;
    }
}

for(i=0; i<count; i++) {
    if(delay[i] > 0) {
        n_to_n_delay = n_to_n_delay + delay[i];
    }
}

n_to_n_delay = n_to_n_delay/count;
print "\n";
print "GeneratedPackets = " seqno+1;
print "ReceivedPackets = " receivedPackets;
print "Packet Delivery Ratio = " receivedPackets/(seqno+1)*100 "%";
print "Total Dropped Packets = " droppedPackets;
print "Average End-to-End Delay = " n_to_n_delay * 1000 " ms";
print "\n";"