# ENHANCING A CLUSTER-BASED TDMA MAC PROTOCOL FOR VEHICLE-TO-VEHICLE COMMUNICATIONS

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Field of Study: Mobile Ad Hoc Network (Computer Science)

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**ENHANCING A CLUSTER-BASED TDMA MAC PROTOCOL FOR VEHICLE-TO-VEHICLE COMMUNICATIONS**

## ABSTRACT

Vehicular Ad hoc Network technology (VANET) is one of the emerging and promising wireless technology, providing support for vehicles to communicate and share resources, (such as safety messages) through vehicle-to-vehicle (V2V) communications. Sequel to that the Time Division Multiple Access (TDMA) MAC protocol using a cluster-based topology has been proposed by the research community. Most of the existing research works focused on the cluster head (CH) election with very few addressing other critical issues, including cluster formation, efficient time slot allocation, and cluster maintenance. These challenges result in an unstable cluster, which could affect the timely delivery of safety applications. In this thesis, a new approach called enhanced cluster-based TDMA MAC (EC-TMAC) protocol was developed to address these challenges. To achieve that, two CHs were proposed to provide strong cluster stability within the clusters; the primary cluster head (PCH) as the main CH and the secondary cluster head (SeCH) to act as a backup to the PCH. Furthermore, a new algorithm was also developed to provide an efficient CH leadership transition from PCH to SeCH when the PCH can no longer continue with the leadership responsibility. A dynamic time slot allocation strategy using a binary tree algorithm has been proposed to prevent vehicles from the adjacent clusters to reserve the same time slot. The proposed EC-TMAC protocol was evaluated through simulation and validated using a statistical analysis tool. The simulation results obtained show a better performance with increased cluster stability, low rate of merging collision and less communication overhead to the system.

Keywords: Vehicular Ad Hoc Network, MAC Protocol, CH, SeCH, TDMA.

# MENINGKATKAN PROTOCOL MAC TDMA BERBASIS CLUSTER UNTUK KOMUNIKASI KENDERAAN-KE-KENDERAAN


## ABSTRAK

Teknologi Rangkaian Ad hoc Kenderaan (VANET) adalah salah satu teknologi tanpa wayar yang muncul dan menjanjikan, yang memberikan sokongan kepada kenderaan untuk berkomunikasi dan berkongsi sumber, (seperti mesej keselamatan) melalui komunikasi kenderaan-ke-kenderaan (V2V). Sejajar dengan itu protokol MAC Time Division Multiple Access (TDMA) menggunakan topologi berasaskan kluster telah dicadangkan oleh komuniti penyelidik. Sebilangan besar kajian yang ada menumpukan pada pemilihan kepala kluster (CH) dengan sangat sedikit menangani masalah kritikal lain, termasuk pembentukan kluster, peruntukan slot waktu yang efisien, dan penyelenggaraan kluster. Tantangan ini menghasilkan kelompok yang tidak stabil, yang dapat mempengaruhi pengiriman aplikasi keselamatan tepat pada waktunya. Dalam tesis ini, pendekatan baru yang disebut protokol TDMA MAC (EC-TMAC) berdasarkan kluster ditingkatkan dikembangkan untuk mengatasi tantangan ini. Untuk mencapai itu, dua CH dicadangkan untuk memberikan kestabilan kluster yang kuat di dalam kelompok; kepala kluster utama (PCH) sebagai CH utama dan kepala kluster sekunder (SeCH) untuk bertindak sebagai sandaran kepada PCH. Selanjutnya, algoritma baru juga dikembangkan untuk memberikan peralihan kepemimpinan CH yang cekap dari PCH ke SeCH apabila PCH tidak lagi dapat meneruskan tanggungjawab kepemimpinan. Strategi peruntukan slot masa yang dinamik menggunakan algoritma pokok binari telah dicadangkan untuk mengelakkan kenderaan dari kelompok bersebelahan menempah slot masa yang sama. Protokol EC-TMAC yang dicadangkan dinilai melalui simulasi dan disahkan menggunakan alat analisis statistik. Hasil simulasi yang diperoleh menunjukkan prestasi yang lebih baik dengan kestabilan kluster yang meningkat, kadar perlanggaran penggabungan yang rendah, dan overhead komunikasi yang kurang ke sistem.

Kata kunci: Rangkaian Ad Hoc Kenderaan, Protokol MAC, CH, SeCH, TDMA.

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| | | |
|---|---|---|
| 1PPS | : | One-Pulse-Per-Second |
| AfS | : | Announcement for Service |
| BSM | : | Basic Safety Message |
| CCH | : | Control Channel |
| CCO | : | Cluster Coverage Occupancy |
| CCW | : | Cooperative Collision Warning |
| CDMA | : | Code Division Multiple Access |
| CG | : | Cluster Gateway |
| CH | : | Cluster Head |
| CIL | : | Cluster Information List |
| CM | : | Cluster Member |
| CSMA | : | Carrier Sense Multiple Access |
| CTS | : | Clear to Send |
| $CW_{max}$ | : | Maximum Contention Window |
| $CW_{min}$ | : | Minimum Contention Window |
| DOT | : | Department of Transportation |
| DSRC | : | Dedicated Short Range Communication |
| EC-TMAC | : | Enhanced Cluster-based Time Division Multiple Access Medium Access Control |
| EDCA | : | Enhanced Distribution Coordination Access |
| FDMA | : | Frequency Division Multiple access |
| GI | : | Guard Interval |
| GPS | : | Global Positioning System |
| GUI | : | Graphical User Interface |

| | | |
|---|---|---|
| ITS | : | Intelligent Transportation System |
| LC | : | Lane Change |
| MAC | : | Medium Access Control |
| MANET | : | Mobile Ad hoc Network |
| NS-3 | : | Network Simulator 3 |
| OBU | : | On-board Unit |
| ONL | : | One-hop Neighbor List |
| OSM | : | Open Street Map |
| PCH | : | Primary Cluster Head |
| QoS | : | Quality of Service |
| Res | : | Response |
| RfS | : | Request for Service |
| RSU | : | Road Side Unit |
| RTS | : | Ready to Send |
| SDMA | : | Space Division Multiple Access |
| SeCH | : | Secondary Cluster Head |
| SCH | : | Service Channel |
| SUMO | : | Simulator of Urban Mobility |
| TDMA | : | Time Division Multiple Access |
| Tx Power | : | Transmission Power |
| Tx Gains | : | Transmission Gains |
| Rx Gains | : | Reception Gains |
| V2V | : | Vehicle-2-Vehicle |
| V2I | : | Vehicle-2-Infrastructure |
| VANET | : | Vehicular Ad hoc Network |
| WAVE | : | Wave Access for Vehicular Communication |

| | | |
|---|---|---|
| WCA | : | Weight-based Clustering Algorithm |

## LIST OF APPENDICES

# CHAPTER 1: INTRODUCTION

## 1.1 Background

Road traffic crashes on the highways are one of the major causes of fatal injuries and death globally. It was expected to become the 7th leading cause of death among all the age groups by 2030 if precautionary measures are not taken into consideration (Antoniou & Kostovasilis, 2017; Violence, Prevention, & Organization, 2013). One of the recent developments in wireless networks technology that was able to tackle this problem of traffic crashes is vehicular technology. This technology results in the emergence of one of the promising and main components of the Intelligent Transportation System (ITS) called vehicular ad hoc network technology (VANET) (Qureshi & Abdullah, 2013). The vehicles are equipped with numerous sensors and wireless communication devices in VANET. This type of network provides support for vehicles to communicate and share resources while moving on the road through vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communications (Yan & Rawat, 2017). As a result of this, vehicular technology can provide a communication framework for the dissemination of different types of applications, which can benefit both drivers and passengers. These applications include safety related applications, infotainment services (such as video streaming), and traffic management applications (Ahmad, Noor, Ali, Imran, & Vasilakos, 2017).

Safety related applications have been considered to be more critical than the other types of applications in VANET (Almeida, 2015). Each vehicle transmits basic safety messages automatically at a regular interval to discover nearby vehicles as well as share its current status (such as vehicle's direction, position, speed, and acceleration) to its neighbors so that unwanted situations could be avoided on the road such as accident or any other incident before it takes place. In contrast to the basic safety messages, the emergency messages are broadcast to make sure that all the vehicles within the communication range get aware of any instant occurrence of an emergency incident (Anjum, Noor, & Anisi, 2017; Tanuja, Sushma, Bharathi, & Arun, 2015). To broadcast these messages, VANET relies on the Medium Access Control (MAC) protocol. The MAC protocol is required to fulfill all the requirements of safety related applications in VANET, such as time requirement for reliable and timely delivery to the destination. The reliability of safety applications solely depends on the efficiency of the MAC protocol (Gillani, Shah, Qayyum, & Hasbullah, 2015). However, conventional MAC protocol is not suitable for VANET safety applications (He, Tang, O'Farrell, & Chen, 2011; X. Ma, Chen, & Refai, 2009; Miao, Djouani, Van Wyk, & Hamam, 2013) as a result of the frequent changes in the network topology due to the vehicle's high mobility, which lead to many researchers proposing enhanced mechanisms in order to support the implementation of these applications.

To provide reliable broadcasting of safety messages, a cluster-based time division multiple access (TDMA) MAC protocol has gained a lot of attention by researchers in recent years (Aslam, Santos, Santos, & Almeida, 2019; Cao & Lee, 2017; Jiang & Du, 2016; Lin & Tang, 2019; Y. Liu, Zhou, & Huang, 2019; Lyu, Zhu, Zhou, Qian, et al., 2018; Mammu, Hernandez-Jayo, & Sainz, 2013; Pal, Prakash, & Tripathi, 2018; Regin & Menakadevi, 2019; T. Zhang & Zhu, 2016). This type of protocol minimizes access collision and limits channel access contention among the contending vehicles. A cluster-based approach is a method that improves communication within the network. Clustering provides efficient resource utilization and load balancing in a large scale network. In a cluster-based approach, the moving vehicles are grouped based on some identified parameters; where one of them will be selected to become a cluster head (CH) and the remaining vehicles are considered to be the cluster members (CMs). The selected CH is responsible for managing all the intra-cluster communication within the cluster to avoid interference between the cluster members and coordinating the time slot scheduling as well. In this case, each vehicle in the cluster does not need to broadcast the message directly to all the CMs but rather to the CH which will then broadcast to all the CMs. This can minimize the transmission collision and interference as well.

Many clustering algorithms have been proposed for TDMA MAC protocols in vehicular network to support efficient deployment of VANET safety applications (Bali, Kumar, & Rodrigues, 2014; Cooper, Franklin, Ros, Safaei, & Abolhasan, 2017; Lang, Wang, Mei, & Deng, 2019; Pal, Gupta, Prakash, & Tripathi, 2018; Senouci, Harous, & Aliouat, 2020; Shah, Ilhan, & Tureli, 2018; Sucasas et al., 2016; P. Yang, Wang, Zhang, Tang, & Song, 2015). Generally, a clustering technique in a TDMA-based MAC protocol comprises five distinct stages namely; the cluster formation, cluster head election, inter-cluster communication, cluster maintenance, and time slot allocation. It is worthy to note that, efficient clustering algorithm requires producing a CH that can stay for a long period within the cluster before it moves out of the cluster (Vodopivec, Bešter, & Kos, 2012). Unfortunately, once a CH moves out of the cluster, a new one has to be elected to maintain the communication within the cluster. This re-election process could result in a cluster reconfiguration causing high overhead to the communication system. Additionally, to minimize the inter-cluster interference between the adjacent clusters within the CMs, which could result in a merging collision problem, a cluster-based TDMA MAC protocol requires an efficient and dynamic time slot scheduling scheme within the cluster (Alsuhli, Khattab, & Fahmy, 2019; Dragonas, Oikonomou, Giannakis, & Stavrakakis, 2018b; Lyu, Zhu, Zhou, Xu, et al., 2018; Nguyen et al., 2019; Torabi & Ghahfarokhi, 2014; R. Zhang, Cheng, Yang, Shen, & Jiao, 2015). Vehicles dynamics such as high mobility and rapid topology changes also generally affect the stability of the cluster (Aissa, Belghith, & Bouhdid, 2015). These problems subsequently, affect the efficient delivery of safety related messages. Hence, new algorithms are required to enhance the cluster stability for efficient and reliable delivery of safety related messages to minimize any unwanted event that may occur on the road.

## 1.2 Motivation

The growing rate of road accidents in the world has motivated the development of Intelligent Transportation Systems (ITS) along with other applications to increase road traffic safety and driving comfort. Over the last few years, vehicular technology as one of the main categories of the intelligent transportation system has been receiving a lot of attention as a result of its different variety of applications that could impact the lives of the road users (Gokulakrishnan & Ganeshkumar, 2015; Hadded, Muhlethaler, & Laouiti, 2018; R. Singh & Mann, 2019). It is worthy to note that an efficient and reliable MAC protocol is required for the timely delivery of these safety related applications (Batth, Gupta, Mann, Verma, & Malhotra, 2020). However, recent studies have shown that it is very difficult for the conventional MAC protocol to satisfy the delivery delay demand of the safety related messages, which are constrained by the time requirement that is caused by the contention-based approach in accessing the wireless medium (Ji, Yu, Fan, Sun, & Chen, 2018; Khabazian, Aissa, & Mehmet-Ali, 2013; U. A. Khan & Lee, 2019; S. Li, Liu, & Wang, 2019; Y. Ma, Yang, Fan, Fang, & Hu, 2018; Santamaria, Tropea, Fazio, & De Rango, 2018; Stanica, Chaput, & Beylot, 2014; Yin, Ma, & Trivedi, 2014). The fast topology changes due to the vehicle's high mobility also make real-time and reliable broadcasting of the safety messages more challenging. It is required that each vehicle within the communication range exchange its current status periodically to the nearby vehicles so as to assists the drivers in taking care of some emergency situations, such as a potential danger. This can be achieved by taking a proper action or by providing warning messages in order to avoid any hazardous situation to occur (X. Ma, Zhang, Yin, & Trivedi, 2012). For example, in a hazardous situation, an accident can happened on the road, sudden brake failure or slippery road due to heavy rains. In such situations, a timely alert message by the vehicle to its neighbors can prevent the chain of accidents by helping the drivers to take appropriate action at the right time. In addition, the communication channel could also be congested thereby causing a high transmission collision rate among the contending vehicles due to hidden node problems, especially when the network size increases. This collision problem could result in packets drop or increase packet delay, which may subsequently lead to a serious problem to the lives of the drivers and passengers as well.

Therefore, a possible solution to these problems mentioned above is by using a clustering technique where the CH will be solely responsible for coordinating the vehicles within the clusters. A TDMA based scheduling approach also is very crucial since it allows each vehicle to be allocated a specific time slot to send its messages without interference among the contending vehicles. Similarly, accessing the wireless channel among the competing vehicles is also required so that each vehicle can get a fair chance of channel access for prompt broadcasting of the required safety message. Furthermore, since VANET was envisaged to provide applications which could impact the life of drivers and passengers, frequent topology changes in the vehicular environment affect the reliable delivery of these messages. Besides, the reliability and effectiveness of the safety related applications solely depend on the efficiency and the performance of the MAC protocol. Hence, an efficient clustering algorithm and efficient time slot allocation strategy are required within the cluster to improve reliable communication among the neighbor vehicles. These facts motivated us to come up with a new clustering algorithm using an efficient time slot scheduling strategy to enhance the cluster-based TDMA MAC protocol so that reliable and timely delivery of safety related messages could be achieved.

## 1.3 Problem Background

The realization of the proposed VANET envisioned applications generally depends on the efficiency and reliability of the MAC protocol (Oliveira, Montez, Boukerche, & Wangham, 2017). The most essential applications envisioned by the vehicular technology are the safety applications (such as emergency messages), which are required to be disseminated timely in a reliable fashion to the vehicles within the vicinity (Hadded, Muhlethaler, Laouiti, Zagrouba, & Saidane, 2015). These applications have a stringent requirement with respect to the Quality of Service (QoS) in terms of timely delivery of the broadcasted message, which cannot be significantly assured by the conventional MAC protocol, especially in a dense traffic situations (Gillani et al., 2015; N. Gupta, Prakash, A., & Tripathi, R., 2015). The absence of acknowledgment for these messages (i.e., because of the broadcast nature of the safety messages) results in the problem of the hidden terminal. This problem occurs when two or more vehicles simultaneously transmit data to a third vehicle, which is in an overlapping area of transmission range of the transmitting vehicles. For example, when node B is in the range of both nodes A and C but nodes A and C are not in the range of each other, so both nodes can send data to node B, thereby congesting the control channel (CCH), which can lead to the high collision rate. Consequently, the problem resulted in increased packets drop, delay, and reduction of throughput (Al-Sultan, Al-Doori, Al-Bayatti, & Zedan, 2014; Aslam et al., 2019; Bastani & Landfeldt, 2016; Booysen, Zeadally, & Van Rooyen, 2012; Joseph, Liu, & Jaekel, 2018; U. A. Khan & Lee, 2019; Lyu, Zhu, Zhou, Qian, et al., 2018; Nguyen et al., 2019). Consequently, loss of any safety message may result in a serious problem for the lives of drivers and passengers as well. These challenges lead to proposing a TDMA MAC protocol using a cluster-based topology, where each vehicle access the wireless medium for its broadcast message during its allocated time slot only (Hadded et al., 2015; Hassanabadi, Shea, Zhang, & Valaee, 2014).

However, despite significant research efforts to enhance the cluster-based TDMA MAC protocols' effectiveness, frequent changes in the network topology as a result of the vehicles' high mobility, pose a great challenge in the existing clustering algorithms. Thereby, resulting to the cluster instability and this subsequently affects the reliable delivery of the safety related messages (Thakur & Ganpati, 2020). Moreover, other critical issues, which include cluster formation process, cluster maintenance, and time slot allocation strategy, seriously affect the efficiency of the cluster-based TDMA MAC protocol for the timely and reliable delivery of the safety applications. For example, safety related messages are expected to be disseminated and shared among all the vehicles within the neighborhood irrespective of any speed characteristics to avoid any unwanted event to occur, hence requires proper and careful considerations for cluster formation procedure to involve the entire vehicles within the transmission range.

Similarly, maintaining the cluster stability is also a serious issue in a cluster-based approach (Abdel-Halim, Fahmy, & Bahaa-El Din, 2019; Arkian, Atani, Pourkhalili, & Kamali, 2015; Chaurasia, Alam, Prakash, Tomar, & Verma, 2019; X. Cheng & Huang, 2019; Ji et al., 2018; Rawashdeh & Mahmud, 2012; Ren, Khoukhi, Labiod, Zhang, & Vèque, 2017; Senouci, Harous, & Aliouat, 2019). This is because a CH can either take an exit or decided to stop along the road for whatever reasons or sometimes it merges with another CH within the vicinity. It is worthy to note that none of the existing clustering algorithms proposed a suitable solution to take care of an incident where the elected CH exit the cluster. This is because, whenever a CH leaves the cluster for any reason, the cluster architecture must be altered and reconfigured again. Accordingly, the absence of this CH can result in the loss of channel access schedule and consequently, lead to the safety messages delivery delay problem. Moreover, inefficient time slot allocations strategy within the cluster members that were proposed by the existing approaches are faced with the problem of transmission collision among the contending vehicles (Abbas et al., 2020; Abd El-Gawad, Elsharief, & Kim, 2019; Alsuhli et al., 2019; Dragonas, Oikonomou, Giannakis, & Stavrakakis, 2018a; Hadded, Zagrouba, Laouiti, Muhlethaler, & Saidane, 2014; Haq, Liu, & Latif, 2019; Nguyen et al., 2018; Nguyen, Kim, Dang, Kim, & Hong, 2015; Sheu & Lin, 2014; W. Yang, Pan, & Zhu, 2013). The transmission collision can be classified as an access collision or merging collision (Omar, Zhuang, & Li, 2013; Tianjiao & Qi, 2017). Access collision usually occurs when two or more vehicles that are within the same communication range are trying to access the same time slot concurrently. On the other hand, merging collision occurs when two or more vehicles that are not within the same communication range are using the same time slot. This is because some vehicles are moving faster than others on the highway and subsequently, these vehicles can become within the same communication range of each other. The problem of access collision has been significantly minimized in a cluster-based TDMA MAC protocol, in contrast to the merging collision problem, which is still a serious challenge (Haider, Abbas, Abbas, Boudjit, & Halim, 2020; S. Li, Liu, & Wang, 2019; S. Li, Liu, et al., 2019a). This problem of merging collision occurs between the nodes in the adjacent clusters. For example, the merging collision problem occurs among the vehicles that are not within the same transmission range of each other but in a communication range with another node at the adjacent cluster that is using the same time slot. It is sometimes called inter-cluster interference and significantly affects the efficiency of this class of MAC protocol, particularly for the timely and reliable delivery of the safety messages, which are delay bounded. Hence, increases delay and sometimes loss of data packet. For that reason, a new approach is very necessary to resolve these problems for the successful deployment of safety applications in a vehicular environment, especially in emergency situations.

## 1.4 Research Questions

To achieve the research objectives of this research, research questions are formulated to help the researcher in adhering to the research objective. The following are the Research Questions (RQs) for this study:

i. RQ1: How does the safety related messages be delivered reliably within the vehicle neighborhood?
ii. RQ2: How to enhance cluster stability in a cluster-based TDMA MAC protocol?
iii. RQ3: How to minimize merging collision problem within the adjacent clusters?
iv. RQ4: How does the proposed approach be evaluated?

## 1.5 Research Aim

The main aim of this research work is to propose a new clustering algorithm and a dynamic time slot allocation strategy that can enhance a cluster-based TDMA MAC protocol to provide a timely and reliable delivery of VANET envisioned safety related applications in a vehicular environment. To achieve this aim, the following objectives were identified in Section 1.6

## 1.6 Research Objectives

The main research objectives for this study are:

i. To enhance a cluster formation process and cluster head election process by:

- Developing a new procedure for cluster formation process.

- Developing an integrated weight-based clustering algorithm for the CH election process.

ii. To enhance cluster stability within the cluster by:

- Electing a backup node called secondary cluster head (SeCH) to take the cluster leadership before the primary cluster head (PCH) moves out of the cluster.

iii. To develop a dynamic time slot allocation scheme to minimize merging collision problem between the CMs within the adjacent clusters.

iv. To evaluate and validate our new approach using simulation tools (NS-3 with SUMO) and compares the results with the state-of-the-art approaches in the literature.

## 1.7 Scope and Limitation of the Study

This research work is intended to cover the challenges associated with the cluster-based TDMA MAC protocols for the timely delivery of the VANET envisioned safety related applications. Specifically, these challenges include the cluster instability and inefficient time slot allocation strategy due to the frequent topology changes in the vehicular environment. The proposed approach considers only cluster formation and CH election process, cluster stability maintenance, and time slot allocation strategy by CH to the contending CMs

On the other hand, one of the main limitations of this research work is the exclusive utilization of the full DSRC channels, whereby the SCHs have not been implemented for the non-safety messages. Other limitation includes inter-cluster communication between the CMs of the adjacent clusters. Finally, the research work also considered only the V2V communication on a highway, while infrastructure based communication is reserved for the future work.

## 1.8 Significance of the Research

Cluster-based TDMA MAC protocols are sensitive to the network topology changes due to the vehicle's high mobility. This effect consequently, could result in cluster instability and merging collision problem within the cluster transmission range. Considering the fact that the safety related messages are very critical in terms of a strict time requirement to reach the required destinations, cluster instability could affect the timely delivery of this type of messages. Similarly, the incomplete or inaccurate information can lead to taking the wrong decision by the driver, which might be due to the CH changes during an emergency event. For example, there are several instances where the reliable delivery of the safety related messages could be affected due to the existing cluster formation process in a cluster-based TDMA MAC protocol, which necessitated the enhancement of the existing cluster-based TDMA MAC protocol in order to support the envisioned VANET safety related applications

Therefore, the significance of this research work is specifically presented below:

i. To provide a suitable and reliable approach for a timely delivery of safety related applications. For example, with the proposed cluster formation procedure, every vehicle within the communication range will participate in the cluster formation to form a particular cluster group, so that it will not be affected by missing any important safety message.

ii. This proposed approach can result in creating fewer clusters, and consequently, minimize the inter-cluster interference because we would not have CHs and CMs from different clusters mixed up.

iii. Furthermore, the introduction of the secondary cluster head (SeCH) significantly improved the stability of the cluster, because any time before the primary cluster head (PCH) moves out of the cluster, there will be a leadership transfer to the SeCH. The cluster reconfiguration, which can increase the high overhead to the communication channel, is avoided. Similarly, the risk of missing any safety message or inaccurate information due to the CH exit was also minimized.

iv. To mitigate the merging collision problem in a vehicular environment, this research work also has proposed a dynamic time slot allocation scheme.to minimize the inter-cluster interference within the adjacent clusters.

Thus, the proposed approach effectively enhanced the efficiency of the cluster-based TDMA MAC protocol significantly.

## 1.9 Thesis Organization

The remaining chapters of this dissertation are organized as follows:

Chapter 2:

This chapter presents the general concepts of vehicular ad hoc networks, highlighting its applications and the standards deployed for vehicular communications to support the implementation of these applications. Discussion on the basic concepts of the MAC protocols for VANET, clustering techniques and the benefits of using clustering for TDMA MAC protocols was presented. Additionally, the chapter also presents the state-of-the-art cluster-based TDMA MAC protocols highlighting some challenging issues affecting the reliable delivery of safety related applications using a cluster-based TDMA MAC protocols in vehicular ad hoc network.

Chapter 3:

This chapter presents the methodology and the steps adopted in enhancing the cluster-based TDMA MAC protocol. The detail information concerning the metrics involved in the cluster head election was presented. Different simulation tools for VANET such as commercial network simulation tools, open-source network simulation tools, and mobility generation tools were also presented. Furthermore, the detail explanation of the modules of NS-3 used in the implementation of the developed enhanced cluster-based TDMA MAC (EC-TMAC) protocol was presented in the chapter.

Chapter 4:

This chapter presents the detail implementation of the enhanced cluster-based TDMA MAC protocol framework. Similarly, the cluster formation and cluster head election procedure, detail of the cluster maintenance procedure involving leadership transfer from the primary cluster head to the secondary cluster head was also presented in this chapter. A dynamic TDMA slot allocation strategy for the enhanced cluster-based TDMA MAC protocol was presented, highlighting the time slot reservation mechanism on both the CCH and the SCHs.

Chapter 5:

This chapter presents the evaluation of the enhanced cluster-based TDMA MAC (EC-TMAC) protocol. The results obtained from the simulation were discussed and compared with the state-of-the-art approaches in the literature using some performance evaluation metrics.

Chapter 6:

This chapter presents the summary of the research findings, research contributions and gives highlights and suggestions on possible research direction for future work.

# CHAPTER 2: LITERATURE REVIEW

This chapter presents a review of the state-of-the-art cluster-based TDMA MAC protocols for vehicle-to-vehicle communications. Consequently, the chapter is organized into seven Sections. Section 2.1 provides an overview of the vehicular ad hoc network, VANET applications and the deployed standards use for vehicular communications in implementing the envisaged VANET applications. The brief introduction to MAC protocols for VANET has been outlined in Section 2.2. A brief discussion of TDMA MAC protocol and the challenges associated with this class of MAC protocol are presented in Section 2.3. In Section 2.4, clustering techniques are presented as well as the benefits of using clustering for TDMA MAC protocol. Furthermore, Section 2.5 presents the existing cluster-based TDMA MAC protocols, highlighting some challenging issues affecting the reliable delivery of VANET safety related applications using a cluster-based TDMA MAC protocols for vehicular ad hoc network. Section 2.6 summarizes the chapter.

## 2.1 Overview of the vehicular ad hoc network

The emergence of the Intelligent Transportation System (ITS) has been motivated by the increasing road traffic accidents in the world (B. Singh & Gupta, 2015). Furthermore, vehicular ad hoc network technology, which is regarded as the essential part of the ITS, have generated considerable attention from both the researchers in academia and industries in order to come up with some applications aimed at improving the road traffic safety as well as providing comfort to the road users (Kolte & Madnkar, 2014; Qureshi, Abdullah, & Anwar, 2014). VANET is regarded as a special case of a mobile ad hoc network (MANET) where the vehicles act as mobile nodes to provide communication among the nearby vehicles and roadside infrastructure. It has some unique features different from MANET such as vehicles high speed, which results in frequent topology changes. Some of these features of VANET include predictable mobility, dynamic topology, variable network density, high energy, and computing power, etc. (Cunha et al., 2016). VANET is also considered as a promising technology that is set to revolutionize the transportation system. Each vehicle is equipped with an on-board unit (OBU) in VANET, making them act more intelligently and share information with each other via a wireless medium so that the level of awareness is increased among the neighborhood (Dua, Kumar, Bawa, & Rodrigues, 2015; Palazzi, Roccetti, & Ferretti, 2010). In the control channel, all OBUs in the vehicles are required to broadcast their updated information through hello message at regular intervals to allow each OBU to acquire real-time information of all its neighbors within the communication range (Bazzi, Masini, Pasolini, & Andrisano, 2013). The communication can be done either directly between vehicles (V2V) or through infrastructure-based communication (V2I) (Yan & Rawat, 2017). This communication provides support for the implementation of numerous VANET envisioned applications that aimed towards improving the safety of the lives of road users as well as providing comfort services (Al-Sultan et al., 2014). In V2V communication, each vehicle within the communication range wirelessly exchanges their current information (such as speed, location, direction, etc.) to each other without any infrastructure support. On the other hand, in the V2I approach, vehicles communicate with fixed access points stationed by the roadside known as the roadside units (RSUs). These RSUs act as a gateway to access services for example, traffic lights and signs, parking spaces, etc. from the centralized server on the Internet (Hadded, Muhlethaler, Laouiti, & Saidane, 2016; R. Zhang et al., 2015). VANET communication architecture is illustrated in Figure 2.1.

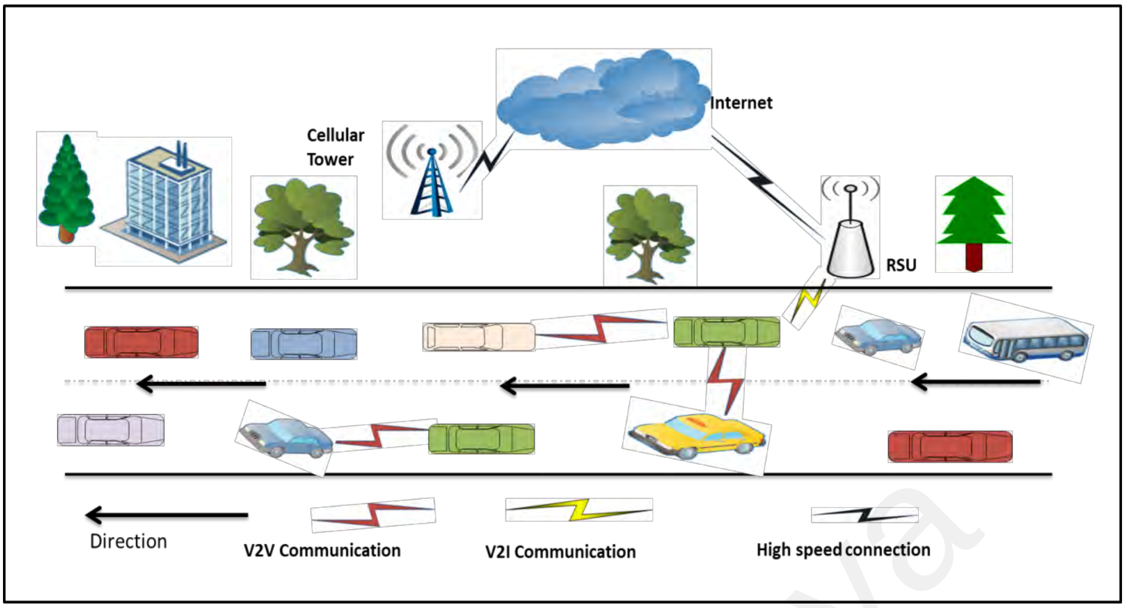



**Figure 2.1: VANET communication architecture**

### 2.1.1 VANET Applications

The main concept of vehicular network technology is to offer numerous advantages to the real-world scenarios that can impact the lives of road users such as drivers, passengers, and pedestrians. For example, vehicles can automatically detect the condition of the surrounding environment, such as blind spot, and share this information with the neighborhood in order to enable drivers to take necessary action on time so that potential danger can be avoided (Mitropoulos et al., 2010). The US Department of Transportation (DOT), in collaboration with other automobile industries, proposed several VANET applications projects (Kenney, 2011). These applications are classified into two main groups, namely; safety applications and non-safety applications.

- Safety applications are the most desirable group of VANET envisioned applications, for example, accident prevention applications. They usually benefit from V2V communication for immediate transmission of messages to neighbor vehicles. These groups of applications aimed to increase the level of safety for road users and therefore considered to be more critical than non-safety applications. They have the highest priority and require very small latency in terms of delivery, for example, the unexpected change in the lane or sudden brake notification. These applications can lead to a decrease in many road accidents if reliably delivered in time (Thenmozhi, Yusuf, Vignesh, & Dinesh, 2014). The status of the neighbor vehicles and the condition of the road is determined between the vehicles by sharing the periodic safety messages to assist the drivers to handle potential danger or emergency events such as accident by taking an appropriate action automatically (Liang, Li, Zhang, Wang, & Bie, 2015). Safety messages are in two forms, which include basic safety messages (BSM) known as periodic messages and event-driven messages also known as emergency messages. Broadcast transmission is the main traffic for both safety messages (X. Ma, Zhang, et al., 2012). Each vehicle within the communication range broadcast periodic messages to all its surrounding neighbors periodically at a regular interval to prevent the manifestation of any dangerous conditions, while the emergency messages are generated only when an emergency incident occurs in order to get instant action from the driver. Some of the examples of these applications are cooperative collision warning (CCW), lane change warning (LC), stop sign assistant and blind spot warning, etc.

- In contrast, non-safety applications provide services that include traffic management and infotainment services to both drivers and passengers. These applications, aimed at enhancing the efficiency of the traffic on the road, and provide comfort to the road users while traveling (Moustafa & Zhang, 2009). Usually, non-safety applications require most importantly fair access to the wireless channel and generation of high throughput, but they can tolerate more transmission delay (F. Yang, Tang, & Huang, 2014). Some examples of these applications include weather information, traffic information system, electronic toll collection, restaurant or petrol station location finder, and interactive communication such as video download or having internet access.

### 2.1.2 Standards for vehicular communications

This section briefly discusses the various standards employed to implement vehicular communications. The approved standard specified for vehicular communication is IEEE802.11p, which adds wireless access in vehicular environment (WAVE) (Karagiannis et al., 2011). Descriptions of these standards are given below.

#### 2.1.2.1 Dedicated Short Range Communication (DSRC)

The first standard defined to provide support for vehicular communication in VANET is Dedicated Short Range Communication (DSRC) by the US Federal Communication Commission (FCC) (Kenney, 2011). To satisfy the vehicular communication requirement for the DSRC underlying radio technology in a vehicular environment, the IEEE802.11p amendment was approved, which extended the existing 802.11e standard (Group, 2010). The DSRC supports a high rate of data transfer and low latency communication that is required to support the VANET applications. It covers communication range from 300 m to 1000 m using 6Mb/s to 27 Mb/s of data rate. The FCC allocated 75 MHz frequency in the range of 5.850 GHz to 5.925 GHz band (Bettisworth et al., 2015; Y. J. Li, 2010). This spectrum band is divided into 7 channels, each with a frequency of 10 MHz bandwidth (1 control channel and 6 service channels) with 5 MHz guard band, as illustrated in Figure 2.2.

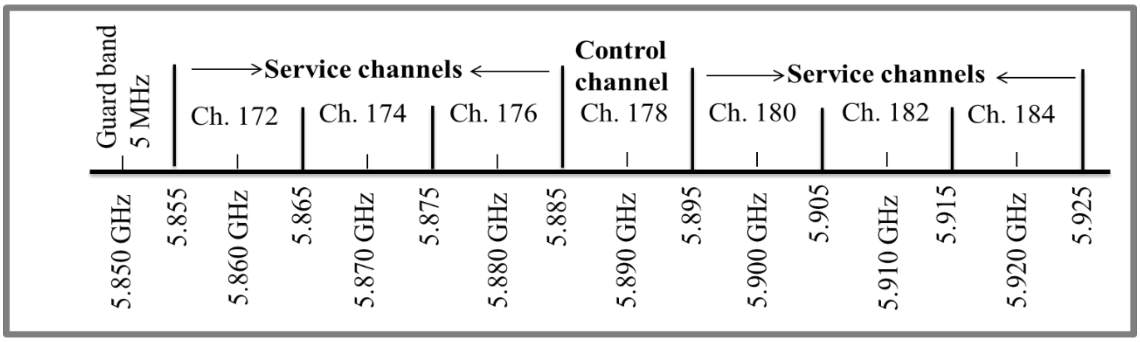



**Figure 2.2: DSRC channel allocation by the US FCC (Kenney, 2011)**

The Control Channel (CCH) denoted as channel 178 located at the frequency center is mainly used for transmitting safety messages, which involves high priority messages (such as basic safety messages and event-driven messages) and control information that specifies the available time slot a vehicle should reserve. On the other hand, the 6 service channels (SCHs) include channels 172, 174, 176, 180, 182, and 184, and they are generally used for transmitting non-safety messages that are meant for different services.

#### 2.1.2.2 Wireless Access in Vehicular Environment (WAVE)

The IEEE1609.4 standard is an extension of the IEEE802.11p MAC that was defined to provide support for the multichannel operations in the wireless access in vehicular environment (WAVE) protocol stack (Group, 2010). However, the scope of IEEE802.11p MAC is strictly at the media access control (MAC) and the PHY layers, while the IEEE1609.4 resides above the IEEE802.11p, which is responsible for the operation of the higher layers (Zeadally, Hunt, Chen, Irwin, & Hassan, 2012). The WAVE MAC protocol stack is illustrated in Figure 2.3.

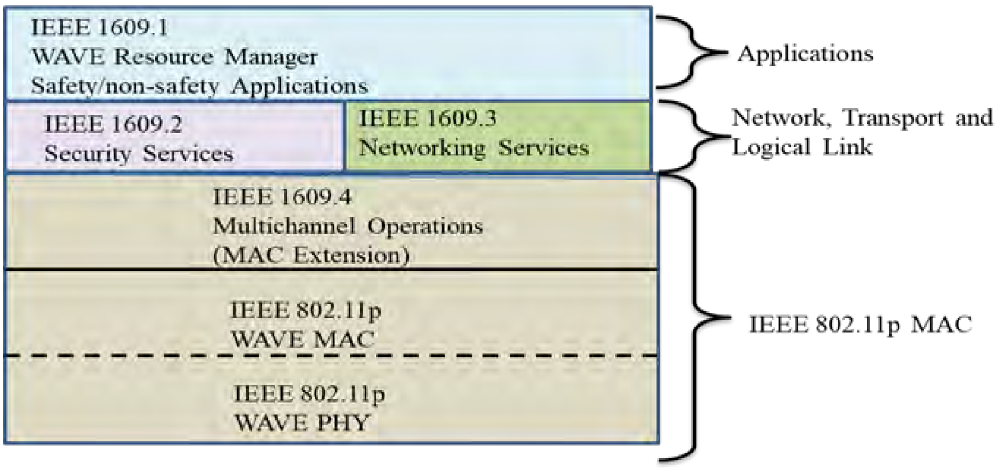



**Figure 2.3: WAVE MAC protocol stack (Tanuja et al., 2015)**

This standard specifies operations such as priority Access Categories (AC), Synchronization Interval (SI), CCH, and SCH operations (Ghandour, Di Felice, Artail, & Bononi, 2014). It is assumed that all vehicles maintain strict synchronization with the Universal Time Coordination (UTC) acquired from Global Positioning System (GPS) devices. Based on this time information, vehicles alternate between CCH and SCHs separated by guard interval (GI) of 4 ms, that uses synchronization interval of 100 ms comprising of equal duration (50 ms) between the CCH interval (CCHI) and SCHs interval (SCHI) as illustrated in Figure 2.4. Vehicles broadcast safety messages or negotiate the SCHs on the CCH during the CCHI, while on the other hand switch to the negotiated SCHs for their non-safety message transmission.

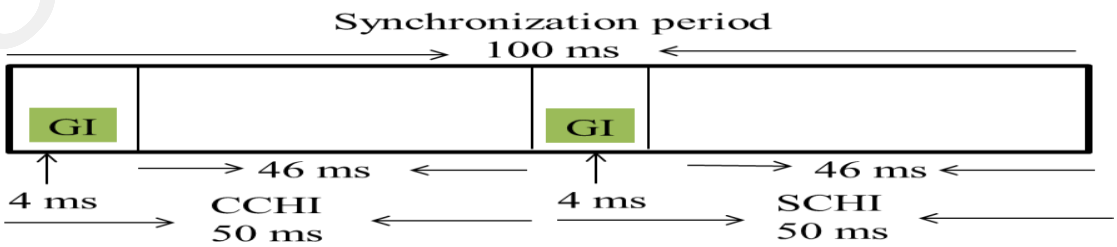



**Figure 2.4: Synchronization period between CCH and SCH in WAVE protocol stack**

## 2.2 Medium Access Control (MAC) protocols for VANETs

The medium access control protocol is a wireless medium that provides communication services in a vehicular environment without any central coordination. The main challenge facing the successful future deployment of VANET applications is the efficiency and reliability of the MAC protocol. This section discusses the various classes of MAC protocols for vehicular ad hoc networks, which are grouped by considering the procedure they use in accessing the wireless medium (Miao, Djouani, van Wyk, & Hamam, 2012). The two main classes of the VANET MAC protocols consist of the contention-based and contention-free MAC protocols, as shown in Figure 2.5.

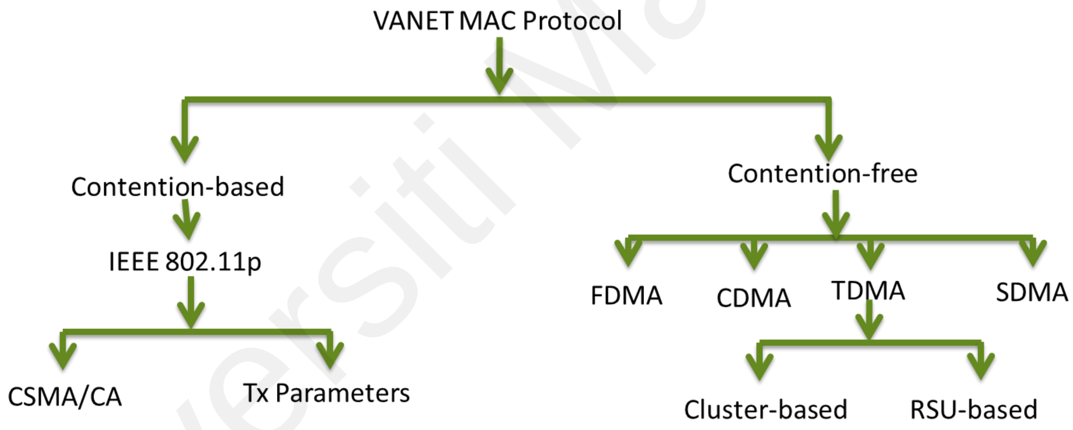



**Figure 2.5: VANET MAC protocols classification**

### 2.2.1 Contention-based MAC protocols

Contention-based MAC protocol uses a MAC method known as an enhanced distributed channel access (EDCA) mechanism, which was initially provided by the IEEE802.11e for accessing a wireless channel (Gallardo, Makrakis, & Mouftah, 2009). This class of MAC protocol provides the concepts of quality of service (QoS) and prioritization of safety-critical messages in accessing the wireless channel. The IEEE802.11p MAC is an example of a contention-based MAC protocol proposed for vehicular communications. The MAC layer of IEEE802.11p uses a carrier sense multiple access with collision avoidance (CSMA/CA) method for accessing the wireless channel, where each vehicle within the vicinity accesses the medium randomly without a predetermined schedule. Conventional MAC protocol typically depends on some specified parameters, including carrier sensing, transmission power control, and contention window size for it to perform effectively (Reinders, van Eenennaam, Karagiannis, & Heijenk, 2011). In a contention-based approach, more than one vehicle can sense a free wireless channel and decide to broadcast their message at the same time, especially when the vehicles' density is very high. Consequently, as the density of vehicles increases, the CCH becomes saturated with a high collision rate, which could result in increased packet delay or loss of safety messages. Furthermore, the absence of ready to send / clear to send (RTS/CTS) and acknowledgment (ACK) exchange messages between the competing vehicles results in a high probability rate of transmission collision of the broadcast messages (Omar, Lu, & Zhuang, 2016).

Additionally, the problem of hidden terminal as a result of the frequent topology changes affects the reliability of safety applications (Bastani & Landfeldt, 2016). Consequently, to ensure channel access fairness and reliable transmission of safety messages, it is very vital to minimizes collision on the CCH. Safety applications which have a stringent QoS requirement cannot be guaranteed by the contention-based MAC such as IEEE802.11p MAC protocol, especially in heavy traffic conditions (Booysen et al., 2012).

### 2.2.2 Contention-free MAC protocols

This type of VANET MAC protocol necessitates that each vehicle in the network acquires a wireless channel for communication among the neighbor vehicles in a predetermined fashion. Examples of this class of MAC protocol are as follows;

Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA), Space Division Multiple Access (SDMA), and TDMA (Hadded et al., 2015). These types of protocols increase fairness in accessing the wireless channel between the competing vehicles, resource utilization as well as reduce the high rate of transmission collision. However, to provide support for the delay bounded safety applications, time synchronization is needed between the contending vehicles. Generally, it is assumed that the time synchronization for the vehicles is realized by using a Global Positioning System (GPS) or a Galileo receiver (Lott, 2001). In this regard, each vehicle shares its current clock value to its neighbors within the communication range at regular intervals through a hello packet called beacons (Elson, Girod, & Estrin, 2002). This procedure can allow each vehicle to acquire precise real-time status information about its neighbors regarding the position, speed, and exact time of a particular vehicle. Furthermore, there is a need for another synchronization sequence that is transmitted in parallel to improve the synchronization accuracy, which is known as fine synchronization. An algorithm is required, particularly in a distributed topology to generate a timing synchronization (Huang & Lai, 2002). Accordingly, instead of a vehicle to depend on the sensing mechanism to identify the available free wireless channel for its data transmission, in this case by synchronization and sharing the beacons messages between the neighbor vehicles, each vehicle within the communication range would be aware of the available wireless channel to use. This method of acquiring wireless channel by the contention-free MAC protocols for the contending vehicles helps to improve the efficiency of this class of VANET MAC protocol, thereby eradicating the use of sensing method in the conventional IEEE802.11p MAC protocol. Thus, the channel access time-bounded delay is significantly minimized, particularly when the vehicles' traffic density is very high. In addition, they also have the benefit of ensuring reliability and satisfying the QoS stringent requirements in terms of timely delivery of safety messages. The contention-free MAC protocols also enhance the channel access fairness between the neighbor vehicles and are more efficient than the contention-based MAC protocols (Zain, Awang, & Laouiti, 2017). The description of each class of these protocols follows below.

#### 2.2.2.1 Frequency Division Multiple Access MAC Protocol

FDMA is a method that involves partitioning the bandwidth into two or more frequency bands, whereby each wireless channel is allocated to a different vehicle per frequency on demand. In the FDMA MAC protocol, each communicating vehicle within the communication range is synchronized using the same frequency channel. Basically, the carrier frequency and the available bandwidth are expected to be identified via the CCH (Ferdous & Murshed, 2011), although there is a need for an algorithm to be created that will be used for synchronizing the CCH frequency. To acquire the available channel for message transmission, each vehicle would contend and share the same frequency sub-channels among themselves. Likewise, in a situation when the topology in the network changes, the control message is generated by each vehicle including the available channels, which subsequently can be shared with the neighbor vehicles. Nevertheless, this operation can generate an extensive message exchange among the contending vehicles within the vicinity in the order of $O(d^2C)$ where $d$ is the average number of neighbors and $C$ is the number of sub-channels (Veyseh, Garcia-Luna-Aceves, & Sadjadpour, 2009). As a result, this procedure makes the FDMA MAC method very difficult, and consequently, results in generating high transmission delay especially for safety-related messages along with high communication overhead on the CCH. Also, other problems include the frequency synchronization and the presence of Doppler effects, as a result of the vehicle's high mobility proved that the FDMA MAC method is not appropriate for vehicular communications (Bazzi, Zanella, & Masini, 2015).

#### 2.2.2.2 Code Division Multiple Access MAC Protocols

CDMA is a method based on the spread spectrum (SS) that is intended to support multiple communications between vehicles within the same communication range by utilizing the same frequency channel simultaneously. In a CDMA-based MAC method, a specific code sequence known as Pseudo-Random Noise (PN) code is used, whereby vehicles share the same frequency channel simultaneously for data transmission (Ali, Huiqiang, Hongwu, & Chen, 2014). Contrary to the FDMA method, in a CDMA-based protocol, before the two neighbor vehicles start communication, each of them has to agree on the code to be used for the communication in order to decrease the rate of collision during the data transmission (Shen, Cheng, Zhang, Jiao, & Yang, 2013). Each of the communicating vehicles is required to have prior information about the PN code to use for communication between its neighbors (Menouar, Filali, & Lenardi, 2006). Furthermore, in a CDMA-based method, an assignment algorithm is required to be created to allow the exchange of codes as well as to allocate these codes for every transmission between the communicating vehicles. The major problem in this method is to determine how to allocate the PN codes to the various vehicles specifically when the traffic density of the vehicles is very high. Authors in (Watanabe, Fujii, Itami, & Itoh, 2005) proposed a solution to tackle this problem by using distributed PN codes. In this case, each vehicle within the communication range would be provided with numerous matched filters corresponding to the available PN codes shared by all vehicles in the vicinity. Subsequently, each vehicle then would try to choose a specific PN code that corresponds to the matched filter within its transmission range. It is worthy to note that when the vehicles' size increases, there would be likelihood of having more than two vehicles attempting to choose the same PN code, thereby increasing the contention between the vehicles to find an available PN code within the communication range, for instance, if the available PN codes are very small.

Nevertheless, this problem could lead to the problem of the hidden terminal, thereby increasing the channel access delay between the competing vehicles. Equally, satisfying the constraint of a matched filter for each PN code on the basis of the vehicle's location makes its implementation so difficult and not proper in a vehicular environment, where reliable and time-bounded transmissions are very essential among the neighbor vehicles (Inoue, Nakata, Itami, & Itoh, 2004; Shagdar et al., 2010). Likewise, as a result of high packet error probability and interference between the communicating vehicles, CDMA-based MAC protocols suffer significant communication overhead and low packet delivery ratio (I.-S. Liu, Takawira, & Xu, 2008).

#### 2.2.2.3 Space Division Multiple Access MAC Protocols

SDMA-based MAC protocol utilizes a geographical location to allocate a wireless channel to a vehicle that is moving on the road for its data transmission. This MAC protocol provides an opportunity for the vehicles that are spaced far enough within the network to be allocated and use a single channel simultaneously. Unlike the CDMA-based MAC method, in this case, the procedure of creating a code that is required for each transmission is eliminated, hence results in minimizing the transmission delay and generating less communication overhead on the control channel. In SDMA-based MAC, a road segment is partitioned into smaller units called cells. Each vehicle within the communication range can transmit a message to its neighbors depending on its precise spatial location on the road segment (Doukha & Moussaoui, 2016). A road is divided into smaller segments, where each vehicle according to its position in the segment can reserve its wireless channel for broadcasting periodic messages to the neighborhood. SDMA-based MAC method is divided mainly into three parts (Surabhi, 2016) ;

- Spatial discretization technique: This is a procedure of dividing a road segment into equal small size areas called cells.

- Mapping function: it is defined as a function that reserves time slots for each identified cell. In this case, each cell within a predefined range is uniquely reserved a specified time slot. No two cells can share the same time slot within a road segment.
- Assignment rule: This is a procedure used to allocate a specific time slot to every vehicle within the road segment with respect to a vehicle's position.

Accordingly, the SDMA-based MAC method allows a vehicle within the network to identify its current position in order to reserve a particular wireless channel for its data transmission between the neighbor vehicles (Torabi & Ghahfarokhi, 2017). For example, let us consider the geographical area Y, which is partitioned into k segments as given in Eqn. (1), whereby each cell in the segment will consist of one vehicle at most.

$$Y = (Y_1, Y_2, Y_3, \dots Y_k) \qquad (1)$$

Additionally, the channel bandwidth or time slot, which is needed by each vehicle to access the wireless medium, is denoted by T, and it is partitioned into s slots as represented in Eqn. (2):

$$T = (T_1, T_2, T_3, \dots T_s) \qquad (2)$$

As a result, the SDMA-based MAC can be considered as a one-to-one mapping function, by allocating to every cell within the road segment a unique channel bandwidth (Bana & Varaiya, 2001) as follows:

$$F: Y \rightarrow T \qquad (3)$$

However, considering the frequent topology changes in a vehicular environment, the location of a vehicle *A* at time t may not be the same as a location at time t' such that:

$$Y_A(t) \neq Y_A(t') \quad (4)$$

Therefore, the time by which vehicle $A$ access a wireless channel differs as it changes to another position. These critical changes as a result of the dynamic nature in the vehicular environment are necessary to be taken care of and updated at regular intervals. It is worthy to note that in SDMA-based MAC protocol, the communication overhead generated is low and it also improves channel access utilization. Nevertheless, map error merging, the imprecise position of the vehicles, and the synchronization process can limit the effective performance of the SDMA MAC protocol (Blum & Eskandarian, 2007; Gillani et al., 2015). For instance, consider vehicles $A$ and $B$ located in space division $Y_A$ and $Y_B$, the positioning error of vehicle $A$ might result in the assumption that it is located in a geographical area of $Y_B$, causing a transmission collision. Equally, in a low traffic network, for example, it always results in bandwidth wastage, especially in a situation when a certain location has been allocated a time slot, but there is no vehicle to occupy the allocated space because of the low traffic density of the vehicles.

## 2.3 Time Division Multiple Access MAC protocols

TDMA-based MAC protocol, as one of the emerging areas in vehicular technology, allows multiple vehicles within the communication range to share the same frequency channel without any interference from the nearby vehicles. This could be achieved by distributing the bandwidth resources fairly between the communicating vehicles. Accordingly, the time slot is partitioned into a number of logical frames and each logical frame also is subdivided into several time slices as depicted in Figure. 2.6. In a TDMA-based MAC protocol, each vehicle is required to be equipped with a Global Positioning System (GPS) and the one-Pulse-Per-Second (1PPS) signal to aid the communicating vehicles to get an effective real-time synchronization. Besides, it also provides a precise three-dimensional real-time position (such as latitude, longitude, and altitude), velocity, and direction of all the vehicles within the network. To access a wireless medium using a TDMA-based MAC protocol, each contending vehicle within the communication range is allocated a unique time slot for message broadcast to the neighborhood, whereas, during its neighbors' allocated time, the vehicle will be in listening mode to avoid interference (Hadded, Laouiti, Muhlethaler, & Saidane, 2016). Contrary to the FDMA-based MAC protocol where channel interference occurs, in this case, all the vehicles utilize the same frequency channel simultaneously, though, at a variable time without channel interference (Bazzi et al., 2015).

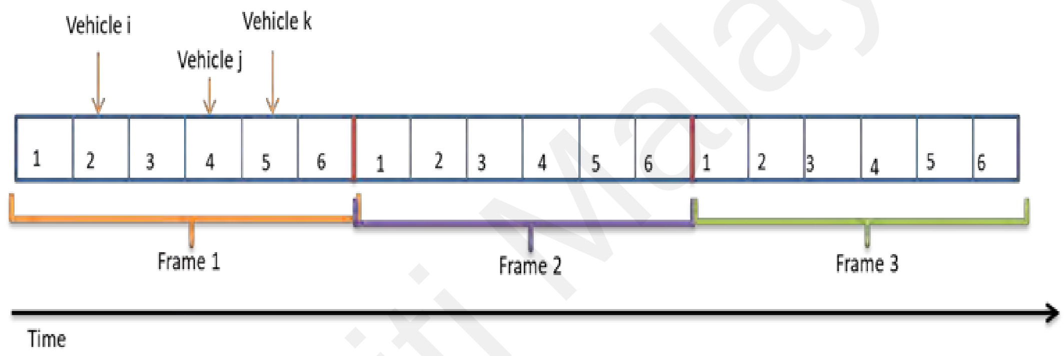



**Figure 2.6: TDMA frame structure**

The main aim of the TDMA-based scheduling scheme in the vehicular environment is to provide collision-free channel access, thereby assigning a unique time slice to the competing vehicles in the network for transmitting data packets to the neighborhood. For TDMA-based MAC to perform effectively, each vehicle within the communication range must share its status information through a hello packet that is broadcast at a regular interval to increase the level of awareness between the neighbors. Generally, there are two broad scheduling schemes in a TDMA-based MAC protocol, which include distributed and centralized scheduling scheme (Hadded et al., 2015). In a distributed TDMA-based scheduling, a vehicle is required to manage its reserved time slot devoid of any central coordinator. It is worthy to note that, acquiring and maintaining a unique time slot using this approach, each vehicle is required to exchange updated status information between its one-hop neighbors through a hello packet which contains the time slot status of all the vehicles (Borgonovo, Capone, Cesana, & Fratta, 2004). For instance, a vehicle that initially joins a network will receive hello packets (periodic messages) from the nearby vehicles that are within the same transmission range. The hello packet received usually comprises all the necessary information regarding the current status of the neighbor vehicle and the time slots reserved for each of the vehicles within the transmission range of the one-hop neighbors. Based on this procedure, a vehicle that joins the network would be able to identify all the available time slots, which can allow it to select and reserve for its message broadcast to its neighbors (Bharati, Omar, & Zhuang, 2017; Han, Dianati, Tafazolli, Liu, & Shen, 2012). Once the vehicle successfully made the time slot reservation, it can only use that specific time slot to access the wireless channel for the transmission of its generated messages to its neighbors (Tianjiao & Qi, 2017). Each vehicle can only broadcast its generated messages during its reserved time slot while it would be in listening mode for its neighbors during their reserved time slot.

On the other hand, in a centralized scheme, it involves a central coordinator who is responsible for controlling and maintaining the time slots schedule within the network (Nguyen, Kim, Dang, & Hong, 2016; Tomar & Verma, 2010). It is required that the coordinating vehicle must get the current status of every vehicle within the transmission range in order to conduct a proper scheduling decision on the basis of some defined criteria (Sgora, Vergados, & Vergados, 2015). It’s quite well known that the TDMA-based scheduling scheme ensures that the available resources are utilized efficiently because many vehicles within the network could be allocated different time slices. In contrast to the other classes of the contention-free MAC protocols, the TDMA-based MAC improves the efficiency and reliability of the VANET MAC protocol for the future deployment of the envisaged VANET applications. Nonetheless, Section 2.4.1 discusses the identified problems that are inherent in the existing TDMA-based MAC protocols.

### 2.3.1 Challenges associated with TDMA MAC protocols

This section discusses the identified challenging issues that are related to the existing TDMA-based MAC protocols for VANET. In the vehicular environment, there is a rapid topology change as a result of the high speed of the vehicles that are moving on the road. However, because of these rapid changes in topology and hidden terminal problems that are characterized in the vehicular environment, the TDMA-based MAC protocols are challenged with the transmission collision. This usually happens due to the inefficient time slot allocation strategy between the contending vehicles in the network (T. Zhang & Zhu, 2016). The transmission collision is identified to be access collision and merging collision (Hadded et al., 2015) as described in the following sections.

#### 2.3.1.1 Access collision

Access collision problems generally occur in a situation when there is more than one vehicle that is within the same communication range attempting to reserve the same available time slot, as depicted in Figure 2.7. The problem of access collision is more prominent usually in a distributed scheduling scheme. This is because every vehicle within the communication range will attempt to reserve its time slot based on the hello packet received from its neighbor vehicles. However, a situation could arise whereby several vehicles that joined the network simultaneously, may attempt to reserve specifically any available time slice. As a result, a problem of access collision occurs between these contending vehicles, and none of them would be able to broadcast its message (Haq et al., 2019; Lin & Tang, 2019). For instance, if vehicles D and E are moving in the same direction and received a hello packet from their neighbors specifying that the time slice index number 5 is free. At that moment, attempting to reserve that free time slice index number 5 by these vehicles could result in the problem of access collision.

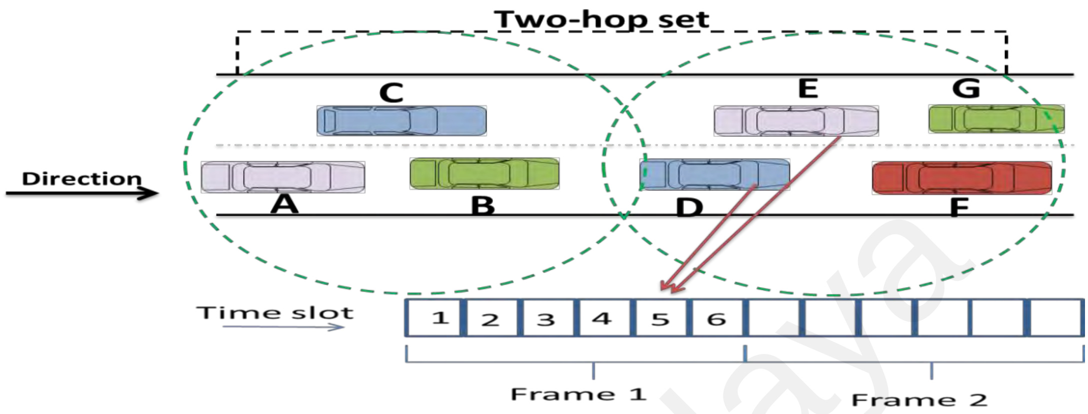



**Figure 2.7: Access collision**

#### 2.3.1.2 Merging collision

The problem of merging collision occurs in a situation when two or more vehicles that are using the same time slot initially were not within the same communication range (two-hop set neighbors). But because of the vehicles' movement and the rapid topology changes in the vehicular environment, these vehicles become within the same communication range (S. Li, Liu, & Wang, 2019; S. Li, Liu, et al., 2019b; Luo et al., 2018). Accordingly, the merging collision can occur in any one of the situations.

- It can occur between the vehicles that are moving with variable speed in the same direction.
- It can occur between the vehicles that are moving in opposite directions.
- It can also occur as a result of the problem of the hidden terminal.

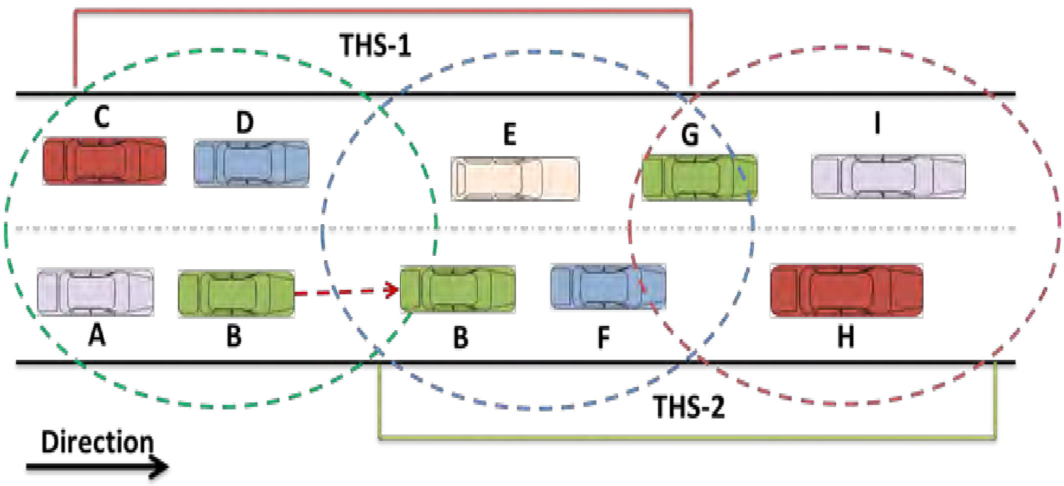



**Figure 2.8: Merging collision between the vehicles moving in the same direction due to vehicles speed**

The scenario in Figure 2.8 shows that vehicle B in two-hop set1 (THS-1) is moving in the same direction with vehicle F in two-hop set2 (THS-2), and these vehicles are using the same time slot. If vehicle B due to its high speed becomes a member of THS-2 as vehicle H, then it will result in merging collision problems.

Figure 2.9 shows the merging collision caused by vehicles moving in opposite directions. Vehicle B in the first two-hop set moving in opposite directions to vehicle H in the second two-hop set is using the same time slot as vehicle H. Since vehicles B and H become members of the same two-hop set, a merging collision occurs at vehicle F.

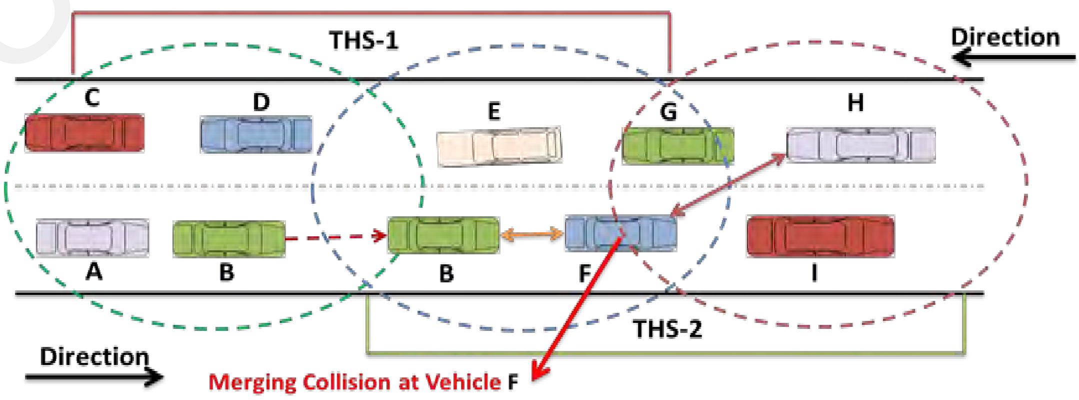



**Figure 2.9: Merging collision due to vehicles moving in the opposite directions**

Equally, the problem of the hidden terminal could result in a merging collision, as depicted in Figure 2.10. This occurs especially between two or more vehicles that are not within the transmission range of each other, but both of them are in communication range with another vehicle. For instance, if vehicle B in cluster 1 and vehicle D in cluster 2 are using the same time slot, but they are not within the same communication range of each other. However, if vehicle C is within the same transmission range for both vehicles B and D, then a merging collision problem will occur at vehicle C. This is because both vehicles would attempt to transmit simultaneously.

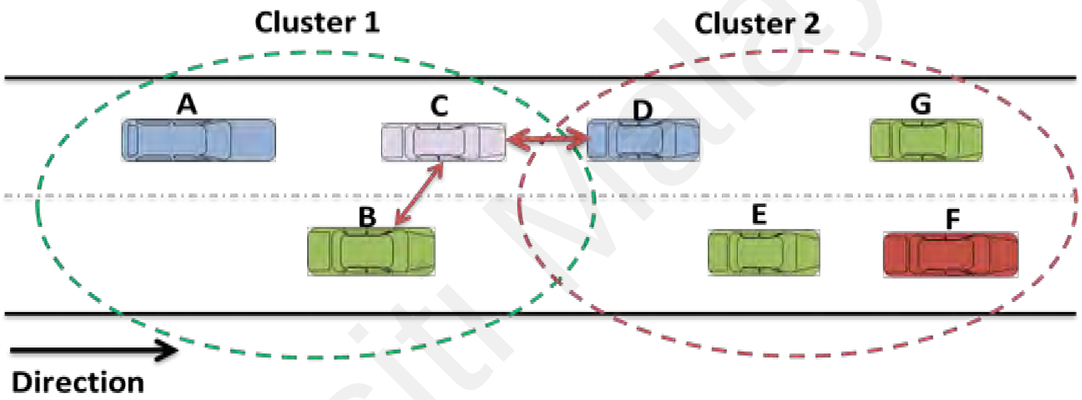



**Figure 2.10: Merging collision due to hidden node problem**

Therefore, to reduce the problem of transmission collision in the vehicular environment, vehicle's high mobility and the traffic density of vehicles need to be given more considerations. Hence, delay in accessing the wireless medium can be minimized and timely delivery of the VANET envisaged applications could be achieved. In the next section, the concept of clustering techniques for the vehicular technology will be discussed. This is with the aim of addressing the existing challenges so that the TDMA-based MAC protocols could be deployed for the implementation of the VANET proposed applications especially the safety related applications that have a stringent requirement in terms of reliable and timely delivery to the neighbor vehicles.

## 2.4 Clustering techniques in VANETs

Network stability and scalability issues for designing the TDMA MAC protocol in the vehicular environment due to the vehicle's high mobility can be addressed by the clustering technique (Wahab, Otrok, & Mourad, 2013). Clustering is a process of dividing of vehicles into virtual groups together to form a cluster using some specified rules. Clustering techniques have been introduced to provide and realize a robust and scalable vehicular network as well as limit the communication interference among the vehicles within the vicinity. It also handles congested network scenarios as well as provides efficient propagation of broadcast messages in VANET. Clusters are formed using a defined clustering algorithm, whereby in every cluster, there has to be at least one CH and several CMs. In every cluster, there should be a cluster head, which can act as a relay node in charge of all the communication between the CMs, manage media access and allocate channel bandwidth to the CMs (Aissa et al., 2015). Because of the high mobility in a vehicular environment, the clustering algorithm should converge fast so that communication overhead could be minimized on the CCH, thereby improving the reliable delivery of safety related applications. Generally, cluster stability which is one of the important attributes in the clustering scheme determines the time at which the cluster stays connected without cluster reconfiguration; thus, strong cluster stability means less number of time a CH status changes (J. Zhang, Ren, & Labiod, 2016). The cluster-based architecture is depicted in Figure. 2.11.

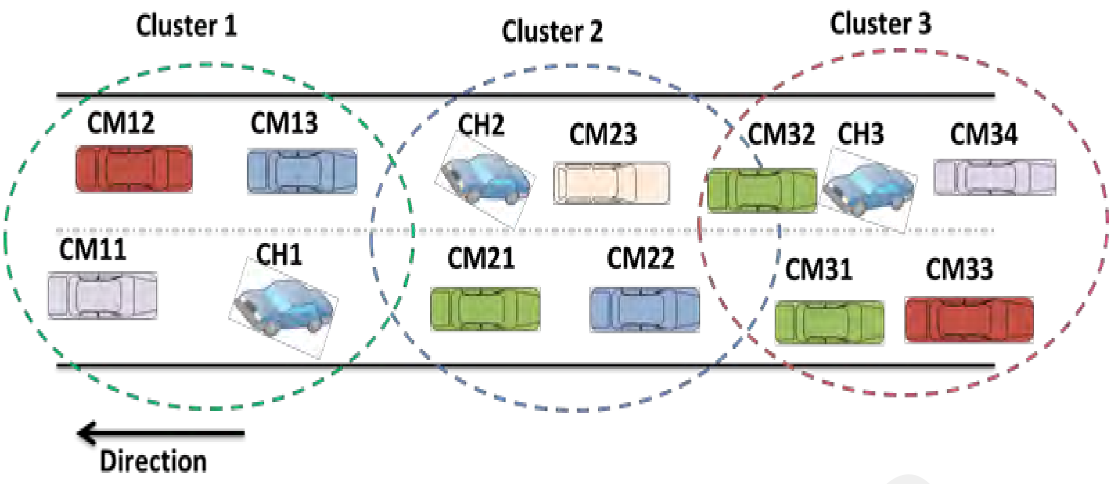



**Figure 2.11: Cluster-based communication architecture**

In recent years, there has been several research works focusing on the development of clustering algorithms for VANET MAC protocols which were the extensions of the MANET clustering algorithms such as Lowest ID (Cooper et al., 2017). The most prominent existing clustering algorithms include the following:

- **Lowest ID** (LID) clustering algorithm. This is the simplest clustering technique, which was presented by (Baker & Ephremides, 1981), where every node within the network is given a specific identifier (node_id). Each node within the transmission range will broadcast its node_id to its neighbors at a regular interval through periodic messages. The node with the lowest identifier is selected to become the CH. However, this clustering approach is not appropriate in a vehicular environment because of the vehicle's frequent topology changes. Equally, selecting a vehicle with the lowest ID arbitrarily can result in electing a CH that may not stay longer in the network (Nguyen et al., 2015). Hence affect cluster stability and degrade the efficient performance of the VANET MAC protocol.

- **Highest degree (HD)** clustering technique. It is also called the connectivity-based clustering technique presented by (Gerla & Tsai, 1995). In this technique, it was proposed that the vehicle with the highest number of neighbors within the cluster transmission range is elected to become the CH. It is required that each vehicle broadcast its node_id to all its neighbors through hello message periodically. Based on this received message, every node will calculate the number of nodes it can communicate with (connectivity level). However, in a situation when two or more vehicles are detected to have the same connectivity level, then the one with the lowest node_id is elected as the CH. Furthermore, considering the vehicle's high mobility and frequent topology changes in vehicular environment cluster re-affiliation is inevitable (Pathak & Jain, 2016). This problem can result in an increased high communication overhead to the CCH and alter the cluster stability due to the frequent cluster re-configuration. Consequently, affect the reliable delivery of safety related messages.
- **Weight-based Clustering Algorithm (WCA).** This technique involves taking an account of multiple metrics such as speed, direction, position, and vehicles' connectivity level to determine which among the contending nodes will be elected to become the CH as presented by the authors in (Chatterjee, Das, & Turgut, 2002). Each metric is given a weight value with regard to the relative importance of the selected metric for the particular scenario. The computed weighted sum of the various metrics of each node known as suitability value is advertised through a hello message to all the nearby nodes within the communication range. The node with the lowest or highest suitability value is elected and suitable to become the CH depending on the algorithm requirement. This technique is aimed at providing an optimal

selection of the CH is ensured within the cluster communication range. Similarly, this technique creates a cluster structure that aggregates several metrics simultaneously in the election of a suitable CH for the cluster (H. Cheng, Cao, Wang, Das, & Yang, 2009; Daeinabi, Rahbar, & Khademzadeh, 2011). However, it is noted that one of the challenging issues of this clustering scheme is the high re-affiliation frequency due to the high rate of topology changes, which require new strategies for the improvement of this technique (Tambawal, Noor, Salleh, Chembe, Anisi, et al., 2019).

Despite the fact that network disconnection is inevitable because of the rapid topology changes in the vehicular environment, employing a suitable cluster formation procedure and maintenance technique can assist in reducing the effect of the vehicle's re-affiliation frequency. It is also noteworthy that, to optimize the communication for effective delivery of the envisioned VANET safety related messages, in recent years several cluster-based TDMA MAC protocols have been proposed (Omar et al., 2013; Qureshi, Abdullah, Bashir, Iqbal, & Awan, 2018; Ramakrishnan, Nishanth, Joe, & Selvi, 2017; Ren, Zhang, Khoukhi, Labiod, & Vèque, 2018; Shahin & Kim, 2016). These cluster-based TDMA MAC protocols minimize packet loss and improve fairness in accessing the wireless medium among the contending vehicles. However, the frequent CH changes and re-clustering are obvious as a result of the high dynamics of topology in the vehicular network, which subsequently degrades the performance of the MAC protocol.

### 2.4.1 Benefits of clustering

A significant amount of research has been spent on clustering recently due to the various benefits gained from the implementation of the clustering technique in the vehicular environment. The cluster-based technique provides significant spatial reuse of the network resources and effective control of the network topology especially in a highly dense network (Fahad et al., 2018; Gunter, Wiegel, & Grossmann, 2007). Furthermore, employing a contention-free MAC scheme especially TDMA can minimize the contention among the contending vehicles because each vehicle can get a fair chance of accessing the wireless medium through the elected CH. Other benefits of using clustering technique also include reducing interference within the cluster environment, improving network scalability and providing low network overhead on the communication system (Chen, Fang, Shi, Guo, & Zheng, 2015; N. Gupta, Prakash, & Tripathi, 2016; Mammu et al., 2013). In a cluster-based TDMA MAC scheme, efficient slot allocation provides all cluster members to share a common CCH for both cluster formation and maintenance without any conflict, while the other six SCHs allocated for transmission of non-safety messages (Hou & Tsai, 2001). Consequently, communications between adjacent cluster nodes do not interfere and also minimize the effect of merging collision problems.

## 2.5 Cluster-based TDMA MAC protocols

The reliability and effectiveness of the safety related applications solely rely on the efficiency and the performance of the MAC protocol. With this regard, a number of cluster-based TDMA MAC protocols have been proposed in the literature so that the desired goal of the envisioned VANET safety related applications could be attained.

As discussed in Section 2.5, each vehicle within the transmission range recognizes its neighbors by exchanging its current status through the hello packet periodically. Depending on the clustering technique implemented, for each cluster group, there should be a cluster head to be elected, and the remaining vehicles become cluster members. In a cluster-based TDMA MAC protocol, efficient time slot allocation is required to avoid inter-cluster interference for vehicles that are adjacent to each other and within communication range, which can result in a merging collision problem (Tambawal, Noor, Salleh, Chembe, & Oche, 2019). However, it was discovered that despite several benefits derived from this technique, there are still some challenging issues bedeviling its successful deployment.

### 2.5.1 Review of the existing cluster-based TDMA MAC protocols

This section explores some of the existing clustering techniques proposed using a TDMA scheme in the literature. Several approaches have been used to mitigate the challenges posed by the clustering technique in the literature to increase the efficiency and reliability of the TDMA MAC protocols in a cluster-based topology. Authors in (Sheu & Lin, 2014) presented a cluster-based TDMA MAC protocol (CBT) intending to increase the scalability of the network as well as to minimize the high collision rate for the dissemination of safety messages between the neighbor vehicles. To achieve that, they used a transmit-and-listen procedure for the CH election among the neighbor vehicles. The vehicle that first successfully transmits its hello packet will be the one to be elected as a CH. The first TDMA frame in CBT MAC is reserved for the vehicles to acquire the time slot and subsequently compete for the CH election process. On the other hand, the time slots in the remaining TDMA frames are reserved for intra-cluster communication between the neighbor vehicles. Nevertheless, the randomly CH election process in the CBT MAC could result in electing a CH that may not stay longer in the cluster. Consequently, this can affect the cluster stability and affect the reliable delivery of safety applications. Furthermore, the authors did not evaluate the effect of both access collision and merging collision to determine the effective performance of the CBT MAC protocol. In (Gao, Tang, Li, & Chen, 2014) a hybrid clustering based MAC protocol (HCMAC) was proposed to provide efficient communication within the cluster members. In this approach, the authors used mobility information of the competing vehicles for the CH election process. However, the authors did not provide any details on how the competing vehicles reserve their time slots.

A TDMA cluster-based MAC protocol (TC-MAC) in (Almalag, Olariu, & Weigle, 2012) has been proposed and further modified in (Almalag, El-Tawab, Olariu, & Weigle, 2013) to provide support for the dissemination of non-safety messages without affecting the stringent requirements of the safety related messages. Contrary to the IEEE1609.4 standard architecture, in the proposed TC-MAC protocol the vehicles within the network can use any of the CCH or SCHs during the SI depending on the generated message by the vehicle. Similarly, for cluster formation procedure, the authors adopted the Traffic flow algorithm (Mohammad & Michele, 2010). The frame length in TC MAC protocol is basically identified by the size of the cluster. The CH allocates a local identifier to every CM within the cluster ranging from 0 to k-1 where k represents the size of the cluster. Accordingly, the CH always ensures the updated status information of each vehicle within the cluster is disseminated and shared to CMs. Furthermore, to guarantee a fair allocation of the time slot between the CMs, the authors employed an integer division theorem, thereby minimizing the problem of access collision. Nonetheless, in the TC-MAC approach, the problem of inter-cluster interference can generate a high rate of merging collision problems. Equally, given more emphasis on the transmission of the non-safety messages could also degrade the timely delivery of the safety related messages. Additionally, another proposal from (Shahin & Kim, 2016) called enhanced TDMA cluster-based MAC protocol (ETCM) modified the existing TC-MAC by introducing a switch operation procedure between the CCH and SCHs using a radio interface. Contrary to the TC-MAC protocol, every CM is allocated two mini-slots on the CCH to allow simple channel negotiation between the CMs. Similarly, the unused time slots are dynamically reallocated to any CM requiring more than one slot transmitting non-safety messages; hence the level of

SCHs utilization is increased. However, inter-cluster interference, which can generate a high rate of merging collision, has not been highlighted.

A Cooperative ADHOC MAC (CAH MAC) (Bharati & Zhuang, 2013) was also proposed to provide cooperative communication among the neighbor vehicles. The CAH MAC method introduced a helper node between the neighbor vehicles. When a packet failed to reach a target destination, the helper node cooperatively will use the unreserved time slot to retransmit the failed packet to the desired destination. However, in the process of accessing the available time slot by the helper node can lead to the access collision problem in a situation when other vehicles attempt to reserve those available free time slots. The problem of fairness in accessing a wireless channel has been addressed in (Torabi & Ghahfarokhi, 2014) by implementing the Jain's index approach between the competing vehicles. Equally, the authors proposed using the number of bit rate required by each vehicle for the allocation of time slots to increase the efficiency of the MAC protocol. However, this time slot allocation strategy could affect the efficient utilization of the bandwidth resources because some vehicles might not use the entire transmission token allocated to them. Authors in (Hadded et al., 2014) proposed an adaptive TDMA slot assignment strategy (ASAS). In ASAS, vehicles are divided into several clusters based on Euclidean distance, and subsequently used some specified metrics including the vehicles' direction and the position of the vehicle in the CH election process. Accordingly, for each vehicle to obtain its unique time slot in ASAS, a request message has to be sent to the CH through the hello packet. The TDMA logical frame in ASAS is partitioned into two parts, namely; adaptive broadcast frame (ABF) and contention-based reservation frame (CRP) period, as it was presented in (Lu, Ji, Liu, & Wang, 2010). The ABF part in ASAS holds the time slots that were allocated by active vehicles within the cluster as its basic channel (BCH) for broadcasting safety messages and other control messages. To improve the scalability in the network, the

TDMA frame can be adjusted dynamically on the basis of the network topology. Conversely, the CRP uses the procedure of CSMA/CA concept where vehicles reserve the SCHs for non-safety messages. However, the authors did not provide any solution in a situation of a high-density network, for example, when several vehicles attempt to acquire their time slot. Since, ASAS is using the CRP method for the allocation of the time, access collision is inevitable. Using bidirectional traffic in ASAS also makes it very challenging to maintain the cluster stability.

A TDMA-based multichannel MAC (TM MAC) protocol was proposed in (Babu, Patra, & Murthy, 2016). The main aim was to improve the reliable delivery of the safety messages and to increase throughput for the non-safety messages. Regarding the CH election process, each vehicle competing to become a CH is required to transmit its leadership quality indicator (LQI) together with the hello packet periodically to the neighbor vehicles. Any vehicle with less relative velocity and with the higher leadership quality is elected to become the CH. Furthermore, the TDMA frame in TM MAC is subdivided into four sets of time slots, namely; RSU, left, right, and leader slot. Each vehicle is allocated an appropriate time slot depending on its position within the cluster. In a situation when a merging collision occurs between the CMs, it is required that the vehicle that newly joined the cluster will release its reserved time slot, so that, the already existing CM will not be affected by this merging collision problem. However, cluster stability maintenance in TM MAC is not possible because it is implemented in a bidirectional traffic environment. In recent years, a weight-based clustering algorithm was presented in (Xie & Li, 2016). In this approach, WCS-MAC was proposed to improve the efficiency of the time slot allocation within the cluster. The authors indicated that any vehicle that needs to transmit a message and has not been allocated its time slot, it can borrow from the neighbor vehicles within the cluster based on an access probability. Nevertheless, this can result in inter-cluster interference, hence causing the problem of merging collision, which can subsequently, affect the effective performance of the proposed approach. Adaptive Beaconing in Mobility Aware Clustering-based MAC (ABM-MAC) protocol in (N. Gupta, Prakash, & Tripathi, 2017), was presented. In this approach, the authors partitioned the TDMA logical frame into two parts, each part representing CCH and SCHs with an equal number of slots. The time slot is allocated between the CMs within the cluster, based on the message priority generated by the CM. However, this approach did not consider the adjacent CMs between the adjacent clusters, which can result in merging collision problem within the adjacent CMs due to this inefficient scheduling strategy.

In (Mohammad & Michele, 2010), the authors proposed a lane-weight clustering algorithm in a traffic scenario with several intersections. They used some specified mobility parameters with respect to the traffic flow of the vehicles for the CH election process. For a vehicle to be suitable to participate in the CH election process, it has to be moving on the middle lane. The reason behind this idea was, the authors anticipated that those vehicles moving on either side (left lane or right lane) might take a turn and exit the cluster, especially at the intersections. But it is quite well known that, in a realistic scenario, a driver can decide to take any available lane (left, middle or right) he so wishes irrespective of whether the vehicle will take an exit soon or not. However, this perception of considering only the vehicles in the middle lane to participate in the CH selection process could result in selecting a CH that may not stay for a long period within the cluster, hence, causing a cluster reconfiguration and affect the cluster stability. Furthermore, it is worthy to note that vehicles' high mobility and frequent network topology in the vehicular environment limit the effectiveness and the reliability of the conventional MAC protocol for VANET. Sequel to that, authors in (Ahizoune & Hafid, 2012) proposed a stability-based clustering algorithm (SBCA). Two CHs were proposed in this approach to improve the cluster stability, where a vehicle with the highest number of neighbors and with minimum velocity difference is elected to become the CH. However, the procedure for electing a SeCH and how it works was not presented as claimed by the authors. In another development, authors in (Mammu, Hernandez-Jayo, & Sainz, 2015), presented a direction-aware clustering algorithm, where the future position of each vehicle is predicted. In this approach, a vehicle's direction of movement was given more priority with respect to electing a suitable CH, which subsequently helps to improve the cluster stability. Nonetheless, the periodic prediction of every vehicle within the cluster can lead to an increase in the communication overhead to the CCH, and as a result, affect the MAC protocol efficiency in implementing the safety related messages. Authors in (Lai, Lin, Liao, & Chen, 2011) presented a region-based clustering algorithm (RCM) for VANET MAC protocol to increase the MAC protocol scalability. The whole network is divided into a number of small segments, where each segment is allocated to a certain number of vehicles. A group of non-interfering channels is assigned to each segment in order to decrease the contention between the neighboring vehicles.

A mobility-based clustering algorithm (Hassanabadi et al., 2014) was presented using an affinity propagation called APROVE. Each vehicle competes to become a CH periodically with respect to the message it received from the neighborhood through a hello packet. The decision is made independently at a regular interval by comparing the mobility status information of the vehicle with the remaining vehicles within the transmission range, in addition to the other specified metrics; responsibility and availability. Once a vehicle determines the highest positive value for both the responsibility and availability metrics compared to the remaining vehicles, it becomes a CH. However, periodically electing a CH, can generate the high possibility of cluster reconfiguration, thereby, creating a high communication overhead on the CCH. Authors In (Arkian et al., 2015), proposed a stability-based clustering algorithm for VANET

MAC protocol considering several metrics, including both the mobility and the QoS metrics. Each vehicle competes to become a CH by computing its weight value and compare this value with the value received from all its stable neighbors within the communication range. Correspondingly, a threshold-based clustering algorithm (Rawashdeh & Mahmud, 2012) was proposed to form stable clusters in a highway traffic scenario. The authors presented that only stable neighbors can participate in the cluster formation and election process. They defined stable neighbors as those vehicles that their speed difference is less than ± Δth (predefined threshold); or else, they are regarded to be unstable neighbors. A combination of mobility metrics was used for the CH election process, where each metric was given a weight value with regard to the importance of the metric. The vehicle with the highest weight value is given priority to be elected to become the CH. However, it was observed that both approaches (Arkian et al., 2015; Rawashdeh & Mahmud, 2012) suggested that not all the neighboring vehicles within the communication range are appropriate to be in the same cluster. This perception can significantly affect some neighbor nodes that are within the same communication range but not in the same cluster. For example, an emergency incident can happen within the vicinity and being the vehicle not in the same cluster with the CH that broadcasts the alert message, the vehicle will not receive the messages, which can result in a hazardous situation to occur. Also, interference within the two or more adjacent clusters is inevitable, along with generating an unstable cluster; as a result, affect the efficiency and the reliability of the MAC protocol for timely delivery of the safety messages.

The main aim of mobility prediction-based efficient clustering scheme (MPECS) was to develop a novel efficient clustering scheme, which could allow better coordination in a vehicular environment by dividing the vehicles into different distinct areas using a Voronoi algorithm (Abdel-Halim et al., 2019). Each vehicle can identify its current position and predicts its future position using Gauss-Markov Mobility model within the communication range. To elect a CH, the proposed scheme uses the predicted vehicle longevity and cost to compute the vehicle lifetime value (VLV) of each vehicle. Vehicle with highest VLV was selected to become the CH. However, the risk of high collision rate is inevitable among the adjacent cluster nodes due to the fixed time slot allocation scheme. Similarly, variation in the accuracy of the prediction could result in an unstable cluster, which consequently, leads to generating high communication overhead among the neighbor vehicles.

To address the issue of merging collision and inefficient resource utilization, authors in (Haq et al., 2019; Lin & Tang, 2019), proposed a conflict-free clustering-based MAC protocol. For the cluster formation procedure in this approach, location of each vehicle within the communication range together with its mobility information was considered, so that the hidden terminal problem could be avoided. They used deterministic time slot allocation scheme within the cluster to resolve the problem of access collision as well as bounded delay for efficient resource utilization. Equally, disjoint slot assignment strategy has been proposed with respect to the vehicle's direction of movement to lessen the challenges of merging collision problem within the network. Recently, the motion parameters-based cluster medium access (MPMAC) protocol was proposed, which uses mobility parameters for cluster formation procedure without including the need for a cluster head election (Chaurasia et al., 2019). It also uses the RSUs to enhance channel utilization and solve hidden terminal problem. The cluster parameters include the speed and acceleration. Vehicles are grouped on the basis of their velocity and acceleration (fast, slow and transition vehicles) irrespective of their lane and position. These parameters were chosen in order to minimize the overhead in the formation of clusters as well as cluster maintenance. The technique also uses an RSU to determine and monitors the density of the vehicles within the network through the CCH. MPMAC does not require the presence of a CH for channel access between the CMs because the allocation is trivial once the clustering and channel categorization have been done. However, the authors claimed that the vehicles use their mobility parameters to cluster themselves without the need of any message exchanges between the neighbor nodes, which are impractical as each vehicle must be aware of the status of its neighbor by exchanging their status information. A Priority-Based Enhanced TDMA MAC Protocol for Warning Message Dissemination in VANETs was also proposed (Abbas et al., 2020) The authors proposed a priority-based direction-aware media access control (PDMAC) for both inter-cluster and intra-cluster communication. The main aim was to improve the delivery of warning messages between the neighbor nodes. The cluster formation method was proposed using the k-medoids algorithm. In this approach, a CM broadcast warning messages directly to the intended destination nodes, unlike in other clustering techniques, which broadcast to the CH for onward dissemination to all the vehicles within the cluster. Consequently, this approach could result in increase in the communication overhead to the CCH. The summary of some of these proposed MAC protocols for VANET is shown below in Table 2.1.

**Table 2.1: Summary of some of the cluster-based TDMA MAC protocols**

| Reference | Method | Benefit(s) | weakness(es) |
| --- | --- | --- | --- |
| TB_MAC<br><br>(Rawashdeh & Mahmud, 2012) | - Speed difference based on predefined threshold (for cluster formation).<br>- Highest weight value for CH election. | - Fast cluster formation for vehicles with the same speed characteristics. | - Using a specified speed to form clusters can affect the reliable delivery of safety messages to all neighbors.<br>- Low stable cluster. |
| TC-MAC<br><br>(Almalag et al., 2013; Almalag et al., 2012) | - Traffic flow algorithm (based on Lane weight) for CH election<br>- Integer division theorem for time slot reservations to CMs. | - Support multi-hop intra-cluster communication<br>- High throughput for non-safety applications. | - High transmission rate for non-safety application may degrade the reliable delivery of the safety applications<br>- Merging collision problem<br>- Re-clustering overhead. |
| CAH-MAC<br><br>(Bharati & Zhuang, 2013) | - Helper node utilizes unreserved time slots cooperatively to relay the message | - Minimized transmission failure cause by the poor channel condition. | - Use of the unreserved time slots by the helper node can result in the problem of access collision and inter- |

**Table 2.1, continued**

| | | | |
|---|---|---|---|
| | which failed to reach target destination. | | cluster interference.<br>- Cluster formation and CH election procedure not mentioned. |
| CBT<br><br>(Sheu & Lin, 2014) | - Used transmit-and-listen procedure for the CH election process.<br>- Random allocation of time slot to the CMs. | - Improved vehicle's intra-cluster communication.<br>- Minimized access collision. | - Low stable cluster.<br>- Merging collision problem is possible due to inter-cluster interference. |
| ASAS<br><br>(Hadded et al., 2014) | - Weight-based algorithm for CH election.<br>- Used disjoint set of time slot (L & R) allocation strategy to assign time slot to CMs moving on both directions. | - Minimized rate of access collision on the CCH.<br>- Support both safety & non-safety messages as well as providing QoS requirements for the safety messages. | - Considering Bidirectional movement can result in a low stable cluster, because the CH cannot stay longer time within its CMs.<br>- Inter-cluster interference between the adjacent CMs can result in a merging collision problem. |
| SB_MAC<br><br>(Arkian et al., 2015) | - Integrate mobility and QoS metrics.<br>- Highest weight value. | - Using QoS metrics for CH election increases link connectivity reliability and coverage. | - Only neighbor nodes with the same speed characteristics can participate to form a particular cluster.<br>- Inter-cluster interference can result in a merging collision. |
| CTDMA-LID (Nguyen et al., 2015) | - Lowest ID algorithm.<br>- Random allocation of time slot. | - Introducing gateways within the clusters minimized the effect of inter-cluster interference. | - Using a lowest ID only to elect CH can result in electing a CH that is not the best to lead the cluster, thereby affect the stability of the cluster.<br>- Merging collision problem. |
| DA-CMAC<br><br>(Mammu et al., 2015) | - Direction of vehicle's movement (highest priority).<br>- Disjoint set of time slot (L, R & RSU). | - Predicting future position of each vehicle within the cluster minimized the cluster reconfiguration. | - Consider both directions to form cluster.<br>- Employing many Gateways will reduce the stability of the cluster and can also cause merging collision problem.<br>- Periodic prediction process can increase high overhead to the CCH. |
| ETCM<br><br>(Shahin & Kim, 2016) | - Traffic flow algorithm (based on Lane weight) for CH election.<br>- Vehicles are allocated two mini-slots on the CCH.<br>- Dynamic reallocation of unused time slots for SCHs. | - Increased channel access fairness among the contending vehicles.<br>- Minimized access collision.<br>- Support both safety & non-safety applications. | - Low stable cluster.<br>- The mechanism for handshake procedure to exchange non-safety messages was not explained.<br>- Merging collision problem due to inter-cluster interference. |
| TM-MAC<br><br>(Babu et al., 2016) | - Used LQI and mobility metrics for CH election.<br>- Disjoint set of time slot (L, R & RSU). | - Improved the time slot scheduling scheme within the CMs.<br>- Minimized access collision. | - Considering both directions to form a cluster can affect the stability of the cluster.<br>- Merging collision problem. |

**Table 2.1, continued**

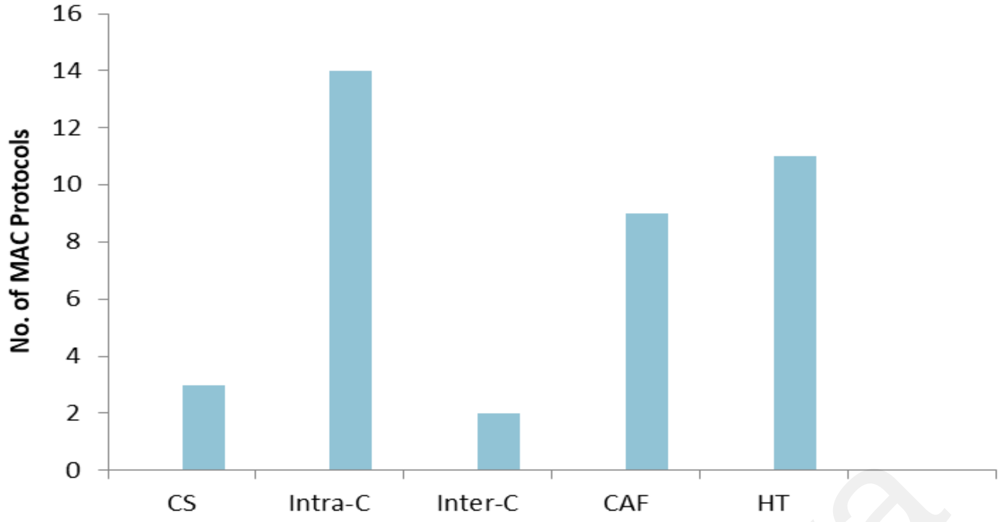
| | | | |
|---|---|---|---|
| WCS-MAC<br><br>(Xie & Li, 2016) | - Weight-based algorithm.<br>- Time slot based on access probability. | - Increased channel access fairness. | - Low stable cluster.<br>- Inter-cluster interference can result in merging collision. |
| ABM-MAC<br><br>(N. Gupta et al., 2017) | - Node mobility.<br>- Slot allocation to CMs was based on message priority. | - Minimized inter-cluster interference.<br>- Support both safety & non-safety applications. | - Low stable cluster.<br>- Problem of merging collision within the adjacent CMs due to the inter-cluster interference. |
| LMA-CT MAC<br><br>(Haq et al., 2019) | - Time slot & channel allocation was based on the direction of vehicles' movement<br>- Cluster formation was based on the vehicle's location & mobility information | - Utilized full DSRC channels to support both safety & non-safety applications<br>- Employing the use of the gateway nodes that were represented as edge nodes for both sides of the cluster decreases the problem of the hidden terminal. | - Low stable cluster due to bidirectional movement<br>- Merging collision problem is inevitable when vehicles access time slots of the opposite direction at traffic high density. |
| MPECS<br><br>(Abdel-Halim et al., 2019) | - Used Gauss-Markov mobility model to predict the future position of vehicles<br>- Cluster formation was based on vehicle's life time value (VLV)<br>- Fixed time slot allocation scheme by the CH to the contending CMs | - The technique used, minimize the overhead in the formation of clusters<br>- | - Variation in accurate prediction could result in unstable cluster and high communication overhead<br>- The high risk of merging collision is very likely due to fixed time slot allocation scheme |
| MPMAC<br><br>(Chaurasia et al., 2019) | - Used mobility parameters for the cluster formation<br>- Grouped vehicles based on their speed (fast, slow and transition)<br>- Employed a fixed time slot allocation scheme within the cluster | - It does not require the presence of CH for channel access because the allocation is trivial<br>- Use of RSU to identify and enhance channels utilization<br>- Flexible for broadcasting of safety messages | - Cluster formation without exchanging periodic messages between the neighbor nodes is impractical<br>- Merging collision is very possible due to the grouping of vehicles<br>- Absence of the CH in the cluster could result in generating high overhead to the network |
| PDMAC<br><br>(Abbas et al., 2020) | - Used k-medoids algorithm for the cluster formation<br>- CH was elected based on direction of movement | - Safety critical messages were given high priority over the other safety related messages<br>-CMs directly broadcast the messages to the intended destination nodes without going through the CH | - Very difficult to maintain stable cluster due to the bidirectional movement<br>-broadcasting of safety messages by the CMs to the intended destinations could increase the communication overhead to the network |

### 2.5.2 Comparative analysis of cluster-based TDMA MAC protocols

A number of research efforts in the literature with the reference to Table 2.1 in section 2.6.1 presented different proposed algorithms to support cluster-based TDMA

MAC protocols, to provide effective deployment of VANET envisioned applications. From Figure 2.12, it shows that more than 60% of the existing literature attempted to tackle the problem of hidden terminal and the channel access fairness. It is worthy to note that there was a general improvement for the contending vehicles to have the chance of accessing wireless channels fairly and minimize transmission delay within the cluster members. These proposed techniques also were able to address some of the problems inherent for the cluster-based TDMA MAC protocols, even though with little improvement such as increasing the cluster head lifetime within the cluster.

However, the existing proposed approaches did not provide a feasible solution, particularly when a CH moves out of the cluster. As a result, this problem could cause delay in accessing the wireless channel, and consequently, result in message delivery delay or packet loss. Figure 2.12 demonstrated that less than 30% of the proposed approaches addressed the problem of cluster stability and with very less significant enhancement. The techniques proposed by authors in (Almalag et al., 2013; N. Gupta et al., 2017; Hadded et al., 2014; Shahin & Kim, 2016; Torabi & Ghahfarokhi, 2014) provide support for the deployment of VANET envisaged applications, nevertheless the performance decreases due to the problem of merging collision especially when the vehicles density increases.




CS: Cluster Stability; Intra-C: Intra-Cluster Interference; Inter-C: Inter-Cluster Interference; CAF: Channel Access Fairness; HT: Hidden Terminal

**Figure 2.12: Challenging issues addressed in a cluster-based topology for TDMA MAC protocol**

It was observed that vehicles that are moving in different directions (moving from left to right or from right to left) were considered by the authors (Babu et al., 2016; Hadded et al., 2014). The approaches were provided to allow all the vehicles within the vicinity to be involved in the cluster formation considering some certain rules specified in the algorithm irrespective of the direction of their movement. However, consideration of bidirectional traffic could affect the cluster connection time and consequently minimize the cluster convergence. Hence, it results in an unstable cluster due to the vehicle's high mobility. This is because, in bidirectional traffic, the movement of vehicles is in opposite directions, and subsequently, the CH can lose communication from some of its members, thus causing cluster reconfiguration. Consequently, a new CH must be elected. As a result, decrease the efficiency of the existing MAC protocols.

Additionally, more than 80% of the existing literature addressed the problem of intra-cluster interference; which significantly minimized the problem of access collision. Nevertheless, it was discovered that less than 20% of the proposed approaches tried to address the problem of inter-cluster interference, which presently remains a challenging issue. The problem of inter-cluster interference results in a merging collision problem, and can decrease the reliability of the TDMA MAC protocol for vehicular communication in supporting the real-time applications. Consequently, the timely delivery of the safety messages can also be affected due to the probability of a high rate of transmission collision especially, merging collision problems, causing packet loss or delay to reach the desired destination, because broadcast messages have a very short life span.

### 2.5.3 Limitations of the existing literature

In the existing cluster-based TDMA MAC protocols, the inter-cluster interference and cluster instability are some of the major challenges faced in order to provide support for a timely delivery of safety related messages. The previous study has shown that maintaining the stability of a cluster due to the high mobility of vehicles is a serious issue, which can affect the reliability of cluster-based TDMA MAC protocol. This is because the CH can either leave or merge with another CH. It has been observed that most of the proposed clustering algorithms did not provide proper mechanism to deal with a situation when the elected CH moves out of a cluster. Moreover, this CH is responsible for coordinating all the CMs within the cluster, if it moves out of the cluster for any reason the clustering architecture has to be reconfigured. This operation can also lead to the loss of channel access schedule and may lead to the transmission collision or delay delivery of safety related messages. Therefore, it is required that a new technique should be proposed to further improve the cluster stability for future development of this class of protocols. This could be achieved by enhancing the existing clustering algorithms. This thesis has proposed the introduction of assigning one vehicle to act as a backup to PCH. The backup CH can replace the primary CH whenever it moves out of the cluster; so that the overhead of executing a clustering algorithm could be reduced thereby maintaining a stable cluster as well as improving the performance of the cluster-based TDMA MAC protocol.

Considering the literature survey conducted, it was found that the rate of access collision has been minimized significantly especially in a cluster-based TDMA MAC protocol. On the other hand, merging collision is still a serious issue. This problem generally happens due to inefficient time slots allocation strategy. It has a great effect on the efficiency of cluster-based TDMA MAC protocols especially for broadcasting safety related messages, which are delay bounded. Therefore, an effective slot assignment strategy has been proposed in order to allow vehicles to use their time slot without collision.

## 2.6 Chapter Summary

This chapter has discussed the background literature on the main concept of vehicular ad hoc network technology and the different standards employed to support vehicular communication such as DSRC and IEEE1609.4. The realization of the VANET envisaged applications solely depends on the efficiency of the medium access control protocol to broadcast both safety messages and non-safety messages. Sequel to that, we discussed extensively the different categories of VANET MAC protocols giving emphasis on the time division multiple access MAC protocol scheme. Considering the challenges faced by this class of MAC protocols, we also give highlight on how the clustering technique addressed some of these challenging issues due to vehicle dynamics and the benefits that could be derived from using the clustering algorithms to minimize these challenges. Furthermore, the state-of-the-art literature on the cluster-based TDMA MAC protocols has also been discussed extensively in this chapter. Finally, we extract the comparison between the existing literature that we have discussed to identify the area that needs to be further investigated and enhanced for future deployment of the cluster-based TDMA MAC protocol to provide reliable delivery for VANET safety related applications.

# CHAPTER 3: RESEARCH METHODOLOGY

This chapter discusses the design process carried out to address the identified problems to meet the outlined objectives in Chapter 1. The chapter is organized into nine sections. Section 3.1 explains the overall research methodology, while Section 3.2 highlights the proposed protocol limitations and assumptions. The detailed descriptions of the identified metrics for the clustering process are given in Section 3.3. Section 3.4 highlights the simulation tools for vehicular communications, while Section 3.5 discusses the simulation tools for the proposed EC-TMAC protocol. Section 3.6 explains in detail the simulation setup. Evaluation parameters are highlighted in Section 3.7, while Section 3.8 discusses the result validation and analysis tools used for the proposed EC-TMAC protocol. Finally, Section 3.9 concludes the chapter.

## 3.1 Overall research framework

The methodology adopted in this research work consists of the following phases:

i. Literature review and problem identification. In this phase, it begins by exploring the general concept of VANET and the standards deployed to support the vehicular communications for the implementation of VANET envisioned applications. The reliable delivery of safety related applications in the vehicular environment is reliant on the efficiency of the MAC protocol. Sequel to that, the different categories of VANET MAC protocols including, the contention-based MAC protocol and contention-free MAC protocol have been discussed briefly. Subsequently, a comprehensive review of the state-of-the-art of the cluster-based TDMA MAC protocols for VANET has been conducted, focusing on the clustering techniques and the time slot allocation strategies used. This extensive review gives the opportunity in this research work to identify the existing challenges posed by this class of MAC protocols for effective delivery of safety related applications reliably and in a timely passion.

ii. Development of a clustering mechanism for enhancing a cluster-based TDMA MAC protocol. In this phase, an enhanced cluster-based TDMA MAC (EC-TMAC) protocol has been developed using two approaches. The first approach is the clustering procedure. This involves the cluster head and the secondary cluster head election algorithm, by using the weight-based and lowest ID clustering techniques. Subsequently, a cluster formation procedure has been proposed using inclusive criteria for every vehicle within the communication range because of the significance of any safety message that may be generated by the vehicles. Furthermore, the cluster maintenance mechanism has been proposed to provide an efficient cluster head leadership transition from PCH to SeCH. Secondly, a time slot scheduling scheme that will take care of inter-cluster interference between the adjacent cluster members of the adjacent clusters has also been proposed. This takes cognizance of the cluster member position with respect to the PCH position. The design methodology discusses all the details of the proposed approaches, process flow, and algorithms.

iii. Verification and validation. In this phase, the research work focused on the testing and running the simulations to evaluate our proposed approach. The simulation is conducted using the network simulator 3 (NS-3) simulation tools. The mobility pattern of vehicles at different traffic density is generated using a micro-traffic simulator known as a simulator of urban mobility (SUMO) that has realistic mobility traces. To determine the efficiency of our proposed approach, the obtained results with the results obtained from the benchmark approaches in the literature have been compared. Subsequently, the performance evaluation is compared with respect to the cluster stability, number of clusters formed, safety messages delay report generated, rate of merging collision, and protocol communication overhead generated. Figure 3.1 summarized the methodology adopted in this research.

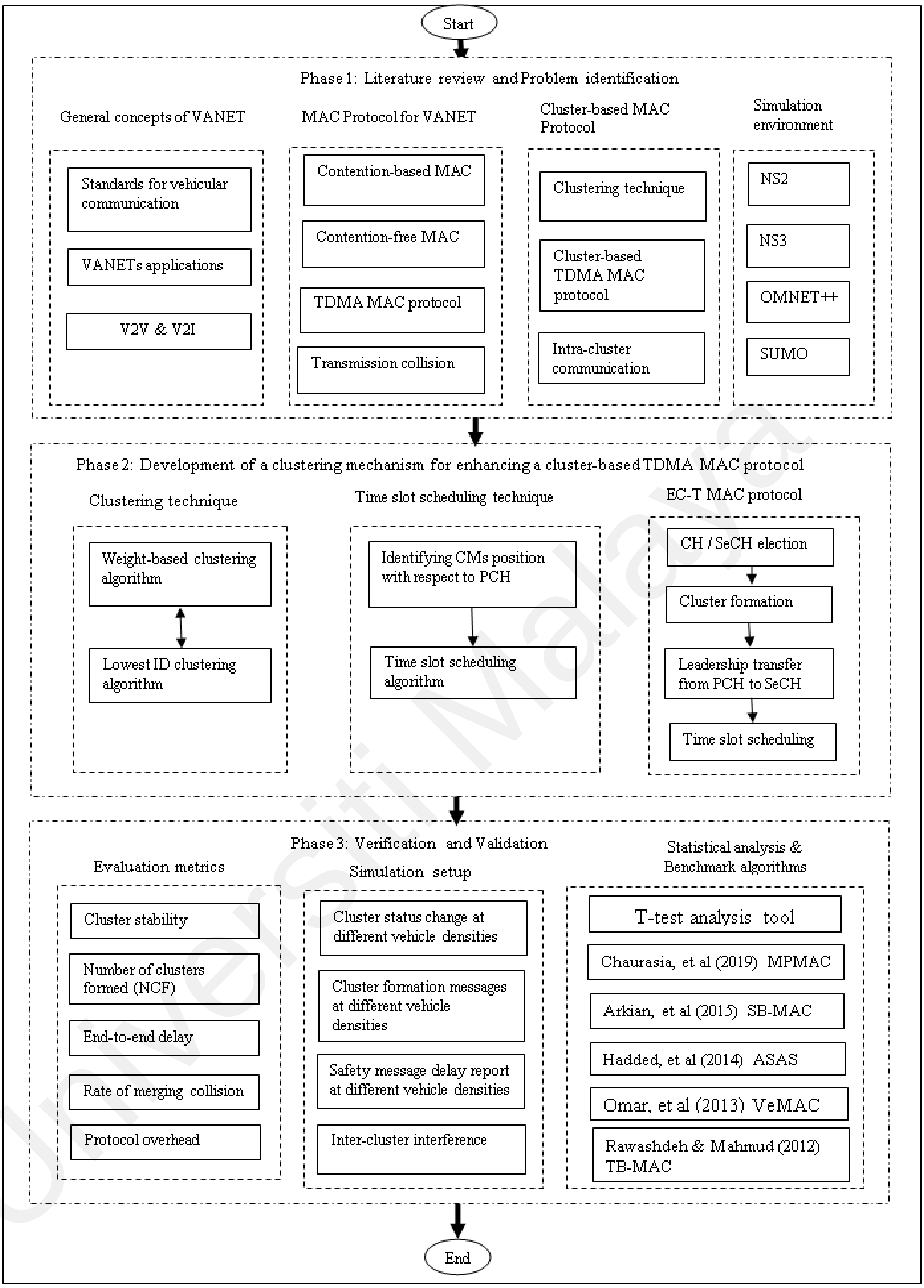



**Figure 3.1: Methodology for enhancing a cluster-based TDMA MAC protocol**

## 3.2 EC-TMAC protocol Limitations and Assumptions

A vehicular ad hoc network in a highway scenario comprises of several moving vehicles based on different traffic conditions on the road, for example, speed and density. Sequel to this background, it is assumed that all the vehicles in the network are equipped with either a Galileo receiver or a global positioning system (GPS), and the one-pulse-per-second (1PPS) signal to support the communicating vehicles get an efficient real-time synchronization. This would provide precise three dimensional (3D) real-time positions (such as latitude, longitude, and altitude), velocity and direction of each vehicle within the network. It is also assumed that each vehicle in the network can identify its road ID through a digital map. Any vehicle that joined the network will be assigned an identifier known as node id. The node id, which will begin with zero (0), is allocated to each vehicle within the network on the basis of the vehicles' arrival to the network. Two vehicles are regarded to be stable neighbors if they are within the communication range of each other. Only vehicles moving in the same direction and with the same road ID will be considered to form a cluster group within a road segment on a highway. A message from the neighbor node moving in a different direction is not considered and should be ignored. The arrival rate of the vehicles is assumed to be a Poisson process (Z. Zhang, Mao, & Anderson, 2014).

## 3.3 Metrics for CH election

In this section, the specifically identified metrics considered for the CH election process are defined. These metrics comprise the mobility information of each vehicle such as the vehicle's direction of movement, road ID, mean speed of a vehicle, vehicle's connectivity level, and mean distance of a vehicle to its neighbors. A vehicle recognizes its neighbors by exchanging this mobility information through periodic messages. The direction of movement of a vehicle and the road ID is recognized first for any neighboring vehicle before it can accept and process the broadcast message from its neighbors. Conversely, the remaining metrics (i.e., the mean speed of a vehicle, the vehicle's connectivity level, and the mean distance of a vehicle) are calculated to decide the vehicle's suitability to become a CH. Each of these metrics is associated with a real value weight representing its importance (Pathak & Jain, 2016). A brief explanation of these metrics is given below.

### 3.3.1 Node connectivity level

Two vehicles *A* and *B* are considered neighbors if the distance between them is less than *r*, where *r* is the communication range defined by the DSRC standard. The total number of vehicles directly connected to vehicle *A* is called its connectivity level. In general, the number of neighbors of node *A* at time *t* in a cluster as given by (Xie & Li, 2016) is calculated as follows:

$$N_A(t) \ = \sum_{B=1}^{n} dist(A, B, t) < Txrange \qquad (5)$$

Where *B* represents the potential neighbor of vehicle *A, dist(A, B, t)* is true if a connection between vehicles *A* and *B* exist at time *t*, otherwise it is false and *Txrange* is the transmission range of node *A*. Consequently, after the computation, the node with the highest connectivity level has a better chance to play the role of a CH.

### 3.3.2 Mean speed

Speed is one of the important mobility characteristics involving vehicles moving on the road. It has been widely accepted that the speed of a vehicle is assumed to be a normal distribution (Zarei, Rahmani, & Samimi, 2017) in a free flow traffic state. Each vehicle can determine how close the mean speed of its neighbors is to its current speed. Consequently, the vehicle whose speed is closest to the mean speed of its neighbors will have the highest priority of becoming a CH. The mean speed $\mu_{veh}$ of all the neighboring vehicles is expressed in Eq. (6) as follows:

$$\mu_{veh} = \sum_{B=1}^{n} \frac{\Delta d}{\Delta t} \qquad (6)$$

Where $\Delta d$ represents the total distance, $\Delta t$ represents the total time covered and $B=1...n$ represents the neighboring vehicles within the transmission range. However, to avoid having this value dominate and affect the result of the computation, a normalization technique was adopted (Rawashdeh & Mahmud, 2012). Therefore, both the mean speed and the mean distance could be modeled using a normal distribution with the mean and variance of all the corresponding neighboring nodes. The normalized mean speed $v_{normal}$ is given in Eq. (7):

$$v_{normal} = \frac{v_A - \mu_{veh}}{\sigma_{veh}} \qquad (7)$$

Where vehicle's speed is represented by $v_A$

### 3.3.3 Mean distance

Based on the Euclidean distance, the mean distance of each vehicle that is connected to vehicle $B$ directly is calculated. The distance between these communicating vehicles (i.e., sender and receiver) is very important in networking scenarios, especially for safety related messages. The shorter the distance, the faster the message will be transmitted or received by the neighboring nodes. Each node position $n_p$ can be derived from the position coordinates of the vehicles. This is represented as follows:

$$n_p = (x_1, y_1) \qquad (8)$$

Where the position coordinates of the vehicles are represented by $x$ and $y$; therefore, the mean distance $\mu_d$ of all the vehicles could be expressed in Eq. (9) as follows:

$$\mu_d = \frac{\sum_{B=1}^{n} \sqrt{(x_A - x_B)^2 + (y_A - y_B)^2}}{N_A(t)} \qquad (9)$$

The variable *B* is any neighboring vehicle that is connected to vehicle *A*. $N_A(t)$ is the total number of vehicles that are directly connected to vehicle *A* at time *t*. The normalized mean distance $d_{normal}$ is defined in Eq. (10):

$$d_{normal} = \frac{n_p - \mu_d}{\sigma_d} \tag{10}$$

The node position is represented by $n_p$, and $\mu_d$ represents the mean distance while $\sigma_d$ represents the standard deviation.

Each node computes its weight value $ßi$ in Eq. (11) based on the specified metrics discussed in Section 3.3.1 to determine its suitability of becoming a CH.

$$ßi = \big(wf1 * N_A(t)\big) + (wf2 * v_{normal}) + (wf3 * d_{normal}) \tag{11}$$

Subject to:

$$wf1 + wf2 + wf3 = 1 \tag{12}$$

Where, *wf1, wf2,* and *wf3* are the weight factors associated with each parameter respectively. The vehicle with the highest weight value $ßi$ is elected as a CH.

### 3.4 Simulation tools for vehicular communications

In a vehicular environment, performing a real experiment is a challenging task and very expensive to implement. Therefore, the alternative and most popular technique employed to evaluate the various VANET scenarios without real-world implementation is by the use of network simulation tools (Mussa, Manaf, Ghafoor, & Doukha, 2015; Zhou & Tian, 2016). Network simulation tools provide the capabilities of using a discrete-event simulation approach in a non-real-time fashion (Raj, Upadhayaya, Makwana, & Mahida, 2014). They have been extensively used by the research community to model and evaluate the performance of the proposed algorithms because they are cost-effective, highly scalable and also provide very reliable results (Bilalb & Othmana, 2013; do Vale Saraiva & Campos, 2019; ur Rehman, Khan, Zia, & Khokhar, 2013). Network simulation tools for vehicular communications are specifically identified as network simulators and mobility generators (Patel, 2012).

Network simulators assist the researchers and network designers to identify the behavior of the network protocol and its performance under different conditions. Several simulation tools have been developed such as NS-2, NS-3, JiST/SWANS, MATLAB, QualNet, OMNeT++, OPNET, etc. to simulate the behavior of the communications between vehicles and analyze various scenarios at the micro and macro-scale stages (Martinez, Toh, Cano, Calafate, & Manzoni, 2011).

One of the most important parameters to consider for the simulation in the vehicular environment is node mobility (Fogue et al., 2012). Consequently, using a realistic mobility model is highly required to influence the activities of the traffic simulator based on the communications between the vehicles so that simulation results can correctly reflect the real-world performance of a VANET (Karnadi, Mo, & Lan, 2005; Lan & Chou, 2008). The pattern of vehicles' movement can be generated at any stage of the traffic density by a mobility generator, otherwise known as a micro-traffic simulator that has realistic mobility traces. The generated mobility traces are later used as an input to the network simulator. Some of the examples of mobility generators use for VANET simulation are FreeSim, VanetMobiSim, SUMO, and MOVE. Furthermore, there are some other tools such as iTETRIS, Veins and VSimRTI that can enable the mobility generators and network simulators to interconnect and interact with each other (Ribeiro et al., 2017; Sommer et al., 2019).

The choice of VANET simulation tools is one of the crucial decisions to take because a wrong choice may result in a disappointing result (A. R. Khan, Bilal, &

Othman, 2012; Saluja, Dargad, & Mistry, 2017). Hence, numerous commercial and open-source simulation tools are readily available for the research community as well as the commercial organizations to choose for the simulation of various VANET scenarios (Kaisser, Gransart, & Berbineau, 2012). However, in this thesis, we focused on the simulation tools with the functionalities that could be used for the implementation of the MAC protocol (i.e. IEEE802.11p/1609.4 WAVE protocol stack) in a cluster-based topology using a TDMA scheduling scheme. The following subsections briefly explained some of the commercial and open-source simulation tools that could be used for various vehicular communication scenarios in the vehicular environment.

### 3.4.1 Commercial network simulation tools

This category of simulation tools requires a license before the user can acquire them. It means that the source code of the software or any of its related packages would not be provided to the general public for free by the distributors of the commercial software. To use any of the commercial simulation software, the user or the organization must pay to get the license or pay to order some specific packages for their specific usage requirements. Most of the commercial simulators are simplified, simple to use, and graphical user interface (GUI) driven. They have the advantage of complete and up-to-date documentation from the distributors, which can be maintained by the customers frequently. Some of the commercial simulation software includes OPNET (Optimized network engineering tool), MATLAB (Matrix Laboratory), and QualNET. However, our brief discussion focused only on those simulation tools, which have been used by the research community for the simulation of VANET MAC protocol, such as OPNET and MATLAB.

i. Optimized network Engineering tool (OPNET): OPNET modeler is a commercial discrete-event network simulation tool developed by OPNET Inc.

technologies, which is presently under the license of Riverbed technologies (Modeler, 2019). Considered as a suite of software designed to simulates the behavior of nodes and evaluate the efficiency of the communication network protocols. It is one of the most commonly used simulation software that provides highly intuitive graphical support for the users and also supports both random mobility and trajectory mobility of vehicles. OPNET modeler is very powerful and versatile across application components for a data-driven approach in analyzing performance in contrast to other network simulation tools with regard to providing pre-defined libraries of protocols, thereby allowing the user to create and simulate different topology scenarios at ease. OPNET modeler simulation software has been used previously (Çalhan, 2015) to simulate VANET scenarios. It has a good graphical user interface supporting model creation, running the simulation, and analysis using a built-in statistical analysis tool more simply. However, neither new protocols nor existing ones could be modified and the implementation of realistic mobility, which is very crucial in VANET is very limited (Kaisser et al., 2012). The OPNET simulator does not have a built-in module for IEEE802.11p to evaluate the MAC protocol for VANET applications (Islam, Hu, Onur, Boltjes, & de Jongh, 2013; S. Yang, He, Wang, Li, & Lin, 2014). Therefore, OPNET is not suitable for simulating the EC_TMAC protocol to determine its effectiveness.

ii. MATLAB (Matrix Laboratory): It is a commercial discrete-event simulation tool developed by Math works to support matrix manipulations and implementation of algorithms for numerical computing environment (Lim, Lee, Chin, Yeo, & Teo, 2016). MATLAB comprises various communication tools that can be used for specific tasks such as analysis of the signal to noise ratio (SNR), and other real-world applications in engineering, for example, smart power grids systems, LTE cellular networks, automotive active safety systems, etc. However, the MATLAB simulation tool does not fully implement the IEEE802.11p MAC layer module as well as the IEEE1609.4 WAVE module. Similarly, there is no module to support the implementation of the clustering model for vehicular communications. As a result of these reasons and the cost implication involved in acquiring the MATLAB simulation software, it is considered not suitable for simulating the proposed EC-TMAC protocol.

Generally, besides the cost implication involved in acquiring the commercial simulation software, another limiting factor is the strict underlying architecture that cannot allow the research community to develop additional modules, modify or extend the existing models to test their algorithms (Optimus, 2015). Therefore, in this thesis, open-source simulation tools are considered for the implementation of the proposed EC-TMAC protocol.

### 3.4.2 Open source network simulation tools

Open-source simulation software is acquired free by any user or organization without paying anything to the developers. This simulation software can be downloaded free without any restrictions by the developers or distributors. The research community can freely modify the source code and apply their new or modified patches at will. Because a large number of users can have access to the source code, there is a high probability that more bugs are easily identified when compared to the commercial simulation software with smaller development staff. Consequently, this typically results in fixing the bugs faster and improves the efficiency of open-source software. The main benefit of open-source simulators is that it is very flexible and every individual or organization can contribute to its future improvement to reflect the most recent technological development (S. G. Gupta, Ghonge, Thakare, & Jawandhiya, 2013). The open-source simulation software includes but not limited to the following; OMNET++, NS-2, NS-3, and JIST/SWANS. A brief description of some of these open-source simulation tools follows below:

i. OMNeT++ (Objective modular network testbed in C++). This simulator (OMNeT++, 2019) was initially developed and made available to the general public since 1997 (Varga & Hornig, 2008). OMNeT++ is open-source discrete-event simulation software that was written in C++ programming language with a very large number of users to simulate various wired and wireless networks. It offers a necessary framework for the reusability of models because it was developed using a component-oriented based approach with an extensive graphical user interface and intelligence support. Some of the most popular frameworks developed for OMNeT++ include INET framework, mobility framework and Veins framework providing a comprehensive set of wireless protocol support for different purposes such as simulation for the network layer and higher layers in the TCP/IP communication network model (Sommer, Härri, Hrizi, Schünemann, & Dressler, 2015). INET framework contains various models for all the various types of network protocols such as TCP, UDP, Ethernet, IEEE802.11, etc. as well as the implementation of radio wave propagation model for wireless networks. The mobility framework is specifically for the implementation of the routing operations in MANET (Shafiee, Lee, Leung, & Chow, 2011). Similarly, the Veins framework is mainly developed for the simulation of the vehicular communications, where the IEEE802.11p MAC layer and IEEE1609.4 DSRC/WAVE models were fully implemented. However, none of these frameworks provide any module for the implementation of the clustering of vehicles for the deployment of VANET safety related applications. Therefore, OMNeT++ is not considered as an appropriate simulation tool for the implementation of the EC-TMAC protocol.

ii. Network Simulator-2 (NS-2) was developed at the University of California Berkeley as one of the most popular open-source discrete-event network simulation software that has been used in the VANET communities for academic research to understand the behavior of the wireless communication networks (NS2, 2011). The NS-2 simulation tool was built and implemented using a C++ programming language (i.e. regarded as the backend). The simulation interface is provided through an object-oriented tool control language (OTcl), which is an extension of Tcl (i.e. regarded as the front-end) (Issariyakul & Hossain, 2009). The topology of the network can be generated by writing some OTcl codes, while based on some specified parameters the simulation scripts simulate the generated topology. The NS-2 simulator is very flexible and modular gaining substantial contributions from a wider research community such as virtual internetwork testbed (VINT) project and other developers in the research community. It supports the simulation of network communication protocols, including wired and wireless network protocols for example, TCP, UDP, routing protocols, etc. The basic architecture of the NS-2 simulation tool is given in Figure 3.2.

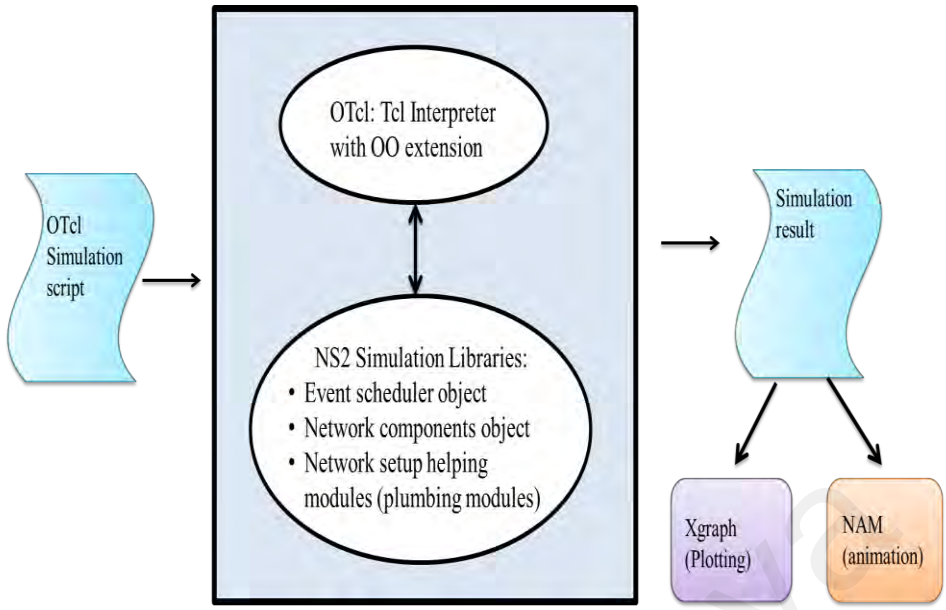



**Figure 3.2: Simplified basic architecture of NS-2 simulation tool**

It is a quite known fact that NS-2 does not fully implement the IEEE802.11p standard MAC module for many wireless communication scenarios and the dynamic nature of the vehicular environment where realistic modeling is needed. However, to support vehicular communications, the PHY and MAC layers have been extended and validated in NS-2 simulation software by Chen et al. (2008). But other implementations such as functionalities of IEEE1609.4 needed to support periodic channel switching operations between CCH and SCHs proposed by (Gukhool & Cherkaoui, 2008) have not been provided in the official release. Additionally, due to the high memory and CPU requirements, NS-2 is not suitable for simulating scenarios with a large number of vehicles (Stanica, Chaput, & Beylot, 2011). The NS-2 project was not active since 2010 (ns2-wiki, 2014), which consequently limits further enhancement of the software and the research community shifted their contributions to the development of NS-3. Therefore, implementation of the EC-TMAC protocol in NS-2 is not possible due to the absence of some models that can allow its functionalities such as the clustering model and TDMA model.

iii. The network simulator-3 (NS-3) is an open-source, discrete-event network simulation tool that is considered as a promising option and a major replacement of NS-2 (ns-3, 2019). The core architecture of the simulation kernel of the NS-3 has been simplified and implemented using a C++ programming language with optional python bindings. It was built as a set of libraries that are linked to the main simulation scripts defining the network topology, hence making it less complex and more simplified compared to the NS-2 simulation tool. Consequently, this increases the scalability of the simulation by handling a large number of scenarios. The simplified NS-3 architecture is presented in Figure 3.3.

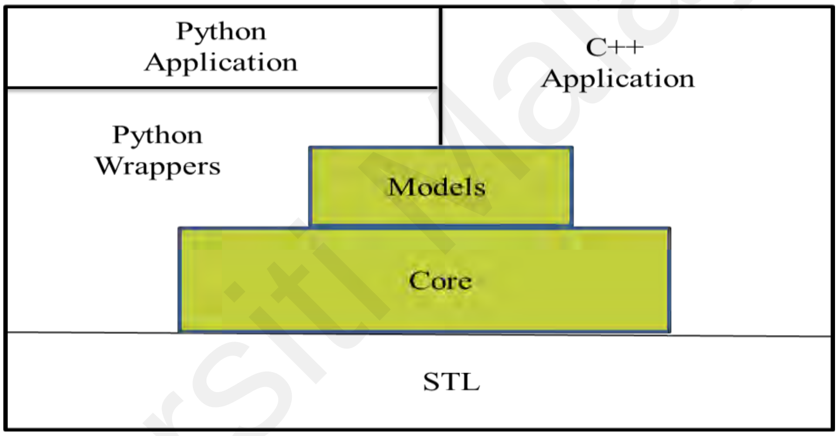



**Figure 3.3: The architecture of the NS-3 (ns-3, 2019)**

It has been identified that NS-3 has some distinguishing features in contrast to the NS-2 and other simulation tools, which makes it more popular in conducting scientific and academic research. Some of these features include the following:

- Modularity. This is whereby a set of libraries can be integrated with other external software libraries, in contrast to other tools that make available to users with only a single integrated user interface where all tasks are carried out.

- Support for multiple operating systems. Though designed primarily to use on Linux or MAC operating system but also support windows frameworks through virtual machine
- Maintenance. Actively maintained by responsive users mailing list because it is not supported software tool officially for any company but rather on the basis of the best effort through the NS-3 users' forum (groups, 2019) in contrast to NS-2 where there were no significant contributions for more than a decade.
- Implementation. It provides features such as allowing users to run the real implementation of the code in the simulator. It also supports the use of real network analysis tools directly such as Wireshark or tcpdump that are not available in NS-2 or OMNeT++ simulation tools.

The current architecture of NS-3 and implementation of IEEE 802.11 was inherited from Yans (Lacage & Henderson, 2006). The PHY and MAC layers of IEEE 802.11 have been modified and extended by (Mittag, Schmidt-Eisenlohr, Killat, Torrent-Moreno, & Hartenstein, 2010) and ported these modules to the official release of NS-3. Consequently, allow the implementation and modeling of most of the IEEE802.11p/IEEE1609.4 standard for vehicular communications scenarios. However, the WAVE module provided by NS-3 does not support realistic mobility of the vehicles but rather relies on the other mobility models, for example, Random Way Point (RWP) model. Even though there are several mobility generation tools deployed for simulating realistic vehicular scenarios, in this thesis, we considered SUMO as a mobility generator for the EC-TMAC protocol due to its many advantages over the other generation tools. In the next section, we briefly explain some of these mobility generation tools.

### 3.4.3 Mobility generators for vehicular communications

Vehicles' mobility is one of the important parameters that need to be modeled for simulation in vehicular communication scenarios. It is quite obvious that the vehicle's movement on the road is restricted by the road topology as well as the traffic flows. The traffic pattern of the vehicles could be modeled as either microscopic or macroscopic modeling based on the level of details describing the traffic flow (Barceló, 2010; Härri, 2010). Microscopic modeling describes the behavior of the different mobility patterns of a specific vehicle and the interactions with other vehicles and other related infrastructures placed on the road within the simulation environment in detail. On the other hand, instead of considering a mobility pattern of a particular vehicle, macroscopic modeling concerned with all aggregated traffic flows influencing the vehicular traffic of a particular road segment, for example, road topology, speed, number of lanes, and traffic density (Zarei & Rahmani, 2017). Therefore, mobility generators are required to increase the level of realism in the VANET simulations scenario. There have been several mobility generators developed for the simulation of vehicular scenarios, which include but not limited to MOVE, SUMO, VanetMobiSim and FreeSim. The simulation tools use the mobility traces generated from the mobility generators to build the network topology. The quality and effectiveness of the mobility model used generally determines the reliability of the simulation results because unrealistic mobility models could result in an unrealistic network topology, which consequently could lead to an unreliable evaluation result (Celes, Silva, Boukerche, de Castro Andrade, & Loureiro, 2017). The brief description of these mobility generators is given below:

i. VanetMobiSim: This is a traffic simulator built in JAVA programming language supporting various simulation and emulation tools, for example, NS-2 and NS-3. Some of the salient features of VanetMobiSim are supporting macro and micro mobility features, several multi-lanes traffic signs at intersections as well as differentiated speed constraints, which can be used for modeling vehicular mobility to generate realistic vehicular mobility traces in different formats. The simulator also supports an intelligent driver model with intersection management (IDMIM), which can be used to generate a realistic mobility model (Martinez et al., 2011). Users can either define the road topology or import the road map from the database. Subsequently, other specifications are then defined, such as road structure, the flow of vehicles and other traffic signs. Furthermore, to realize more realistic vehicle mobility, VanetMobiSim has been designed to model the variations in the individual vehicle's speed, especially at the intersection, during the traffic congestion or overtaking (Shafiee et al., 2011). However, VanetMobiSim is not suitable for complex road networks and does not provide a user-friendly environment. Moreover, it was not active in the research community since the latest version, which was released in 2007. Therefore, VanetMobiSim is not considered and suitable as the mobility generator for EC-TMAC protocol.

ii. FreeSim**:** FreeSim is one of the open-source realistic mobility generators licensed under the GNU & general public license. It is very portable and easy to use traffic simulator by allowing traffic algorithms to be created and executed easily for either individual vehicles or the entire network. FreeSim is considered as one of the best realistic mobility tools for intelligent transportation system by supporting both macroscopic and microscopic level simulation (Bariah, Shehada, Salahat, & Yeun, 2015). However, FreeSim cannot be integrated with other formats available. As a result, the generated mobility traces from the FreeSim are not supported by the simulation tools including NS-2 and NS-3. Additionally, it was not active in the research community currently. Hence, these limit its functionalities and also not appropriate in generating mobility traces for the EC-TMAC protocol.

iii. Simulation of urban mobility (SUMO): It is a free and open-source microscopic road traffic simulator, licensed under the GNU general public license (version 2 or later). This traffic mobility software provides users with various functionalities so that real-world mobility models can be generated for vehicular communications simulations scenarios. It is highly portable and easy to use. The generated mobility traces also support both NS-2 and NS-3 simulation software (Piorkowski et al., 2008). SUMO can provide a detailed representation of large scale vehicular traffic scenarios in different geographical locations when combined with the OpenStreetMap database (Behrisch, Bieker, Erdmann, & Krajzewicz, 2011). Several significant features that make SUMO very popular for the simulation of vehicular communications scenarios include collision-free with respect to vehicle movement, inter-connectivity with other applications during simulation, portable libraries as well as multi-lanes topology with lane changing capability and easy simulation set-up. It also has the capability of importing and editing real road network from the map databases directly, for example, OpenStreetMap (OSM) and TIGER (Lim, Lee, Chin, Yeo, & Teo, 2017; Martinez et al., 2013). These features make SUMO the most widely used traffic simulator for simulating vehicular communications scenarios. Consequently, we opted to consider SUMO in this thesis to generate the mobility traces for the proposed EC-TMAC protocol.

iv. Mobility model generator for vehicular networks (MOVE): This software is a realistic mobility model built on top of SUMO. It was deployed in JAVA programming language and comprises two main parts: the mobility model which is used for creating road topology and vehicle movement, and traffic model that deals with the network traffic (Abdelgadir, Saeed, & Babiker, 2017). The output generated from the MOVE software is a realistic mobility traces, which contain information about vehicles movement which can be sent to the SUMO and then use by a network simulator such as NS-2 or QualNet (Mittal & Choudhary, 2014). The enhanced graphical user interface (GUI) editor in MOVE simplifies the way users generate the traffic simulation scenarios without writing the code and also helps to generate mobility traces more quickly and easily.

## 3.5 Simulation tools for EC-TMAC protocol

This section presents the detail explanation of the modules deployed in NS-3 for the implementation of the proposed EC-TMAC protocol. Similarly, the procedure for the generation of realistic vehicular mobility scenarios utilizing SUMO mobility generation software has been presented. As explained earlier in the preceding sections, these software tools were considered for the implementation of the EC-TMAC protocol due to the many benefits they provided over the existing tools. This begins with the NS-3 modules and consequently, followed by SUMO later. The basic architecture of the components used for the simulation in this research work is illustrated in Figure 3.4.

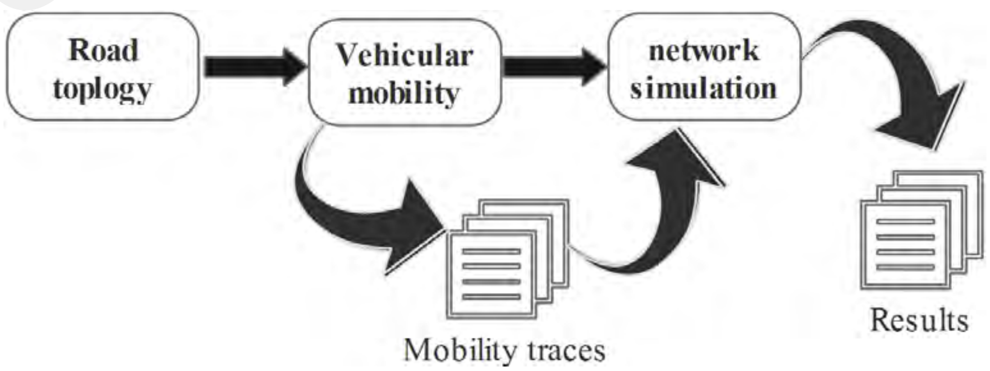



**Figure 3.4: Basic architecture of the components used for the simulation**

### 3.5.1 Network simulator 3 (NS-3)

To enhance and maintain the cluster stability for a cluster-based TDMA MAC protocol, the V2V clustering module presented in (Katsikas, Chatzikokolakis, & Alonistioti, 2015) have been modified and extended, to implement the clustering algorithms for the EC-TMAC protocol in NS-3. A detailed description of the communication messages exchanges in the algorithm for the cluster formation and maintenance among the neighbor vehicles have been presented. Furthermore, the TDMA model, which was built on top of the simple wireless channel model in the NS-3 WAVE module by (S. Li, Liu, et al., 2019a) has also been modified and implemented to allow the CH allocates the time slices to the CMs within the cluster coverage. The various classes implemented in the V2V clustering module are explained below.

#### 3.5.1.1 V2V clustering module

The V2V clustering module provides a set of classes in NS-3 to allow the formation and maintenance of the cluster among the vehicles within the transmission range. The main idea here is to model the behavior of the communicating vehicles by implementing and exchanging the new header messages to assist vehicles in forming and maintaining the cluster efficiently so that effective communication could be realized among the neighbor nodes. To achieve that, the *V2VFormClusterHeader* and *V2VInitiateClusterHeader* classes have been extended to allow the CH election process to include every neighbor node within the communication range participate in the election process as well as the election of the SeCH. Another functionality provided by the V2V clustering module was *the V2VClusterInfoHeader* class. This contains message structure with the mobility information of the vehicle, node id, clusterID, reserved time slot, and other related parameters use for the update process, which the CH broadcast periodically to its CMs. Similarly, the extended application model in NS-3 (Katsikas et al., 2015) has been reused to effectively determine the performance of the proposed EC-TMAC protocol with regard to the safety related messages. The control application model *V2VControlClient* provides support for the implementation of the safety related messages. Every vehicle within the cluster can either transmits or receives a message when an incident occurs using the *V2VIncidentEventHeader* communication header message. In this regard, the safety related messages, which include periodic safety messages and emergency messages were generated randomly during the simulation using a random variable.

#### 3.5.1.2 WAVE Module

WAVE is wireless-based communication architecture in a vehicular environment specified by the IEEE standard focusing on two layers i.e. the MAC layer and the MAC extension layer. Accordingly, in NS-3, the implementation of the WAVE module could be found in the source directory *src/wave.* The module focuses on the MAC layer and the multichannel coordination layer, specifically to simulate the IEEE802.11p and IEEE1609.4 standard protocols for vehicular communications. IEEE802.11p MAC layer devices allow outside the context of a basic service set (OCB) communication, where the MAC does not require any association between the communicating devices in contrast to an ad hoc WIFI MAC. This functionality was modeled in NS-3 using a class *ns3::OcbWifiMac*. Consequently, by using this OCB features, the IEEE802.11p MAC layer and IEEE1609.4 MAC extension layer can provide devices with the capability of multichannel switching operation between the CCH and the SCHs using either a single radio or multiple radios in order to provide the transmission of safety messages and non-safety messages in a vehicular environment. Similarly, in NS-3, the PHY layer still maintains the 802.11a OFDM technology with a 10 MHz channel bandwidth. Thus to use an *802.11p NetDevice* to provide support for both the MAC and PHY layers the class *ns3::Wifi80211pHelper* is used. Also, to implement the WAVE module involving both the MAC layer and the MAC extension, the *WAVE NetDevice* is required using a class *ns3::WaveHelper* for providing multichannel operation mode. This feature also allows users to configure some of the wave communication attributes such as *TxPowerStart*, *TxPowerEnd*, and *TxPowerLevel* of the *YansWifiPhyHelper* class because 802.11p maximum transmits power is larger than that of Wifi and was not implemented in the WAVE module. Therefore, for the implementation of the EC-TMAC protocol, these attributes were configured to ascertain how the WAVE communication parameters alter the clustering process at variable traffic densities. Additionally, another important class in this module that is responsible for the channel coordination and scheduling is *ns3::ChannelCoordinator*. This class defines the CCHI, SCHI, and GI which can also allow users to alternatively change these values by configuring the class attributes. The detailed description of the WAVE module can be found at (*http://nasnam.org/docs/release/3.29/models/singlehtml/index.html#document-wave*).

However, VANET does not only involve communication protocols, but also the vehicular environment which involves vehicular mobility. The MAC layer in this module only adapts to MAC changes due to vehicular movement. It is quite evident that one of the main limitations of the existing WAVE module is the absence of support for customized vehicular mobility patterns. Therefore, to implement mobility pattern during the simulation in NS-3, users may decide to use *ns3::RandomWayPointMobilityModel* (RWP), even though, it does not capture the realistic mobility pattern of the vehicles. Another alternative is to generate NS-2-style playback mobility trace files using a third-party tool such as SUMO and then playback those generated mobility traces using *ns3::Ns2MobilityHelper* class. In the implementation of the EC-TMAC protocol, the WAVE module is used with the mobility traffic pattern generated using a SUMO software tool.

### 3.5.2 Simulation of Urban Mobility (SUMO)

SUMO, a microscopic and time-discrete traffic flow simulation tool has been used for the simulation of a defined scenario, usually vehicular communications and other applications such as traffic lights evaluation, etc. For proper execution, SUMO requires the configuration files and the data files which can be created and edited using a text editor by following the procedure below:

*Start → Windows Accessories → Notepad*

Similarly, two files are needed to define a network in a SUMO simulation, which includes the nodes file and the edges file. The nodes file with the extension *.nod.xml* consists of information about the nodes (intersections or junctions) defined by the variables x and y coordinates. Each node is defined on a separate line as shown below:

*<node id=”<string>” x=”<float>” y=”<float>” [type=”<type>”]*

The *node id* identifying the name of the node, while *x and y* parameters represent the position of the node in meters for both coordinates. An optional parameter *type* is enclosed in the square bracket *[ ]*, which can have different attributes and meanings. On the other hand, the edges file with the extension *.edge.xml* consists of information about the streets or roads. The edge is a connection between the two nodes (junctions). Every single edge can be described separately, as shown below:

*<edge id>=”<string>” from=”<node_id>” to=”<node_id>” [type=”<string>”] [numlanes=”<int>”] [speed=”<float>”] [priority=”<float>” [disallow=”< vehicle_class > [<vehicle_class>]*”]/>.*

The *edge id* is used to identify the street or the road, the node’s starting point and the destination point are defined using *from=”<node_id>” to=”<node_id>”*. Other attributes for the road, for example, the number of lanes, priority, speed limit, and the road access restrictions using allow or disallow parameter can also be defined as presented above.

After these two files are generated, the SUMO command-line application *Netconvert* is used to generates the road networks from different formats into the SUMO format. The output file generated is saved in a file using an extension *.net.xml* as shown below on the command line:

*Netconvert --node-files=name.nod.xml --edge-files=name.edge.xml --output-file=name.net.xml*

The configuration file formally with the extension *.sumo.cfg* contains the combination of the network file with the extension *.net.xml* and the traffic file also with the extension *.rou.xml* together with the simulation time. The output of this configuration file generates the mobility traces use by other third-party tools in an *xml* format. Generally, simulation can be implemented by calling this configuration file (*.sumo.cfg)* using the SUMO command-line application or through SUMO graphical user interface (SUMO_GUI). The detailed description of the SUMO implementation was presented in (Krajzewicz, Erdmann, Behrisch, & Bieker, 2012).

## 3.6 Simulation Setup

In this thesis, the simulations will be conducted using Network Simulator 3 (NS-3) version 3.21. The scenario set up is built on 2-lanes per direction in a highway road segment of 10 km. The realistic mobility pattern of the vehicles at variable densities will be generated using a SUMO tool, which is a micro-traffic simulator that has realistic mobility traces. This is achieved by using an OpenStreetMap (OSM) to generate a realistic map and fed as input to the SUMO. The OSM provides the required attributes such as road types, speed limits, traffic lights, and turns restrictions that are compatible with SUMO. As a result, the road map of Kuala Lumpur was extracted from the OSM database and is illustrated in Figure 3.5.

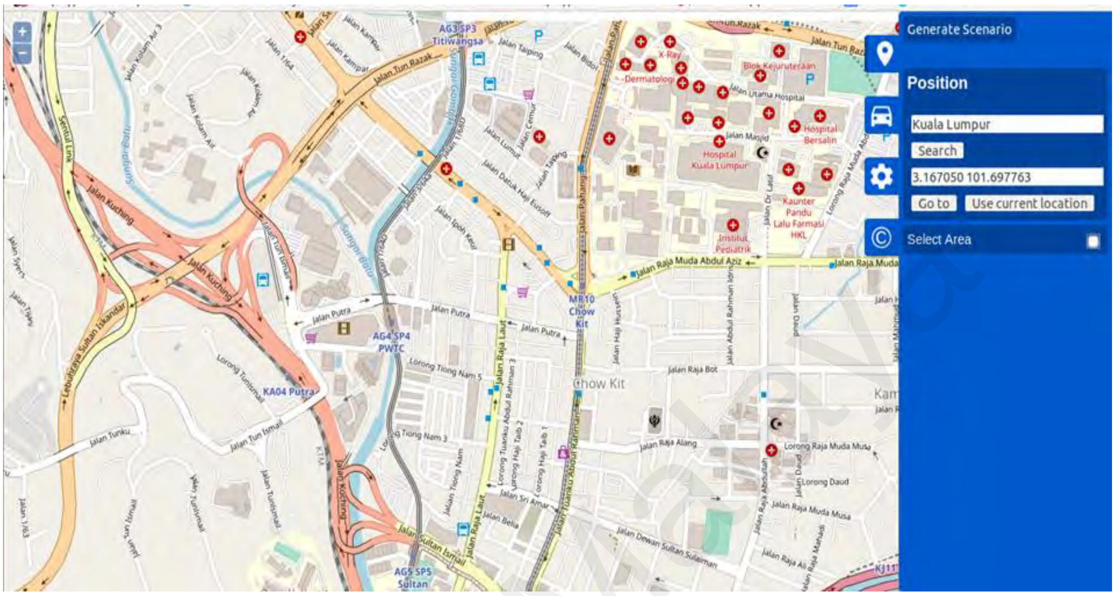



**Figure 3.5: Extracted road map of Kuala Lumpur from the OSM database**

The output file of the extracted map of Figure 3.5 is in the *xml* format, which is saved as *map.osm*. This output file is later converted into a network file using the *Netconvert* command as shown below:

*Netconvert –osm-files map.osm –output-file ectmac.net.xml*

The *ectmac.net.xml* file defines the nodes, edges, junctions and many other different traffic information related to the network environment. Similarly, to generate the mobility trace, a configuration file *ectmac.sumo.cfg* is used, which acts as an input to the SUMO. The map representation of the configuration file used by the SUMO is depicted in Figure 3.6.

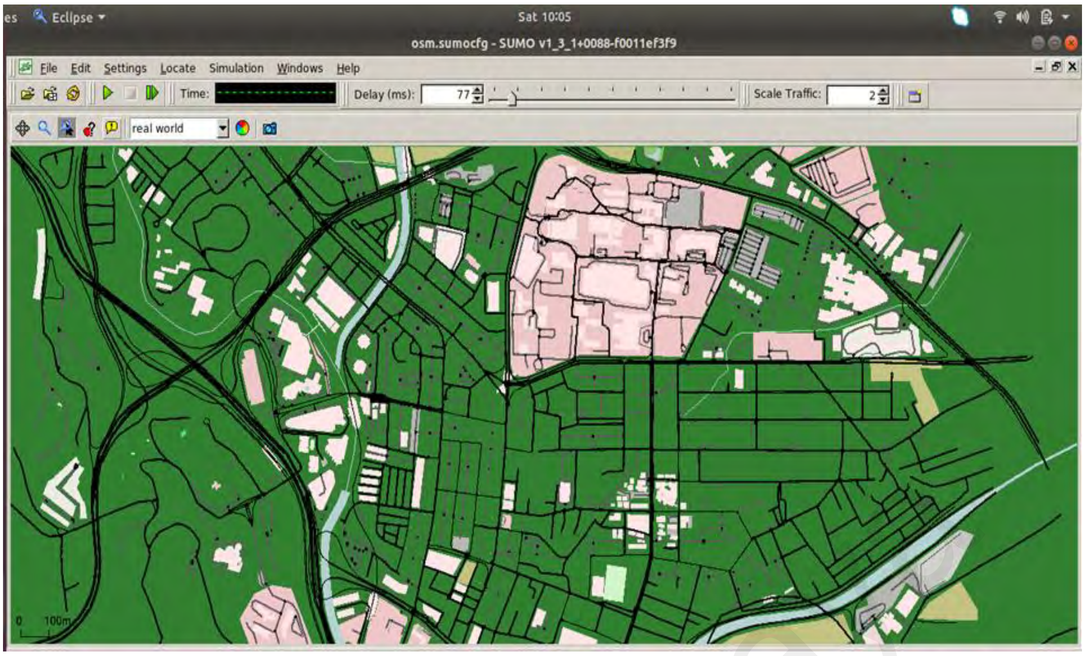



**Figure 3.6: OSM file imported into SUMO format**

However, this file cannot be used directly as a trace file for either NS-2 or NS-3. Hence, the need to convert the generated file into the *xml* format as shown below:

*sumo-c ectmac.sumo.cfg --fcd-output ectmacTrace.xml*

Finally, to generate the mobility trace for the ns3, the *ectmacTrace.xml* file is converted to vehicular traces that are compatible with ns2 using the *TraceExporter* command as shown below:

*traceExporter.py –fcd-input ectmacTrace.xml –ns2mobility-output ectmacmobility.tcl*

For communication over conventional DSRC channels, this research work employed the use of WAVE module that defines the IEEE802.11p/IEEE1609.4 standards for the PHY layer and MAC layer. The vehicles traveled towards the same direction with a mean velocity of 30 m/s and a mean deviation of 5 m/s in free traffic flow. Furthermore, the weight factor value associated with each metric for the PCH election process was arbitrarily defined based on the importance of each metric (Chatterjee et al., 2002; Xie

& Li, 2016). The weight value for the speed was 0.4, while for the remaining metrics, which include the vehicle's connectivity level and the position was 0.3 each. These weight factors provide the flexibility of adjusting the effective contributions of each metric. For instance, in this case, the vehicle's speed is more important than the other metrics, and therefore, the weight value associated with the speed metric can be made larger. The traffic density for the simulation was varied to show the different behavior of the proposed clustering algorithm. The vehicles at low, medium and high density were considered (i.e. 50, 100, and 150 vehicles). To specify how the wave communication parameters, affect the clustering process, this research work adopt the use of variable transmission ranges based on the different values of the tx power and the tx/rx gains (Aslam et al., 2019) at variable vehicular densities as shown in Table 3.1. This is because increasing the transmit power of the neighbor vehicles increases the spatial coverage, hence causing more neighbors to be known and consequently, resulting to more collision.

**Table 3.1: WAVE communication parameters configuration for the clustering scenarios (Katsikas et al., 2015)**

| Parameter | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| tx power | 24 dBm | 28 dBm | 32 dBm |
| tx gains | 6 dBm | 9 dBm | 12 dBm |
| rx gain | 6 dBm | 9 dBm | 12dBm |

Equally, as explained in Section 4.1, once algorithm 1 was executed, each vehicle within the vicinity of the transmission range exchanged information and the cluster groups are formed. The application model for the safety application provided by (Katsikas et al., 2015) was modified and reused. This was done with the view of determining the delay report generated during the transmission of safety messages to the CMs within the cluster. To validate the simulation results, different simulation runs were repeated for the same scenario. The simulation parameters are shown in Table 3.2.

**Table 3.2: Simulation parameters for SUMO and NS-3 and their values**

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Map dimension | 12 km x 14 km | DSRC channel bandwidth | 10 MHz |
| Highway length | 10000 m | DSRC channel frequency | 5.9 GHz |
| Lane distance | 3 m | Transmission rate | 6 Mbps |
| Mean velocity | 30 m/s | Message size | 200 bytes |
| Mean deviation | 5 m/s | Weight factors value | 0.4, 0.3, 0.3 |
| Simulation time | 400 s | Vehicles density | 50, 100, 150 |
| MAC/PHY | WAVE/IEEE802.11p | Maximum transmission range | 300 m |
| TDMA frame size | 100 msec | Cluster coverage occupancy (CCO) | 0.24 – 1.00 |
| Slot duration | 0.001 s | | |

## 3.7 Evaluation parameters

This section identifies the parameters that will be used to evaluate the performance of the proposed EC-TMAC protocol specifically, considering both the clustering process and the time slot allocation strategy among the neighbor nodes. An analysis will be conducted to evaluate the efficiency and the reliability of the proposed clustering algorithm by comparing its performance with the state-of-the-art benchmark algorithms presented in (Arkian et al., 2015), (Rawashdeh & Mahmud, 2012), (Hadded et al., 2014), and (Chaurasia et al., 2019). Similarly, the efficiency of the proposed time slot allocation approach will be evaluated. These state-of-the-art approaches will be compared using similar simulation environment by means of the following variable performance metrics: cluster stability, number of clusters formed, average end-to-end delay report generated for emergency messages, rate of merging collision and the communication overhead generated within the network.

### 3.7.1 Cluster stability

This metric assesses the effectiveness of the clustering algorithm in improving the stability of a cluster. The number of cluster changes as the vehicle's dynamics affect the cluster stability and this depends on the clustering algorithm. To ensure long cluster duration and provide support for reliable data delivery of safety applications, cluster stability should be given more priority while designing the clustering algorithm. In the proposed approach, the stability of a cluster has been evaluated by determining the number of times each vehicle changed its state in a cluster. This could be determined as follows:

- A CH moves out of its cluster
- A vehicle leaves and joins a nearby cluster
- Two nearby clusters merge

### 3.7.2 Number of clusters formed (NCF)

To evaluate the efficiency and the performance of the clustering algorithm, identifying the total number of clusters formed is one of the essential metrics to be considered. It is a known fact that less formation of clusters can decrease the network communication overhead. For that reason, it is always required that the cluster formation rate is maintained and minimized as much as possible to provide a stable cluster environment. Accordingly, this could be realized once the cluster formation messages are significantly minimized. In this proposed approach, any vehicle within the communication range can initiate the cluster formation.

### 3.7.3 Average end-to-end delay

Maintaining the same simulation parameters, this metric would attempt to evaluate the delay report of the incident messages generated specifically safety related messages, as a result of the cluster changes considering the worst-case scenario as discussed in Section 4.3.3. This generally occurs when there is an emergency incident message generated by the CM and transmitted to the PCH for onward broadcast to the CMs within the cluster.

$$\text{CM} \longrightarrow \text{CH} \longrightarrow \text{Cluster}$$

However, in a situation when the CH moves out of a cluster or when cluster merges happen as discussed in the previous chapter, the message will either be dropped or delayed before it reaches the CMs because of the absence of the CH that has the responsibility of broadcasting this message to the remaining CMs. The aggregation of the time of this delay during the broadcasting of this incident message is computed using the timestamp field that was included in the header message.

### 3.7.4 Rate of merging collision

The metric, rate of merging collision could be defined as the average number of merging collisions per frame per area within the cluster coverage, otherwise known as cluster coverage occupancy (CCO). This is because, the merging collision problem happens only as a result of the vehicles' movement, which is insignificant in terms of the length of one time slice. If several vehicles that lie within the adjacent clusters with the same time slot broadcast messages simultaneously, a merging collision will occur. This problem occurs only within the vehicles that already acquired their time slots. To determine the merging collision rate between the adjacent clusters, we considered various speed deviations for different cluster coverage occupancy values to define the optimal values for these parameters.

A parameter $(N_v \times R)/(L_h \times T_{spf})$ for cluster coverage occupancy (CCO) was defined (VeMAC, 2013) based on a highway traffic scenario, where $N_v$ is the total number of vehicles within the cluster, $R$ is the communication range, $L_h$ is the length of the highway segment and $T_{spf}$ is the number of the slots per frame on the CCH for each cluster. The CCO specifies the ratio of the number of time slots needed by a cluster to the total number of time slots available for a cluster.

### 3.7.5 Communication overhead

The communication overhead is one of the important parameters to evaluate the effectiveness of the clustering algorithm. This could be determined by identifying the extra control messages that are exchanged periodically within the cluster. The exchanged messages are required for the cluster formation process, channel allocation with respect to acquiring a time slot for every vehicle within the transmission range, and the cluster maintenance. The communication overhead generated, in this case, includes the hello packet overhead, cluster formation process overhead, cluster maintenance overhead, and the time slot allocation scheduling overhead.

## 3.8 Result validation and analysis

To determine the confidence level of the effectiveness of the proposed approach over the benchmark techniques, validation of the results has been conducted using a statistical analysis tool. In this research work, the T-Test analysis tool has been used to verify the significance of the proposed algorithms with respect to the benchmark techniques. This is because the T-Test analysis tool always confirms how statistically significant the differences between the two groups are or if their differences happened only due to random chance. In addition, it can also improve the level of confidence in the conclusion of the research work. The most important elements of the T-Test analysis are the t-value and the p-value or sometimes called the confidence level. The t-value identifies the ratio between the differences between the two or more groups. If the t-value is large for a particular group, it demonstrates that there are a significant difference and less similarity among the groups. In contrast, a p-value is the probability of confidence level describing whether the results from the data occurred by chance or not and is particularly ranges from 0% - 100%.

## 3.9 Chapter summary

This chapter discussed the detailed procedure undertook in this research work to effectively enhance the cluster-based TDMA MAC protocol. The overall research framework highlighting the different phases to be involved for this research work has been explained. Identified metrics for the clustering process have also been discussed in detail in Section 3.3. Similarly, the various network simulation tools required for the simulation in the vehicular environment which include both the commercial and open-source simulators as well as the mobility generators, in particular, have been discussed in Section 3.4. The justification for the selection of NS-3 and SUMO simulation tools for this research work is highlighted in Section 3.4.2 and Section 3.4.3. The chapter also goes further and discussed the necessarily needed functionalities from the NS-3 and SUMO tools that are essential for the implementation of the proposed EC-TMAC protocol in Section 3.5. Furthermore, the evaluation parameters as well as the results validation and analysis tool that will be used to determine the effectiveness of the proposed EC-TMAC protocol against the benchmark techniques have also been highlighted in Section 3.7 and Section 3.8 respectively.

# CHAPTER 4: ENHANCED CLUSTER-BASED TDMA MAC PROTOCOL

This chapter presents the implementation procedure of the EC-TMAC protocol based on the methodology proposed in Chapter 3. The detailed description of the designed proposed clustering process to enhance the cluster stability has been presented in Section 4.1. Also highlighted in Section 4.2 are, the needed functionalities required for the maintenance of the proposed EC-TMAC protocol. Section 4.3 presents in detail the time slot scheduling scheme for the proposed EC-TMAC protocol. The modified and the extended classes used in NS-3 to support the clustering process and the TDMA modeling have been highlighted, as well as the description of the worst-case scenario implementation for the safety related messages. Finally, Section 4.4 presents the chapter summary.

## 4.1 Cluster formation and CH election procedure

This section describes the detailed procedure for cluster formation and the CH election for the proposed EC-TMAC protocol. Two CHs were proposed to provide strong cluster stability within the clusters; the PCH as the main CH and the SeCH to act as a backup to the PCH. A combination of two clustering techniques, including weight-based and lowest ID were used to implement our clustering algorithm. The reason behind this is that a situation could arise when two or more vehicles may have the same weight values, in this situation, the lowest ID technique will be incorporated to determine the best suitable node to become the CH. The detailed description of the procedure follows below.

Initially, when a vehicle joins a network, it is considered a free node and shares its current mobility information (through hello message) with the neighboring vehicles within its transmission range. Similarly, it receives the same information from its nearby neighbors. Based on this received information (hello message), if a vehicle finds a PCH, it will affiliate and join the existing PCH, consequently, changing its status to become a CM. In a situation, when a vehicle finds more than one PCH within its transmission range, a decision needs to be taken by the vehicle to determine the most suitable PCH to join. This is achieved by comparing the position and the relative speed of the vehicle to the position and the relative speed of the available PCHs. The vehicle accepts to join the PCH if the position of the PCH is greater than the position of the vehicle. This is because safety messages are always better to be received from the vehicle ahead so that a decision can be taken in time to avoid the occurrence of any hazardous situation. If at the same time, two or more PCHs are ahead of the vehicle, then the vehicle will join the PCH with lower relative speed to the vehicle. Furthermore, if a CM loses connectivity to its PCH because of the vehicle's mobility, it will scan for nearby neighbors through the exchange of periodic messages where a new cluster may be detected. In contrast, if there is no any PCH nearby, the cluster formation process will be initiated. Any vehicle with the best suitable weight value within the communication range can initiate the cluster formation process, unlike the existing approaches. Each node will compete to become a CH based on its computed weight value $ß i$. The mobility information of each vehicle, together with the computed value is exchanged between the neighbors through periodic messages via the CCH. The node with the highest weight value is chosen as a CH. The vehicle that wins the election changes its status to PCH and is assigned a clusterID, which will be broadcast to the entire neighborhood. However, if two or more vehicles have the same weight value as the highest value, then the vehicle with the lowest id and having more neighbors will be elected as a CH. Each vehicle that joins the network will be assigned an identifier known as node id. The node ids are assigned based on the vehicles' arrival to the network beginning with zero (0). This can minimize the conflict of electing the PCH and the SeCH. Consequently, the elected PCH selects a vehicle from the CMs to become the SeCH. Figure 4.1 below shows the proposed clustering transition states.

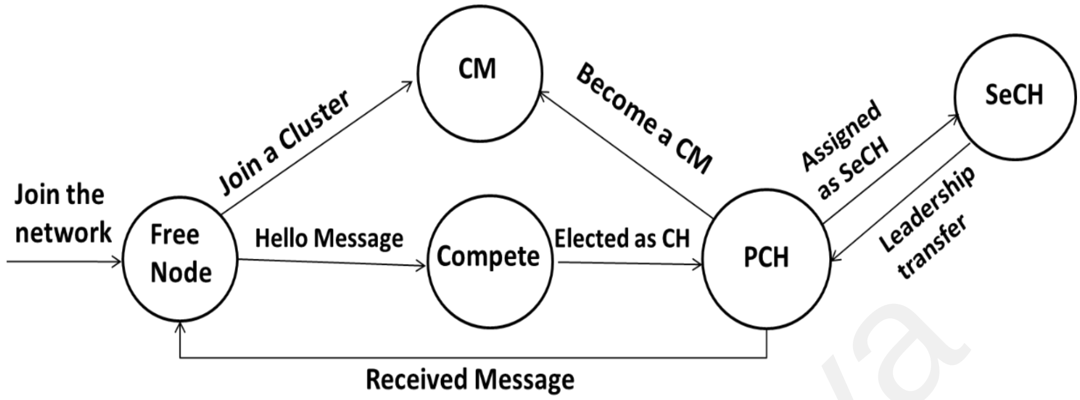



**Figure 4.1: Clustering transition states**

The flow chart in Figure 4.2 depicts the flow of the implementation of algorithm 1 for the cluster formation and PCH/SeCH election process. The following explains the description of this algorithm.

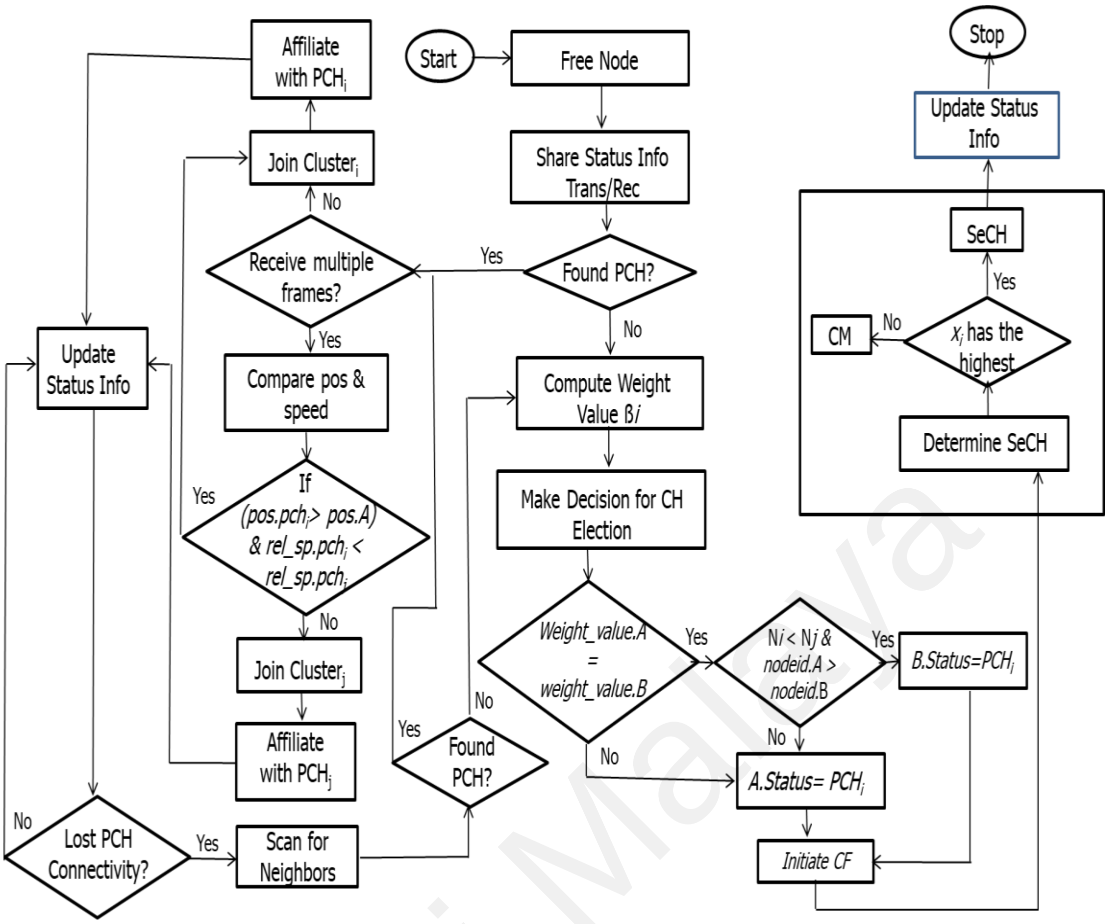



**Figure 4.2: Cluster head election flow diagram**

Each vehicle is assumed to maintain a list of its entire one-hop neighbor list (ONL) within its transmission range. Therefore, vehicle *A* builds a neighborhood relationship by exchanging a hello message initially with the other vehicles within its communication range. If it receives a cluster join message $C_{jrm}$, it means there is already an existing cluster within the vicinity; consequently, it will acknowledge and join the cluster. This is shown in Algorithm 1 from lines 1 – 11. In contrast, if vehicle *A* does not receive $C_{jrm}$, then there is a need for cluster formation and CH election. At this stage, each vehicle has the information about its neighborhood, and can hence allow the computation of the suitability value to determine which vehicle will become the PCH. This new status information will be broadcast to all its neighbors' within the cluster. On receiving this information, the vehicle executes the CH election algorithm to determine the highest weight value. If it has the highest weight value, then it will declare itself as the PCH by assigning its ID as the CH ID; otherwise, it will wait for some time $T_x$ for a cluster join message request. When the waiting time for vehicle *A (A.*$T_x$) expires and the vehicle does not receive any request from any neighboring vehicle, then the vehicle initiates the cluster formation.

For a vehicle *A* to initiate the cluster formation as stated earlier, it has to wait for some time $T_x$ before accessing the wireless medium to announce its eligibility of becoming the PCH. It is quite known that the MAC layer is controlled by the distributed coordination function (DCF) (Bianchi, 2000; X. Ma, Yin, & Trivedi, 2012), where vehicles utilize both the minimum contention window size ($CW_{min}$) and the maximum contention window size ($CW_{max}$) values. For each unsuccessful transmission, the vehicle doubles the $CW_{min}$ value until it reaches the max value. The time required for a vehicle to wait is defined in Eq. (13).

$$T_x = \left[\frac{Nmax - \beta i}{Nmax} * (CWmax - CWmin) + CWmin\right] \tag{13}$$

$N_{max}$ is the total number of vehicles within the transmission range. When two or more vehicles with the same $T_x$ sends form cluster message concurrently, a collision will occur; accordingly, none of the vehicles will be able to form a cluster. In this situation, the vehicles would start new iterations of competition until one of them wins. If a collision still occurs, and the maximum number of contention window size is reached, then a vehicle with the lowest id will be elected and will win the election. Subsequently, the elected vehicle will send the form cluster message through InitiateCluster () to all the vehicles. At this time, the vehicle will change its status to PCH and set its ID as the clusterID. The procedure is shown in Algorithm 1 from lines 12 – 35.

**Algorithm 1:** Cluster formation and CH election process

**Inputs:** Number of neighboring nodes, position, speed, road id, direction, Hello message, nodeid

**Outputs:** Weight value

1: $A$.Broadcast$_{hello_message}$ // vehicle A broadcast a hello message to the neighbor vehicles
2: **If** $A$ receive $C_{jrm}$ **Then** // already existing cluster within the vicinity
3: **If** multiple beacon frames received **Then** // determine the best suitable PCH to join
4: **If** (pos.pch$_i$ > pos. $A$) & (rel_sp.pch$_i$< rel_sp.pch$_j$) **Then** // compare the position and the relative speed of the PCHs
5: Join Cluster$_i$ // join cluster$_i$ and affiliate with PCH$_i$
6: $A$.status = CM // vehicle A acknowledges the request and joins the cluster
7: **Else**
8: Join Cluster$_j$ // join cluster$_j$ and affiliate with PCH$_j$
9: **End If**
10: **End If**
11: **End if**
12: Goto step 35
13: **If** $A \in x_L$ **Then** // where $x_L$ is the set of all vehicles within $T_{range}$
14: Suitability. $A$ () // calculate the suitability value of a vehicle
15: $A$.Broadcast$_{hello_message}$ // vehicle A broadcast status information together with its weight value
16: $A.T_x \longleftarrow T_x$ ( ) // calculate the waiting time for a cluster head response
17: **While** $A.T_x > 0$ **do**
18: **If** InitiateCluster (CH$_{id}$) is received **Then**
19: StopCompetition () // CH found
20: Process InitiateCluster (CH$_{id}$) // process the received message
14: **Else**
21: Decrement waiting time $A.T_x$
22: **End if**
23: **If** weight_value.$A$ = = weight_value. $B$ **Then**
24: **If** ($N_A < N_B$) & *(nodeid.A> nodeid.B)* **Then** // determine the vehicle with more neighbors

```
                    B.status ←—— PCH   // vehicle B changes its status to PCH
                    nodeid.B ←—— CHid  // vehicle's id is set as a clusterID
               Else
                    A.status ←—— PCH   // vehicle A changes its status to PCH
                    nodeid.A ←—— CHid  // vehicle's id is set as a clusterID
               End if
          End if
     End while
     Send InitiateCluster(CHid    // CH broadcasts its id to all neighboring vehicles
  End if
End                               // end cluster formation and CH election process
```

The next step, therefore, is for the new PCH to determine the SeCH within the CMs. The vehicle with the highest weight value among the remaining vehicles will be elected by the PCH. The elected vehicle will be assigned the SeCH status while the remaining ones will become the CMs. This is shown in Algorithm 2 from lines 1-9.

**Algorithm 2:** To determine the secondary cluster head (SeCH) by the elected PCH

**Input:** nodes weight value

**Output:** highest weight value

```
1:   highest_ wv = array [0]
2:   For each vehicle do   // iterate all to determine the CM to be assigned as the SeCH
3:       If (array [i] > highest_ wv Then
4:           highest_ wv = array [i]
5:           Status. A ←—— SeCH    // assign the node status as SeCH
6:       Else
7:           Status. A ←—— CM      // node status assigned as cluster member
8:       End if
9:   End for
```

## 4.2 Cluster maintenance

In the VANET environment, vehicles can either join the highway at any time or leave because of some reason. However, this behavior can affect cluster stability as well as the reliability of the MAC protocol, particularly if it involves CH. Hence, a suitable mechanism is required for maintaining the stability of the cluster. Below are the situations that trigger the maintenance procedure:

### 4.2.1 Leadership transfer from PCH to SeCH

When the primary CH can no longer be a CH or moves out of the cluster by taking an exit, the SeCH will take over the leadership role within the cluster instead of cluster reconfiguration. Eventually, this primary CH will change its status to a CM. This change does not affect the cluster structure, only the role of a CH will be transferred to the SeCH. The new primary CH will then select a new SeCH. Figure 3.4 shows the CH leadership transfer procedure flow diagram, which is implemented in Algorithm 2.

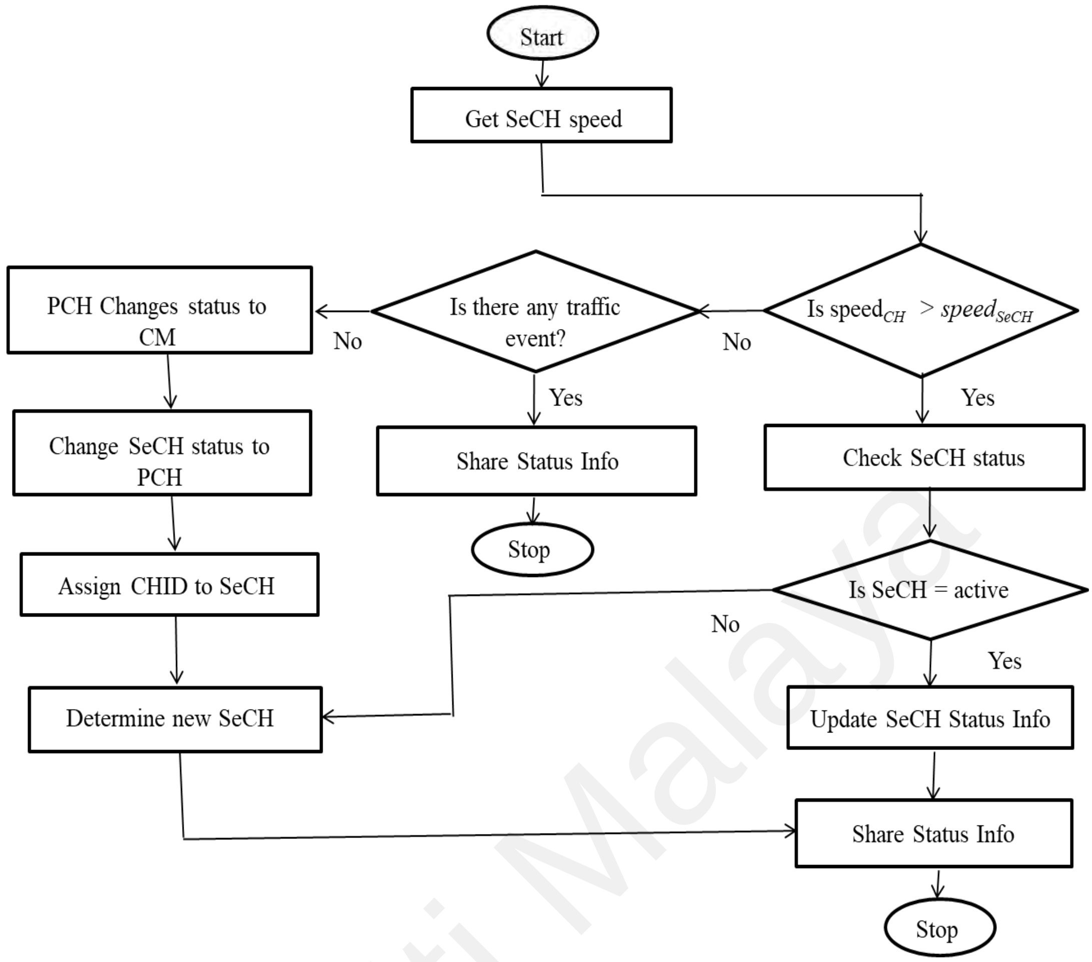



**Figure 4.3: CH leadership transfer flow diagram**

Note that a vehicle that is about to stop by reaching its destination or wants to take an exit must slow down. Therefore, this research work considers speed as the main criterion to determine whether the PCH is suitable to continue with its leadership or not. Furthermore, the PCH needs to maintain the status information of its SeCH periodically in order to ensure that it is active for taking the responsibility when the need arises. This is attributed to the fact that the SeCH might have left the cluster when the primary CH is trying to take an exit as well. Therefore, in the process of this update whenever it determines the current speed of the primary CH is greater, the PCH continues with its leadership. Consequently, it will update the status information of the SeCH and share this information to all the CMs.

However, in a realistic scenario, a vehicle may be forced to slow down because of some incidences that might occur on the road, such as a traffic jam due to an accident or a blockage on the road. In this case, the PCH will not give up its responsibility. However, when the current speed of the SeCH is greater than that of the PCH without any incidence happening on the road, the primary CH slows down and is about to take an exit. Hence, the primary CH resigns its responsibility for leadership and changes its status to CM. The SeCH then changes its status to PCH and assigns its ID as clusterID. A new SeCH is later determined by the new PCH using the same procedure as described in Algorithm 2 above. The updated status information is then broadcast to all the CMs within the cluster.



**Algorithm 3:** Transfer of leadership from CH to SeCH

**Input:** current speed

**Output:** status information

Get $speed._{SeCH}$ // get the current speed of SeCH for the periodic update

**If** $speed._{CH}$ > $speed._{SeCH}$ **Then** // check whether the current speed of CH is greater than the speed of SeCH

Broadcast$_{hello_message}$ // update SeCH status information

**Else If** any traffic incidence **Then** // check whether there is any incidence happening on the road such as a traffic jam

Update and share status information with the CMs

**Else**

$x_{CH} \longleftarrow$ CM // cluster head status changes to cluster member

$x_{SeCH}$.Status = CH // change CH leadership to SeCH as PCH is about to take an exit

$x_{CH} = x_{SeCH}$ // assign CID to the SeCH vehicle

| | |
|---|---|
| 10: | **End if** |
| 11: | Assign a new SeCH and share status information with the CMs |

### 4.2.2 Cluster merging

A situation where two CHs are within the same communication range of each other, traveling in the same direction, and the same road id, it requires cluster merging. In this scenario, after the two CHs exchanged their status information through hello message, they can determine among them the one with the best suitability value. The CH with a higher weight value as computed by Eq. (11) will continue with the cluster leadership, while the other CH will give up its leadership and change its status to CM. The remaining CMs will determine whether they can communicate with the new CH. If they cannot communicate with the existing CH, a nearby cluster will be located using the received hello message. However, in the absence of any cluster within their communication range, a new cluster formation process will be initiated, as discussed in Section 4.1.

### 4.2.3 Leaving a cluster

Because of the dynamic nature of the vehicles on the road and rapid changes in the network topology, a vehicle might just take an exit along the highway or moves out of the cluster as a result of reaching its destination. Therefore, when a CH does not receive a hello message from its CM in one TDMA frame cycle, it will assume that the CM is disconnected and leaves. This could result in the CH removing the record of that CM from its list by declaring its allocated time slot and local id as free. Consequently, the CH sends the updated information to all its current CMs.

## 4.3 Time slot allocation scheme for EC-TMAC protocol based on binary tree algorithm

This section gives a detail description of our proposed time slot scheduling scheme for the EC-TMAC protocol. It is quite obvious that due to the vehicle's high mobility, two adjacent clusters can share an overlapping transmission area, which mostly can cause interference and result in transmission collision. As a result, a dynamic time slot scheduling scheme using the binary tree algorithm capable of decreasing the effect of the inter-cluster interference problem have been proposed.

Using a multichannel access scheme a CCH denoted as $c_0$ is dedicated to transmitting high priority short applications (i.e. basic safety messages or emergency messages) and other control information. In contrast, the SCHs are mostly use for transmitting non-safety messages and denoted as $c_1$, $c_2$ … $c_n$, where n is the maximum number of SCHs, as depicted in Figure 4.4.

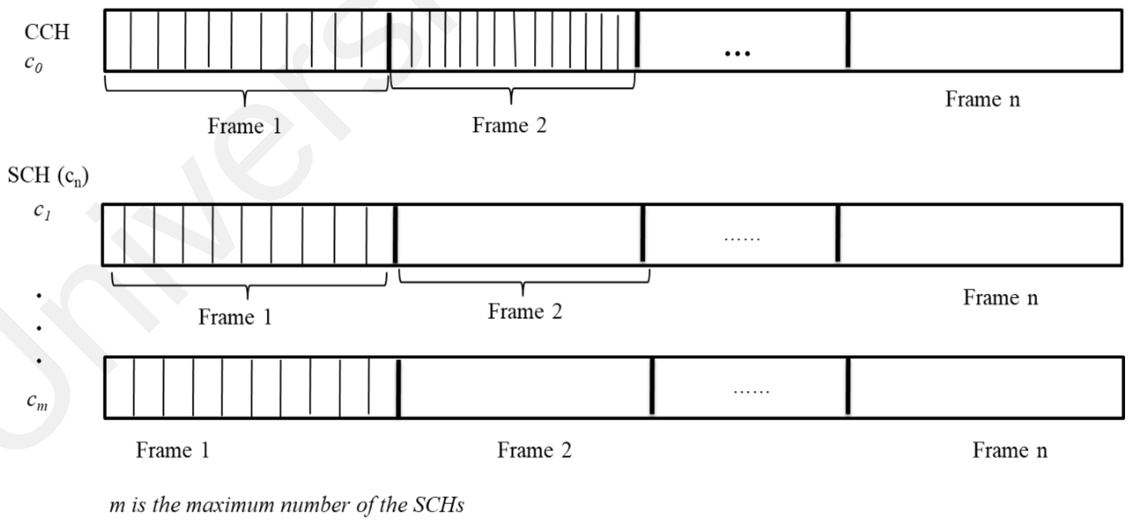



**Figure 4.4: EC-TMAC frame structure**

Each logical TDMA frame is of the same size and must transmit a hello message after every 100 msec in each frame using its allocated time slot in order to meet up the requirement of the safety related messages. Each frame consists of several time slices with a slot duration represented by τ. The time slice duration is corresponding to the size of the transmission latency of the safety message packet (Ahizoune, Hafid, & Ali, 2010), which should be enough to transmit a data packet completely without requiring any defragmentation. This is given in Eq. (14) by (Guo, Huang, Chen, Xu, & Xie, 2012):

$$\tau = \frac{P}{T_{rate}} \tag{14}$$

Where, $p$ is the size of the packet and $T_{rate}$ is the data transmission rate.

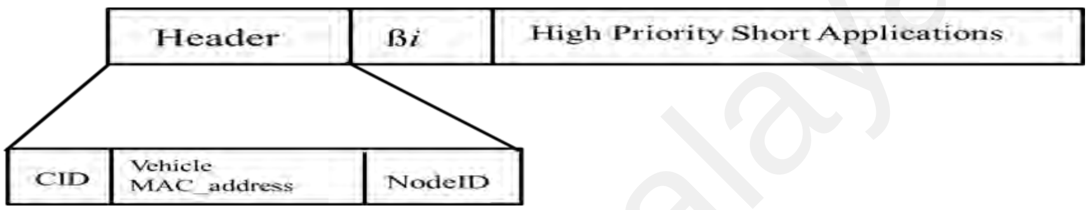
Furthermore, all vehicles are assumed to have fixed transmission power levels. Similarly, they also utilized a single transceiver for multichannel operation as specified in IEEE802.11p/WAVE standard (Group, 2010). The coverage area of each cluster is determined by the communication range of the CH, i.e. R meters (Sheu & Lin, 2014).

### 4.3.1 EC-TMAC protocol packet structure

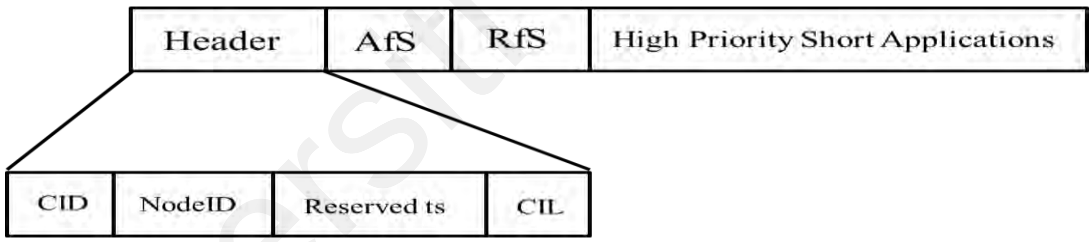
This scheduling scheme operates on a stable cluster utilizing two forms of packet structure, which include Type A and Type B packets, as shown in Figure 3.6. The information is included in the header packet of each node, which is communicated within the cluster through the CCH. The main idea here is for the PCH to use the position of a vehicle to decide which time slot should be assigned to it.

Type A packet is transmitted by a node to request and acquire a time slot from the PCH on the CCH. Once the PCH determines the position of this vehicle based on the received hello message, it can reserve any available time slot to it accordingly, as specified in algorithm 4. In contrast, the Type B packet is used by both the PCH and CMs respectively, for a status update and other control information purposes. Similar to the VeMAC protocol (Omar et al., 2013), each Type B packet consists of four different fields; the header field, the announcement for service (AfS), request for service (RfS) and high priority short applications (i.e. message type which could either be periodic or emergency message).

However, on the contrary to the VeMAC protocol, in the header field included is the clusterID and the cluster information list (CIL).




**(a): Type A packet structure**




**(b): Type B packet structure**

**Figure 4.5: Format of each packet transmitted on the CCH (Omar et al., 2013)**

The header field consists of the following information:

- CID: The clusterID represents the cluster head ID which identifies the cluster a vehicle belongs to.
- Vehicle MAC_address: This identifies the vehicle MAC address.
- NodeID: A short identifier used to identify a particular node within the cluster. It is assigned to the node based on the arrival to the network.

- Reserved ts: Identify the time slot reserved by the node on the CCH.
- CIL: The CIL provide the list of all the CMs with the associated reserved time slot on the SCHs.

### 4.3.2 Time slot reservation mechanism on the control channel

Basically, our scheduling scheme on the control channel is implemented using the binary tree algorithm. It is considered that the CH position is the root of the tree and lays in layer zero (L) where all the other vehicles' positions within the cluster would be compared. The position of the vehicle *A* in the left subtree is less than the position of the CH (i.e., vehicles behind the CH, b = pos.CH > pos.*A*), and the position of the right subtree vehicle is greater than the position of the CH (i.e., vehicles ahead of the CH, f = pos.CH < pos.*A*). If the root node is $r_i$ (i.e. a binary number), then the left child will be represented by 0 and the right child represented by 1, meaning that there are $2^L$ nodes in the layer L of a binary tree. This is shown in Figure 4.6. Each layer in a binary tree would result in two child nodes.

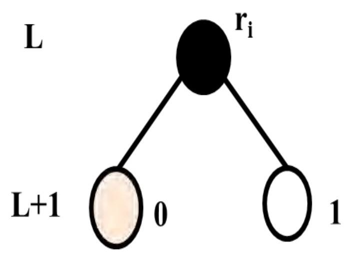



**Figure 4.6: Binary tree structure**

Based on the binary tree algorithm, the CH determines the position of each CM. Depending on the position of the vehicle with regard to CH, it could either be ahead or behind (*f* or *b*) of the CH, as shown in Figure 4.7. Each frame is designed to accommodate vehicles within the cluster based on their position with respect to CH.

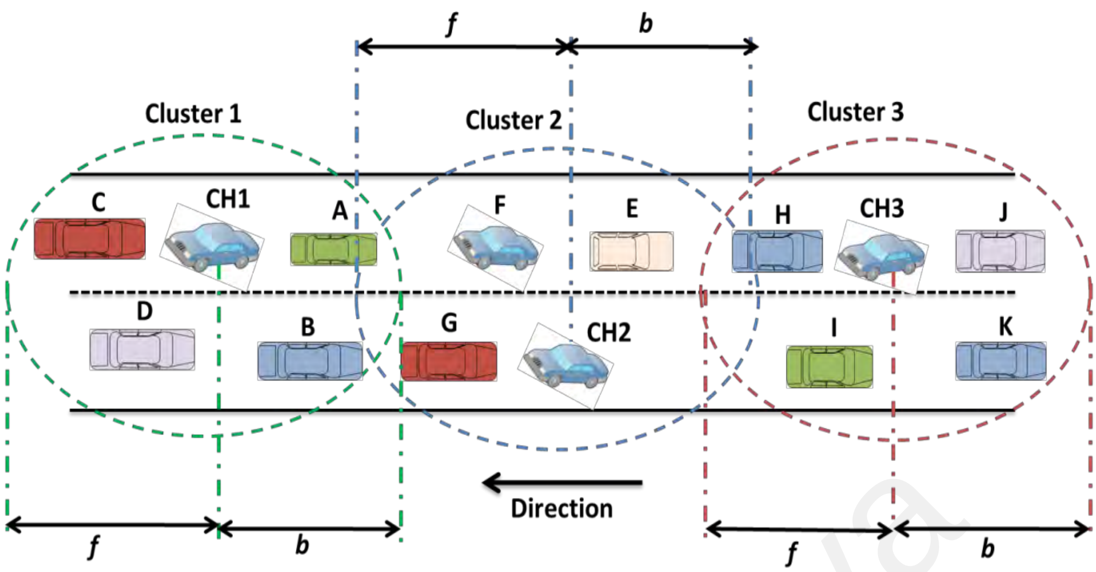



**Figure 4.7: Vehicles position in a cluster**

The nodes on the left subtree $N_{b(x)}$ represent the vehicles moving behind the CH, while the nodes on the right subtree $N_{f(x)}$ represent those moving ahead of the CH. The time slots reserved for each set of vehicles are defined as follows:

- The subset of time slots reserved for vehicles belonging to $f$ set is $S_{f(x)}$ ∀ $N_{f(x)}$.
- The subset of time slots reserved for vehicles belonging to $b$ set is $S_{b(x)}$ ∀ $N_{b(x)}$.

The vehicles at the front of the CH will get the odd index value while those behind the CH will get the even index value of the time slice.

A vehicle *A* requesting for a time slot sends a Type A packet to the CH. Using the binary tree algorithm, the CH can determine the position of this vehicle with respect to its position. If the position of the CH is greater than the position of the vehicle *A* (*pos.CH* >= *pos.A*) then the CH allocates any available slot from the set of time slots $S_{b(x)}$ to the vehicles behind the CH as specified in algorithm 4, where vehicle $A \in N_{(X)}$,

$\forall N_{b(x)} \in N_{(X)}$. Otherwise, the position of vehicle *A* is greater (*pos.CH* <= *pos.A*), then allocate any available slot from the set of time slots $S_{f(x)}$ to the vehicles ahead of the CH, $\forall N_{f(x)} \in N_{(X)}$. The same procedure will continue until all the vehicles within the cluster are assigned the required time slot. Once the CH completes the slot allocation to each of the vehicles within the cluster, it then broadcast this scheduled update through the Type B packet to all its CMs. The process flow of this time slot scheduling scheme on the CCH for the EC-TMAC protocol is illustrated in Figure 4.8.

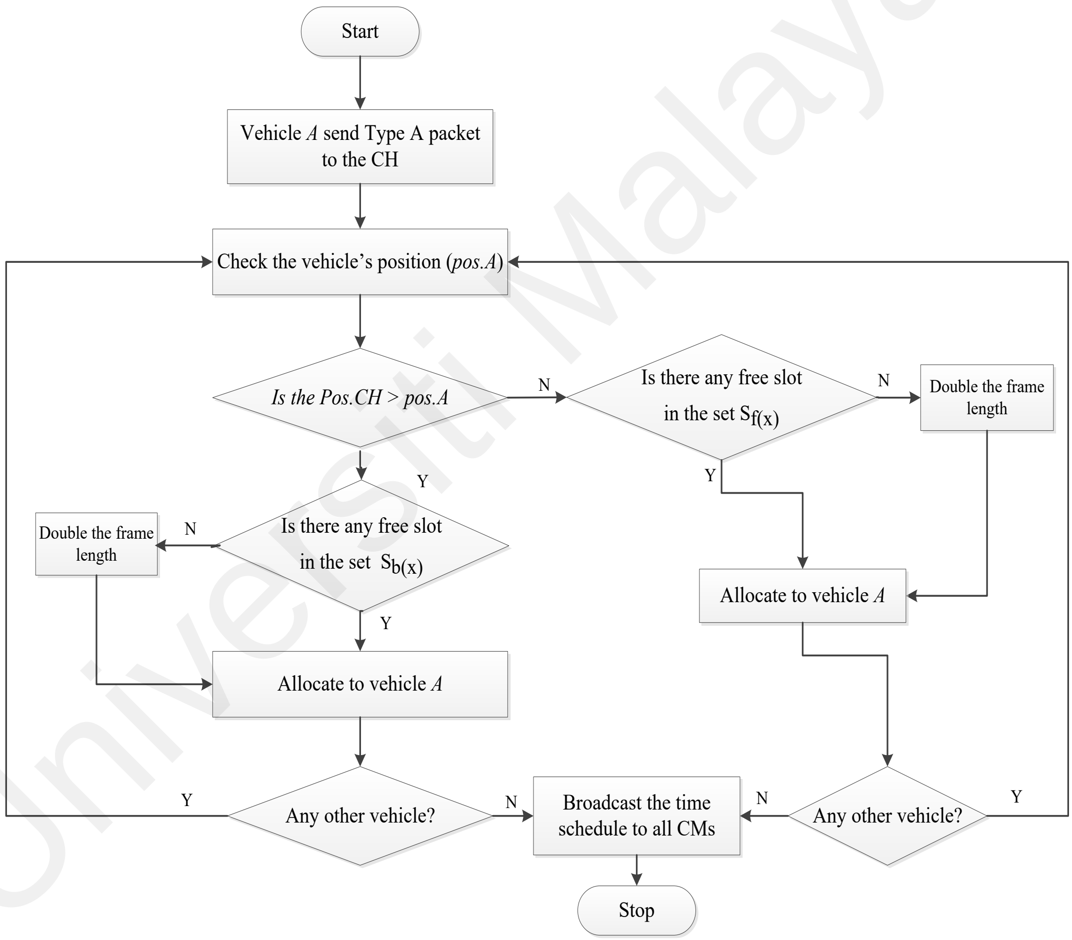



**Figure 4.8: Time slot scheduling scheme on the CCH process flow diagram**

Algorithm 4

Input: *Hello message*, *pos.CH, pos.A*, $N_{(X)}$, $S_{(x)}$

Output: $N_{b(x)}$, $N_{f(x)}$, $S_{b(x)}$, $S_{f(x)}$,

vehicle *A* sends Type A packet through hello message

**If** vehicle $A \in N_{(X)}$ **Then** // check if the vehicle is a cluster member

Determine_position ()

**If** *pos.CH >=pos.A* **Then** // identify the position of the vehicle with regard to the CH

$A \in N_{b(x)}$ // vehicle *A* belongs to the vehicles moving behind the CH

**Else**

$A \in N_{f(x)}$ // vehicle *A* belongs to the vehicles moving ahead of the CH

**End If**

**Else**

Discard the message // vehicle *A* does not belong to the cluster

**End If**

Determine_setofTimeSlots () // identify and allocate the time slots to cluster members

**For** i = 1 to N -1 **do**

$S_{(x)}$ = Rand[1, N-1] // generate time slots from 1 to N-1, where N is the maximum no. of slots

reserve the last index value of the time slot for the CH

```
17:       If (i mod 2 = 0)   Then      // identify the set of index value of the time slice
18:           assign the available time slot to vehicle A
                                  // set of even index value of the time slots reserved
                                  // for vehicles moving behind the CH
19:           Else If no any available time slot to allocate   Then
20:                   double the frame length
21:                   Go to 14
22:           End If
23:       Else
24:           assign the available time slot to vehicle A
                                   // set of odd index value of the slots reserved
                                     for vehicles ahead of the CH
25:           Else If no any available time slot to allocate   Then
26:                   double the frame length
27:                   Go to 14
28:           End If
29:      End If
30:    End For
31:    broadcast this allocation to all cluster members
32:   end
```

From Figure 4.7, based on our proposed scheduling scheme in Figure 4.9 and Figure 4.10, vehicle B in cluster 1 and vehicle G in cluster 2 are assumed to acquire a disjoint set of time slots. Thus, vehicle B would be allocated among the set of the available even index value of the time slots (e.g. *2, 4, 6, . . . n*). On the other hand, vehicles G would be allocated within the set of available odd index value of time slots (e.g. *1, 3, 5, . . . n-1*). This technique avoids inter-cluster interference within the adjacent CMs. Hence, it minimizes the merging collision problem. Because each adjacent CM, even if it is within the communication range of each other, the transmission will not be affected, since they are using a disjoint set of time slots. Consequently, each vehicle also will continue to maintain its reserved time slot for all the remaining frames.

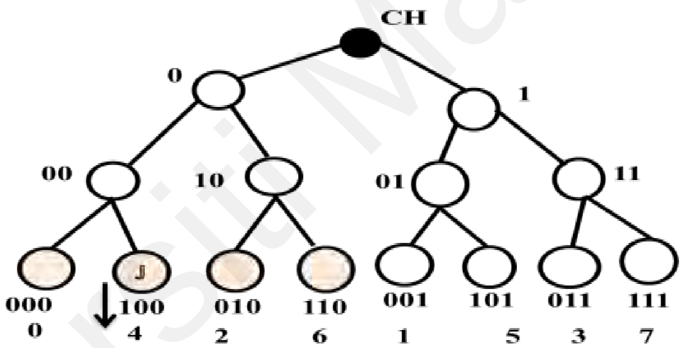



**Figure 4.9: Binary tree representation of the time slots allocation for the EC-TMAC protocol**

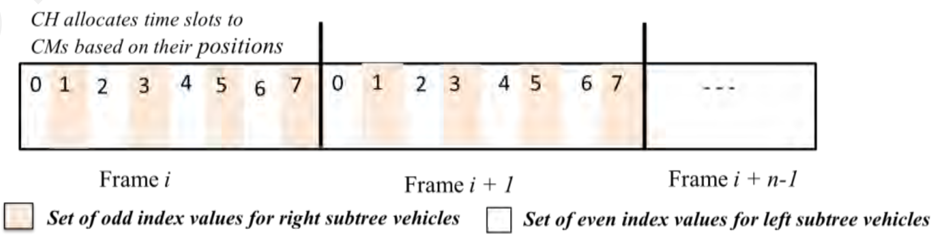



**Figure 4.10: Time slots allocation for the EC-TMAC protocol on the CCH**

Accordingly, each CM must be assigned a unique time slot in a frame on the CCH and keep accessing it for all remaining frames within the transmission range unless detected a merging collision. However, this problem could happen because of the rapid topology changes in the vehicular environment, as shown in Figure 4.11.

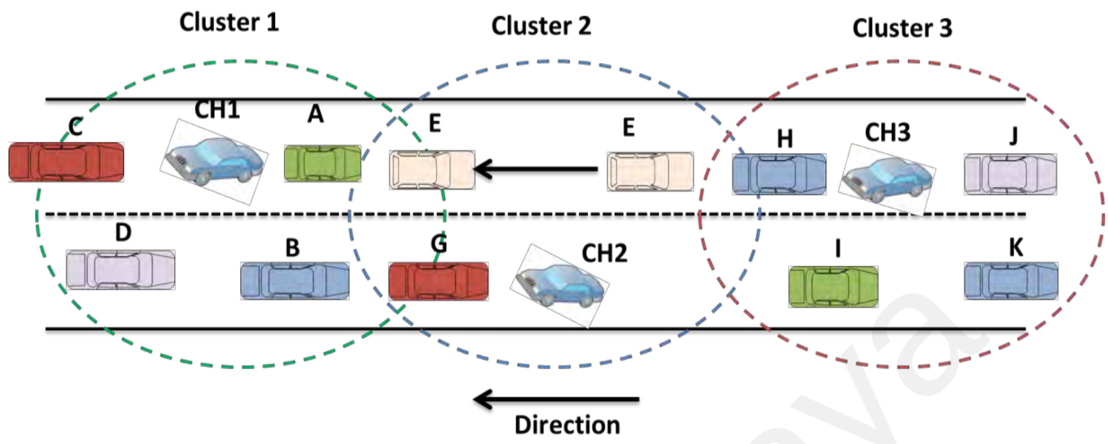



**Figure 4.11: Merging collision conflict resolution**

Initially, vehicle E in cluster 2 was moving behind CH2 and allocated the same time slot index value with the vehicle A in cluster 1, also moving behind its cluster head (CH1). If vehicle E becomes within the transmission range of vehicle A because of the nodes' mobility, then it could result in a merging collision problem. As a result, if a vehicle detected a merging collision, in this case, the vehicle moving behind will surrender its reserved time slot to resolve the problem. The reason behind this is to avoid missing any safety message that could be generated by the vehicle moving ahead. It is quite well known that the safety messages are considered more important with regard to the safety of the lives of the passengers and drivers, hence need to be broadcast backwardly to the neighbor vehicles within the vicinity. Consequently, a Type A request packet would be sent to the proper CH by the concerned vehicle to acquire a new time slot.

Furthermore, another scenario could happen when a CH experiences an unbalanced traffic situation which is very possible in a realistic scenario. In this case, the TDMA frame can be adjusted dynamically to maintain the size of the cluster. This can be achieved by doubling the existing frame length. For instance, consider a scenario in Figure 3.11, where all the vehicles moving ahead of the CH were allocated all the available time slots on the left subtree $S_{f(x)}$. If another vehicle joins the network and happens to be ahead of the CH, the CH will double the frame length if the ratio between the number of vehicles in the cluster and the time slots does not exceed the maximum cluster threshold $CL_{th}$ that the cluster can hold as given in Eq. (15).

$$\frac{N_{(x)}}{S_{(x)}} \geq CL_{th} \qquad (15)$$

Consequently, this will not affect the original schedule of the existing CMs and provide another free slot for the new arrival. This is depicted in Figure 4.12 and Figure 4.13, where vehicle J was allocated to time slot index value 4, and hence after the dynamic adjustment of the frame length, it still maintained the allocated time slot together with the free additional slots for the incoming vehicles.

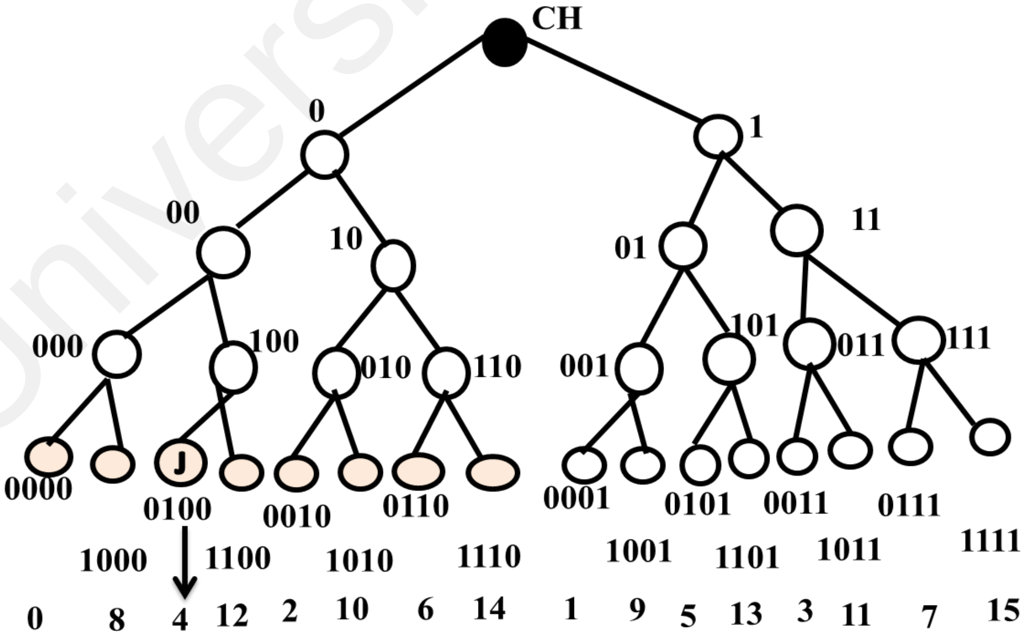



**Figure 4.12: Binary tree adjustment due to traffic condition**

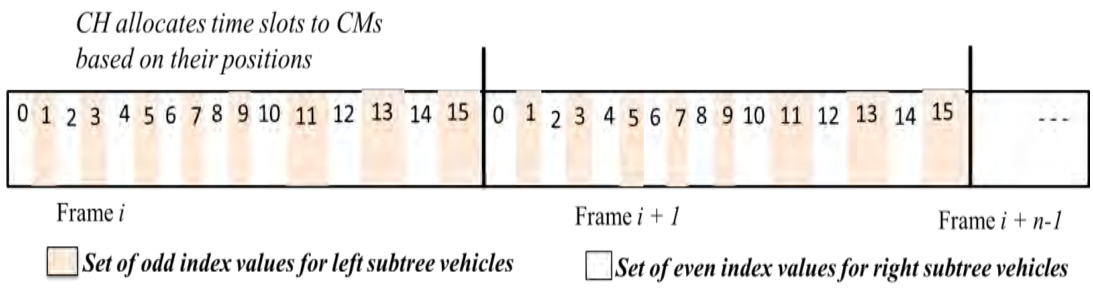



**Figure 4.13: Dynamic time slots adjustment for the EC-TMAC protocol on the CCH**

### 4.3.3 Service channels access using a 3-way handshake mechanism

In contrary to the CCH, the SCHs transmit non-safety message, which is denoted by $c_n$, where n = 1 . . . m. Each SCH synchronized with the CCH and contain the same number of frames as shown in Section 4.3. The time slots on the SCHs (Ts) can have different indices such that $i \neq j$ for channels $c_i$ and $c_j$ since slot $Ts_i$ is not necessarily equal to slot $Ts_j$.

To exchange the non-safety messages for any vehicle within the cluster, a 3-way handshake mechanism is used through a Type B packet as explained in Section 4.3.1. A vehicle that has any service to deliver to its neighbor or want to request for a service, it needs to exchange the Announcement for Service or Request for Service (**AfS/RfS**) packets during its allocated time slot on the CCH via a CH. For instance, if node ***A*** has a service to offer to its neighbor node ***B***, then node ***A*** has to transmit **AfS** message to the CH, which consequently, the CH broadcast to all the CMs. Therefore, node ***B***, which requires the service, can send the acknowledgment (ACK) during its time slot on the CCH. The service provider which is node ***A*** can now confirm by sending the Response (**Res**) message. Figure 4.14 shows how nodes *A* and *B* exchange non-safety messages between them.

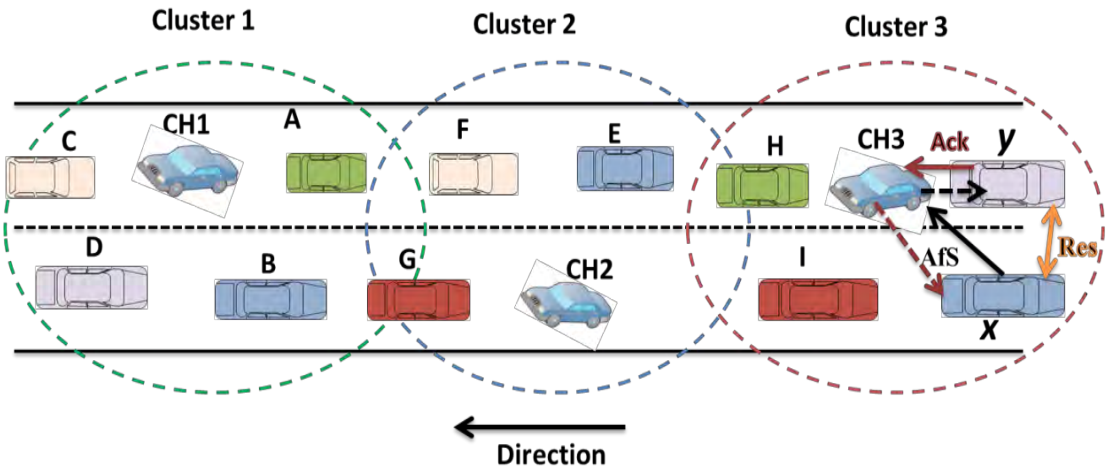



**Figure 4.14: Exchange of non-safety messages between nodes *x* and *y* on the SCH**

Similarly, nodes that wish to request for a service within the cluster can send **RfS** message through CH during their reserved time slots on the CCH. The CH broadcast the message to all the CMs. Any CM with the specified service can send a reply back to the CH that it has the service. The node requesting the service can now respond by sending the **Res** message. Before initiating the communication, the sender and the receiver has to check Cluster Information List (**CIL**) which maintains the list of all the CMs and the associated SCHs time slot already reserved by each node respectively (that is service channel number ($SC_n$) and the reserved time slot on the SCH (Ts)). Consequently, the receiver node can select a common available free SCH and slot number. The CIL format is shown in Figure 4.15.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| NodeID_1 | ts | $SC_n$ | Ts | NodeID_2 | ts | $SC_n$ | Ts | - - - NodeID_n |

**Figure 4.15: Cluster information list format**

The following are the steps involved for communication between the cluster members through the SCHs as shown in Figure 4.14:

*i.* AfS ($A \xleftrightarrow{\text{Via CH}} B$): AfS/ACK/Res. Communication between sender node $A$ to the receiver node $B$ through the CH. Common SCH and slot number will be selected for both nodes $A$ and $B$

ii. RfS ($A \xleftrightarrow{\text{Via CH}} B$): RfS/ACK/Res: Communication between sender node $A$ to receiver node $B$ through the CH. Common SCH and slot number will be selected for both nodes $A$ and $B$.

iii. Data Transmission begins ($A \longleftrightarrow B$): Data exchange starts between node $A$ and node $B$ using the same channel and slot number

Consider a scenario where node $A$ has a service to offer in one of the SCHs. Let $slot_A^n$ be the set of time slot that node $A$ cannot use on channel $c_n$ in the next frame, where n = 1 . . . m. Similarly, the set of time slots accessible by node $A$ to offer the service on channel $c_n$ is denoted by $aslot_A^n$ such that:

$$aslot_A^n \cap slot_A^n = \emptyset \tag{16}$$

This is to avoid access collision on the specified service channel among the cluster members. Once node $A$ announces the service, it will wait for the destination node to respond by sending an acknowledgment packet. If node $B$, for example, decided to use the service, it will include the acknowledgment packet and send during its reserved time slot via the CCH including the accessible time slots $aslot_B^n$ such that:

$$aslot_B^n \nexists slot_B^n \tag{17}$$

The provider for the service will then respond to the received acknowledgment by selecting the common service channel and time slot for the needed service based on the information from the CIL. It is assumed that using Table 4.1, the service provider node *A* has common free slots [1, 2, 5] on service channel 1 with node *B* that requires the service. So, the provider can choose any of the free slots on service channel 1 for the communication. Consequently, the data exchange starts between the provider node (node *A*) and the receiver node (node *B*).

**Table 4.1: Service channels with associated time slots for nodes *A* and *B***

a. Node *A*

| Service channel | Free slots (aslot) | Reserved slots (slot) |
|---|---|---|
| 1 | **1**, **2**, **5** | 0, 3, 4, 6, 7 |
| 2 | 0, 2, **4**, 5 | 1, 3, 6, 7 |
| 3 | 3, 6, 7 | 0, 1, 2, 4, 5 |

b. Node *B*

| Service channel | Free slots (aslot) | Reserved slots (slot) |
|---|---|---|
| 1 | **1**, **2**, 4, **5** | 0, 3, 6, 7 |
| 2 | **4**, 6, 7 | 0, 1, 2, 3, 5 |
| 3 | 0, 1, 2, 4 | 3, 5, 6, 7 |

### 4.4 EC-TMAC implementation through simulation

This section presents the detail description of the implementation of the EC-TMAC protocol through simulation. Initially, a new module called *ectmac* has been created to enhance the existing V2V clustering module. However, to create a new module in NS-3, usually, a special Python application command called *create-module.py* is used using a Linux command and could be found in the source directory *src*. The module usually houses some related classes for the overall functions of the module. Consequently, through the source directory we created the new module as follows:

*$ . / create-module.py ectmac*

This command results in the creation of *ectmac* module with five directories *helper, model, examples, test and doc* together with the scripting file called *wscript.*

### 4.4.1 Implementation of the clustering process

All the important classes for the implementation of the EC-TMAC protocol are contained in the directory *src/ectmac/model.* In this regard, two classes are implemented for the clustering process, namely: cluster formation process class (*cf_process)* and cluster maintenance process class (*cm_process)* together with their associated header files; *cf_process.h* and c*m_process.h* respectively. The description of each class follows below:

a. *cf_process*: some of the important methods in this class include *FoundChead(), CompeteForPriClusterHead(), InitiateClusterForm(), DetermineSecClusterHead(), and UpdateStatusInfo()*. The *FoundChead()* is a method first called after a vehicle received the initial information messages from its neighbors that there is a PCH within the transmission range. Meaning that there is an existing cluster nearby and does not require the formation of a new cluster. This method provides a potential suggestion for the appropriate cluster to join by the vehicle in a situation when there is more than one cluster within the communication range. The detailed procedure is explained in Section 4.1. Furthermore, the *CompeteForPriClusterHead()* method is used to calculate the suitability value for becoming the PCH by each vehicle. It uses the parameters as described in Section 3.3 where the vehicle with the highest value after exchanging these messages will initiate the cluster formation by calling the *InitiateClusterForm()* method. Consequently, the elected PCH determines the SeCH from the available CMs with the highest weight value by calling the *DetermineSecClusterHead()* method. And finally, the *UpdateStatusInfo()* allows the updated status information message to be broadcast to all the CMs within the cluster.

b. *cm_process:* Due to the nature of vehicular technology, the vehicle's movement on the highway could lead to the number of cluster changes by moving out of the PCH from the cluster. The cluster maintenance procedure has been discussed in detail in Section 4.2. Some of the important methods that could be triggered during the maintenance process to enhance the cluster stability include *CheckSuitabilty(), LeadershipTransfer(), DetermineSecClusterHead()* and *CheckClusterMerge()*. The *CheckSuitabilty()* method is responsible for determining the suitability of the PCH to continue with its leadership or not. Once confirm its suitability to continue with the leadership responsibility, the *UpdateStatusInfo()* is called. Otherwise, it releases its responsibility to the SeCH. This is also achieved by calling the *LeadershipTransfer()* method. Similarly, the *DetermineSecClusterHead()* method is called to select the SeCH from the available CMs after the leadership transferred to the existing SeCH by becoming the PCH. Consequently, the *UpdateStatusInfo()* method is called where the PCH update the current status information of the cluster to the CMs by notifying the ID of the current PCH and the SeCH. *CheckClusterMerge()* is a method that is called in a situation when two or more PCHs approached each other. The detailed procedure is explained in Section 4.2.2.

### 4.4.2 TDMA model implementation

The TDMA scheduling strategy was built on top of the simple wireless channel model in NS-3 *"ns3::SimplewirelessChannel"* where all the nodes within the PCH communication range will get their time slot with regard to the position of the PCH. The time slots are usually of fixed time intervals separated by a guard interval. In this case, the PCH is the central coordinator for allocating the time slots to the various CMs within the cluster range. The two most important classes implemented for modeling the time slot scheduling strategy are *TdmaControllerPch and TimeslotforSch_access*. The description of each of these classes with their associated methods is discussed below:

a. *TdmaControllerPch:* This class takes control and responsibility for all the scheduling processes within the cluster communication range. It maintains the list of all the allotted time slots associated with each CM. Some of the important methods implemented by this class include; *Determine_position(), Determine_SetofTimeSlots(), Allocate_TimeSlot() and Broadcast_Schedule()*. The *Determine_position()* method is called initially after the vehicle requesting a time slot sends Type A packet to the PCH. Therefore, using the proposed binary tree algorithm discussed in Section 4.3.2, the PCH determines the position of the vehicle, which can either be ahead of the PCH or behind the PCH. Once the position is determined, the *Determine_SetofTimeSlots()* is called to identify the set of the category of the time slots that would be allocated to the vehicle. If there is no available free slot within the set, the frame length will be doubled, then subsequently execute the *Allocate_TimeSlot()* method. By completing the allocation of the time slots to all the vehicles within the cluster range, the PCH broadcast this scheduled time slots by calling the *Broadcast_Schedule()* method using the Type B packet. The detail description of this implementation has been discussed in Section 4.3.2.

b. *TimeslotforSch_access:* This class was implemented to allow each vehicle within the cluster that needs to exchange non-safety messages through any of the SCHs to its neighbor to acquire an appropriate time slot. Some of the important methods that support the implementation of this class include; *Announce_Service(), Request_Service(), CheckCil(), and*

*Select_Slot()*. Any vehicle within the cluster that has any service to offer to its neighbor, trigger the *Announce_Service()* method. In a similar situation, the *Request_Service()* method is also called when a vehicle needs any service from among its neighbors within the cluster communication range. Once any of these methods are invoked, the corresponding vehicle will use the *CheckCil()* method, which provides the information about all the cluster members within the cluster. Accordingly, the receiver node can select a common available free SCH as well as the slot number by invoking the *Select_Slot()* method. The detail description of this implementation has been discussed in Section 4.3.3.

### 4.4.3 Safety application scenario description

The main goal of the application scenario was to describe how the proposed clustering algorithm deals with emergency situations that could take place on the highway based on a worst-case scenario. In our simulation, the first step was to execute the clustering algorithm to form clusters and elect the PCH among the contending vehicles. After forming a cluster, the status information is shared among the cluster group members, which can allow the elected PCH to determine its backup node called the SeCH and broadcast this updated information to all its CMs within the cluster. Periodically, the cluster maintenance algorithm is triggered to have a smooth transition in case the PCH is about to move out of the cluster. Furthermore, each vehicle in the cluster supports the transmission of a safety message (notification or emergency event), which can be initiated randomly during the simulation. Whenever a CM detects any incident along the road such as a blind spot or a sudden break as shown in Figure 4.16, it will send this message to the PCH with the description of the event for onward broadcast to the remaining CMs within the cluster. To determine the effectiveness of the proposed clustering algorithm for the timely delivery of these event-driven messages, each CM that sends the event message will track the record of the event from the time when it occurred to the time when this event message was broadcast by the PCH to the CMs. However, for the worst-case scenario, in a situation when an incident happens and the PCH that is supposed to broadcast the alert message to the CMs leaves the cluster at the time, the message can either be delayed or dropped before arriving at the destination (i.e. before reaching the PCH). By implementing the proposed approach, this challenge can be minimized, because the PCH periodically updates its status with respect to the SeCH. Once it determines that it can no longer continue with the leadership responsibility, the SeCH can take over the leadership; consequently, avoid the abrupt exit of the PCH from the cluster. As a result, the timely and reliable delivery of safety related messages is achieved.

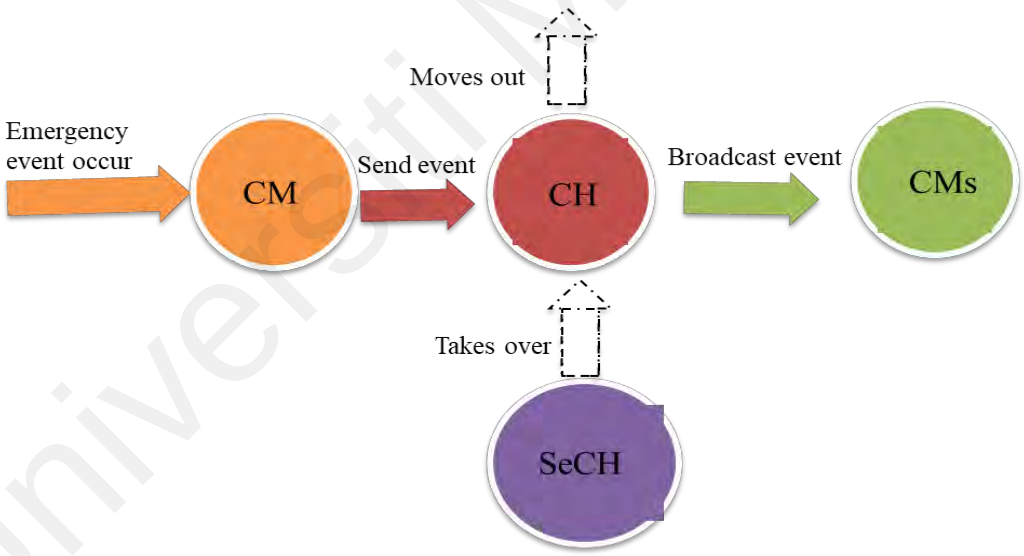



**Figure 4.16: Safety application implementation scenario using proposed approach**

## 4.5 Chapter summary

This chapter has discussed the detail designed implementation of the proposed EC-TMAC protocol. The detailed description of the proposed clustering mechanism, that is, an enhanced weight-based clustering algorithm (EWCA) is presented in Section 4.2. In this research work, a weight-based clustering algorithm for the cluster head election has been adopted. However, in a situation when there are two or more nodes with the same weight value, the use of the lowest_id clustering algorithm has been employed to resolve the competition conflict. To provide strong cluster stability, two cluster heads were introduced, including the PCH and the SeCH so that cluster lifetime is increased and minimize the high overhead caused by cluster reconfiguration. It is also worthy to note that, in a vehicular environment, high mobility of vehicles affects the reliability of the MAC protocol in a cluster-based topology. Sequel to that, a new mechanism has been proposed and explained in detail in Section 4.2 Maintaining the cluster stability improves the reliability of the VANET MAC protocol for timely delivery of safety related messages. The procedure for the successful leadership transfer from the PCH to SeCH has been discussed in detail in Section 4.2.1. Other issues leading to cluster maintenance have also been discussed.

Furthermore, in this chapter, the detailed procedure for the time slot allocation for the proposed EC-TMAC protocol in Section 4.3 has been clearly explained in detail. In Section 4.3.1, we began by describing the packets type structure and the information included by each packet as well as the requirement for the transmission of each packet by each vehicle within the cluster. The time slot reservation mechanism on the CCH has been proposed and implemented using a binary tree algorithm in Section 4.3.2. This is because using this technique can reduce the effect of merging collisions between the adjacent clusters. The CH allocates the set of the odd index value of the time slots to the vehicles ahead of it, while allocates the set of even index value of the time slots to the vehicles behind it. Similarly, without loss of generality with the original DSRC protocol, Section 4.3.3 discussed in detail the time slot reservation on the SCHs using a 3-way handshake mechanism. This is to provide services for the non-safety messages for the vehicles that need the services without compromising the stringent requirements of the safety related messages, which can only be transmitted through the CCH. Finally, in Section 4.4, the chapter discussed the detailed implementation of the proposed EC-TMAC protocol through the simulation. This was achieved by implementing the cluster formation process class, the cluster maintenance class, time slot allocation strategy classes together with their associated methods and header files.

# CHAPTER 5: RESULTS AND DISCUSSION

Sequel to the implementation details presented in the preceding chapter, this chapter discusses the results of the simulation conducted to achieve the identified objectives. Section 5.1 discusses the performance of the proposed EC-TMAC protocol by observing the vector traces implemented in the simulation scenario. Consequently, it is compared with the other existing cluster-based TDMA MAC protocols that have been proposed in the existing literature using some selected metrics to clearly show how it achieves the stated objectives in Chapter one. In Section 5.2, the chapter presents results validation with respect to the benchmark techniques. Section 5.3 concludes the chapter finally.

## 5.1 Performance evaluation of the EC-TMAC protocol

In this section, the main goal is to evaluate the performance of the proposed EC-TMAC protocol specifically, considering both the clustering process and the time slot allocation strategy among the neighbor nodes. An analysis was conducted to evaluate the efficiency and the reliability of the proposed clustering algorithm by comparing its performance with the four benchmark algorithms implemented in the following; namely the stability-based (SB), the threshold-based (TB), the adaptive TDMA slot assignment strategy (ASAS), and the motion parameters-based cluster medium access (MPMAC) techniques presented in (Arkian et al., 2015), (Rawashdeh & Mahmud, 2012), (Hadded et al., 2014), and (Chaurasia et al., 2019). Similarly, the efficiency of the proposed time slot allocation approach have been evaluated by comparing its performance with the VeMAC, ASAS, and the MPMAC protocols presented in (Omar et al., 2013), (Hadded et al., 2014), and (Chaurasia et al., 2019). The first technique called the threshold-based clustering algorithm (Rawashdeh & Mahmud, 2012) was proposed to form stable clusters in a highway traffic scenario. The authors presented that only stable neighbors can participate in the cluster formation and election process. They defined stable neighbors as those vehicles that their speed difference is less than ± Δth (predefined threshold); or else, they are regarded to be unstable neighbors. A combination of mobility metrics was used for the CH election process, where each metric was given a weight value with regard to the importance of the metric. The vehicle with the highest weight value is given priority to be elected to become the CH. Another technique in (Omar et al., 2013) presented a multichannel TDMA MAC protocol called VeMAC. It was achieved by allocating a disjoint set of time slots to vehicles moving in opposite directions. The paper employs a fixed time slot allocation strategy to vehicles and RSU. Additionally, each node announces its time slot periodically to all nearby neighbors within one-hop range. Another technique in (Hadded et al., 2014), proposed an adaptive TDMA slot assignment strategy (ASAS). In ASAS, vehicles are divided into several clusters based on Euclidean distance, and subsequently used some specified metrics including the vehicles' direction and the position of the vehicle in the CH election process. Accordingly, for each vehicle to obtain its unique time slot in ASAS, a request message has to be sent to the CH through the hello packet. The TDMA logical frame in ASAS is partitioned into two parts, namely; adaptive broadcast frame (ABF) and contention-based reservation frame (CRP) period. The ABF part in ASAS holds the time slots that were allocated by active vehicles within the cluster as its basic channel (BCH) for broadcasting safety messages and other control messages. Conversely, the CRP uses the procedure of CSMA/CA concept where vehicles reserve the SCHs for non-safety messages. Another technique also in (Arkian et al., 2015), proposed a stability-based clustering algorithm for VANET MAC protocol considering several metrics, including both the mobility and the QoS metrics. Each vehicle competes to become a CH by computing its weight value and compare this value with the value received from all its stable neighbors within the communication range. Recently, the motion parameters-based cluster medium access (MPMAC) protocol was proposed, which uses mobility parameters for cluster formation procedure without including the need for a cluster head election (Chaurasia et al., 2019). Vehicles are grouped on the basis of their velocity and acceleration (fast, slow and transition vehicles) irrespective of their lane and position. These parameters for clustering process were chosen in order to minimize the overhead in the formation of clusters as well as cluster maintenance. Accordingly, these techniques were considered as benchmark techniques for the proposed clustering process, cluster maintenance procedure, and time slot allocation strategy because they used weight-based clustering algorithm as well as different time slot allocation scheme to improve the cluster stability for timely delivery of safety related messages on which this research work is based.

These approaches were compared using similar simulation environment by means of the following variable performance metrics: cluster stability, number of clusters formed, average end-to-end delay report generated for emergency messages, rate of merging collision and the communication overhead generated within the network.

### 5.1.1 Cluster stability

This metric assesses the effectiveness of the clustering algorithm in improving the stability of a cluster. The number of cluster changes as the vehicle's dynamics affect the cluster stability and this depends on the clustering algorithm. Therefore, a good clustering algorithm should be able to minimize the number of times the cluster changes because of the changes in the status of the vehicle. CH is the node that bears all the responsibility of the management tasks within the cluster and should stay as long as possible in this state. To ensure long cluster duration and provide support for reliable data delivery of safety applications, cluster stability should be given more priority while designing the clustering algorithm. In the proposed approach, the stability of a cluster has been evaluated by determining the number of times each vehicle changed its state in a cluster. This could be determined as follows:

- A CH moves out of its cluster
- A vehicle leaves and joins a nearby cluster
- Two nearby clusters merge

This scenario was tested with a varying density of vehicles using different transmission ranges, as depicted in Figures 5.1 – 5.3.

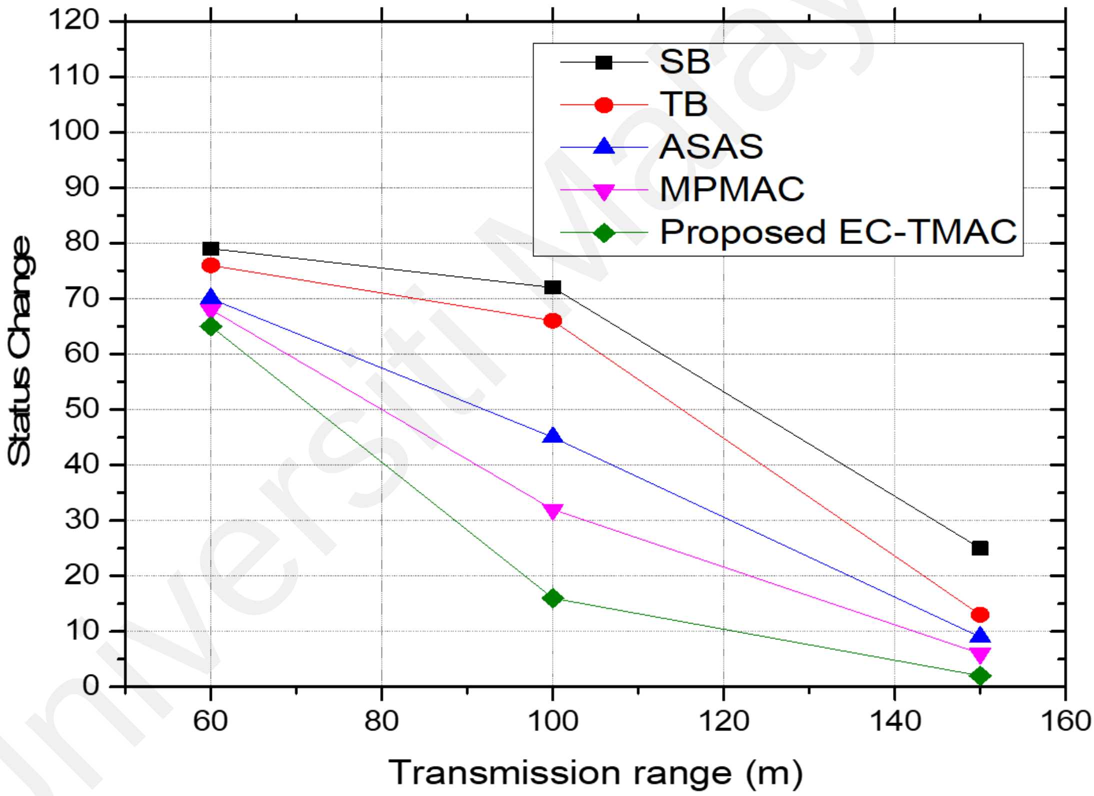



**Figure 5.1: Status of a cluster for 50 vehicles**

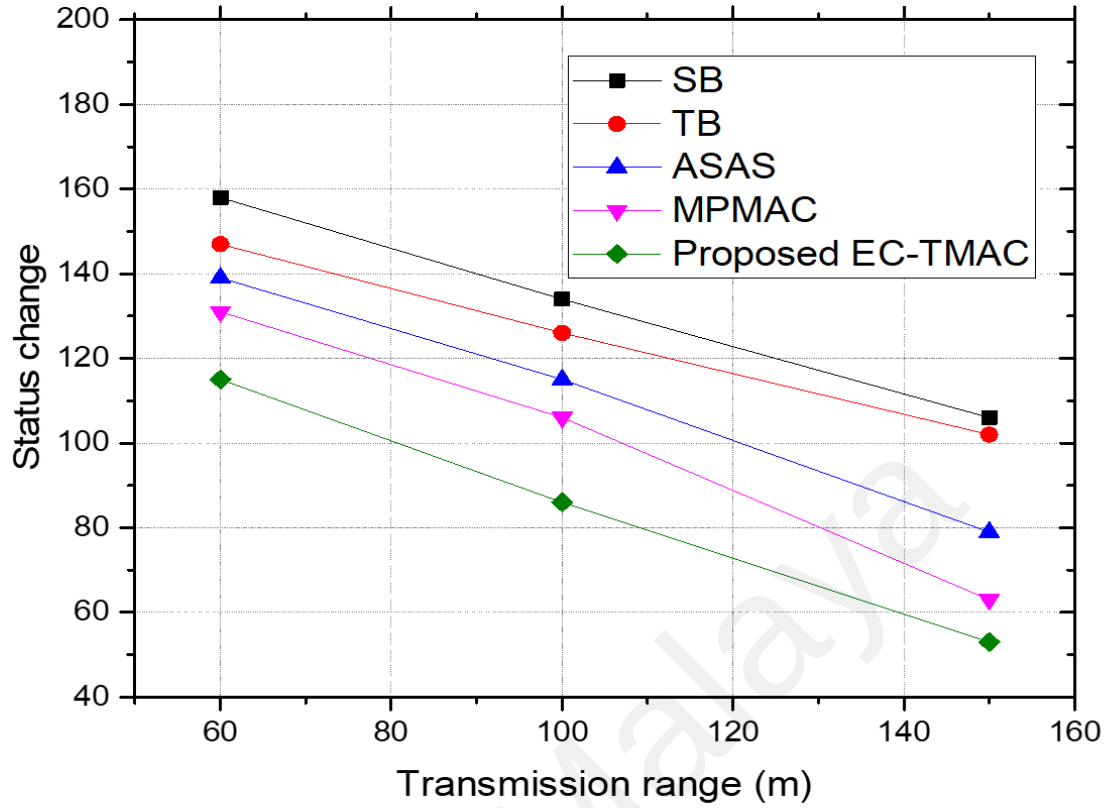



**Figure 5.2: Status of a cluster for 100 vehicles**

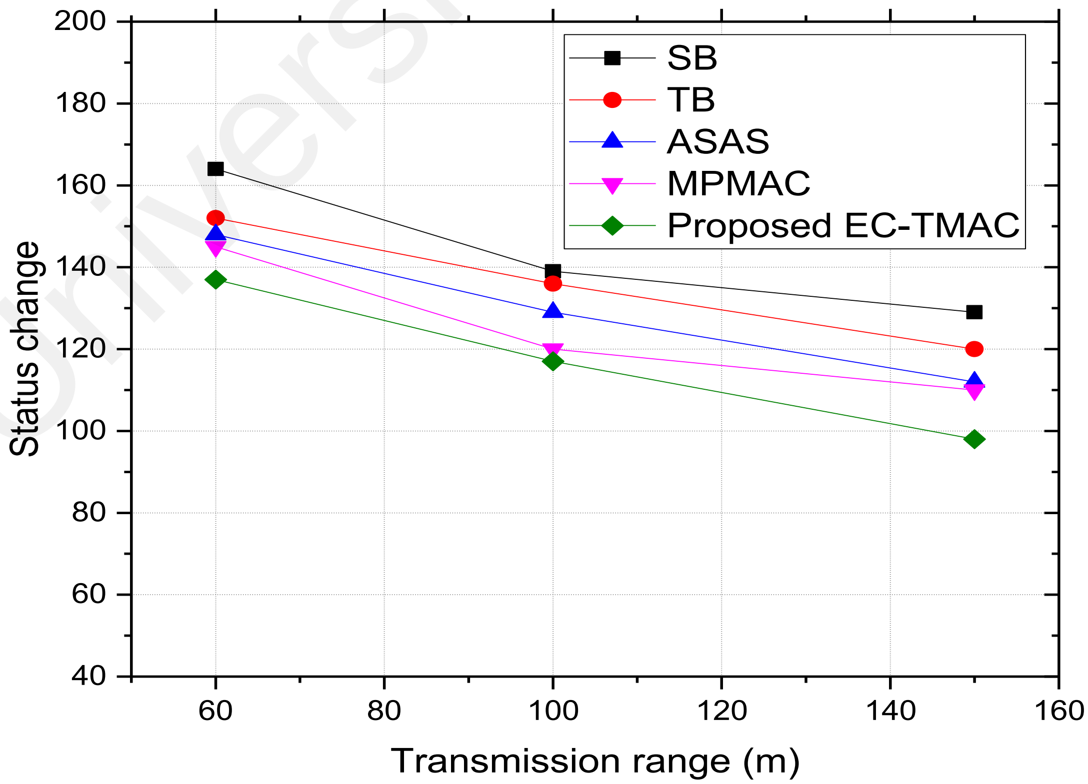



**Figure 5.3: Status of a cluster for 150 vehicles**

It was deduced from the Figures 5.1 – 5.3 that based on the three different scenarios, the enhanced weight-based clustering algorithm for the EC-TMAC protocol proposed has performed better with fewer cluster status changes than in the SB, TB, ASAS, and the MPMAC techniques. This was attributed to the proposed procedure for the cluster formation, which considered any vehicle within the transmission range to be qualified to join the cluster. Secondly, the introduction of the SeCH significantly minimized the possible cluster status change when the primary CH moved out of the cluster. The vehicles stayed connected with the existing cluster without the need for re-clustering or joining a nearby cluster. Consequently, the proposed approach improved cluster stability by approximately 40% – 45%, as the vehicle density and the transmission range increased as compared to SB, TB, ASAS, and MPMAC techniques.

### 5.1.2 Number of clusters formed (NCF)

To evaluate the efficiency and the performance of the clustering algorithm, identifying the total number of clusters formed is one of the essential metrics to be considered. It is a known fact that less formation of clusters can decrease the network communication overhead. For that reason, it is always required that the cluster formation rate is maintained and minimized as much as possible to provide a stable cluster environment. Accordingly, this could be realized once the cluster formation messages are significantly minimized. In contrast to the proposed approaches in (Arkian et al., 2015; Rawashdeh & Mahmud, 2012) where the cluster formation messages could be from either the slowest or the fastest vehicles, in our proposed approach, any vehicle within the communication range can initiate the cluster formation. Figures 5.4 – 5.6 show the results of the simulation.

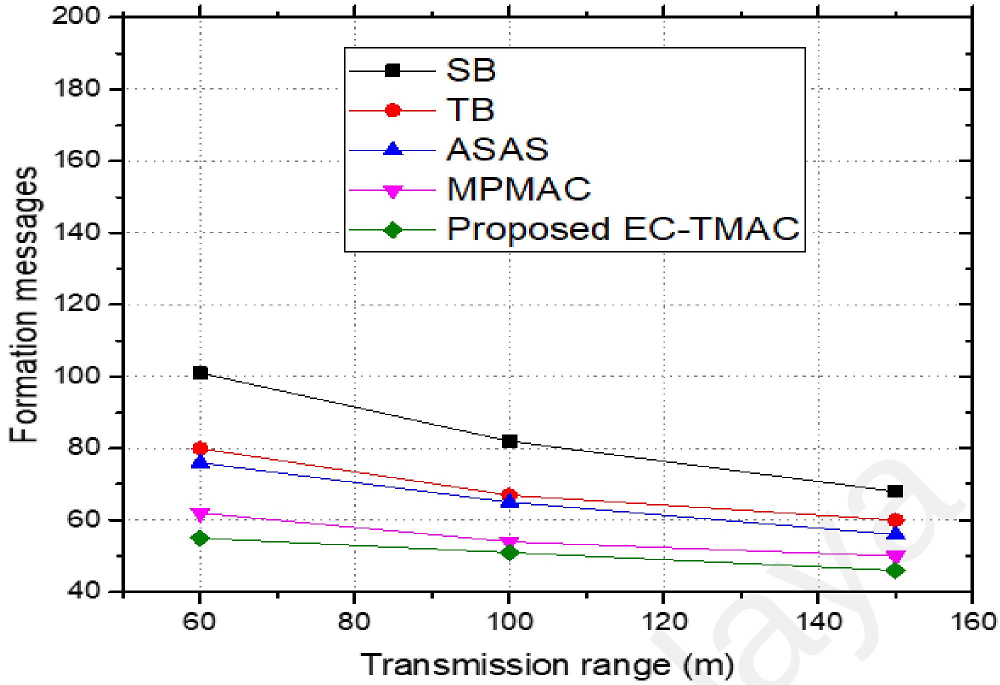



**Figure 5.4: Cluster formation messages for 50 vehicles**

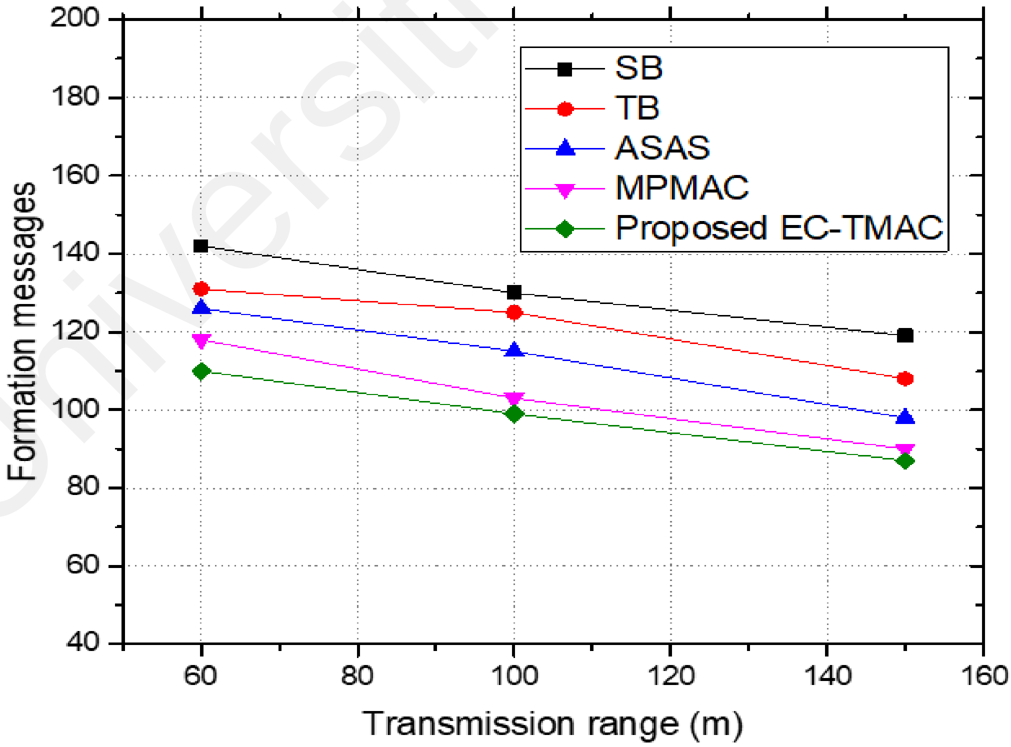



**Figure 5.5: Cluster formation messages for 100 vehicles**

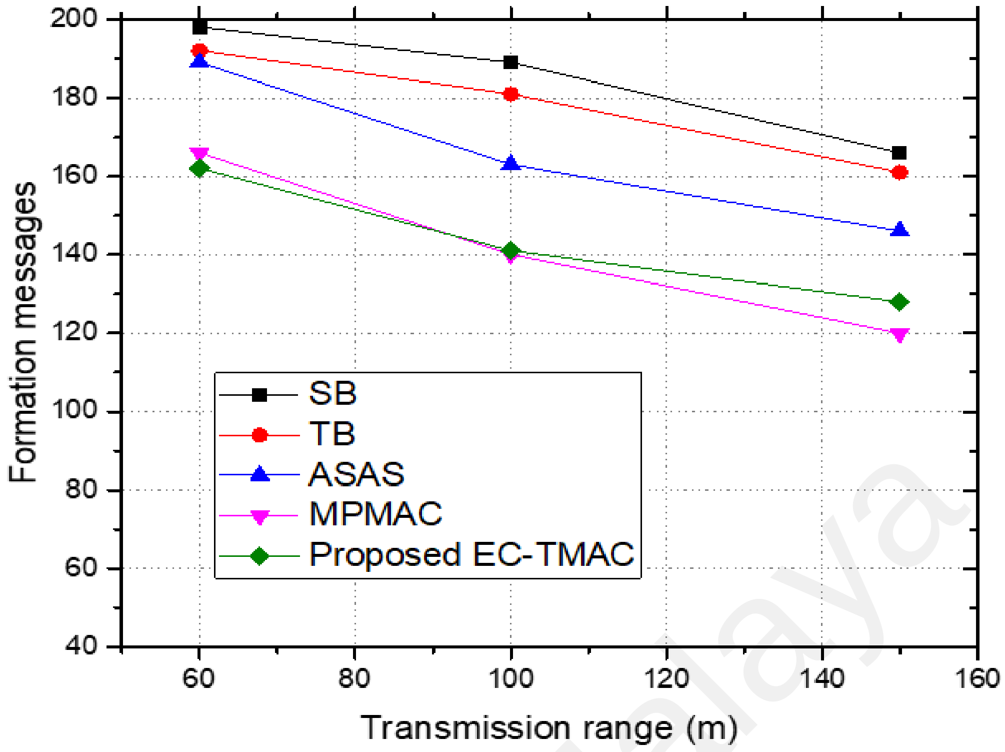



**Figure 5.6: Cluster formation messages for 150 vehicles**

It was discovered that when the transmission range increases, the number of cluster formation messages generated by the competing vehicles also reduces, which subsequently minimizes the number of clusters to be formed within the network. The proposed clustering algorithm for the EC-TMAC protocol demonstrated better performance for all the considered variable transmission ranges and vehicular densities. From the graph in Figures 5.4 – 5.6, it was found that the proposed approach (EC-TMAC) generated less cluster formation messages when compared to the SB technique, TB technique and ASAS protocol with approximately 46%, 42%, and 31% respectively. This was based on the fact that the proposed approach, avoided classifying the competing vehicles based on the speed characteristics as proposed by these benchmark techniques. Because classifying the vehicles based on their relative speeds can result in generating the formation of several clusters within the network due to the variable speed among the neighbor vehicles moving on the highway road. For instance, a scenario where two or more vehicles are moving in the same direction and within the same communication range, these vehicles might be in a different cluster if their speed difference is not within the predefined threshold. This means that the vehicle will not receive an alert message from that PCH because they are not in the same cluster. As a result, this can significantly affect the reliable delivery of the safety messages, which might cause a hazardous incident to occur. In the case of MPMAC protocol, as the number of vehicles increases it showed similar characteristics with the proposed EC-TMAC protocol in generating small number of clusters. This is due the fact that the MPMAC protocol does not require CH to manage the cluster formation, but rather uses the RSU, which minimizes the exchange of status information among the neighbor vehicles.

### 5.1.3 Average end-to-end delay

Maintaining the same simulation parameters, in this scenario, it was attempted to evaluate the delay report of the incident messages generated specifically safety related messages, as a result of the cluster changes considering the worst-case scenario as discussed in Section 4.4.3. This generally occurs when there is an emergency incident message generated by the CM and transmitted to the PCH for onward broadcast to the CMs within the cluster.

$$\text{CM} \longrightarrow \text{CH} \longrightarrow \text{Cluster}$$

However, in a situation when the CH moves out of a cluster or when cluster merges happen as discussed in the previous chapter, a cluster reconfiguration will occur, resulting in electing a new CH. Consequently, the message will either be dropped or delayed before it reaches the CMs because of the absence of the CH that has the responsibility of broadcasting this message to the remaining CMs. The aggregation of the time of this delay during the broadcasting of this incident message is computed using the timestamp field that was included in the header message. Figures 5.7 – 5.9 show the safety related messages delay report generated at different vehicle densities.

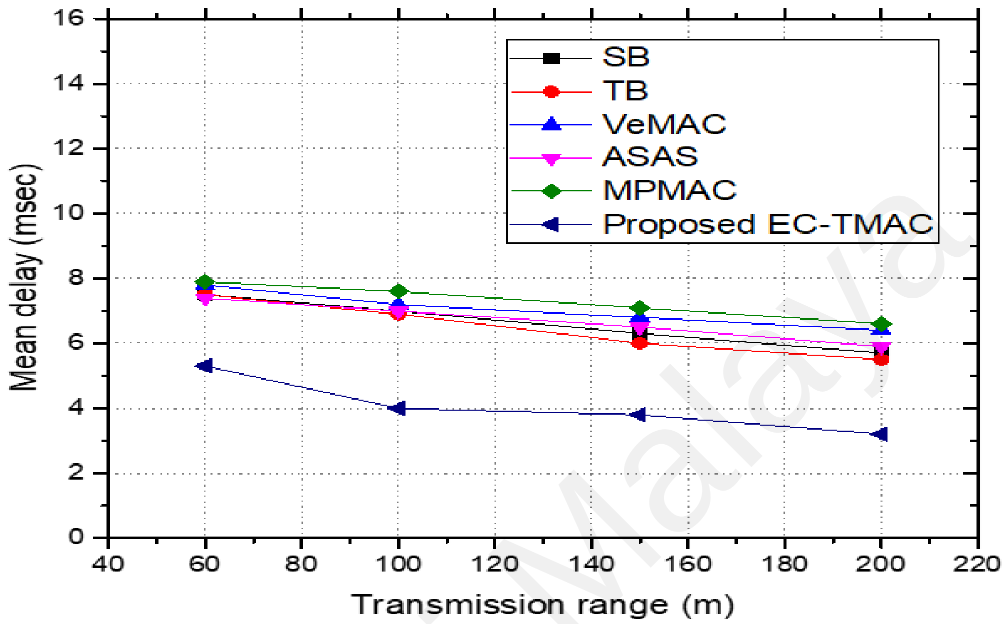



**Figure 5.7: Safety messages delay report for 50 vehicles**

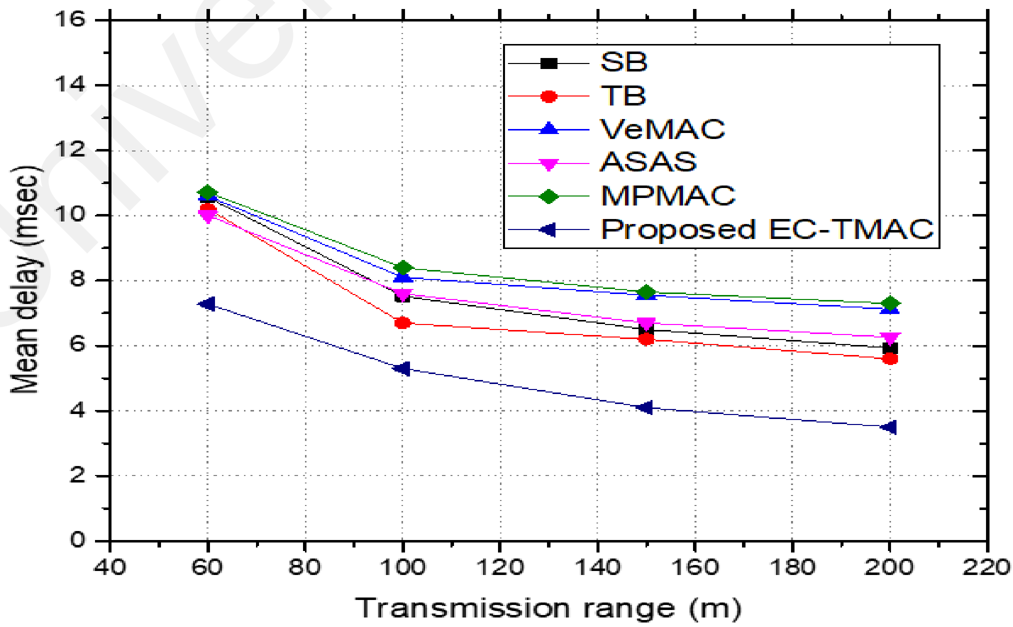



**Figure 5.8: Safety messages delay report for 100 vehicles**

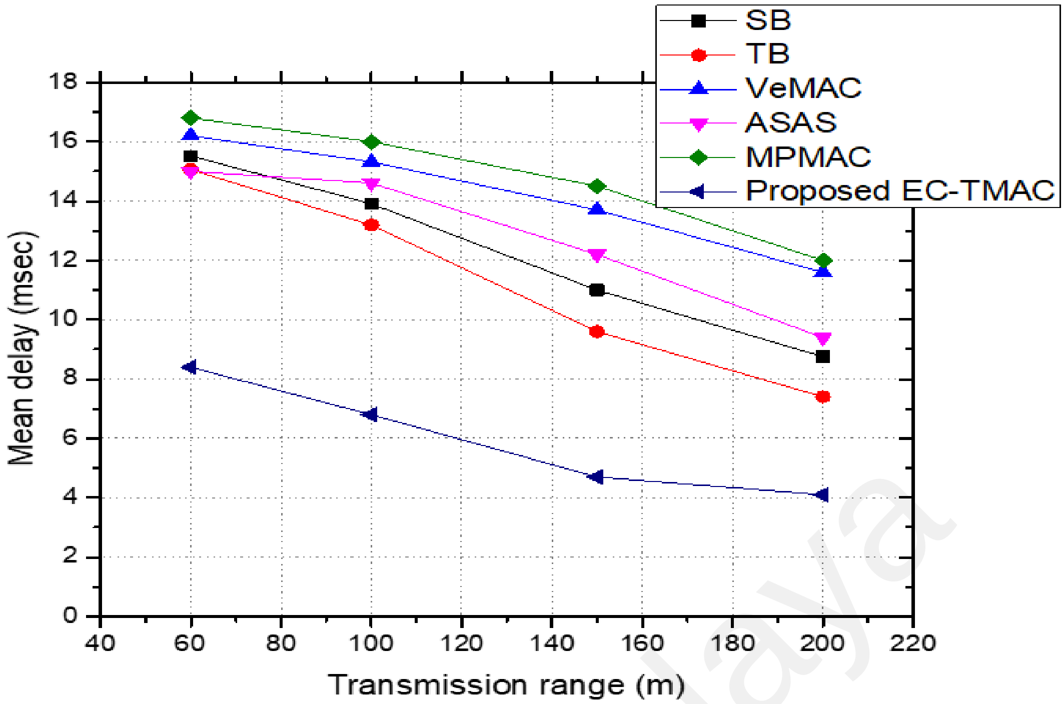



**Figure 5.9: Safety messages delay report for 150 vehicles**

Figures 5.7 – 5.9 shows that the density of the vehicles and the transmission range affect the broadcasting of the safety related messages, as a result, affect the timely delivery of these messages. It is observed that when the number of vehicles increases, the delay report generated also increases, especially in the existing approaches. For example, the VeMAC and the MPMAC protocols experienced a high increase in delay due to the distributive nature of the fixed time slot allocation strategy. Though, ASAS protocol generated less delay compared to the VeMAC and the MPMAC protocols for all the different scenarios but conversely, generated more delay especially when the vehicles' densities increases compared to SB and TB techniques. This is because, broadcasting a message in ASAS protocol by a CM, a request message has to be sent first to the CH for its time slot reservation through a contention-based method called CRP period which is not suitable for broadcast messages due to the high contention and consequently causes some messages to either be dropped or delayed. However, the proposed approach EC-TMAC protocol results in decreasing the transmission delay to a minimal percentage when compared to the result obtained from the SB technique (Arkian et al., 2015) and TB technique in (Rawashdeh & Mahmud, 2012). It was found that there was approximately 50% reduction in the transmission delay. This was based on the fact that the SeCH introduced in the proposed approach results in minimizing the time taken for cluster reconfiguration whenever the CH moved out of the cluster, consequently decreases the delay of broadcasting these safety messages to the CMs. Similarly, it was also observed that increasing the transmission range could also reduce the message delivery delay.

### 5.1.4 Rate of merging collision

The main goal of TDMA technique is to minimize the interference between the neighboring nodes and the adjacent clusters so that transmission collision and inter-cluster interference can be reduced by ensuring that each CM acquires a unique time slot for its message transmission. Nevertheless, the high mobility of vehicles and the frequent topology changes in VANET is very challenging. Hence, it requires that an efficient time slot scheduling within the cluster is provided for reliable and timely delivery of VANET applications, especially for safety related messages, which have very stringent requirements. As discussed previously in Section 2.3.1.2, merging collision problem affect the reliable and timely delivery of the safety messages as a result of the inefficient time slot scheduling strategy. The metric, rate of merging collision could be defined as the average number of merging collisions per frame per area within the cluster coverage, otherwise known as cluster coverage occupancy (CCO). This is because, the merging collision problem happens only as a result of the vehicles' movement, which is insignificant in terms of the length of one time slice. If several vehicles that lie within the adjacent clusters with the same time slot broadcast messages simultaneously, a merging collision will occur. This problem occurs only within the vehicles that already acquired their time slots. To determine the merging collision rate between the adjacent clusters, we considered various speed deviations for different cluster coverage occupancy values to define the optimal values for these parameters.

A parameter $(N_v \times R)/(L_h \times T_{spf})$ for cluster coverage occupancy (CCO) was defined (VeMAC, 2013) based on a highway traffic scenario, where $N_v$ is the total number of vehicles within the cluster, $R$ is the communication range, $L_h$ is the length of the highway segment and $T_{spf}$ is the number of the slots per frame on the CCH for each cluster. The CCO specifies the ratio of the number of time slots needed by a cluster to the total number of time slots available for a cluster. The rate of merging collision is shown in Figure 5.10.

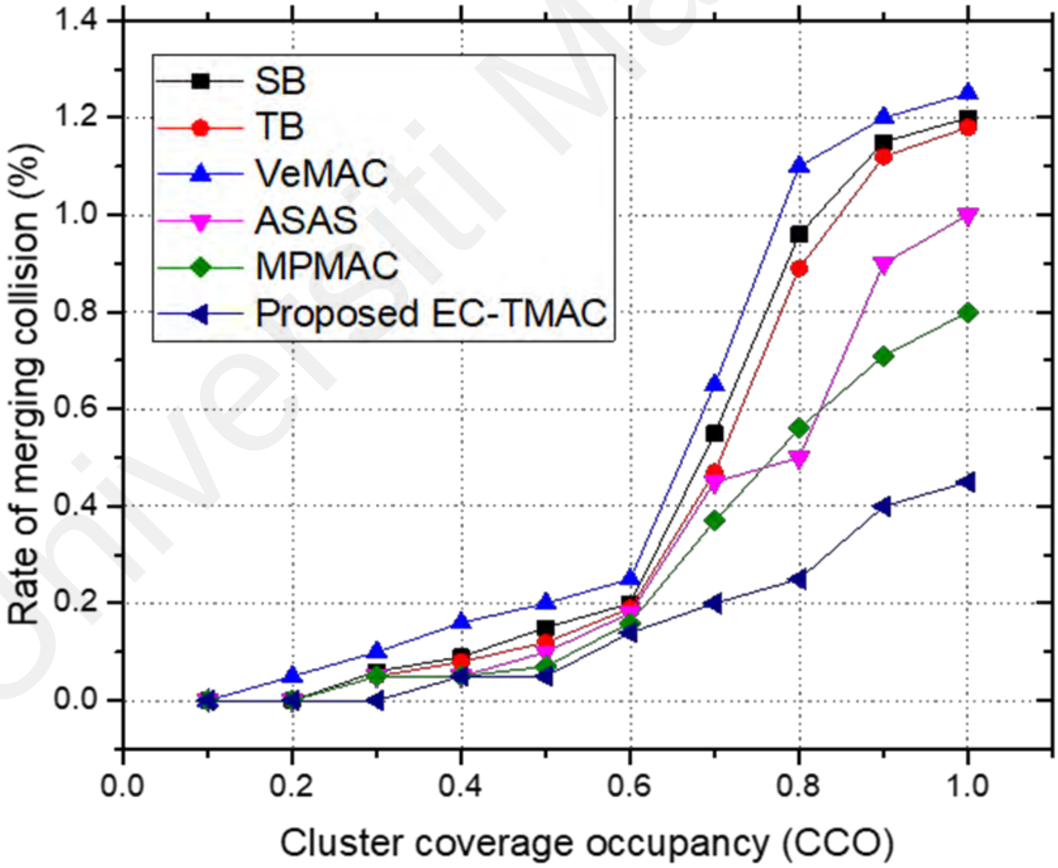



**Figure 5.10: Rate of merging collision**

The proposed EC-TMAC protocol when compared to the benchmark techniques, namely; SB, TB, VeMAC, ASAS, and MPMAC protocols show a significant decrease in the rate of merging collision problem generated. This was achieved because of the use of a disjoint set of time slots to the vehicles that are moving either behind or ahead of their PCH. In EC-TMAC, the merging collision is only expected to happen when two or more adjacent CMs from the adjacent cluster change position as a result of the vehicles' high mobility and the frequent changes in the topology. It was noted that even when the cluster coverage area is large with a greater number of vehicles, the effect of merging collision is still very small compared to the benchmark techniques. One of the most important reasons is that, for example, in VeMAC protocol, once the vehicles cannot find any available time slots reserved for their direction, attempting to reserve any available time slot by the vehicles associated with any direction results in increasing the rate of merging collision, especially at high traffic density.

However, for the stability-base and threshold-base techniques, it was observed that they generated a similar merging collision rate. This was based on the fact that the method implemented for the cluster formation by both techniques implied a similar approach, whereby two or more vehicles from a different cluster can be within the vicinity of a different cluster due to the differentiation of speed characteristics. Consequently, this problem can cause an inter-cluster interference, which could result in a merging collision problem. Similarly, for the case of ASAS protocol, even though, it performed better than the other benchmark techniques, but it needs every CH to send its frame information to the two neighboring clusters through its cluster gateways (CG) to avoid the occurrence of merging collision problem. However, the CG might move out of the cluster during the process of broadcasting this updated information and consequently result in a merging collision. Equally, for the MPMAC protocol it has been observed that for most of the time when the cluster coverage occupancy is greater than or equal to 0.6, it experienced a high rate of merging collision compared to the proposed EC-TMAC protocol. This is because as the number of vehicles increases, fast-moving vehicles overlap with the slow-moving vehicles, which consequently result in the merging collision problem. It is worthy to note that, there was approximately a 47% reduction of the merging collision rate against the VeMAC protocol, 28% against the ASAS protocol, and 22% against the MPMAC protocol compared to our proposed EC-TMAC protocol. Consequently, this demonstrates the level of improvement in the proposed approach.

### 5.1.5 Communication overhead

The communication overhead is one of the important parameters to evaluate the effectiveness of the clustering algorithm. This could be determined by identifying the extra control messages that are exchanged periodically within the cluster. The exchanged messages are required for the cluster formation process, channel allocation with respect to acquiring a time slot for every vehicle within the transmission range, and the cluster maintenance. The communication overhead generated, in this case, includes the hello packet overhead, cluster formation process overhead, cluster maintenance overhead, and the time slot allocation scheduling overhead.

The messages that could generate communication overhead in the proposed EC-TMAC protocol are summarized in the Table 5.1.

Table 5.1: Summary of the EC-TMAC messages generating communication overhead

| s/n | EC-TMAC protocol Processes | Messages generating communication overhead |
|---|---|---|
| 1 | Hello packet for status update | - *UpdateStatusInfo* message |
| 2 | Cluster formation process messages | - *CompeteForPriClusterHead* message<br>- *InitiateClusterForm* message<br>- *DetermineSecClusterHead* message |
| 3 | Cluster maintenance process messages | - *CheckSuitabilty* message<br>- *LeadershipTransfer* message |
| 4 | Time slot scheduling message | - *Allocate_TimeSlot* message |

The hello packet overhead is generated through the periodic broadcast of *UpdateStatusInfo* message by each vehicle to its neighbors via the PCH within the cluster. This type of overhead is minimized, because in this case, the CM broadcasts the periodic message to all its neighbors only through its PCH, contrary to the VeMAC protocol where each node broadcasts directly to all its neighbors within the one-hop communication range. Furthermore, for the cluster formation process, three messages resulted in the overhead generated for the clustering process. The first one is the *CompeteForPriClusterHead* message, where each vehicle will process the received message from its neighbors to determine its suitability of becoming the PCH. The second one is the *InitiateClusterForm* message after a vehicle succeeds in becoming the PCH by assigning its nodeid as the clusterid and broadcast the message to all its neighborhoods. The third one is the *DetermineSecClusterHead* message, which the PCH process to elect the SeCH that can act as its backup. Similarly, the overhead generated due to the time slot scheduling and the maintenance processes includes three messages. The *CheckSuitabilty* message, which the PCH process periodically to determines its suitability to continue with the leadership of the cluster. The *LeadershipTransfer* message allows the exchange of message between the PCH and SeCH when the PCH is about to take an exit. Finally, the *Allocate_TimeSlot* message, which provides every vehicle within the cluster, gets its fair share of the time slot. Figure 5.11 shows the overhead generated by each of the protocol under study.

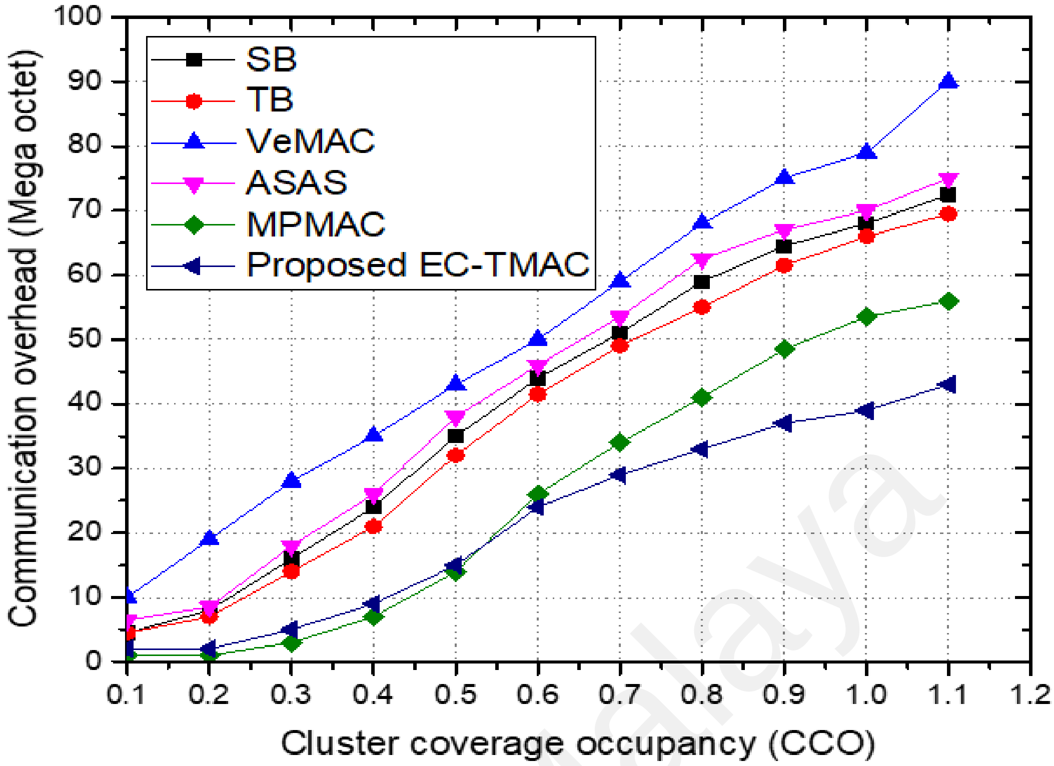



**Figure 5.11: Communication overhead**

The overhead generated in EC-TMAC when compared to MPMAC protocol is not very significant, especially when the traffic density is low i.e. at CCO <= 0.6, as illustrated in Figure 5.11. However, when the density of the vehicles increases, the overhead also increases for all the benchmark techniques due to the frequent cluster disconnections and re-configuration among the neighbor vehicles within the cluster coverage area. The main reason is that the clustering algorithm needs to be frequently executed whenever the CH moves out of the cluster, which could result in the exchange of the hello messages periodically among the CMs. It is worthy to note that all the control messages are transmitted by the PCH through the CCH in EC-TMAC, providing the required information to all the vehicles within the cluster. This generally results in minimizing the overhead to the entire network, because it involves only the PCH. Conversely, for the MPMAC protocol, since it does not require the use of the CH in the clustering process, the exchanges of the control messages between the neighbor vehicles for the CH election process are also not needed. Subsequently, resulting to generating low overhead similar to the proposed EC-TMAC protocol. However, it is observed that when the density of vehicles increases, the RSU that is coordinating all the vehicles irrespective of the speed difference within its coverage area will be overloaded. Consequently, resulting to generating high communication overhead to the network compared to the proposed EC-TMAC protocol. Furthermore, despite the fact that in EC-TMAC, there is always transmission of type 1 packet, which includes the list of all the vehicles together with their associated information within the cluster, it still performs better than all the benchmark techniques. Contrary to the EC-TMAC protocol, the time slot allocation to the neighboring vehicles that are within the communication range is done in a distributed manner for the VeMAC protocol, where each vehicle will periodically broadcast the frame information to its one-hop neighbors for it to maintain the TDMA scheduled table, otherwise, a collision would occur. Therefore, as the density of vehicles increases the communication overhead also increases, thereby decreasing the effective performance of the MAC protocol for the timely delivery of the safety related messages within the neighbor vehicles.

Figure 5.11 shows that the VeMAC protocol generated high communication overhead when compared with all the protocols under study. This is due to the distributive nature of the VeMAC protocol, where each node must communicate directly to all its one-hop neighbors for both message dissemination and status updates periodically. Similarly, it was observed that the communication overhead generated by the ASAS protocol was significantly minimized when compared to the VeMAC, but generated higher communication overhead than both SB and TB techniques. One of the important reasons that resulted in the generation of this high overhead was the introduction of the cluster gateways in both sides of the cluster, which added extra communication messages to the network, especially due to the periodic re-election of these cluster gateways. However, Figure 5.11 shows that EC-TMAC generated low overhead when compared with all the benchmark techniques. For example, when the CCO >= 0.80, the overhead was reduced by approximately about 15%, 28%, and 47% respectively for the MPMAC, ASAS, and VeMAC protocols.

## 5.2 Results validation using T-Test

The efficiency of the proposed approach EC-TMAC protocol and the selected benchmark techniques were recorded considering the cluster stability, cluster formation messages, delay report generated, rate of merging collision and the communication overhead under different simulation scenarios. To determine the confidence level of the effectiveness of the proposed approach over the benchmark techniques, validation of the results has been conducted using a statistical analysis tool. In this research work, the T-Test analysis tool has been used to verify the significance of the proposed algorithms with respect to the benchmark techniques. This is because the T-Test analysis tool always confirms how statistically significant the differences between the two groups are or if their differences happened only due to random chance. In addition, it can also improve the level of confidence in the conclusion of the research work. The most important elements of the T-Test analysis are the t-value and the p-value or sometimes called the confidence level. The t-value identifies the ratio between the differences between the two or more groups. If the t-value is large for a particular group, it demonstrates that there are a significant difference and less similarity among the groups. In contrast, a p-value is the probability of confidence level describing whether the results from the data occurred by chance or not and is particularly ranges from 0% - 100%.

Consequently, to demonstrate how effective the proposed technique is compared to the benchmark techniques, the two-tailed alternative hypothesis was considered by setting up a confidence level threshold represented by $\alpha = 0.05$ (95%) during the analysis. After completing the T-Test computation, the p-value generated is compared with the threshold value. The smaller the p-value generated, the stronger the confidence that there is a significant difference between the results of the experiment among the groups of data compared. Usually, low p-value means the result from the experiment did not occur by chance, hence considered significant.

The null hypothesis is represented mathematically as follows:

$$H_0: \mu_A \geq \mu_B$$

If the null hypothesis is true, that means the experimental results are assumed to be from the random variation and no much significant difference between the two groups. Otherwise, the alternative hypothesis (HA) must be accepted, demonstrating that there is a significant difference between the groups. The alternative hypothesis can be represented mathematically as follows:

$$H_A: \mu_A \neq \mu_B$$

The detail analysis is given in the proceeding sections below:

### 5.2.1 Analysis of the results regarding the cluster stability

The results of the statistical analysis demonstrating the confidence level that the proposed EC-TMAC is more effective than SB, TB, and ASAS techniques in maintaining the stability of a cluster at different vehicular densities have been shown in Tables 5.2 – 5.4. Considering the confidence level set at 0.05 ($\alpha = 0.05$ or 95%), it was realized that comparing this value with the p-value in the output table, for all the different scenarios, the p-value is smaller than the threshold value ($\alpha$ value). Equally, the t-value is compared with the t critical two-tail value of the Tables 5.2 – 5.4 for all the different scenarios, which show that the t-value is larger. This demonstrates that the null hypothesis is rejected and on the other way round accepting the alternative hypothesis. Consequently, this proved the confidence that there is a significant improvement in maintaining the cluster stability at variable vehicular densities in EC-TMAC protocol compared to the benchmark techniques.

**Table 5.2: The confidence level with which it can be claimed that using 50 nodes the proposed algorithms for EC-TMAC is more effective in maintaining cluster stability**

| **α = 0.05** | **t-value** | **t Critical two-tail** | **p-value** |
|---|---|---|---|
| EC-TMAC/SB | 3.613846856 | 2.131846786 | 0.031073382 |
| EC-TMAC/TB | 2.978179394 | 2.131846786 | 0.036131856 |
| EC-TMAC/ASAS | 3.424779177 | 2.131846786 | 0.041265466 |
| EC-TMAC/MPMAC | 3.211379451 | 2.131846786 | 0.044612237 |

**Table 5.3: The confidence level with which it can be claimed that using 100 nodes the proposed algorithms for EC-TMAC is more effective in maintaining cluster stability**

| **α = 0.05** | **t-value** | **t Critical two-tail** | **p-value** |
|---|---|---|---|
| EC-TMAC/SB | 3.047540654 | 2.131846786 | 0.015670823 |
| EC-TMAC/TB | 2.817860863 | 2.131846786 | 0.031326281 |
| EC-TMAC/ASAS | 2.657842454 | 2.131846786 | 0.035272746 |
| EC-TMAC/MPMAC | 2.921345873 | 2.131846786 | 0.038769213 |

**Table 5.4: The confidence level with which it can be claimed that using 150 nodes the proposed algorithms for EC-TMAC is more effective in maintaining cluster stability**

| α = 0.05 | t-value | t Critical two-tail | p-value |
|---|---|---|---|
| EC-TMAC/SB | 3.739130435 | 2.131846786 | 0.011252824 |
| EC-TMAC/TB | 3.281696099 | 2.131846786 | 0.024009955 |
| EC-TMAC/ASAS | 2.804728222 | 2.131846786 | 0.038085234 |
| EC-TMAC/MPMAC | 2.612316522 | 2.131846786 | 0.040011264 |

### 5.2.2 Analysis of the results regarding the number of cluster formation

Tables 5.5 - 5.7 show the analysis of the results highlighting the level of confidence that the proposed algorithms for EC-TMAC generated fewer cluster formation messages thereby producing a few clusters within the network. As can be seen from the output tables, the p-value generated is smaller for the benchmark techniques for all the different scenarios compared to the threshold value (α value). Similarly, the t-value is greater than the t critical two-tail value for all the different scenarios. This reliably demonstrates the efficiency of the proposed EC-TMAC protocol in forming a lesser number of clusters, which results in minimizing the communication overhead to the network. Consequently, the alternative hypothesis is accepted and rejecting the null hypothesis, as discussed in the preceding section.

**Table 5.5: The confidence level with which it can be claimed that using 50 nodes the proposed algorithms for EC-TMAC is more effective in forming lesser number of clusters**

| α = 0.05 | t-value | t Critical two-tail | p-value |
|---|---|---|---|
| EC-TMAC/SB | 3.429882305 | 2.91998558 | 0.022223387 |
| EC-TMAC/TB | 3.146038083 | 2.353363435 | 0.029111603 |
| EC-TMAC/ASAS | 3.115650686 | 2.353363435 | 0.032103203 |
| EC-TMAC/MPMAC | 3.31226700 | 2.353363435 | 0.037011621 |

**Table 5.6: The confidence level with which it can be claimed that using 100 nodes the proposed algorithms for EC-TMAC is more effective in forming small number of clusters**

| α = 0.05 | t-value | t Critical two-tail | p-value |
|---|---|---|---|
| EC-TMAC/SB | 4.371423845 | 2.131846786 | 0.020006779 |
| EC-TMAC/TB | 3.768892249 | 2.131846786 | 0.031136967 |
| EC-TMAC/ASAS | 3.363877181 | 2.131846786 | 0.0344312245 |
| EC-TMAC/MPMAC | 3.55900213 | 2.131846786 | 0.0401123160 |

**Table 5.7: The confidence level with which it can be claimed that using 150 nodes the proposed algorithms for EC-TMAC is more effective in forming lesser number of clusters**

| α = 0.05 | t-value | t Critical two-tail | p-value |
|---|---|---|---|
| EC-TMAC/SB | 4.258934625 | 2.131846786 | 0.028598412 |
| EC-TMAC/TB | 3.785902085 | 2.131846786 | 0.036291057 |
| EC-TMAC/ASAS | 3.400093571 | 2.131846786 | 0.040040238 |
| EC-TMAC/MPMAC | 3.93121077 | 2.131846786 | 0.044213110 |

### 5.2.3 Analysis of the results regarding the delivery delay generated

Tables 5.8 - 5.10 shows the statistical analysis which claimed that the proposed EC-TMAC protocol generated less delivery delay compared to the benchmark techniques. This was due to the introduction of the SeCH to support the PCH in a situation when it can no longer continue with leadership responsibilities. It can be observed that the t-value generated from the output tables is larger than the t critical two-tail value for all the benchmark techniques at different vehicular densities. Similarly, the p-value is smaller than the threshold value (α value), consequently rejecting the null hypothesis and accepting the alternative hypothesis. Subsequently, this demonstrates that the proposed EC-TMAC protocol is more effective in generating less delivery delay for VANET safety related applications compared to the benchmark techniques.

**Table 5.8: The confidence level with which it can be claimed that using 50 nodes the proposed algorithms for EC-TMAC is more effective in generating less delivery delay**

| α = 0.05 | t-value | t Critical two-tail | p-value |
|---|---|---|---|
| EC-TMAC/SB | 4.302610314 | 1.943180281 | 0.005078274 |
| EC-TMAC/TB | 3.81264706 | 1.943180281 | 0.008836219 |
| EC-TMAC / VeMAC | 5.574723497 | 2.015048373 | 0.002558698 |
| EC-TMAC/ASAS | 4.787587902 | 1.943180281 | 0.003039111 |
| EC-TMAC/MPMAC | 5.682231001 | 2.015048373 | 0.002310624 |

**Table 5.9: The confidence level with which it can be claimed that using 100 nodes the proposed algorithms for EC-TMAC is more effective in generating less delivery delay**

| α = 0.05 | t-value | t Critical two-tail | p-value |
|---|---|---|---|
| EC-TMAC/SB | 3.473623245 | 1.943180281 | 0.034218718 |
| EC-TMAC/TB | 3.044922711 | 1.943180281 | 0.036152753 |
| EC-TMAC / VeMAC | 3.890434056 | 1.943180281 | 0.022677866 |
| EC-TMAC/ASAS | 3.599764814 | 1.943180281 | 0.031249031 |
| EC-TMAC/MPMAC | 3.921106781 | 1.943180281 | 0.021367401 |

**Table 5.10: The confidence with which it can be claimed that using 150 nodes the proposed algorithms for EC-TMAC is more effective in generating less delivery delay**

| **α = 0.05** | **t-value** | **t Critical two-tail** | **p-value** |
|---|---|---|---|
| EC-TMAC/SB | 3.49394818 | 2.015048373 | 0.017396735 |
| EC-TMAC/TB | 2.969938628 | 2.015048373 | 0.030351774 |
| EC-TMAC / VeMAC | 5.806131057 | 1.943180281 | 0.001145133 |
| EC-TMAC/ASAS | 4.182948971 | 1.943180281 | 0.005794466 |
| EC-TMAC/MPMAC | 5.966811023 | 1.943180281 | 0.0010011392 |

### 5.2.4 Analysis of the results regarding the rate of merging collision

Table 5.11 shows the statistical analysis of the results regarding the rate of merging collision. It is worthy to note that both the t-value and the p-value generated for each of the benchmark technique within the cluster coverage gives an indication of the improved significant of the proposed algorithms for the EC-TMAC protocol. The t-value is greater than the t critical two-tail value and similarly, the p-value generated is smaller than the threshold value (α value), thus accepting the alternative hypothesis and rejecting the null hypothesis.

**Table 5.11: The confidence level with which it can be claimed that within the cluster coverage occupancy the proposed algorithms for EC-TMAC is more effective in generating low rate of merging collision**

| α = 0.05 | t-value | t Critical two-tail | p-value |
|---|---|---|---|
| EC-TMAC/SB | 3.722489190 | 1.795884819 | 0.031294015 |
| EC-TMAC/TB | 3.404659161 | 1.795884819 | 0.034514170 |
| EC-TMAC / VeMAC | 4.024696809 | 1.795884819 | 0.021154831 |
| EC-TMAC/ASAS | 3.105283348 | 1.782287556 | 0.04279686 |
| EC-TMAC/MPMAC | 2.966100230 | 1.782287556 | 0.044126710 |

### 5.2.5 Analysis of the results regarding the communication overhead

Table 5.12 shows the statistical analysis of the results regarding the confidence level which claimed that the proposed algorithm for the EC-TMAC protocol is more effective with respect to generating less communication overhead compared to the existing benchmark techniques. From the table, it was observed that the t-value generated for all the benchmark techniques is greater than the t critical two-tail value generated as well. Equally, the p-value generated for all the benchmark techniques is smaller than the threshold value (α value). This clearly indicates that the null hypothesis is rejected. Consequently, demonstrating a significant difference ensured by the proposed EC-TMAC protocol in generating less communication overhead.

**Table 5.12: The confidence level with which it can be claimed that within the cluster coverage occupancy the proposed algorithms for EC-TMAC is more effective in generating less communication overhead**

| α = 0.05 | t-value | t Critical two-tail | p-value |
|---|---|---|---|
| EC-TMAC/SB | 2.154030852 | 1.739606726 | 0.035797228 |
| EC-TMAC/TB | 1.930534419 | 1.739606728 | 0.038194572 |
| EC-TMAC / VeMAC | 3.857441726 | 1.745883676 | 0.006099202 |
| EC-TMAC/ASAS | 2.378467516 | 1.739606726 | 0.029376841 |
| EC-TMAC/MPMAC | 1.950011342 | 1.739606726 | 0.042011761 |

## 5.3 Chapter summary

This chapter has presented and discussed the results of the different simulation scenarios. The different evaluation metrics, including cluster stability, number of clusters formed, average end-to-end delay report generated, rate of merging collision, and the communication overhead were considered for this research work. Consequently, a comparison was made using some specified benchmark techniques to evaluate and assess the efficiency of the proposed clustering technique, along with the time slot scheduling strategy for the EC-TMAC protocol for reliable vehicle-to-vehicle communication. Equally, it is worthy to note that, the results obtained in all the simulation scenarios showed that the proposed algorithms for the EC-TMAC protocol demonstrated high superiority over the benchmark techniques with respect to maintaining cluster stability among the neighbor vehicles, lesser number of clusters within the network, minimum delivery delay of the safety related messages, low rate of merging collision and minimum communication overhead generated. In a similar vein, a validation check for the claim that the proposed EC-TMAC protocol is more effective than the benchmark techniques for V2V reliable communication in supporting the deployment of the envisaged VANET applications has also been conducted using a Student's T-Test statistical analysis tool. It has been shown that for all the different scenarios, the p-value generated is smaller than the threshold value (α value) and the t-value also is larger than the t critical two-tail value, which clearly ascertains that there is a significant improvement between the results obtained for the proposed EC-TMAC protocol with the benchmark techniques. The next chapter concludes the research work by clearly summarizing the research findings and giving some recommendations for the future research direction.

# CHAPTER 6: CONCLUSION AND FUTURE WORK

This chapter concludes the proposed research work on enhancing the cluster-based TDMA MAC protocol for vehicle-to-vehicle communication. In Section 6.1, a summary of the research findings with respect to the stated research objectives in Chapter 1 has been presented. Section 6.2 highlights the research contributions and finally, Section 6.3 explains the research future directions.

## 6.1 Research achievement

To improve road traffic safety in a vehicular environment, an efficient and reliable MAC protocol is required. This could be realized by using a cluster-based approach to satisfy the strict requirements for VANET safety related applications. This research work has presented an enhanced cluster-based TDMA MAC protocol for effective and reliable vehicle-to-vehicles communication.

The following give the details on how each of the stated objectives was achieved in this research work.

✓ Identify the limitations of the existing cluster-based TDMA MAC protocols.

This research objective was achieved by exploring and reviewing the state-of-the-art of the existing literature, as discussed in Chapter 2. It was discovered that network disconnection is inevitable in a vehicular environment due to the high mobility of vehicles and the frequent topology changes, hence poses a great challenge in the existing clustering algorithms for V2V communications. Therefore, to provide an efficient MAC protocol for efficient and timely delivery of VANET safety related applications in a cluster-based topology, three major steps were identified, as highlighted in Table 2.1. These involve (1) the method employed for the cluster formation and the cluster head election procedure; (2) the cluster maintenance procedure, and (3) the time slot allocation scheme. The findings revealed that most of these existing approaches focused on the CH election process with the hope of choosing a CH that can stay within the cluster for a long period and for the intra-cluster communication, which can result in minimizing the effect of access collision problem. However, other critical issues such as cluster formation process, cluster maintenance procedure, and the efficient time slot allocation scheme, which subsequently pose a serious challenge for the reliable delivery of safety related applications, were not given much attention.

Furthermore, it is worthy to note that a stable cluster (i.e. a situation where a CH stays for a long period before it goes out of the cluster) reduces the overhead of re-clustering. However, the findings revealed that maintaining a stable cluster in the existing cluster-based TDMA MAC approaches as a result of the vehicles' high mobility is a serious problem, hence affecting the efficiency and the reliability of the TDMA MAC protocol for the timely delivery of safety related messages. This is for the reason that the CH can either exit the cluster or sometimes merge with another CH within the vicinity. It was learned that the existing clustering algorithms approaches failed to propose any suitable solution to take care of a cluster structure when there is an abrupt exit of a CH in a cluster. Being a CH the central coordinator managing the CMs, so whenever it goes out of the cluster, the cluster structure has to be altered and reconfigured again. Accordingly, this process can result in the loss of channel access schedule between the CMs, delivery delay of the safety related messages or loss of the transmitted packet. It was also discovered that the transmission collision in a vehicular environment is generally classified as access collision and merging collision. In view of the literature presented in Chapter 2, we have learned that the rate of access collision has been significantly minimized by the existing approaches. On the contrary, the problem of merging collisions is still a serious challenge. This problem of merging collision usually occurs as a result of the inefficient scheduling scheme, which subsequently affects the efficiency of the cluster-based TDMA MAC protocol, particularly for V2V communications.

✓ To enhance a cluster formation process and cluster head election by:

- Developing a cluster transition states for the cluster formation process
- Developing a weight-based clustering algorithm for the CH election process

The second objective was achieved by proposing an enhanced weight-based clustering algorithm for the implementation of an enhanced cluster-based TDMA MAC (EC-TMAC) protocol. Two CHs were proposed to provide strong cluster stability within the clusters; the PCH as the main CH and the SeCH to act as a backup to the PCH. A combination of two clustering techniques, including the weight-based and the lowest ID was proposed to implement our clustering algorithm. The reason behind this was that a situation could arise when two or more vehicles may have the same weight values, so in this situation, the lowest ID technique will be incorporated to decide the best appropriate node to become the CH. Equally, the cluster formation procedure provides an inclusive criterion for every vehicle within the communication range to participate in the CH election and the cluster formation, because of the significance of every safety message that may be generated by the vehicles. In Chapter 4, Figure 4.1 shows the cluster transition states and the flow chart in Figure 4.2 illustrates the flow of the proposed procedure for the cluster formation and PCH/SeCH election process.

✓ To enhance cluster stability within the cluster by:

- Developing a novel algorithm for CH leadership transfer between the primary cluster head (PCH) and the secondary cluster head (SeCH) before the PCH moves out of the cluster.

This objective was achieved by proposing a new algorithm that provides an efficient cluster head leadership transfer from PCH to SeCH. When the primary CH can no longer be a CH or moves out of the cluster by taking an exit, the SeCH will take over the leadership role within the cluster instead of cluster reconfiguration. Eventually, this primary CH will change its status to a CM. This change does not affect the cluster structure, but only the role of a CH will be transferred to the SeCH. The new primary CH will then select a new SeCH. Figure 4.3 in Chapter 4 illustrates the flow diagram of the proposed CH leadership transfer procedure.

✓ To develop a dynamic time slot allocation scheme to minimize merging collision problem between the CMs within the adjacent clusters.

This objective was achieved by proposing a dynamic time slot scheduling scheme that takes care of inter-cluster interference between the adjacent cluster members of the adjacent clusters to decrease the problem of the high rate of merging collision. The time slot reservation mechanism on the CCH was implemented using a binary tree algorithm. Using the binary tree algorithm, the CH determines the position of each CM. Depending on the position of the vehicle with regard to the CH, the CM could either be ahead or behind ($f$ or $b$) of the CH, as shown in Figure 4.7. Each frame was designed to accommodate vehicles within the cluster, considering their position with regard to the CH. The set of nodes on the left subtree $N_{b(x)}$ was regarded as the vehicles moving behind the CH, while the set of nodes on the right subtree $N_{f(x)}$ represented the vehicles moving ahead of the CH. The vehicles at the front of the CH will get the odd index value, while those behind the CH will get the even index value of the time slice. This technique minimizes the effect of the merging collision problem between the CMs of the adjacent clusters. Because each adjacent CM, even if it is within the communication range of each other, the transmission will not be affected, because the vehicles are using a different set of time slots. The vehicle maintains the same reserved time slot for all the remaining frames. Equally, the time slot reservation method for the vehicles within the cluster on the SCHs was proposed using a 3-way handshake mechanism. This is to provide services for the non-safety messages for the vehicles that need the services without compromising the stringent requirements of the safety related messages, which can only be transmitted through the CCH.

- ✓ To evaluate and validate our novel approach using simulation tools (NS-3 with SUMO) and compares the results with the state-of-the-art approaches in the literature.

To achieve this objective, we first presented the different simulation tools used for the vehicular communication and highlighted some of the reasons why simulation was necessary as well as the choice for both NS-3 and SUMO tools for this research work. The detail of the implementation of the proposed approach was presented in Chapter 4. Accordingly, in Chapter 5, we presented and discussed the results obtained from the various simulation scenarios. The evaluation metrics used for the comparison include cluster stability, number of clusters formed, safety messages delay report generated, rate of merging collision, and communication overhead generated within the network. Consequently, a comparison was made using some specified benchmark techniques from the literature to evaluate and assess the efficiency of the proposed clustering technique along with the time slot scheduling scheme for the EC-TMAC protocol for reliable V2V communication. It was found that, the results obtained in all the simulation scenarios showed that the proposed algorithms for the EC-TMAC protocol demonstrated high superiority over the benchmark techniques with respect to the maintaining cluster stability among the neighbor vehicles, lesser number of clusters within the network, minimum delivery delay of the safety related messages, low rate of merging collision and minimum communication overhead generated.

Similarly, a validation check has been conducted using a T-Test statistical analysis tool. The results of the analysis for all the different scenarios proved the claim that the proposed EC-TMAC protocol is more effective than the benchmark techniques for V2V reliable communication in supporting the deployment of the envisaged VANET applications, especially safety related applications.

## 6.2 Research contributions

There are several contributions that have been gained from this research work. The following are the key contributions of this research work.

1. A new clustering algorithm combining both weight-based and lowest-id clustering techniques to improve the cluster stability within the network for reliable communication among the neighbor vehicles.
2. A new algorithm for the smooth transfer of leadership between the PCH and SeCH. This minimizes the effect of cluster reconfiguration and communication overhead because the cluster architecture will not be affected. Consequently, improve cluster stability and reliable delivery of VANET safety related applications.
3. A design of a dynamic time slot allocation mechanism on the CCH using a binary tree technique that minimizes the inter-cluster interference, which subsequently reduce the rate of merging collision problem.
4. A new approach on the SCHs access time slot reservation scheme using a 3-way handshake mechanism is provided to allow non-safety applications messages to be disseminated without compromising the stringent requirements of the safety related applications messages.

## 6.3 Future Research Directions

This research work focused on investigating the challenges associated with the cluster-based TDMA MAC protocols along with the factors influencing the reliable and timely delivery of the safety related messages using V2V communications. The simulation results demonstrated that the proposed EC-TMAC protocol is very efficient and reliable, therefore can be deployed for the envisaged VANET safety related applications. However, one of the main limitations of this research work is the exclusive utilization of the full DSRC channels, whereby the SCHs have not been implemented for the non-safety applications. The implementation of the proposed EC-TMAC is quite limited to only safety related messages. Therefore, there is a need to implement both safety and non-safety applications to derive the benefit of utilizing the full channels provided by the DSRC standard and for the support of the future deployment of envisaged VANET applications.

Similarly, several research works have been conducted in the literature to increase the efficiency of the MAC protocol using the TDMA based technique in a cluster-based topology. However, most of those research works did not focus on the inter-cluster communication within the adjacent cluster members. It was learned that in the existing study, two adjacent CHs need to exchange some information before they can establish communication between them. Nevertheless, some certain situations might arise due to the frequent topology changes in the vehicular environment, where the adjacent CMs are within the transmission range but their CHs are not. Therefore, to provide support for the VANET envisaged applications, these adjacent CMs need to communicate and exchange messages to avoid any hazardous situations to occur on the highway roads or to provide comfort for the road users. For that reason, a new technique should be provided for effective inter-cluster communication between the CMs of the adjacent clusters.

Equally, despite much attention, the researchers have given in providing a reliable MAC protocol for VANET envisaged applications, one area that is known as the internet of vehicles (IoV), was envisaged also to create a big impact, by providing traffic safety and comfort to both passengers and drivers. In this case, the vehicles are required to be equipped with several devices, which include RSUs, sensor devices, cellular infrastructure, and any other devices that can support the deployment of V2V or V2I communications in VANET. The IoV is an infrastructure-based technology, which could be achieved by allowing the vehicles to collect various types of data within the vehicular environment and share this data with neighbor vehicles or to the internet through V2I communication. The collected information, which involves both safety and non-safety data, for example, the traffic congestion on the road, blind spot, accidents, etc. are communicated in real-time. Therefore, the vehicles around the vicinity become alerted of the current situation through the contextual data provided by the sensors and ultimately these vehicles can become autonomous. Consequently, this process in IoV creates another challenging issue in the vehicular environment, since there will be many devices requiring to access the same wireless medium similar to vehicles, such as, the sensors that are within the vehicle and on the side of the roads. Therefore, consideration of integrating both V2V and V2I communications is very necessary for the efficient cluster-based TDMA MAC protocol to support the future deployment of IoV, since the proposed approach, only considered V2V communication.

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