COOPERATIVE HETEROGENEOUS VEHICULAR CLUSTERING FOR ROAD TRAFFIC MANAGEMENT

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ABSTRACT

Vehicular ad hoc networks (VANETs) are being incorporated with new wireless and telecommunication technologies for various applications. The incorporation of telecommunication technologies, such as long-term evaluation (LTE), within VANETs offers new application opportunities. The use of LTE for road traffic management, especially categorized under driving efficiency class, is gradually increasing with the increase in vehicles on the road. This increasing LTE network usage incurs added cost. In most cases, multiple vehicles in proximity require the same information from traffic information systems (TISs) while traveling in the same direction. This situation results in redundancy in acquired TIS information and poor LTE spectrum utilization. Vehicular clustering is a solution to minimize the use of LTE and the added cost. The first problem is that vehicular clustering faces traditional VANET constraints of high mobility and rapid topology changes, which increase cluster instability. A clustering solution is ineffective if instability is not addressed properly. The second problem is that, given that a cost factor is involved, a level of cooperation is required to determine who and why one should pay the cost and share accessed information to other cluster members (CMs). The third problem is that unstable cluster has a short lifetime, which is not useful for driving assistance and route planning applications that require temporal location information. Thus, developing a solution for traffic efficiency applications to address the aforementioned problems well is a challenging task. Existing solutions fail to address these problems comprehensively and are not designed specifically for traffic efficiency applications. Therefore, an emerging solution that incorporates new information communication technologies (ICTs) is advocated to reduce LTE usage, instability, and non-cooperation among CMs. This research focuses on the development of a novel heterogeneous network infrastructure-based vehicular clustering framework called destination and interest-aware clustering (DIAC). DIAC assumes that vehicles in proximity that travel toward the same destination or a milestone ahead form a cluster and considers the common interest of vehicles to access the same information. In addition, a clustering criterion is defined to avoid instability. A cooperative mechanism based on strategic game theory (SGT) is also developed to motivate vehicles to participate in cluster formation and to enforce vehicles to share accessed information and cost of use of the Internet. A control mechanism is defined as well to control the non-cooperative behavior and fair-use policy among CMs. Furthermore, a self-location calculation algorithm is developed to enable vehicles to calculate their location in the absence of global positioning system (GPS) signals. This implementation increases the level of synchronization of CMs with a cluster head, thereby increasing cluster stability. The proposed framework is simulated, and benchmarking is conducted with existing state-of-the-art approaches. The system model of the proposed solution is also developed and evaluated at macro level through formal verification. This research redirects existing efforts in acquiring TIS information toward a novel perception that is, designing a stable heterogeneous communication framework for cooperative data access to remote servers to minimize network usage and cost.

Keywords: VANET, ad hoc network, cooperative clustering, road traffic management, LTE network.

Pengklusteran Kenderaan Heterogenik Koperatif untuk Pengurusan Lalu Lintas Jalan Raya

ABSTRAK

Rangkaian Ad Hoc Kenderaan (VANETs) sedang digabungkan dengan teknologi wayarles dan telekomunikasi baru untuk pelbagai aplikasi. Penggabungan teknologi telekomunikasi seperti Penilaian Jangka Panjang (LTE), dalam VANET, membuka peluang aplikasi baru. Penggunaan LTE untuk pengurusan lalu lintas jalan raya, terutamanya dikategorikan sebagai kelas kecekapan memandu, secara beransur-ansur meningkat dengan peningkatan kenderaan di jalan raya. Penggunaan LTE untuk pengurusan lalu lintas jalan raya, terutamanya dikategorikan sebagai kelas kecekapan memandu, secara beransur-ansur meningkat dengan peningkatan kenderaan di jalan raya. Penggunaan rangkaian LTE yang semakin meningkat ini menelan kos tambahan. Dalam kebanyakan kes, pelbagai kenderaan yang berdekatan memerlukan maklumat yang sama dari sistem maklumat trafik (TIS) semasa melakukan perjalanan ke arah yang sama. Keadaan ini menyebabkan kelebihan maklumat TIS yang diperoleh dan penggunaan spektrum LTE yang lemah. Pengklusteran kenderaan adalah penyelesaian untuk meminimumkan penggunaan LTE dan kos tambahan. Masalah pertama adalah bahawa pengklusteran kenderaan dalam tradisional VANET menghadapi kekangan mobiliti yang tinggi dan perubahan topologi yang pesat, yang meningkatkan ketidakstabilan kluster. Penyelesaian kluster tidak berkesan jika ketidakstabilan tidak ditangani dengan betul. Masalah kedua adalah, memandangkan faktor kos terlibat, tahap kerjasama diperlukan untuk menentukan siapa dan mengapa seseorang itu harus membayar kos dan berkongsi maklumat yang diakses kepada ahli kumpulan lain. Masalah ketiga adalah bahawa kluster yang tidak stabil mempunyai jangka hayat yang pendek, yang tidak berguna untuk bantuan memandu dan aplikasi perancangan laluan yang memerlukan maklumat lokasi temporal. Oleh itu, membangunkan penyelesaian untuk aplikasi kecekapan trafik untuk menangani masalah yang disebutkan dengan baik adalah tugas yang mencabar. Penyelesaian yang sedia ada gagal menyelesaikan masalah ini secara komprehensif dan tidak direka khusus untuk aplikasi kecekapan trafik. Oleh itu, penyelesaian baru yang menggabungkan teknologi komunikasi maklumat (ICT) yang baru diperjuangkan untuk mengurangkan penggunaan LTE, ketidakstabilan, dan tiada koperatif antara CM. Penyelidikan ini memberi tumpuan kepada pembangunan rangka kerja kluster kenderaan berasaskan infrastruktur rangkaian kepelbagaian novel yang dipanggil pengklusteran destinasi dan minat-sedar (DIAC). DIAC mengandaikan bahawa kenderaan yang berhampiran dengan perjalanan ke arah destinasi yang sama atau arah ke hadapan membentuk kluster dan menganggap kepentingan bersama kenderaan untuk mengakses maklumat yang sama. Di samping itu, kriteria kluster ditakrif untuk mengelakkan ketidakstabilan. Mekanisme koperatif berdasarkan teori permainan strategik (SGT) juga dibangunkan untuk memotivasi kenderaan untuk mengambil bahagian dalam pembentukan kluster dan menguatkan kenderaan untuk berkongsi maklumat yang diakses dan kos penggunaan Internet. Mekanisme kawalan juga ditakrifkan untuk mengawal tingkah laku bukan koperatif dan dasar penggunaan adil di kalangan CM. Selain itu, algoritma pengiraan lokasi diri dibangunkan untuk membolehkan kenderaan mengira lokasi mereka tanpa adanya isyarat sistem kedudukan global (GPS). Pelaksanaan ini meningkatkan tahap penyegerakan CM dengan ketua kluster, sehingga meningkatkan kestabilan kluster. Rangka kerja yang dicadangkan disimulasikan, dan penandaarasan dilakukan dengan pendekatan terkini yang sedia ada. Model sistem penyelesaian yang dicadangkan juga dibangunkan dan dinilai pada peringkat makro melalui pengesahan formal. Kajian ini mengalihkan usaha sedia ada untuk memperoleh maklumat TIS ke arah persepsi novel iaitu merangka rangka kerja komunikasi yang heterogen bagi akses data koperatif kepada pelayan jauh untuk meminimumkan penggunaan dan kos rangkaian.

Katakunci: VANET, Rangkaian Ad-hoc, Koperatif, Pengurusan Trafik Lalulintas Jalan Raya, Rangkaian LTE.

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LIST OF ACRONYMS

Acronym	Description
β	Weighing factor of Λv
σ	Variance in speed of vehicles
Λv	Aggregated mobility metric
′	Prime
∀	For all
∅	Empty set
∆T	Change in time
∈	Element belongs to set
∧	AND
∨	OR
∪	Union
⊆	Is a subset or equal to
→	Total function
⇸	Partial function
¬a	Negation of predicate ‘a’
•	The predicates whose value is true
3G	Third Generation telecommunication networks
4G	Fourth Generation telecommunication networks
5G	Fifth Generation telecommunication networks
A	Counts accepted offers
A?	The input to an operation
ACK	Acknowledgment
ACKs	Acknowledgments
AF	For All computational paths
C	Variation as per SGTA
CAM	Cooperative Awareness Massages
CCOc	Current coordinates of CH
CCO_m	Current coordinates of CM
CH	Cluster Head
CHID	CH identification
CIAC	Cooperative Interest-Aware Clustering
CMGM	Clustering based Multi-metric adaptive mobile Gateway management Mechanism
CMs	Cluster Members
COc_i	Initial coordinates of CH
Com_i	Initial coordinates of CM
CTL	Computational Tree Logic
C_v	Cluster of vehicles
D2D	Device to Device

dBm	Power ratio in decibels per mW
DIAC	Destination and Interest-Aware Clustering
DIAC-LA	DIAC Location-Aware
DMCs	Data Management Center
$\mathbf{d_s}$	Standard deviation of speed
DSRC	Dedicated Short-Range Communication
EF	Some of the computational paths
ETSI	European Telecom Standard Institute
FCD	Floating Car Data
$\mathbf{f_i}$	Member match requirements
GPS	Global Positioning System
GSM	Global System for Mobile Communication
ICTs	Information Communication Technologies
IoTs	Internet of Things
IoVs	Internet of Vehicles
ITS	Intelligent Transportation System
LQ	Link quality
LQcm	LQ of CM
LQsv	LQ of SV
LTE	Long Term Evolution
LTE-A	LTE- Advance
$\mathbf{L_v}$	Location of vehicle
MANETs	Mobile Ad hoc Networks
MAX	Maximum out of given values
MDMAC	Modified distributed and Mobility-Adaptive clustering
MGSA	Mobile Gateway Selection Algorithm
Mv	Member Vehicle
NCIAC	Non-Cooperative Interest-Aware Clustering
Notify	Multi-cast to several vehicles
NOTIFY	A message to inform CMs of network change
OBU	On-Board Units
$\mathbb{P}$	Subset
PDR	Packet Delivery Ratio
Pr (t)	Received power at time t
QoS	Quality of Service
R	Counts rejected offers
RSS	Received signal strength
RSUs	Road Side Units
$\mathbf{S_a}$	Average speed
SGT	Strategic Game Theory
SGTA	Strategic Game-Theoretic Algorithm
SIAC	Stable Interest-Aware Clustering
SimuLTE	Simulation for LTE
SLCA	Self-Location Calculation Algorithm
$\mathbf{S_r}$	Relative speed

SUMO	Simulation of Urban Mobility
S_v	Speed of vehicle
SV	Source vehicle
t	Time
TIS	Traffic Information System
TMC	Traffic Management Center
TMSs	Traffic Management Systems
UMTS	Universal Mobile Telecommunication System
V2I	Vehicle-to-Infrastructure
V2-LTE	Vehicle-to-LTE network communication
V2V	Vehicle-to-Vehicle
VANET–LTE	Vehicular Ad hoc Network integration with LTE
VCC	Vehicular Cloud Computing
Veins	Vehicles In Network Simulation
VID	Vehicle ID
VMaSC	Vehicular Multi-hop algorithm for Stable Clustering
WAVE	Wireless Access in Vehicular Environment
Wi-Fi	Wireless Fidelity
Z	Z notation or language
Δ	Change in value
ΔLi	Initial difference in location coordinates of CH and CM
ΔSc	Change in speed of CH
ΔSm	Change in speed of CM
ΔS_{thr}	Speed difference threshold
θ	Direction of vehicle
Gↄ	Destination

CHAPTER 1: INTRODUCTION

1.1 Introduction

This chapter introduces the area of heterogeneous vehicular networks formed by incorporating and integrating traditional VANETs with emerging telecommunication technologies, such as LTE. This chapter also discusses the problem statement, motivation, and research objectives. This chapter is divided into six sections. Section 1.2 describes the background of the research, and Section 1.3 explains the motivations and significance of this research and the proposed solution. Section 1.4 highlights the research issues in the form of problem statement, and Section 1.5 states the aim and objectives of the research. Section 1.6 illustrates the organization of the thesis.

1.2 Background

The ever growing number of cars on the road results in road infrastructure congestion, which causes spending long hours on the road, consuming large amounts of fuel, and polluting the environment. This situation also causes wastage of precious time and money. Academia and vehicle industries are working determinedly and investing a large amount of money to ensure easy, efficient, and secure road travel by using emerging technological infrastructures. VANETs play a significant role and provide basic infrastructures for the development of applications for road safety, traffic efficiency, and in-car entertainment. The communication networks in VANETs have distinctive properties, and the routes of the nodes are organized and have great speed. The usefulness of VANETs relies on the establishment of reliable communication among vehicles for the development of various applications for road traffic management (Alam, 2016).

Recent improvements in software, hardware, and communication technologies empower the design and development of cloud computing technology and the Internet of vehicles

(IoVs). The IoVs incorporates multiple access networks and technologies to connect vehicles on the roads. The improved sharing of data and resources among vehicles leads to vehicular cloud computing (VCC). VCC provides access to the dynamically configurable and integrated, underutilized vehicular resources. As a result, developed applications based on VCC can provide various services to users (vehicles and passengers). This situation influences the development of new vehicular traffic management systems (TMSs) potentially. VCC brings new services and solutions but introduces new potential issues and challenges (Ahmad et al., 2017; Whaiduzzaman et al., 2014).

The standards for VANETs, such as wireless access in vehicular environments (WAVE), have already defined vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) types of architecture. An advanced form is vehicle to everything, in which vehicles can communicate with everything around via multiple interfaces, such as with telecommunication networks. Nowadays, vehicles have multiple interfaces for different network types, such as Bluetooth within the car, Wi-Fi, and dedicated short-range communication (DSRC) for short-range communication; and 3G and LTE for long-range communication. Vehicles use these technologies simultaneously to facilitate passengers and assist drivers while moving on the road. Existing TMSs need to be improved with emerging situations and technologies to realize a good intelligent transportation system (ITS) (Fernandes et al., 2016).

The integration of WAVE with 3G or LTE forms a heterogeneous network (Yaqoob et al., 2017). This kind of integration extends VANET capabilities into the IoVs and thus provides seamless data access to vehicles that help address road traffic management issues (Uppoor & Fiore, 2015). IoVs are expanding the traditional VANET application development by exploiting emerging technologies for envisioned use case scenarios.

A vital usage scenario is a traffic information system (TIS) that depends on LTE for delivery of non-safety information to vehicles. TIS comprises centralized data warehouses that collect and process traffic information and subsequently allow vehicles to receive such information before and during a road trip. Each vehicle on the road usually connects to a remote server, such as TIS, over the Internet to upload its status information (speed, location, direction) and to download instructions (alerts, warnings, notifications) regarding driving assistance and route planning. Thus, a vehicle acts by planning and re-routing accordingly. This information is location temporal but less sensitive than safety applications and requires to be transferred at the right place and time (Uppoor & Fiore, 2015). When the vehicle needs information for driving assistance and route planning during the journey, it either connects to the Internet via 3G/LTE network, or it can acquire such information from the neighboring vehicles by forming a cluster. The former incurs more cost than the latter. Therefore, the latter is preferred to save cost and bandwidth.

1.3 Motivation

Smart traffic is vital for economic growth and can only be achieved by reducing the life risk on the road, fuel consumption, environmental impact, and driving time to a minimum. The increasing number of vehicles on the road needs to be solved with emerging information communication technologies (ICTs). Existing technologies are already facing large data traffic tsunami because of the development of smartphones and data-greedy applications. ICTs, such as LTE, are now used to develop improved traffic management applications. The use of LTE is gradually increasing with data increases in smartphones, applications, autonomous vehicles, and vehicular applications (Araniti et al., 2013).

The penetration rate of LTE is increasing, but the mobile network growth is less than data growth as millions of new data devices and connection are being added every year (Mobile, 2017). Cisco visual networking report in 2017 (Mobile, 2017) indicated that the global mobile traffic is expected to increase by 18-fold between 2016 and 2021. Although 4G connections represented only 26% of mobile connections in 2016, they already accounted for 69% of mobile data traffic; 4G connections will have the highest share (53%) of total mobile connections by 2021. The use of LTE in vehicular application is also increasing immensely. Vehicular user traffic proportion increased 2.83 times (10.35%–29.29%) between 2015 and 2016 and will continue to rise in the coming years (Shim et al., 2016).

The popular terms such as connected people, connected devices, and connected vehicles are envisioned due to emerging telecommunication technologies, such as LTE. IoVs introduce prospective scenarios and emerging solutions. The ITS is the major part of smart city projects and development of new solutions, which are important because they improve road traffic management that helps boost the economy, environment, and life. Thus, enhanced solutions based on ICTs should be developed to cope well with traditional VANET constraints hurdled in developing new road TMSs.

LTE and DSRC technologies, which are well suited for providing ITS services under the condition of low vehicle density, are primary candidates. For TIS, message transmission latency should be around 200 ms and should not be greater than 500 ms (worst case) and message frequency should be at least 1 Hz (Mir & Filali, 2014; Zheng et al., 2015). 3G technologies do not satisfy these requirements (ETSI, 2012), but LTE meets these requirements due to its flat architecture. However, the ever-increasing number of vehicles easily overloads LTE networks. The integration of the two technologies can positively affect the performance of applications, especially route planning and driving assistance. Comprehensive analysis of existing literature shows that no such solution that well suites and considers the functional requirements of traffic efficiency applications is available. An end-user side solution that works beyond telecommunication network capacity planning and cooperative data access to remote servers should be developed to minimize network usage and cost of use.

Clustering of vehicles is a developed solution in vehicular applications for road traffic management. Clustering reduces the number of individual connections to the LTE network, which in turn reduces data download and cost. Although clustering is a good solution, traditional VANET constraints on it should be addressed. Clustering of vehicles is conducted to access and share common information from the remote server to the vehicles. This implementation helps communicate a group of vehicles through a single LTE connection.

Most related solutions deal with uploading floating car data (FCD) and downloading (contents) separately. V2V-exploited solutions have not fully considered traffic flow control or TIS aspect to date. These aspects motivate us to develop a vehicle-to-LTE (V2-LTE)-based solution by exploiting V2V communication for decreasing LTE resource utilization through cooperative and stable vehicular clustering.

1.4 Statement of the Problem

Route planning and driving assistance applications have location and time-sensitive information delivery, which necessitates reliable and efficient communication infrastructure development to meet the requirements. The usual working of such application consumes a large number of LTE spectra and should be decreased. The combination of VANET and LTE can provide a solution, such as clustering of vehicles. However, general clustering techniques cannot work well with all types of use cases and network scenarios. Clustering solutions developed for safety and infotainment applications have their own data rate and frequency requirements (Mir & Filali, 2014; Zheng et al., 2015) and cannot work for driving assistance and route planning applications. Clustering solutions developed for content downloading (Gerla, Wu, et al., 2014) are less time sensitive, but TIS cannot tolerate a delay of over half a second. Similarly, clustering solutions for road safety require considerable prompt information, but no cooperation mechanism is an essential requirement in TIS.

A stable cluster, which is developed on the basis of some specific clustering criteria, is required with the cost factor for driving assistance and route planning applications. Although some solutions exist (Benslimane et al., 2011; Ucar et al., 2016; J. Wang et al., 2017; Chuchu Wu et al., 2015), they ignore the above-mentioned factors and are unrelated to road safety and in-car infotainment.

The literature related to road traffic efficiency (driving assistance and route planning applications) that incorporates heterogeneous V2-LTE infrastructure is still in its infancy. The work in (Ucar et al., 2016) is mainly developed for road safety and ignores the stability of the cluster, the cost of use of the Internet, and the mechanism of cooperation. The work in (Chuchu Wu et al., 2015) presents server-assisted cooperation management that is related to infotainment contents and fails to address instability, which is a major concern for network performance. The work in (Benslimane et al., 2011) is developed for 3G network integration with VANET and neglects cost, stability, and cooperation among cluster members (CMs).

In most cases, multiple vehicles require the same TIS information while traveling in the same direction. This condition results in redundancy in acquired TIS information and poor LTE spectrum utilization. Each vehicle on the road usually requires individual LTE connection to send and receive data to and from the remote server to make a smart decision regarding route planning and driving. This condition consumes a large number of LTE spectra. The increasing number of vehicles on the roads not only overwhelms LTE network usage but also incurs cost. These aspects for TIS have not yet been explored.

Clustering helps minimize LTE usage, but high speed of vehicles causes unstable and unreliable connections not only among vehicles but also between vehicles to the LTE network. Instability of connections is a major hurdle in developing cost-effective solutions for deriving assistance and route planning applications.

Non-cooperative behavior among vehicles within a cluster is a bottleneck in sharing costly data acquired from the Internet. The issue of who and why one (vehicle) should pay the cost proliferates the non-cooperative behavior among CMs.

Therefore, we first need to develop a mechanism for TIS information sharing among vehicles to reduce spectrum usage and cost. Second, a stable clustering of vehicles is required to share TIS data because a good solution cannot be developed without addressing traditional VANET constraints. Third, a mechanism to control non-cooperative behavior by motivating vehicle to participate and share the cost should be developed.

1.5 Research Aim and Objectives

This research aims to propose a stable and cooperative mechanism for TIS information sharing among vehicles moving on the road by utilizing minimum LTE spectrum for driving assistance and route planning applications. The objectives are listed as follows.

1. To review the state-of-the-art traffic efficiency related to TMSs and analyze the research problem through real-world field tests.
2. To develop stable clustering by defining a unique criterion and a synchronization mechanism for sharing TIS information through a single LTE connection among multiple vehicles for minimizing LTE spectrum usage and cost.
3. To design a cooperation mechanism and establish fair use among vehicles in the clustering process for discouraging deviation from sharing TIS data.
4. To develop an integrated heterogeneous vehicular clustering framework for stable and cooperative access to TIS servers while consuming a small amount of LTE resources.

1.6 Organization of the Thesis

We organize our thesis into eight chapters. Chapter 2 presents the background of the area of study and review of existing popular solutions (prototypes). We divide Chapter 2 into two main sections: Section 1 is related to the study of existing literature categorized by VCC, and Section 2 describes VANET–LTE-based driving assistance and route planning applications. The first section categorizes the existing solutions in VANETs by cloud integration-based taxonomy and compared those solutions using important metrics. The second section describes VANET–LTE-based existing solutions, presents a functional designed-based taxonomy, and qualitatively compares different properties of popular prototypes to highlight their limitations for finding a potential research gap.

Chapter 3 discusses the methodology of our research, which consists of three main phases. In the first phase, we study state of the arts to identify issues in existing TMSs that are related to road traffic efficiency. We focus on two types of existing TMSs: the first type is based on VCC, and the second type incorporates LTE with DSRC. Real-world field experiments are carried out to investigate and prove that the identified issues exist. The impact of the identified gap is also quantified after taking and summarizing real-world data within the partial scope of the study. In phase two, we develop a VANET–LTE-based heterogeneous clustering framework called destination and interest-aware clustering (DIAC) for driving assistance and route planning applications to minimize LTE spectrum usage and resulting cost. Three submodules are also developed, namely, stable interest-aware clustering (SIAC), cooperative interest-aware clustering (CIAC), and self-location calculation algorithm (SLCA). In phase three, we implement each submodule of DIAC separately by using popular simulation tools specifically developed for vehicular networks. The benchmarking of the system is also performed by comparing its performance with that of popular existing approaches. Second, we formulate the mathematical modeling of the proposed system using the formal language "Z" or Z notations. Macro-level testing of the system model is conducted using a formal testing technique known as model checking.

Chapter 4 provides preliminary research investigation to verify and quantify the research problems by conducting real-world field tests. These tests are performed in Kuala Lumpur, Malaysia and Cambridge, UK by hiring cars and regular taxi drivers for a specific period and by using Waze and Google Map applications. Tests are conducted over selected road segment routes (from short to long), and data are collected to find the trends regarding the use of LTE while cars move on the roads. The average data rate per travel time of the vehicle is estimated by analyzing results in a mathematical form. In other words, we quantify the redundancy in data acquisition from the remote server accessed by vehicles for driving assistance and route planning applications (Waze and Google Map). The outlined problem is highlighted in a diagrammatic form, and other findings are concluded.

Chapter 5 proposes a DIAC framework that comprises three submodules: DIAC algorithm, strategic game theory (SGT) mechanism, and SLCA. These submodules are discussed in three different sections, respectively. The first subsection explains the main clustering process of vehicles traveling in proximity and defines clustering metrics and cluster head (CH) selection algorithm. The second subsection presents SGT mechanism that motivates vehicles to participate in the cluster and a fair-use policy to enforce fairness in the bearing of the cost incurred in accessing remote information from the Internet. SGT strategies are defined with their related payoffs and checked and verified using the open-source software GAMBIT. The third subsection describes a self-location mechanism that is triggered whenever the global positioning system (GPS) signal is unavailable and helps vehicles in maintaining a link with CH. Finally, all modules are conclusively incorporated into one DIAC framework.

Chapter 6 reports the implementation and results of the proposed framework. First, we implement each submodule of DIAC separately (i.e., DIAC, SGT, and self-location mechanisms). The quantitative results are acquired by low-level modeling of the proposed solution using simulations. We use popular simulation tools specifically developed for vehicular networks such as SUMO (Krajzewicz et al., 2012a), Veins, and SimuLTE over the OMNeT++ network simulator (Hagenauer et al., 2014). The maps of road infrastructures are accessed from OpenStreetMap. The simulation environment, parameters, and performance metrics are described in this chapter as well. The results of simulation against different metrics are presented, compared in a graphical form, and evaluated.

Chapter 7 describes the formal verification (methods) used, the specification of the model (system), and the analysis of the model through model checking technique. The schemas are formulated, and the states and properties of the developed system model are explained. The computational tree logic (CTL) of the system is done and confirms that the desired properties hold.

Chapter 8 reports the reassessment of the described objectives and findings of the research. The significance, limitations, and future directions of the research are also presented. Figure 1.1 presents the organization of this thesis.

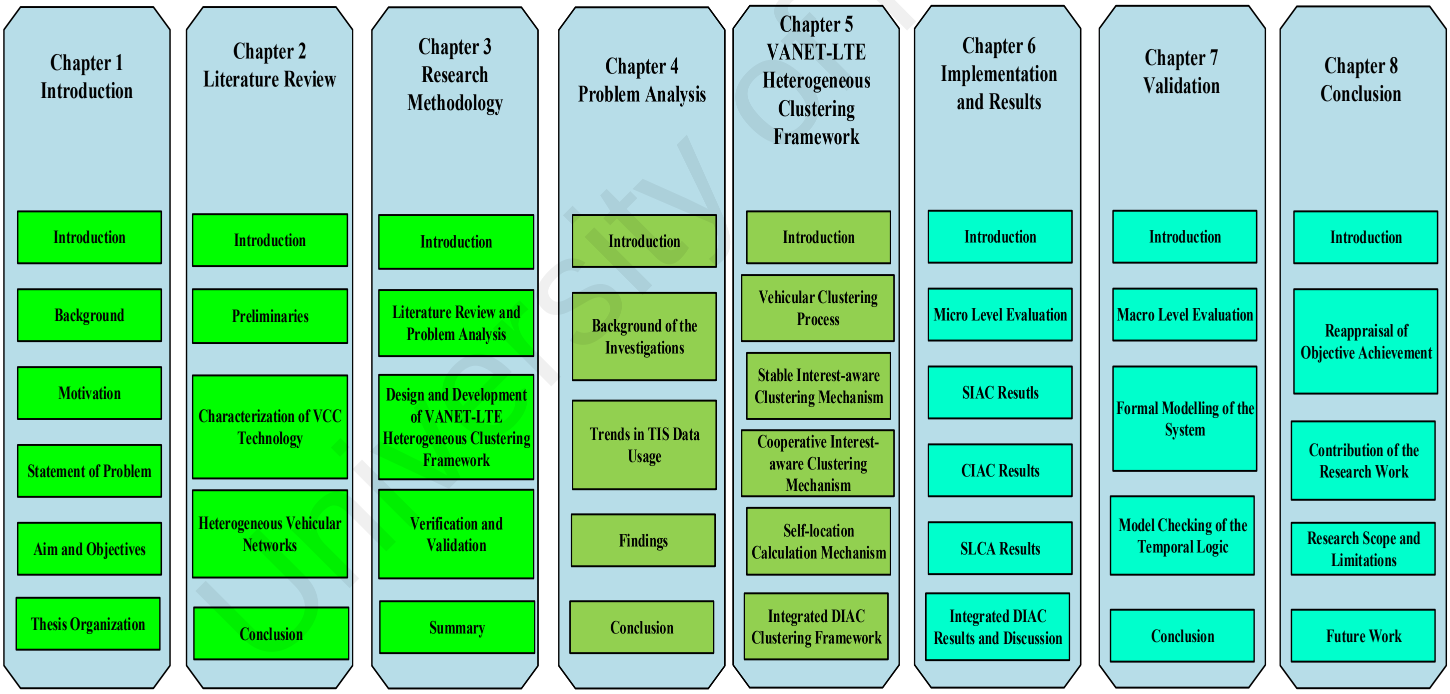

Figure 1.1: Organization of the Thesis

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter is about the background of the area of study and review of the state-of-the-art in road traffic management. Also provides taxonomies, and comparative analysis of existing solutions (prototypes) to get an in-depth understanding and intuitive hallucination. Open research issues and challenges in existing road TMSs are also discussed in this chapter.

We divided chapter 2 into five main sections. Section 2.2 describes the basics concepts of VANETs, road traffic efficiency, LTE, and VCC. Section 2.3 is about the characterization of VCC technology for road TMSs, which categorize the existing solutions in VANETs by cloud integration based taxonomy and comparatively analysis by important metrics. Section 2.4 describes VANET–LTE-based existing heterogeneous solutions, presents a functional designed based taxonomy and qualitatively compare different properties of well-known existing prototypes to highlight their limitations to find a potential research gap. Section 2.5 concludes the discussion.

2.2 Preliminaries

This section describes the basic idea of VANETs, communications in VANETs, main application types, traffic efficiency applications, nutshell of LTE, and cloud computing especially the VCC.

2.2.1 Vehicular Ad-Hoc Networks (VANETs)

Wireless ad-hoc networks are special kind of temporary networks formed on a situational basis for communication of information among the fixed or moving network devices. When such a network is established among moving devices, it is known as mobile ad hoc networks (MANETs) such as a network of Wi-Fi devices. If such a network establishes among vehicles, then this is called a VANET. VANET is different from MANET in some properties such as the high speed of vehicles, known routes, and highly dynamic topology. In VANETs the vehicle is the main entity over which an onboard unit (OBU) is installed. Today's OBUs have multiple interfaces to connect the vehicle to another vehicle and other auxiliary networks such as Wi-Fi, LTE. OBU is also having a GPS receiver and event data recorder (EDR) to send and receive messages. Another component of VANET is road-side units (RSUs) those connect vehicles to roadside infrastructure, may installed on important locations over a road segment(Rasheed et al., 2017).

There are two basic types of communication in VANET; V2V and V2I. In V2V vehicles exchange information among each other and V2I vehicles exchange information with other infrastructure networks such as fixed line networks using dedicated shortage communication (DSRC) protocol. The USA and European Union have already allotted bandwidth for vehicular communication and conceived communication protocol architecture named as IEEE wireless access for the vehicular environment (WAVE) and European telecommunication standards institute (ETSI) ITS respectively(Campolo et al., 2013). The automotive industry and standard institutes across the world continuously seeking emerging ICTs to improve the utilization and implementation of VANET to develop potential applications for road traffic management.

There are two main categories of VANET based applications; road safety applications being developed to the safe driver and passenger life on the roads, traffic efficiency applications to control the flow of traffic and to avoid traffic congestion. These applications can be divided into V2V communication infrastructure based and V2I based applications. Figure 2.1 gives a general view of urban traffic management that is broadly divided into safety and non-safety (traffic flow control) systems.

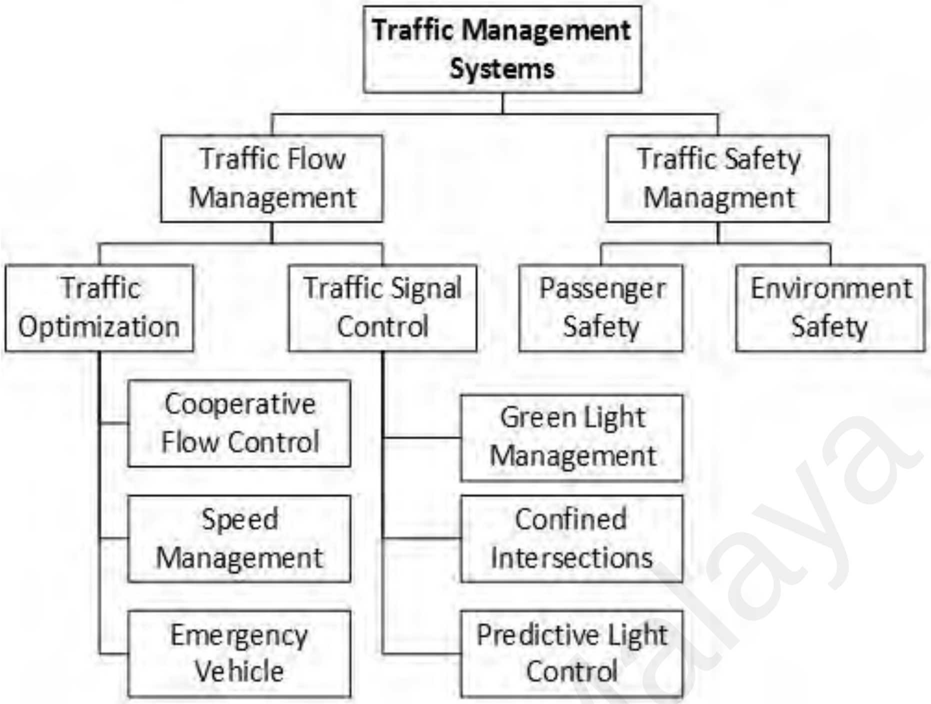

Figure 2.1: Overview of TMSs

The distinction among various vehicular applications nowadays is somewhat getting complex as incorporation new ICTs opening new horizons and applications scenarios. The overwhelming demand for vehicular application is because of innovations in the car industry such as the development of autonomous and semi-autonomous cars that are directly or indirectly controlled through intelligent applications.

2.2.2 Road Traffic Efficiency

Road Traffic Efficiency is the steady and smooth flow of vehicles without any traffic jam on the road. Application developed to control the behavior of vehicle flow on the road to minimize travel time and to reduce/avoid congestion such applications are called traffic efficiency application. These applications are based on Internet services and require quality of service (QoS) communication for delivery of information on time and at the required location. The quality degrades with the increasing number of cars due to the increase in messages exchange, the example of such applications are (FCD) services and extended FCD services. This kind of applications requires periodic transmission of data collected by vehicles via internal and external sensors (road embedded sensors, radars and cameras) to Internet-based remote servers (also known as traffic information servers)(Briante et al., 2014). The servers process collected data, analyze and predict traffic congestion and send up-to-date information to the navigation system of the vehicle for the vehicle to make the right decision regarding route planning. In addition to this vehicles may request related information concerning their route and driving context periodically and be transferred to the occurrence of an event. There are some related examples of today's applications such as Waze and Google Map those can work with OBU to help assist drivers on the roads.

Here, one thing is worthwhile to mention, this kind of applications works and can perform well only if they are enabled to access remote server over the Internet and can get information at right time and place. To, access remote servers while moving on the road, vehicles must remain connected to the Internet via third party network or telecommunication networks such as 3G or LTE. The use of telecommunication networks for Internet access is not free, and the required data rate and latency must not be greater than the threshold value (as defined in (Lottermann et al., 2015)). So which telecommunication network technology suits these requirements (as depicted in Table 2.4) is also needed to be taken care of (Mir & Filali, 2014; Zheng et al., 2015).

Table 2.1: Functional and performance requirements

Functional requirements	Road Safety applications	Traffic efficiency applications	Infotainment applications
Latency	<= 100 ms	<= 200 ms	<= 500 ms
Frequency	10 Hz	1 to 10 Hz	1 Hz
Data rate	1 to 10 Kbps	1 to 10 Kbps	10 to several 100 Kbps

By capturing, evaluating, and disseminating road traffic-related information, a TMS improves traffic flow and reduces traffic congestion. DSRC is the primary technology for such TMSs. The bandwidth restriction of DSRC limits the information frequency and size of the data to be communicated to vehicles (Al-Sultan et al., 2014). QoS-based data aggregation techniques are suitable for DSRC (Ramakrishnan et al., 2015). Vehicles exchange information on route choices, congestions, and traffic and decide by selecting the best option (Gupte & Younis, 2012). The traffic efficiency applications use V2I infrastructure but mostly uses other radio access network such as LTE directly to have a continuous exchange of information with TIS server over the Internet.

2.2.3 Long-Term Evolution (LTE)

LTE is the advanced form of 3G telecommunication networks technologies named as universal mobile telecommunication system (UMTS) and global system for mobile communication (GSM). LTE has flat network architecture with few numbers of network entities and separated user and control plane traffic. LTE has simplified data, voice, and signaling process as compare to UMTS and GSM which reduces round-trip time to 10 mili-seconds. LTE architecture is composed of E-UTRAN for radio access and evolved packet core which includes all network entities as shown in Figure 2.2.

LTE air interface is composed of evolved NodeBs (eNodeB) to manage radio resources and handover process. LTE provides channel width ranging from 1.4 to 20 MHz and enables to support frequency division duplex (FDD), time division duplex (TDD). LTE uses orthogonal frequency division multiple access (OFDMA) and multiple-input and multiple-output (MIMO) techniques. The packet scheduler is important in meeting QoS requirements for various application types. Overall LTE core network manages authentication, mobility management and QoS (Mullner et al., 2009).

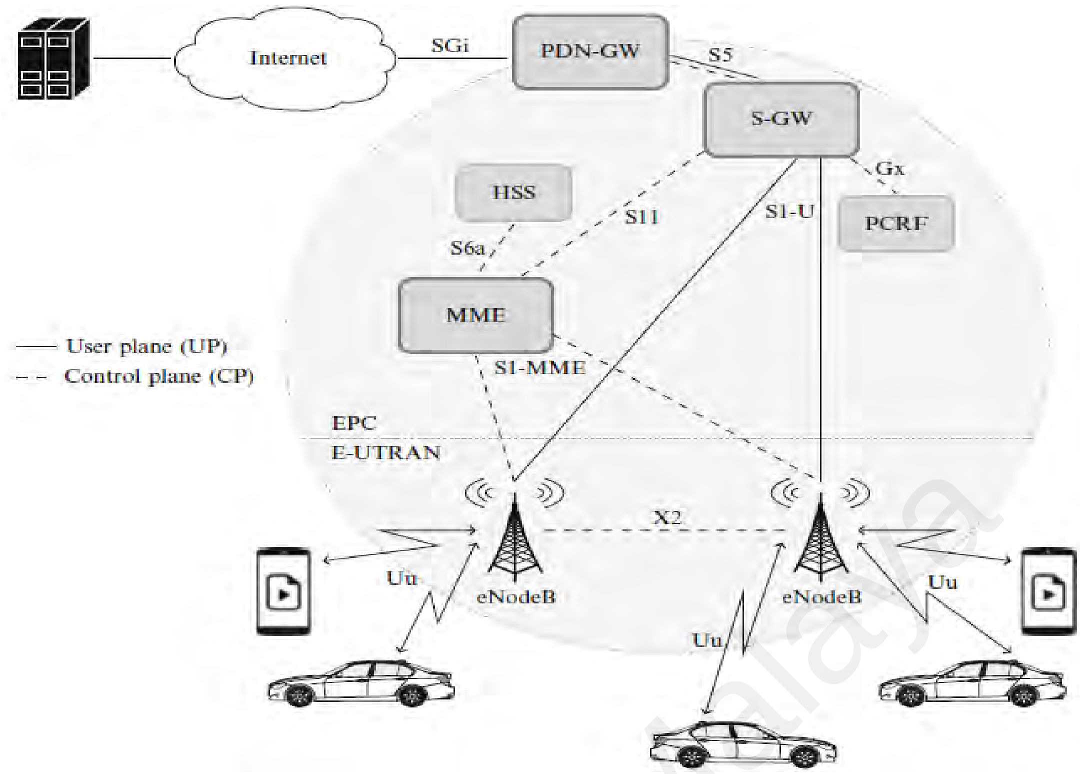

Figure 2.2: LTE architecture with core entities (Lottermann et al., 2015)

LTE offers more data rates, lower latency in communication for real-time services to users. Car industry took a greater interest in LTE to offer a wide variety of cooperative driver assistance services. Investigations are already done to check theoretical delay and reliability under different load conditions and QoS settings as shown in Figure 2.3 and Figure 2.4.

The delay of the LTE network at different cell load regarding a number of cars connected has been investigated by ETSI as shown in Figure 2.3. The doted marron color line shows that maximum of 200 cars can be accommodated at a delay of 500 mili-second when there is no other traditional LTE data traffic over the network. Figure 2.4 shows downlink resource usage of LTE against a various number of cars per cell at a different frequency of events occurrence. An occurrence of events triggers the data exchange among the cars that increase the exchange of information over the LTE network. It is clear that only when there are 40 events, and the number of cars is less than 200 the downlink resources usage is less than 100 percent; otherwise, it remains higher. Also ignoring the fact that more numbers of cars on the road more traffic-related incidents usually occurs and also LTE network is being utilized by only for connecting the cars, and there is no other data or voice from native LTE users. So, it clear that although LTE has various advantages regarding speed and latency enabling TMSs to work well within the threshold value of a number of users at a time within a cell. Whenever there is an increase in a number of users, the applications that required a specific QoS for proper functioning will suffer as the capacity of the LTE network cannot be increased on a runtime basis.

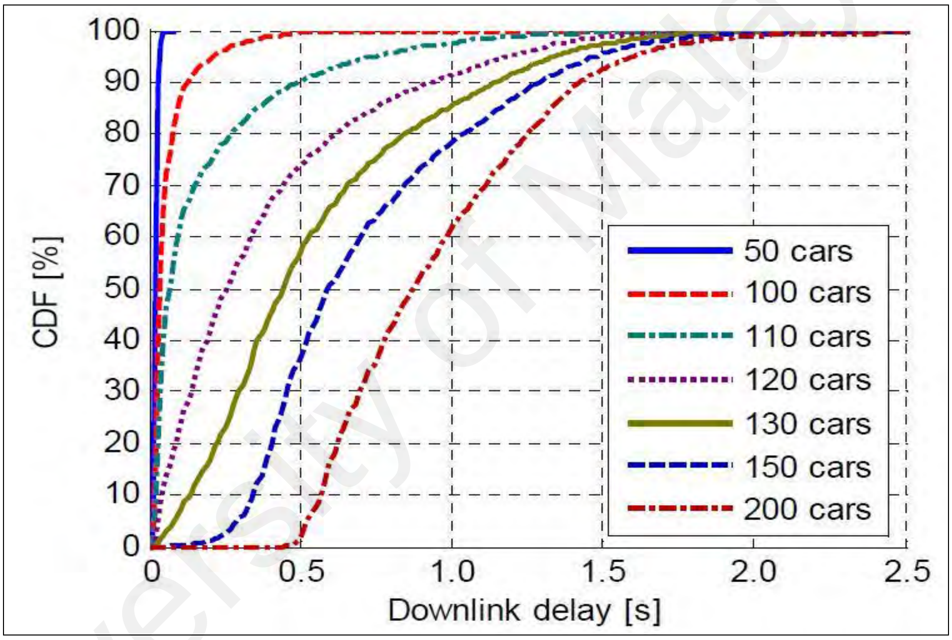

Figure 2.3: Distributed packet delay per cell load (number of cars) (ETSI, 2012)

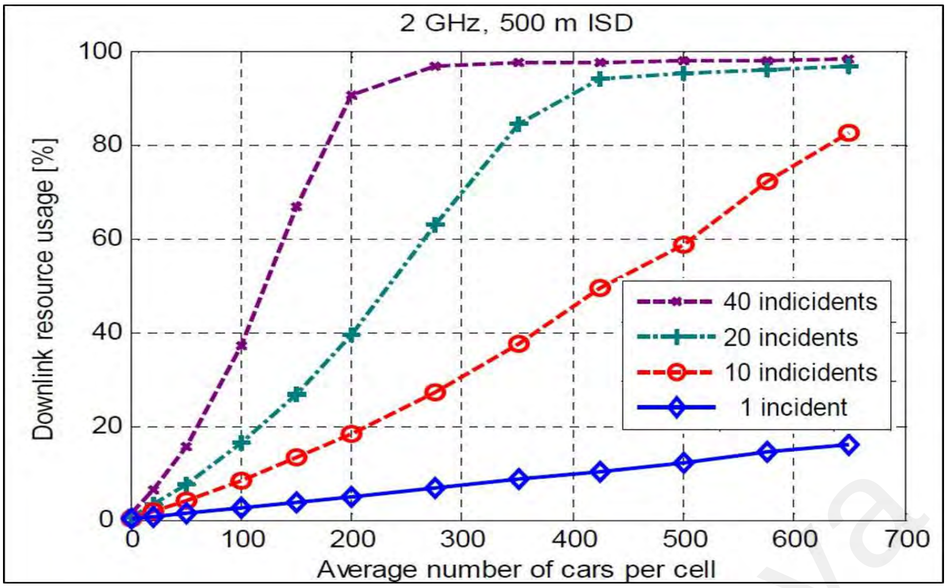

Figure 2.4: Downlink radio resource usage per cell load (Urban scenario) (ETSI, 2012)

Using the only LTE for vehicular applications can make LTE network overloaded because of the CAM, DEMN message transmission as every message has to be pass through LTE centralized infrastructure. Although, LTE can accommodate numerous event notifications within a given area, but the delivery of CAM may suffer poor uplink transmission under heavy load. A simulation study in (Lottermann et al., 2015) shows that performance degrades after increasing the number of vehicles to greater the 150 vehicles per cell. The results show that future automotive applications must have to select the right QoS parameters under the high-load condition of the network. However, the wider coverage range and mobility management of LTE are advantages over IEEE 802.11p but has the problem of the centralized nature of the network and natively do not support V2V connectivity. Another meaningful aspect is the cost of use of LTE network whereas IEEE 802.11p is free and requires no further operational dependency.

2.2.4 Vehicular Cloud Computing (VCC)

The National Institute of Standards and Technology (NIST), gives a formal definition of CC: "Cloud Computing is a model for enabling convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction" (Mell & Grance, 2011). Edge computing is the transfer of the computing process from core or cloud to the edge of the network. Edge computing is not replacing cloud computing but extending the processing capabilities to end user systems(Hu et al., 2018; F. Wang et al., 2018). The formal definition of VCC as follows "A group of largely autonomous vehicles whose corporate computing, sensing, communication, and physical resources can be coordinated and dynamically allocated to authorized users" (Olariu et al., 2013).

VCC is a special type of cloud computing incorporated over VANETs capable of providing shared access to underutilized vehicles resources, Internet, and other services. VCC can be formed on the run dynamically by integrating information and resources to provide low-cost computational services to vehicle drivers that may help in catering road congestion and travel time of vehicles. Further that VCC is envisioned to deliver services to vehicles to provide traffic safety and efficiency. Explicitly, the underutilized resources of vehicles can be shared with other vehicles to manage the traffic during congestion. These resources are but not limited to storage, computing power, and internet connectivity (Florin & Olariu, 2015; Sharma & Kaur, 2015; Whaiduzzaman et al., 2014).

To visualize the cloud computing process, an abstraction of VCC is depicted in Figure 2.5. Starting from the bottom left of the diagram, VANET infrastructure of an urban scenario is abstracted above to vehicular cloud. Vehicular cloud shows the connections among participating members (vehicles) of the cloud and one of the vehicles is acting as a cloud leader or cloud controller. The cloud controller is communicating with the Internet cloud as well for additional services and resources. Over the internet the cloud leader communicates with traffic management authorities at TMC, providing additional information (event-related info or instructions) regarding traffic management for the entire road network of an urban city.

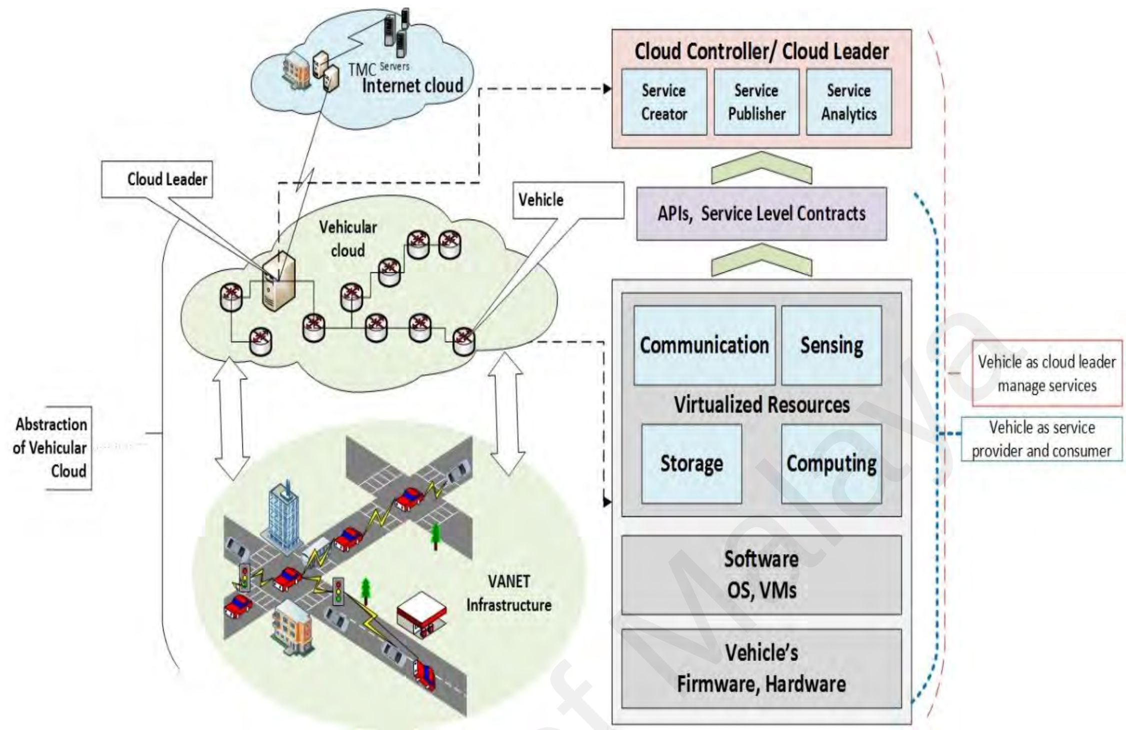

Figure 2.5: Vehicular cloud abstraction

Each vehicle has its pool of resources, and at the same time, a vehicle is primary service provider/consumer, an abstraction of the vehicle is depicted in right part of the diagram as shown in Figure 2.5. Each vehicle has firmware and hardware at a primary level controlled by onboard software such as operating systems and virtual machines. These hardware and software provides storage, computing, and sensing and communication services. Vehicle resources are virtually available to the cloud through service level agreements with the cloud leader. The cloud leader creates, publish and analyze services for vehicles, by continuously assessing and controlling the virtual resources of the participating vehicles. Each vehicle may act as a cloud leader depends upon the procedure adopted for cloud leader selection.

2.3 Characterization of VCC Technology for Road TMSs

This subsection of study reviews the VCC based TMSs to analyze the role and significance of VCC in road traffic management. First, an abstraction of vehicular cloud infrastructure in an urban scenario is presented to explore the VCC process. A taxonomy of vehicular clouds is presented which defines the cloud formation, integration types, and services. A taxonomy of vehicular clouds services is also provided to explore involved object types and their position within the vehicular cloud. Comparison of the current state of the art TMSs is made by parameters such as VANET infrastructure, internet dependency, cloud management, scalability, traffic flow control, and emerging services. Potential future challenges and emerging technologies like the IoVs and its incorporation for traffic congestion control are also discussed. It is envisioned that VCC has a substantial role to play in the development of smart traffic management solutions and also in emerging IoVs.

2.3.1 Background of VCC-based TMSs

Vehicular networks lay out the communication infrastructure for road traffic management applications. Non-safety vehicular applications such as road traffic efficiency and flow control are key applications for traffic control in urban areas. Emerging technologies such as cloud computing and VCC lays the foundation for the development of new applications and shifting the whole application development paradigm. The vehicular networking is gradually converging with ITS to improve traffic flow, driver's safety, and the environment. Various technologies are being incorporated with time to develop new applications in VANET (ITS) (Alam, 2016; Fernandes et al., 2016; Shah et al., 2016). These applications mainly use two control strategies named as predictive and adaptive. VANET based applications or TMSs are classified in Table 2.2, by traffic control strategy being used and underlying VANET infrastructure involved.

Table 2.2: Classification of TMSs

Control strategy	Property	Traffic management	Support	Hybrid VANET
Adaptive	Adapts changes based on actual traffic demands.	-Real-time -reactive	-En-route planning -Intersection management	(Lunge & Borkar, 2015), (Xiao & Lo, 2014), (Shen Wang et al., 2015)
Predictive	Use data analytics to determine congestion and traffic flow.	-Proactive -predictive	-Congestion control -Pattern analysis -Future forecasting	(HomChaudhuri et al., 2015), (Liang & Wakahara, 2013), (Kamal et al., 2015)

Often these TMSs make use of a few common schemes like traffic estimation (density), historical traffic information, future predictions, and more recent schemes like platooning (grouping). The intersection management is done by controlling the traffic signal and by giving priority to emergency vehicles or accommodating lanes as per the number of vehicles in the queue(Collins & Muntean, 2007; Shah et al., 2014).

Traffic information aggregation is useful in utilizing V2V communications bandwidth and handling scalability(Al-Sultan et al., 2014). One of the solutions is the formation of groups of connected vehicles (clusters)(Ramakrishnan et al., 2015). The most appropriate V2V scheme must calculate and detects the congestion in a distributed way without the support of any traffic management authorities (Milojevic & Rakocevic, 2014). The broadcasting scheme should be adaptive enough that can assess the overall congestion level in certain street and road networks. Factors such as vehicle velocity, vehicle position, and the distance between vehicles as well as between vehicles and RSUs greatly affect the performance of TMSs. These factors also affect the reliability and delay of links.

A good approach (l Jaworski, 2013) derived from the existing cloud and grid computing approach and named as cloud-based TMS (CTMS) give dynamic routing by combing intersection control algorithms with intersection approach advice to the vehicles. The CTMS is one of the VCC based solutions, contains a traffic management method that relies on the ITS-Cloud to deliver a detailed traffic simulation image. CTMS integrates an adaptive intersection control algorithm with a microscopic prediction mechanism. Another good example is VCC base TMS is incorporating clustering approach which connects vehicles with similar dynamics and collects the information regarding a road segment (L.-W. Chen et al., 2013). This information is then sent to a roadside cloud for traffic estimation and generalization purpose. The cloud server estimates traffic patterns and predicts trends for particular road segments. Other solutions emerge as a VCC (Gerla, 2012; N. Kumar et al., 2016; Olariu et al., 2013) inspired by traditional cloud computing and mobile cloud computing MCC (D. Huang et al., 2013). These solutions faces(Khalid et al., 2016) traditional VANET mobility and scalability problem with some additional cloud computing related problems of resource heterogeneity and management. A further summary of VCC based TMSs is presented in Table 2.3 to give an insight into the current literature.

The type of VCC based TMSs depends largely on, how traffic data is collected, processed and disseminated. If data is to be processed over the internet, then vehicular cloud must be connected with the Internet cloud. If data is to be processed locally then, it depends on the data distribution scheme and resource allocation scheme. Cloud management, cloud leader selection, cooperation among cloud members, cost and incentive management, are main functions upon which VCC rely. Therefore, the focus should be on, how these functions are incorporated to manage the road traffic efficiently. The VCC has the edge over traditional VANET based TMSs in that the data is collected, processed and disseminated, locally in a distributed manner by renting resources.

Many efforts are made to achieve road safety and traffic efficiency. However, VANET's drawbacks such as high mobility of the vehicle and security issue do not allow researchers to meet these objectives.

Table 2.3: Summary of VCC based TMSs

TMSs	Summary/ Methodology	TMSs	Summary/ Methodology
Smart Traffic Cloud (W. Q. Wang et al., 2012)	Uses GPS, instant speed, bearing, smartphones, GPRS/3G networks for back-end infrastructure. Alatum Cloud as a back-end system and Virtual Machines	**EvacSys (Khalid et al., 2016)**	-EvacSys processes a large amount of real-time sensory data to compute safe and appropriate routes for evacuees and emergency vehicles in disaster situations.
Cloud Transportation System (Ma et al., 2012)	Filters data intelligently collected through crowdsourcing to construct a model and to predict congestion prediction.	**PoW (Gerla et al., 2013)**	Providing users on demand pics via vehicular cloud service by assigning tasks to vehicles on the particular location of the road.
Datacenter At the Airport (Arif et al., 2012b)	Aggregating the computing capabilities of parked vehicles in a stable environment. Assessment of availability of computational resources.	**V- cloud (Abid et al., 2011)**	The vehicular cyber-physical system exploits VANET and its issues and proposes new services for ITS.
CRoWN (Mershad & Artail, 2013)	By service discovery delay and service consuming delay cloud services are discovered.	**IDMS (Alazawi, Alani, Abdljabar, Altowaijri, et al., 2014)**	Uses VANET, MCC technologies. Works on evacuation management during a disaster by taking, demand strategies and speed strategies.
CarSpeak (S. Kumar et al., 2012)	It is a kind of participatory sensing. A car can take sensory data of other cars to use for its purpose. Cars have access to other car's sensors.	**Virtual traffic lights (Munst et al., 2015)**	Uses vehicle addressing, highly accurate positioning, the TMP messaging protocol, a cloud-based controller concept.

2.3.2 Vehicular Cloud Integration and Cloud-centric Computing

The internet and social networking in vehicles connect the vehicle with to the world and makes vehicles aware of situations across the wider geographical area. VANET is now an opportunistic network on the move, for other access networks. The computing and storage resources of vehicles can be shared with network users to facilitate them. VCC services of a particular cloud are dependent on the purpose for which the cloud is formed (Gerla, 2012; Gerla, Lee, et al., 2014). The interaction of vehicles, vehicles to infrastructure and vehicular cloud to commercial clouds (static clouds) is presented in Figure 2.6.

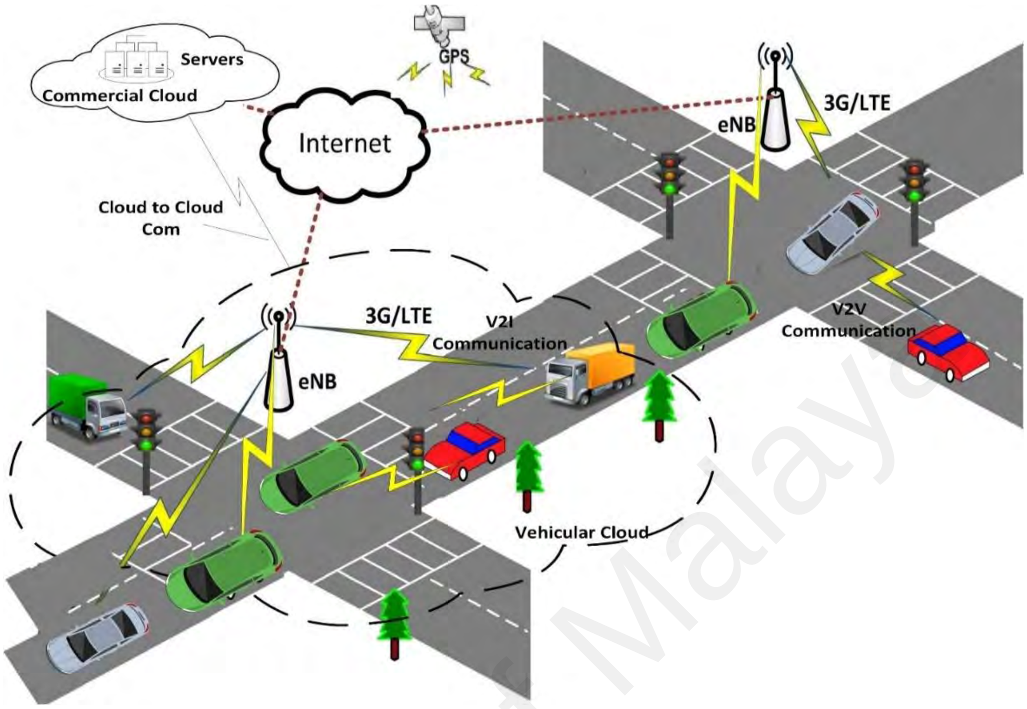

Figure 2.6: Vehicular cloud computing

Data collection and processing at devices: Preliminary process starts from the data collection at device level such as sensors within the vehicle sense and sends data to the local repository of the vehicle for low-level data processing. Application programming interface circulates this data to related hardware (actuators) to generate alarms or warning accordingly.

Communication in the vehicular cloud: The basic communication is within the car device's communication refer to In-Car communication. The second level is V2V communication for resource and information sharing. Vehicle to cloud infrastructure communication is a larger domain of communication for services provided by the cloud computing over underlying ICTs; a prominent one is cellular technologies. The services of the vehicular clouds can be named as contextual services (deriver's behavior), communication services (GPS, road traffic info) and complementary services (parking, toll).

Generally, vehicular clouds provide services (Whaiduzzaman et al., 2014) such as "platform as a service" (PaaS), "infrastructure as a service" (IaaS), "software as a service" (SaaS), "application as a service" (AaaS), and "storage as a service" (STaaS). The explanation of these services is already there in literature like [26-29]. Vehicles interact with the cloud to subscribe to services as required by the vehicle. The VCC improves the collection, processing, and dissemination of traffic-related data. VCC integrates and coordinates the available vehicular resources and enables the road traffic management in a better way, which reduces the risk of life, cost and time. The VCC enables each vehicle participating in the cloud formation to have an additional virtual resource to complete a task required to manage the vehicle's movement on the road. This gives the extra ability to the vehicle to assess the traffic conditions and to take more appropriate decisions while traveling on the road.

2.3.3 Taxonomy of Vehicular Clouds

Vehicular clouds are formed to provide vehicles required services, enabling vehicles to do route planning, safety control and providing comfort to the passengers. For this, vehicular clouds interact with sensor clouds and other commercial clouds. During the cloud formation, the type of cloud interactions is made, for one or more services. There are a variety of services exemplified in the literature, but all of these are relying on basic vehicular cloud services such as communication, processing, sensing, and storage. While on the road, whenever a service is required by the vehicle, the vehicle may join an existing cloud or initiate the cloud formation process. The cloud leader discovers resources within the cloud members and controls the further coming requests from the members dynamically.

Drivers or vehicles can communicate with clouds to subscribe cloud to have services at the right place and time. A focus on the vehicular cloud and its infrastructure

(Khandelwal & Abhale, 2015) can provide technologically change model that enables feasible solutions. To highlight cloud formation aspects, multiple vehicular cloud integration, and their basic services, a taxonomy of vehicular clouds is provided as in Figure 2.7.

By purpose of which a TMS formulate a cloud, the vehicular clouds are classified into three main classes named as V2V clouds, V2I clouds and integrated clouds as shown in Figure 2.7. The classification is done by services for which cloud is to be formed, the infrastructure used and involvement of third-party clouds (The Internet and other commercial clouds).

2.3.3.1 Cloud formation

The vehicular resources cloud be shared with other vehicles to provide service to intending users. The cloud formation is a mechanism, by which vehicles shows interest for service (s) and vehicle having the interested service publishes the related information to the network to form a cloud so that required service can be provided to the subscribed vehicles. The vehicular cloud formation broadly consists of the following steps.

Discovery of resources: During this process, the required resources, those are necessary for the interested services are discovered. These resources such as computing, sensing, and storage, can be used dynamically to provide services to the users. A network as service (NaaS) is one of the services provided by the vehicular cloud where a vehicle, moving on the road use LTE network to connect the internet.

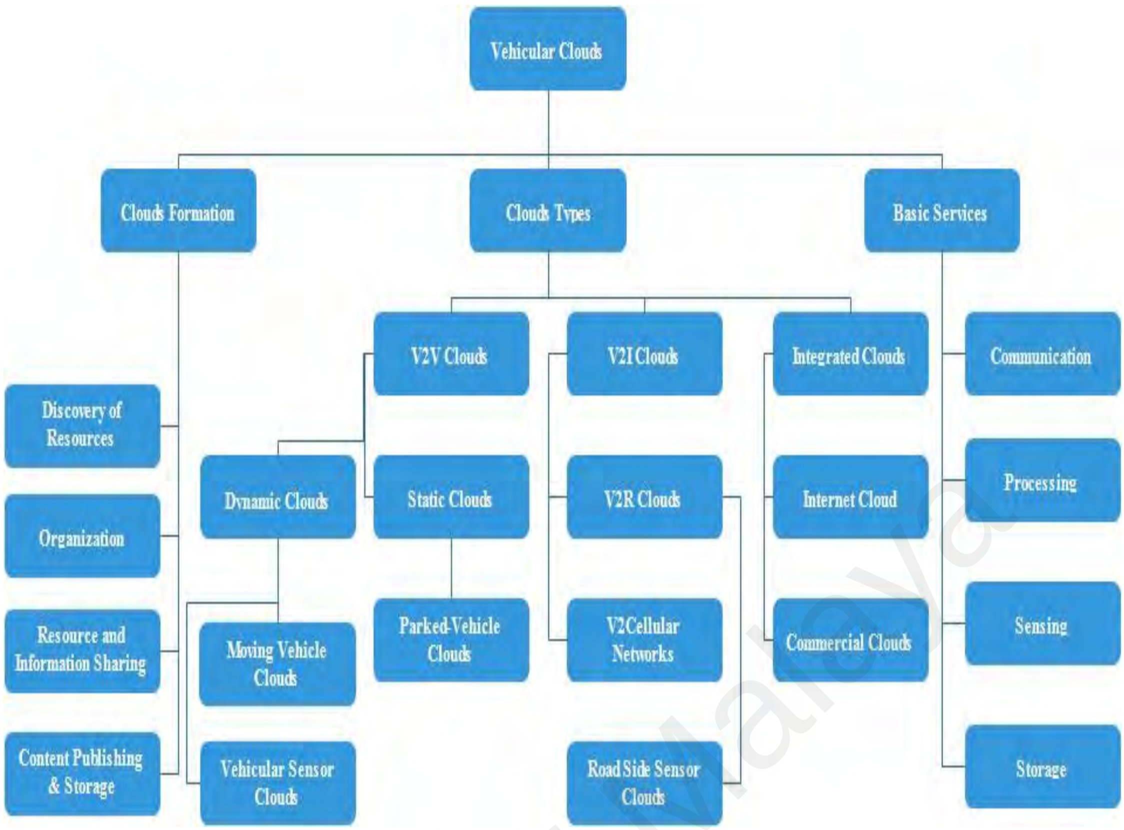

Figure 2.7: Taxonomy of vehicular clouds

Organization: When all the resources are discovered, the related information is stored to keep track of who is possessing what and where within the cloud. These resources are organized in a way to fulfill the asked service(s) requests.

Resource and information sharing: The resources and information are shared in an optimal way. For example, if a vehicle wants to know the real status of the coming intersection, first the vehicle at the intersection is contacted to share sensory information or image of the front camera.

Content publishing and storage: The acquired information is stored and published to fulfill future service requests within the vehicular cloud.

2.3.3.2 Cloud types

The vehicular clouds are categorized into three main classes such as a vehicle to vehicle clouds (V2V clouds), a vehicle to infrastructure clouds (V2I clouds) and vehicular clouds merged with other commercial clouds (integrated clouds) as shown in Figure 2.7.

a) V2V clouds; Vehicles on the roads or in parking form a cloud to share the resource for typical service. These clouds are subcategorized as dynamic vehicular cloud and static clouds. Like vehicles on the road, formulate a cloud to know the status of each other and to make an intelligent decision regarding route planning and driving. Same as the vehicles in the parking lot provide storage and processing services named as a static cloud. These type of clouds rely on V2V communication infrastructure. Vehicular sensor clouds are formed for vehicle or road traffic monitoring. The sensors within the vehicle get vehicle-related data, other vehicles in the cloud can take these services. For example, a vehicle for behind the intersection, send a query to the sensors or camera of a vehicle, to get a real status of the intersection. Such services are given by using vehicular sensor clouds by utilizing sensors that are associated with vehicles.

b) V2I clouds; these type of clouds use V2I infrastructure (roadside infrastructure) to form a cloud. V2I clouds are further categorized into V2R and V2cellular clouds. V2R uses RSUs for control information while V2cellular cloud relies on 3G/LTE for communication. V2Celluar clouds are useful for a larger area, and V2R clouds are better in the smaller road network area. Traffic monitoring sensors, radars, and cameras work together to form a cloud to share real-time information among the vehicles. These type of clouds are known as roadside vehicular sensor clouds. To provide, participatory sensing and cooperative sensing, roadside sensor clouds form a cloud known as the roadside sensor cloud.

c) Integrated vehicular clouds; when other clouds like mobile computing clouds and internet clouds are associated with vehicular clouds, then these clouds are called integrated clouds. If the vehicular cloud is connected with internet cloud for the GPS and other services, then the cloud called as internet-based vehicular cloud, and if the vehicular cloud is taking services of some commercial clouds like Google and Amazon cloud, then the vehicular cloud is named as services dependent integrated cloud.

The clouds in this category involved, a cost factor because the internet and commercial cloud services are not free. There is a need for some incentive-based resource and content (internet downloads) sharing mechanism while incorporating such services within the vehicular clouds.

2.3.3.3 Basic services

Vehicular clouds main basic services are communication, processing, sensing, and storage, provided by incorporating underutilized vehicle's hardware and software. All other complementary services depend on these basic services. "Platform as a service" (PaaS), "Software as a service" (SaaS) and "Storage as a service" (STaaS) are among the pool of services offered to the users.

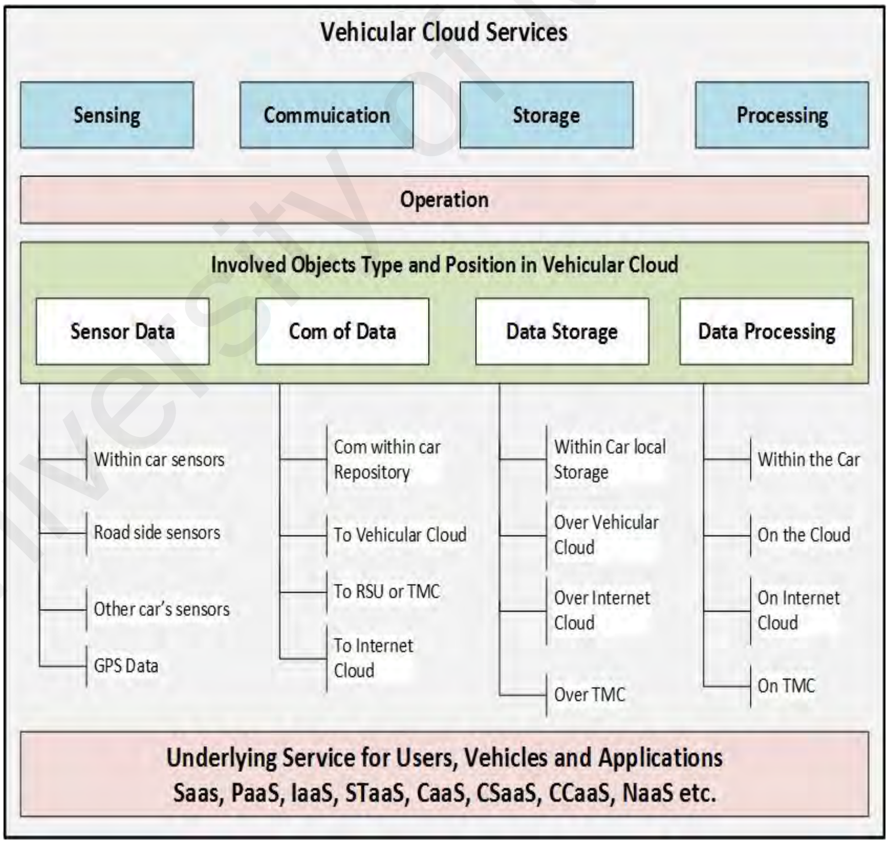

Figure 2.8: Taxonomy of vehicular cloud services

All these services require cooperation among the cloud members and cloud leader. Mobility and high speed of the vehicles may lead to intermittent services; this is what the main difference between a common cloud platform and vehicular clouds.

Vehicular cloud involves a variety of sensing, storage, communication and processing objects (devices, software), those ranges from a very basic sensor within the vehicles to the TMC over the Internet. Services of a vehicular cloud depend upon the type and position of the object within the cloud infrastructure. The four basic services are offered those depends on the operation being performed by the cloud. These operations are sensing data, communicating data, storing data and processing of data. The efficiency of a vehicular cloud is all about the collection, communication, storage and processing of traffic (vehicles) related data to or from related objects in a very right time and at the right location. Figure 2.8 shows the taxonomy of vehicular cloud services, operations and sub-operations with underlying complementary services such as SaaS, PaaS, STaaS, CaaS, NaaS.

2.3.4 Comparative Study of VCC-based TMSs

By adopting "pay as you go," model vehicles can process data on demand anytime from anywhere. The drivers now can connect to the cloud via the internet by using their mobile phones. Existing VCC applications are developed to manage traffic on the roads and to provide the vehicular infrastructure (resources, devices) for supplementary services (storage service by parked vehicles) to users other than vehicular users as well. Comparative analysis is made in table 2.4 to highlight, what actual TMSs proposed so far are lacking in and what needs to accomplish for better VCC based TMSs.

Table 2.4: Comparison of VCC based TMS's proposals and prototypes

VANET Type	References	Internet Cloud Dependency	Purpose	Cloud Management	Scalability	Traffic Flow Control	CCaaS	CSaaS
V2V	(Meneguette, 2016)	Yes	Traffic monitoring	Yes	Yes	Yes	No	No
	(Lu et al., 2016)	No	Traffic Management	Yes	Yes	Yes	Yes	No
V2I	(Mershad & Artail, 2013)	No	Traffic Management	No	No	Yes	No	No
	(Arif et al., 2012b)	No	Data Centre	No	No	No	No	No
	(Zhu et al., 2013)	No	Traffic Management	Use probe vehicle	No	Yes	No	Yes
Hybrid	(Gerla et al., 2013)	No	Traffic Monitoring	Server-based	No	No	No	Yes
	(W. Q. Wang et al., 2012)	Yes	Traffic Management	Yes	No	Yes	No	Yes
	(Ma et al., 2012)	Yes	Traffic Management	Yes	Yes	Yes	No	No
	(S. Kumar et al., 2012)	No	Traffic Management	Yes	No	Yes	No	yes
	(Munst et al., 2015)	No	Traffic Management	Mobile clouds	No	Yes	No	Yes
	(Khalid et al., 2016)	Yes	Evacuation management	Rely on sensory data	No	Yes	No	yes
	(N. Kumar et al., 2016)	No	Data dissemination	No	No	No	No	No
	(Bitam et al., 2015)	Yes	Traffic Management	Extends clouds	No	Yes	No	No
	(Raw et al., 2016)	No	Disaster Management	Yes	No	No	Yes	Yes

The comparison is made by whether the TMSs is using V2V or V2I infrastructure and whether TMS is dependent on internet cloud, mitigating traffic congestion and type of services offered. Most of the examples in table 2.4 are dependent on the Internet cloud, and they are relying on hybrid VANET communication infrastructure. Scalability and cloud management is not fully there in most of the proposed prototypes. For example, the Vehicular Cyber-Physical Systems (Jeong & Lee, 2014) is managed by TMC that maintains the road traffic status, statistics per road segment(s) and the navigations regarding vehicles moving on the road. The (Alazawi, Alani, Abdljabar, & Mehmood, 2014) emergency evacuation during a disaster using in-car systems, can be done by enabling vehicles to evacuate from a disaster area. But, the cooperation between vehicular clouds and the Internet clouds in the context of road traffic management applications has become a critical challenge to researchers.

In “PaaS “the vehicular clouds provide a platform for related services like content downloading and sharing. This also provides a platform for traffic management authorities to have access to all of the vehicles on the road. Another service like STaaS, VCC enable us to have access to huge storage capacity which is distributed over a large number of vehicles. For “CaaS” the VCC utilize the processing power of vehicles and distribute data processing among some vehicles participating in the cloud.

As explained in the cloud taxonomy section multiple clouds cooperate to share services among them. For example, a V2V cloud collaborates with Internet cloud to have access to the Internet-based remote server (TIS). These services are analyzed, and a comparison is provided in table 2.5. It is clear from table 2.5 that the trend is toward more internet cloud independence, and not all the TMSs are really mitigating traffic congestion but just claiming. TMSs are mostly relying on V2I infrastructure then V2V and on both infrastructures as well. The emerging services like cloud cooperation as a service (CCaaS) and cooperative sensing as a service (CSaaS) are not common in recent known VCC based TMSs. Few of them is providing CSaaS only which is in the form of a participatory type of sense, and it is not fully cooperative. So, the VCC directing researcher toward new services those are emerging from multiple cloud cooperation. Some of the proposed TMSs have cloud cooperation properties and may provide emerging service such as CCaaS. These services are only provided by the TMS; those are integrated and dynamic but not all existing are providing this type of service. The dynamic clouds are a more suitable form of clouds for the vehicular environment as mobility and speed not allowing all other clouds to function well as per services requirement.

Table 2.5: Comparatives study of integrated and dynamic vehicular cloud based applications

Reference	Property	Description	Integrated cloud	Dynamic cloud	STaaS	PaaS	CaaS	CCaaS
(Bitam et al., 2015)	Extends clouds	Traffic management	Yes	Yes	Ye	Yes	Yes	No
(Gerla et al., 2013)	Dynamic application	Services and resources shared dynamically	No	Yes	Yes	Yes	Yes	No
(Olariu et al., 2013)	On the run subscription	Pay as you go type model	Yes	Yes	No	Yes	Yes	No
(Arif et al., 2012a)	Network infrastructure as service	Provides networks as service	No	Yes	Yes	Yes	Yes	No
(Gerla, Lee, et al., 2014)	Automatic cloud formation	Multiple cloud cooperation	Yes	Yes	Yes	Yes	Yes	Yes
(Raw et al., 2016)	Disaster handling	Multiple cloud cooperation	Yes	Yes	No	Yes	Yes	Yes
(Lu et al., 2016)	Dynamic application	Scalability and traffic efficiency	No	Yes	Yes	Yes	Yes	Yes
(Khalid et al., 2016)	Sensor cloud	Emergency evacuation	Yes	Yes	Yes	Yes	Yes	No

2.3.5 Limitations and future challenges of current VCC-based TMSs

After deep analysis, some general potential challenges those related to the VCC technology are outlined below. These challenges require solutions through the incorporation of emerging technologies.

2.3.5.1 VCC and Self-reliance

As discussed in this section, the heterogeneous vehicular applications (if not all) mostly are dependent on internet or third party networks. The emerging VCC technology should be incorporated in such a way that it minimizes dependency on the internet. Fully V2V exploited solutions are one of the examples. The VCC and cloud cooperation can be exploited, to process more traffic data locally over the cloud. The Internet cloud dependency can be minimized by exploiting cooperative VCC.

2.3.5.2 Architectural Robustness

When, different clouds collaborate, having their network, hardware, software infrastructure. The successful cooperation needs abstraction and flexibility of their architecture, to provide services. The VCC infrastructure should be flexible enough to incorporate emerging application demands and to share a resource on the move. A level of robustness and service-oriented architecture is more feasible than traditional layered architecture such as virtualization.

2.3.5.3 Resource Heterogeneity and Cloud Management

Vehicles produced by different vendor have a different type of resources available within the vehicle. Also, the number and type of resources in the vehicular cloud is always changing because which, where and when a vehicle leave or join the cloud cannot be predicted and controlled. In cloud cooperation, interoperability is essential to make cloud cooperation synchronized, reliable and efficient. Mobility and heterogeneity should manage efficiently, for different cloud resources to be utilized efficiently. The process of the formation and operation of a vehicular cloud requires standardization, so that cloud management can be done dynamically, to take real-time actions in managing road traffic.

2.3.5.4 Real-time Traffic Management

The important solutions to solve these problems is to allocate the right amount of resources at the right time as compared to the pre-allocation of resources. There is a need for real-time traffic-related information. The VCC can help in finding the appropriate solution by using the available resource of the vehicle without waiting for officials and DMCs.

2.3.5.5 Evacuation Management

The VCC can provide infrastructural support during disaster and emergencies. The disaster management authority can utilize VCC for evacuation. VCC provides efficient information related to time, place and the availability of necessary resources during a disaster. The vehicles during the evacuation procedure form vehicular cloud and coordinates with the rescue response teams.

2.3.5.6 Intersection Congestion Management

Most of the time vehicles must have to, pass through the intersections. Because where there is a congested and highly populated area, there is a greater possibility of shopping malls, hospitals, schools, and other frequently visiting buildings. VCC can play a role in intersection management. The latest updated information on the vehicular cloud can provide an efficient solution to the drivers. This early information or warning is very helpful for the vehicles so that they may decide/ re-rout for the rest of the journey.

2.3.5.7 Communication Challenges

The communication among vehicles, vehicles to RSUs and vehicle to cloud (e.g., internet cloud) is critical. The vehicle's decisions related to safety and comfort depends on successful communication. The probability of successful communication depends on various factors like spectrum congestion, the cost of internet use and on the type of technology being used for communication.

2.3.6 Outlines of VCC based TMSs

While characterizing the role of VCC in road TMSs, it has been realized that VCC provides an effective enhancement to the message dissemination, traffic management, and congestion control. Vehicular cloud infrastructure and its taxonomy explore interaction with other clouds extending the capabilities (services). The comparative analysis shows the purpose oriented scope of vehicular clouds and their use in road traffic management. Vehicular cloud's integration with commercial and Internet clouds opens a potential pool of resources and services. These resources and services are now available to commuters on the go, which changes the vehicular mobility into opportunity.

The impact of new technological advancements in the field of VANET, cloud computing, and IoVs has not yet been fully realized. There is much need for the integration of such technologies to cope with the challenges of traffic congestion and transportation. Furthermore, how to balance the computations among local vehicles, vehicular clouds, and Internet cloud to achieve different goals by IoVs. Future is the internet of things (IoTs) and big data. Therefore the vehicular cloud cooperation is an intermediator in this paradigms shift. The devices and services collaboration among multiple clouds can be done by fully realizing the IoVs.

2.4 Heterogeneous Vehicular Networks

Traffic congestions on roads in urban areas place pressure on transportation infrastructures and cause damage to the economy, human health, and the environment. Countries spend large amounts of money to enable transportation systems to handle increasing traffic on roads. Researchers also focus on telecommunication networks as a part of the solution. The integration of VANET with telecommunication technologies envisioned to has the capability to provide promising solutions for road traffic management.

Heterogeneous vehicular networks (Figure 2.9) are hybrid VANETs that integrate V2V communication infrastructure into other networks, such as Wi-Fi, WiMAX, 3G/LTE, and LTE-Advance (LTE-A). The traffic management application most often requires access to content providers such as internet cloud, remote servers of traffic management centers (TMC) and TIS for smooth functioning. To access these servers the networks other than DSRC such as Wi-Fi, WiMAX, 3G/LTE, and LTE-A are used. The accessed information from these servers is disseminated among vehicles via directly to each vehicle or via DSRC. At the same time data is collected from vehicles and send to these servers for processing. This integration enables real-time vehicle monitoring at large-scale which helps in managing road traffic (Bazzi et al., 2017) and intelligent transportation(Ahmed & Gharavi, 2018).

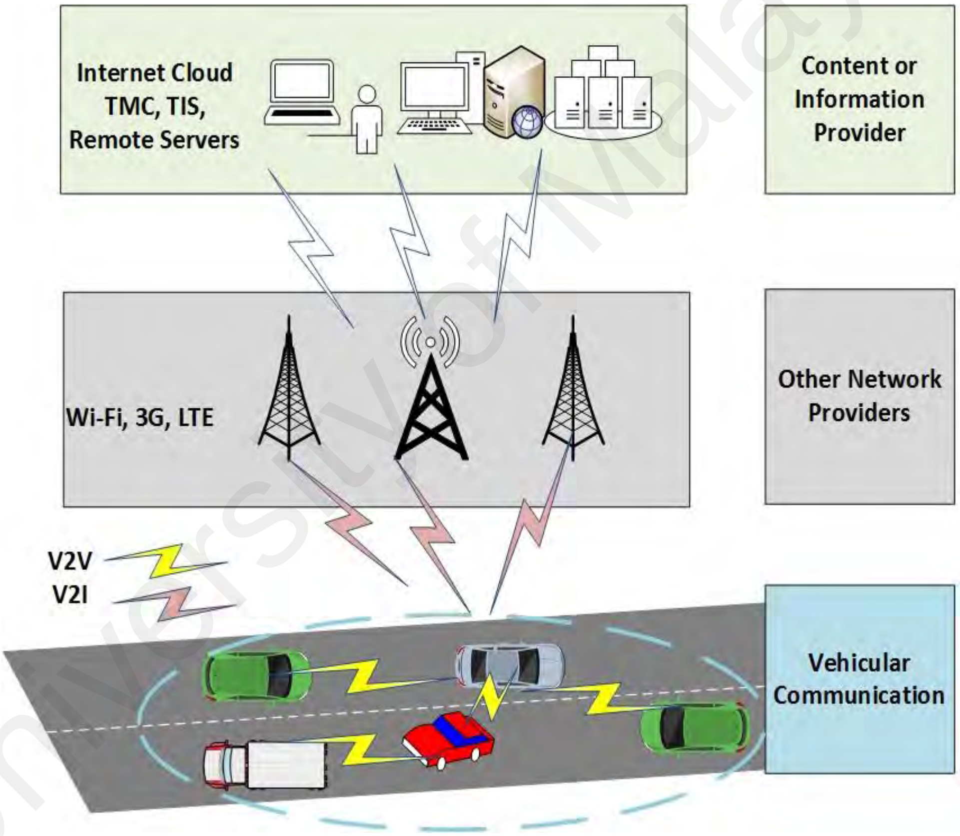

Figure 2.9: Heterogeneous vehicular network

Communication coverage and stability, latency guarantee, and frequency of message delivery are several basic vehicular requirements, and these are essential for primary vehicular safety and traffic efficiency applications. Vehicular applications depend on the type of technology adopted for the network, that is, the capability of the underlying network to meet the basic requirement of vehicular applications. The use of networks, such as Wi-Fi, WiMAX, and 3G/LTE, provides the benefits of the wide coverage area, efficient mobility management, and low cost. However, these networks result in additional problems of heterogeneous infrastructure, increased upload/download cost, and third-party dependency.

In this subsection V2-LTE, applications are investigated to determine their viability and usefulness in the current data-overloaded cellular radio access network infrastructure. Current V2-LTE road TMSs are classified as LTE-assisted, LTE-dependent, and V2V exploited systems to highlight various aspects, such as LTE spectral utilization, data usage, and effect on the QoS of traditional LTE users. A functional design-based taxonomy of proposed mechanisms for LTE utilization in road traffic management applications is presented to categorize the underlying data collection and dissemination schemes. The identified issues indicate that increasing use of LTE for vehicular applications places stress on the capacity of LTE networks and presents a trend opposite of that of distributed data processing. To realize local data processing, clustering of the vehicle is significant, but the problem of instability of vehicular clusters and non-cooperation among CMs are the main hurdles in developing cost-effective solutions.

2.4.1 Background of Heterogeneous Vehicular Network and Applications

Traffic efficiency applications require a heterogeneous network that demonstrates low latency, reliability, and speedy communication to send periodic traffic updates to remote servers. LTE presents advantages over other technologies, such as Wi-Fi, WiMAX, and 3G. The integration of DSRC and LTE technologies provides good communication networks for road traffic management applications. LTE is a promising technology that possesses a large coverage area and high penetration and data rates that could meet the QoS requirements of traffic management applications (Dey et al., 2016). However, various issues, such as the centralized architecture of the LTE network and the data traffic load of periodic updates in congested traffic areas, require attention. Other issues include growing mobile data applications and an increasing number of vehicular users. These issues negatively affect the LTE capacity and QoS requirement of traditional LTE users. The U.S. Department of Transportation also reported that the vehicle is the third place (following home and office) where commuters spend most of their time. The role of LTE as a vehicular technology and the demand for this technology increase as the concepts of "connected cars" and "IoVs" penetrate at a fast pace.

Some of previous surveys and studies have focused on the overview of LTE networking (Dey et al., 2016; Drira et al., 2016; Zheng et al., 2015) for the vehicular environment. None of these focused on road traffic management, and existing work focuses on one of the following: safety, architectural, and performance aspects. Considering that traffic efficiency applications have their own spatial and temporal requirements, the significance of using emerging technologies, such as LTE, should be measured separately. These applications optimize vehicle flow to reduce congestion and travel time and involve the collection, monitoring, and processing of data as well as sending instructions back to vehicles for driving assistance and route planning.

The selection of technology (Wi-Fi, WiMAX, and LTE) (Korowajczuk, 2011; Mir & Filali, 2014; Sommer et al., 2010; Uppoor & Fiore, 2015) for data transfer is based on application requirements and the feasibility of the selected technology for applications (Ucar et al., 2016). The primary option of communication for these applications is DSRC, which is insufficient to meet the current development demands of applications. Cloud computing (Lu et al., 2016) and IoVs (Gerla, Lee, et al., 2014) already combine multiple communication technologies. So, the combination of technologies can be a good choice for better connectivity that is a basic requirement for ITS.

To summarize the current proposal and solutions similar to our work, we identify some similarities among them. There are clustering formation protocols based on one-hop

(Daeinabi et al., 2011), multi-hop (Z. Zhang et al., 2011) using clustering metric of direction, member joins directly to CH and have periodic messaging for cluster updates. Another class of solution uses reactive updates to maintain and control the cluster such as (Rawashdeh & Mahmud, 2012). We organized existing literature into subsections of cooperative and heterogeneous clustering.

2.4.1.1 Cooperative Clustering

The cooperative clustering is about vehicle's motivation for the participation in the cluster(Lin et al., 2017). Usually, an incentive/reward for good cooperation and penalty/disregard mechanism for non-cooperation is devised for the vehicles to enforce/motivate them to participate and cooperate. The purpose of such solution is not to give stability to the cluster instead these are incentive driven solutions enforcing/motivating member vehicles (Mv) to participate in a cluster (C. Wu et al., 2015). One recent study is presented in (J. Wang et al., 2017), which consist of multiple algorithms including a cooperative scheduling algorithm. A vehicle is selected/scheduled for particular data transmission. Another recent approach is presented in (Das & Almhana, 2017) which is primarily related to cooperation in communication link failure. A helper node is selected that helps another participating node during communication failure ultimately helping in link maintenance but not an involved in cost factor. The authors in (Hassanabadi et al., 2014) provide an affinity propagation algorithm to provide stability to cluster while introducing reasonable cluster overhead but is designed for VANET and not considering 3G/LTE access networks. A good user-oriented protocol relying on heterogeneous network architecture and considering both the stability and resource utilization is required in current traffic scenarios.

2.4.1.2 Heterogeneous Clustering

LTE-based vehicular clusters are not cost-effective, and VANET-based solutions do not provide effective communication infrastructure and coverage (Araniti et al., 2013). There are some current state-of-the-art solutions, those are hybrid and integrate current cellular network technologies such as 3G, LTE, LTE-A with DSRC (K. Liu et al., 2015; Ucar et al., 2016; Chuchu Wu et al., 2015) for data collection and dissemination to/from vehicles to manage road traffic. These solutions use multiple parameters for cluster formation and performance measurement. The central problem of the vehicular network is high-speed mobility that causes the instability in links results in less cluster stability. A modified form of a primary algorithm for vehicular clustering named as modified distributed and mobility-adaptive clustering (MDMAC) (Wolny, 2008) algorithm is presented that suit road traffic properties. The MDMAC was designed for basic traffic scenarios not for a heterogeneous network environment. A good hybrid solution is described by (Ucar et al., 2016) by proposing a vehicular multi-hop algorithm for stable clustering (VMaSC) which uses multi-hop to connect a CM to the CH. The only problem with VMaSC is scalability of the cluster. VMaSC reduces the cluster overhead by not connecting every member to CH, but there is no focus on LTE connections for CH. Because if CH loss connection to the Internet then there is a requirement of re-clustering that increases not only the clustering-overhead but also degrades performance. Reducing the CH numbers and increasing the cluster size not allowing CH to control the behavior of all members fully.

Another solution is clustering-based multi-metric adaptive mobile gateway management mechanism (CMGM) (Benslimane et al., 2011) that aim to reduce the number of gateways to connect to the cellular network. Although it integrates VANET with 3G networks for dissemination of data downloaded from the internet, CMGM is designed for UMTS networks, and its performance needs to be re-consider for today's LTE network.

There is the class of applications that are relying on VANET–LTE hybrid network infrastructure such as FCD applications (Salvo et al., 2017). FCD applications collect geo-localized information issued by vehicles moving on a typical road segment and ITS use this traffic data for decision making.

Table 2.6: Organization literature concerning purpose/function

Function	Purpose	Reference
Floating Car Data (FCD) uploading	Data collection and aggregation	(Ucar et al., 2016),(Ancona et al., 2014),(Calabuig et al., 2014), (Salvo et al., 2016)
Content Downloading via LTE	Data downloading and dissemination	(Mezghani et al.),(Chuchu Wu et al., 2015),(Rebecchi et al., 2014)
Testing and feasibility	Performance evaluation and comparative analysis	(Dey et al., 2016),(Drira et al., 2016), (Shim et al., 2016),(Zheng et al., 2015),(Uppoor & Fiore, 2015), (Mir & Filali, 2014),(Salvo et al., 2017)
Traffic management	Traffic flow efficiency and driving assistance	(Shiqiang Wang et al., 2013), (C. Chen & Zhu, 2013)

Another class of such type of applications called content downloading applications (Chiti et al., 2017; W. Huang & Wang, 2016; Luan et al., 2014; C. Wu et al., 2015; Zhou et al., 2017) incorporating not only the VANET–LTE network infrastructure but also exploiting emerging technologies such as IoVs and Big data. The purpose of these applications is to provide road safety and infotainment services to drivers by sending data to/from the Internet, as organized in Table 2.6. There are feasibility and comparative studies conducted initially to check the performance of VANET–LTE-based networks, but applications related to traffic management and driver assistance are lacking. Although these applications provide some support for traffic management, they are not tackled comprehensively because traffic and driver assistance applications require different QoS parameters regarding data rate, latency, and message frequency (Mir & Filali, 2014; Zheng et al., 2015). The only solution (Morales et al., 2012) claims that take destination of the vehicles and propagate information to vehicles based on their current location. The clustering decision is made within from LTE networks such as each vehicle subscribe to service from the server over the internet and VANET is only used to propagate the message further. It did not consider the stability and cost of using LTE networks at all.

The emerging 5G based solution is supposed to be controlled entirely within from cellular networks and is not end-user oriented such as (Lianghai et al., 2017) where a central entity is deployed within 4G network infrastructure to enable direct V2V communication. These solutions still need rigorous research to adopt 5G and its economic model for vehicular networks. Anyhow, 5G is not going to replicate/replace 4G; instead, it is going to augment and complement 4G technologies. Also, the 4G will proceed in parallel with 5G until its full deployment which may take several years from now(Shah et al., 2018).

2.4.2 Use and Viability of LTE for Vehicular Applications

Flexible and improved option of LTE for V2I-based technologies extend VANET capabilities. Previous researchers (d'Orey et al., 2015b; Jia et al., 2014; Remy et al., 2011; Sivaraj et al., 2011) preferred using the LTE network for VANET-based applications. The use of the only LTE for vehicular application is viable in rural areas where vehicular density is low and required service utilization (RSUs) are absent as well as in urban areas where increasing traffic causes V2V solutions to suffering from spectrum congestion. The integration of DSRC with LTE makes a heterogeneous network that works well for traffic efficiency applications such networks are called as V2-LTE (which is V2I). A typical V2-LTE-based vehicular network is presented in Figure 2.10. The network consists of VANET (V2V), Internet connection, 3G/LTE network, traffic management center (consists of remote server and traffic management authorities), and global poisoning system (GPS). Vehicles generate an immense amount of data to be collected, processed, and disseminated by the remote server over the Internet. For these operations, the vehicles need to communicate over the Internet via RSUs or 3G/LTE networks. Frequent and seamless connections are necessary for the dissemination of such data to and from Internet-based servers.

Most V2-LTE-based applications "play" with the choices of LTE technology to be used. The first choice is the use of an LTE-based transport mechanism for the collection of data directly from vehicles. The second choice is the use of an LTE network for data dissemination back to the area of interest. The third choice is indirect data collection and dissemination from vehicles to form vehicle clusters.

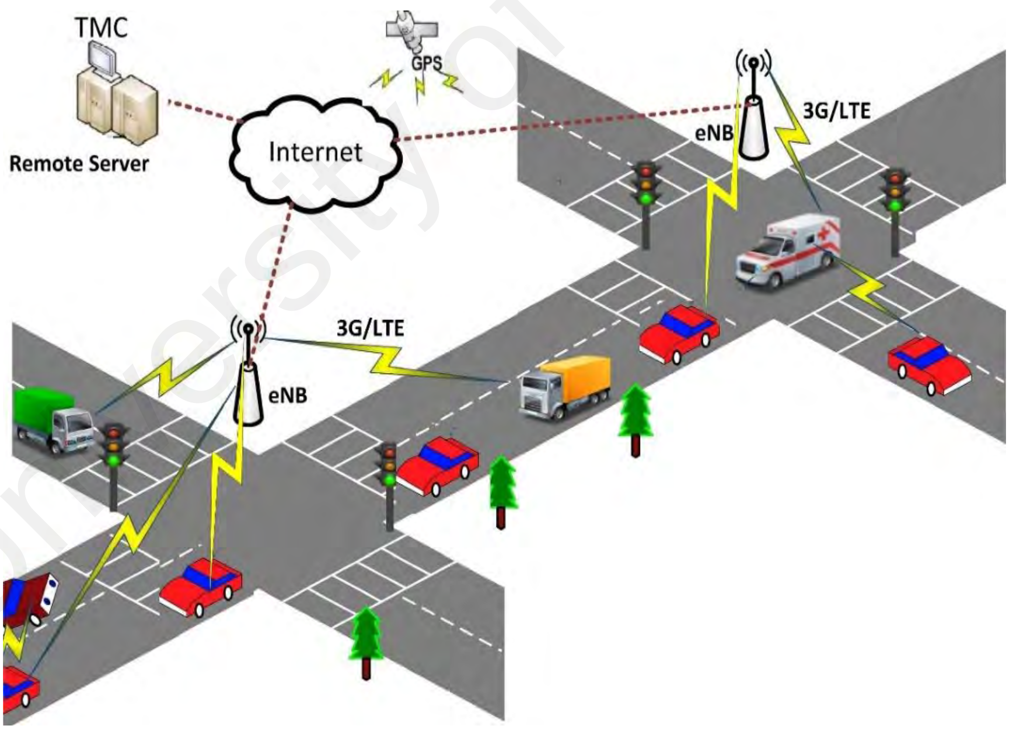

Figure 2.10: Typical example of an LTE-based vehicular network

Vehicle clustering is the main approach adopted by the majority of the proposed solutions, such as the LTE4V 2X system presented in a paradigm (Remy et al., 2011). Clustering is implemented in two forms. The first is to initiate and manage the clusters via an LTE network paradigm (Jia et al., 2014), and the second is to manage via the VANET paradigm (Sivaraj et al., 2011). The clustering process performed with LTE-based eNodeB has a wider regional view (d'Orey et al., 2015b) than V2V-based clustering.

The use of LTE is viable for vehicular applications except for the cost factor which is crucial as LTE is not free to use. However, the cost of use could be controlled and to take benefits from the use of LTE in future applications. To get an insight into how LTE is being used in existing applications, a summary of the current state of the art approaches is provided in table 2.7.

Most of the proposed approaches summarized in table 2.7 attempted to exploit the V2V communication infrastructure instead of using LTE for all purposes because the use of LTE involves high cost, LTE bandwidth, and capacity. LTE networks are already under immense pressure. LTE network capacity planning cannot meet the challenge of growing mobile data traffic, which is increasing dramatically with the development of smartphones and data-greedy applications, as indicated in the Cisco World Visual Networking Index Report 2016 (Mobile, 2017). According to this report, global mobile data traffic will increase by 18 folds in 2021.

The contribution of vehicular users to the growth of mobile data traffic is significant, as revealed by a study (Shim et al., 2016). The traffic proportion of vehicular users is expected to increase by 2.83 times (10.35% to 29.29%), which is larger than the overall growth of mobile data traffic. Therefore, planning on the end-user side is necessary to meet the emerging challenge.

Table 2.7: Summary of current 3G/LTE-based TMSs

References	Aim	Advantages	Disadvantages
(C. Chen & Zhu, 2013)	To share 3G data download via cluster head	Minimizing the cost and maximizing the probability of downloading	Lack of mechanism for successful cooperation among CMs
(Shiqiang Wang et al., 2013)	Geo central server that controls and processes traffic data	High message transmission rate with limited radio resources	Dependent on a third party network
(Drira et al., 2016)	Adaptive data collection of roads segments	Accurately predict the travel time of vehicles	Less stable, more overhead
(Rebecchi et al., 2014)	Cellular operator data offloading	Exploits direct communication among vehicles	The increase in network capacity is difficult to handle
(Calabuig et al., 2014)	System-level cost modeling through eMBMS transmission analysis	System model, shows necessitation of LTE data offloading	Unicast increases the processing burden on ITS servers
(Piro et al., 2015)	Flexible usage of the radio interface and allows direct communication	promises to guarantee the ultra-low latency and reliability requirements of safety applications	By relying on a distributed channel access scheme, D2D poorly scales with the network load
(Aoki et al., 2015)	To avoid heavy overload on LTE networks	New message format called MEP. Communication among multiple clusters	Cluster communication over the LTE network is not defined
(Zheng et al., 2015)	Elaborates heterogeneity and its associated challenges	Through service and use-case analysis, a generic HetVNET framework is proposed	Inefficient scheduling mechanisms for the existing QoS class identifier.
(Chuchu Wu et al., 2015)	Cooperation among CMs by motivating selfish users	Game theoretical model incentive-driven cluster-based content distribution	Only for multimedia content downloading
(Ucar et al., 2016)	High data packet delivery ratio and low delay aiming to utilize LTE at a minimum level	Multi-hopping-based clustering (relaying) reduces the number of CHs	A limit for cluster merging should be set. over-large clustering
(Shim et al., 2016)	Cell association algorithm that exploits user demand diversity for different velocities	Field experiments to analyze vehicle usage perspective	Cellular-based station densification may incur frequent handovers and degrade the spectral efficiency

2.4.3 Categorization and Qualitative Analysis

To determine which type of solution benefits the LTE network on the end-user side, we qualitatively categorized current LTE-based TMSs in this section. After having a thoughtful study of existing literature, and LTE infrastructure properties, vehicular technologies, and applications are categorized, based on the type of network, which vehicular network is merged with, and the level of VANET reliance on another network. Vehicle-to-cellular (V2Cellular) networks are networks in which a VANET is formed by using the telecommunication network's infrastructure. V2Cellular networks and underlying applications are divided into three types, namely, a vehicle to third-generation (3G), a V2-LTE, and vehicle to LTE-A. The advanced form of V2-LTE is V2LTE-A. The LTE-based vehicular application have their unique properties, types and fundamental operations involved. The LTE-based TMSs are categorized into three categories based on data and network management control dependency as presented in Figure 2.11.

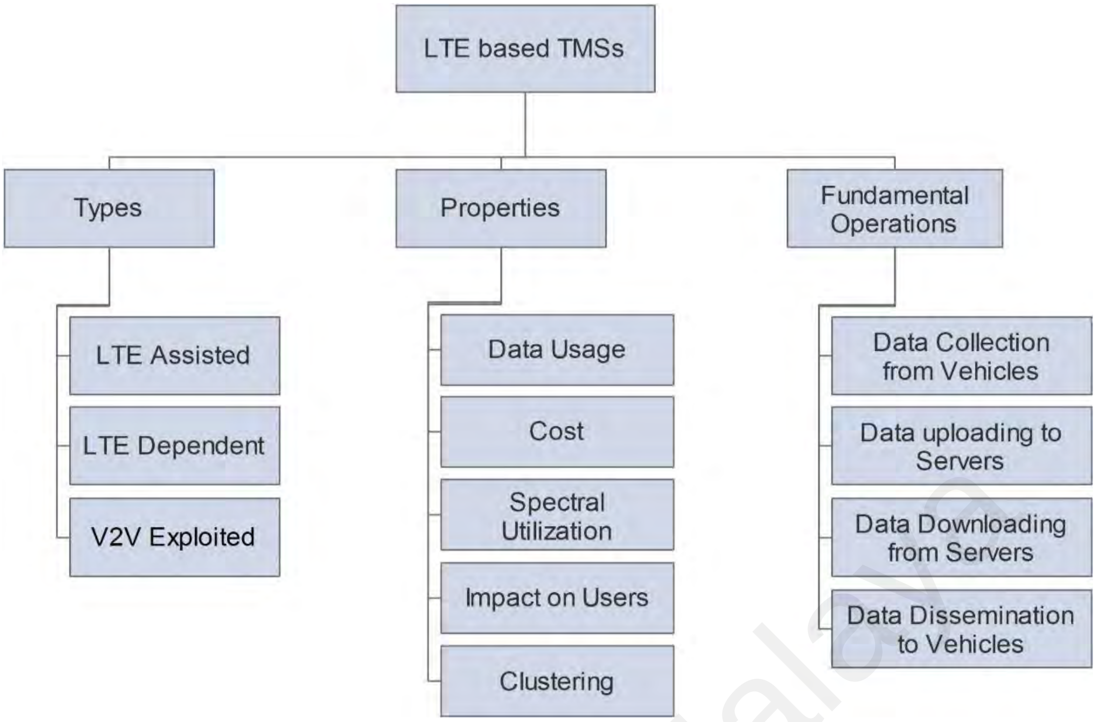

Figure 2.11: Taxonomy of LTE-based TMSs

LTE dependent TMSs: Fully dependent TMSs are managed and controlled within from LTE network are referred to as LTE-dependent. In LTE-based networks, the data and communication in the network are managed within the LTE network. Traffic information servers are maintained within the LTE infrastructure. These systems are costly as LTE network infrastructure is involved in it.

LTE Assisted TMSs: TMSs in which data and network are controlled partially by both LTE and V2V network are referred to as LTE-assisted. LTE-assisted TMSs make use of the vehicular network that is hybrid networks (V2- LTE) that help VANETs operate smoothly.

V2V exploited TMSs: TMSs not fully dependent on LTE (merely utilizing it to access the remote server via the Internet) are referred to as V2V exploited. V2V exploited TMSs control their data and network within from VANET and do not rely solely on LTE network infrastructure. In such systems an effort is made to reduce the cost and LTE network infrastructure use, with the intention of getting more benefits from V2-

LTE integration, to manage the road traffic in a better way. Reliance on the LTE infrastructure indicates operation dependency, entails a high cost and consumes high LTE network capacity.

Specific properties: LTE-based TMSs have their particular properties such as data usage, cost, spectral utilization, impact on tradition LTE users and group formation of users. These properties put some restrictions and limit the use of LTE when used in the vehicular network for road traffic management. Therefore, these properties must be analyzed while developing and proposing LTE-based TMSs. We comprehensively examined these properties to give an insight into the future development of LTE-based TMSs in the next section.

Fundamental operations: LTE-based TMSs entirely rely on some key operations such as data collection from vehicles, data uploading to remote servers, data downloading from the servers (e.g., TMC) and data dissemination among vehicles. The properties of LTE-based TMSs are dependent on these fundamental operations. How data is collected, disseminated and accessed to/from remote servers significantly impact the data usage, cost of use and spectral utilization of LTE network.

2.4.3.1 Qualitative Comparison of V2-LTE TMSs

After careful categorization of V2-LTE applications, we qualitatively compare and analyze current applications lies under these categories. By parameters such as network management, direct upload and download, support for safety and no-safety applications, the cost involved, data usage, LTE spectral utilization, type of clustering, and effect on QoS of traditional LTE users as shown in table 2.8. Vehicular data uploading and downloading are important for various VANET applications. For safety applications, real-time and effective data dissemination are critical. For traffic flow efficiency and entertainment, data cost, usage, and bandwidth utilization of LTE are critical.

Table 2.8: Qualitative comparison of LTE-VANET applications

Type	Network management	Unicast	Traffic efficiency applications	Cost	Data usage	LTE spectral utilization	Clustering	References
LTE dependent	Fully LTE-based	Yes	Yes	High	Very high	Very high	LTE based	(d'Orey et al., 2015a) (S. Chen et al., 2016) (Soleimani et al., 2017)
LTE assisted (hybrid)	Partially by both VANET and LTE	Upload or download	In case of direct download	Low	Medium	Medium	V2V based on upload or download	(Araniti et al., 2013) (Uppoor & Fiore, 2015) (Ancona et al., 2014) (Jia et al., 2014) (Salvo et al., 2017)
V2V exploited	Fully V2V-based	No	Yes	Very low	Low	Low	V2V based	(Chuchu Wu et al., 2015) (Ucar et al., 2016) (Salvo et al., 2017)

Data and communication control means that the data and network are controlled either from within V2V or the LTE network. LTE-dependent applications are applications whose data and communication are managed entirely within the LTE network infrastructure. Vehicles can send and receive directly from LTE and require low-latency LTE-based broadcasts. This application can support the non-safety and safety classes of applications. Cost, data usage, and cellular spectral utilization are high in these applications. Clustering is performed and controlled by LTE networks and consumes a significant capacity and resources of LTE networks, so a significant adverse effect is exerted on the QoS of traditional LTE users.

LTE-assisted applications manage data and network partially within the VANET and LTE network infrastructures, respectively. These applications can either download or upload data directly from the Internet via LTE but only one at a time. Applications that directly download data from the Internet can support non-safety applications, and applications that directly upload data to the servers have good support for safety applications. Cost, data usage, and cellular spectral utilization are not high. Clustering is performed and controlled partially by VANET and LTE networks. These applications consume the capacity and resources of LTE networks and exert an effect on the QoS of traditional LTE users.

V2V-exploited applications are controlled and managed within the VANET. No direct data download and upload exist for all vehicles. Data are collected, aggregated, and transferred to remote servers using LTE networks. Safety and non-safety applications are supported. Cost, data, and LTE network resource utilization are low. Clustering is performed on V2V network infrastructure and has a low adverse effect on the QoS of traditional LTE users. Exploiting V2V communication is better because LTE networks are already under immense pressure from high data and capacity demand.

Most of the applications presented in Table 2.9 deal with uploading and downloading of vehicular information separately. Fully V2V-exploited applications deal with infotainment and do not consider traffic flow control applications.

Centralized LTE-based applications consume much cellular network resources and are highly dependent on LTE networks. Applications that are dynamic are of the V2V type and do not involve the LTE network directly. The QoS of vehicular application is another important factor. Minimum utilization of cellular resources, especially LTE resources, is required to obtain the intended information accurately. In the case of traffic flow efficiency applications, the target is to acquire a remote server or TIS data within socio-temporal limits for the application to operate correctly.

Table 2.9: Comparison of selected V2-LTE TMSs and proposals

Network control	Direct download	Direct upload	Safety control	Non-safety	Data consumption	Spectrum utilization	Group formation	Impact on users	References
Centralized	Yes	Yes	Yes	Yes	Very high	Very high	LTE based	Very high	(d'Orey et al., 2015a)
	No	No	No	Yes	High	High	LTE based	High	(S. Chen et al., 2016)
	No	Yes	No	Yes	Very high	High	LTE + V2V	Low	(Soleimani et al., 2017)
	Yes	Yes	Yes	Yes	Very high	Very high	LTE based	Very high	(Araniti et al., 2013)
	Yes	Yes	No	Yes	Very high	Very high	LTE based	High	(Shiqiang Wang et al., 2013)
	Yes	Yes	Yes	Yes	Very high	Very high	LTE based	Very high	(Sivaraj et al., 2011)
	Yes	Yes	Yes	Yes	High	Very high	LTE based	Very high	(Remy et al., 2011)
Dynamic	No	No	Yes	Yes	Low	Low	V2V based	Low	(Uppoor & Fiore, 2015)
	Yes	No	No	Yes	Low	Medium	Yes	Low	(Ancona et al., 2014)
	No	No	Yes	Yes	High	Medium	Yes	High	(Jia et al., 2014)
	No	No	Yes	Yes	Low	Low	V2V based	Low	(Salvo et al., 2017)
	No	No	Yes	Yes	Low	Low	V2V based	Low	(Aoki et al., 2015)
Centralized and dynamic	Yes	No	In case dynamic	Yes	Low	Medium	Yes	High	(Chuchu Wu et al., 2015)
	Yes	No	No	Yes	low	medium	Yes	High	(Ucar et al., 2016)
	Yes	No	In case dynamic	Yes	low	medium	Yes	High	(Salvo et al., 2017)
	Yes	Yes	Yes	Yes	Very high	Very high	LTE based	Very high	(Shiqiang Wang et al., 2013)
	No	Yes	No	Yes	Very high	high	LTE + V2V	Low	(C. Chen & Zhu, 2013)
	Yes	No	If dynamic	Yes	low	medium	Yes	High	(Rebecchi et al., 2014)
	Yes	Yes	No	Yes	High	Medium	3G + V2V	Low	(Calabuig et al., 2014)

To date, studies are more of simulation types and consider the assumption that no other user is present in the LTE network. A single network is utilized by vehicles, such as ETSI release 10.0, where a simulation study on UMTS, 3G, and LTE network utilization for the vehicular environment is provided. Further field tests would provide a real idea of the ground situation. Vehicular data traffic is increasing drastically with time, and the use of telecommunication cellular networks for ITS is promising.

2.4.4 Functional Organization and Taxonomy

The primary functions upon which all of these V2-LTE systems relying on, are local data processing, well before the data is handled by the remote servers over the internet. The local data processing involved intelligent data collection from the peers (vehicles) and uploaded to the server, and downloading of processed data from the server and distribution to relevant peers.

As for as V2-LTE is concerned, how data are downloaded using LTE is important because traffic flow control applications are delay sensitive and require a specific data rate at the right place and time. The cost incurred and the capacity of the LTE network are other essential factors in selecting an appropriate scheme to utilize LTE networks. In data uploading, the data are FCD, which are generic and related to vehicle kinematics and position updates. In data downloading, the data consist of information from TIS and infotainment-related contents. Functional design of V2-LTE technologies is presented in Figure 2.12, which provides an abstract view of schemes being used for LTE networks. The ultimate goal is to meet the parametric requirements of vehicular applications with the minimum possible use of LTE network capacity.

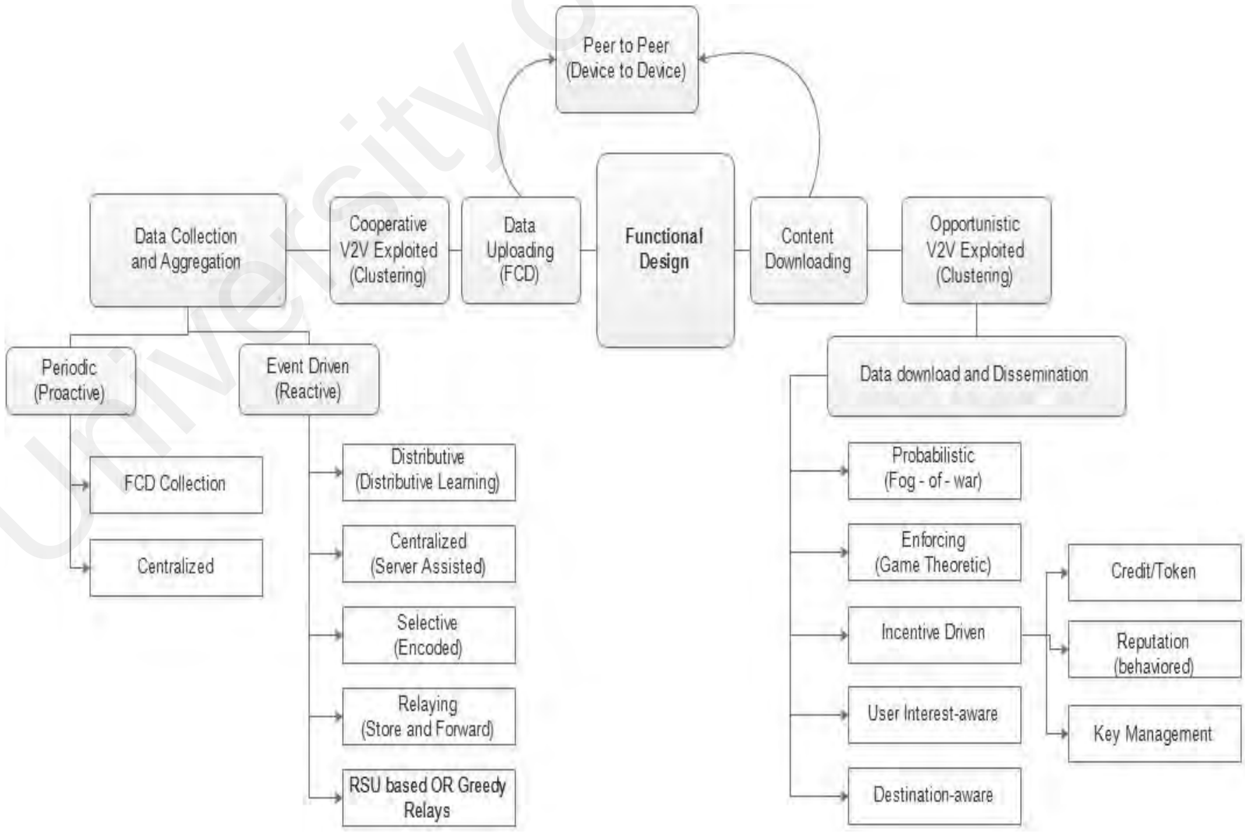

Figure 2.12: Functional-design-based taxonomy of LTE-based TMSs

2.4.4.1 Content downloading schemes in LTE-based TMSs

As presented in Figure 2.12, the content downloading is comprised of data and infotainment contents that are to be downloaded from the vehicle via LTE from the Internet server, respectively. These data are used for safety-related tasks, and the other contents are used for infotainment services. Contents can be download directly by each vehicle through a unique connection to LTE. An efficient means of content downloading is exploiting V2V communication through clustering or cloudlet schemes known as opportunistic downloading (Mezghani et al.). The type of clustering depends on the type of data download and dissemination scheme. It can be probabilistic, enforcing, incentive-driven, user interest-aware, and destination-aware. Probabilistic data dissemination depends on the vehicles' cooperation probability. High cooperation indicates a high possibility of gaining access to shared contents. Incentive-driven data dissemination involves the reward/punishment concept. The user interest-aware scheme depends on the level of user's interest in the download content. The destination-aware scheme is our new scheme that depends on several common attributes in which vehicles are interested in the case of a common destination. A comparative summary of schemes is provided in Table 2.10.

Table 2.10: Data downloading and dissemination schemes in current LTE-based TMSs

Paper	Architecture	Method	Type	Purpose
(Luan et al., 2014)	Cooperative	User interest	Common clustering	Downloading
(Xu & Van Der Schaar, 2013)	Incentive based	Rewards for cooperation	Ticket / credit	Dissemination
(Wu et al., 2012)	Reputation	Probabilistic	Counters	Dissemination
(Chuchu Wu et al., 2015)	Incentive-based	Game theoretic	Key Management	Downloading

2.4.4.2 Prevailing schemes for data uploading in LTE-based TMSs

As indicated in Figure 2.12, the data uploading comprises FCD upload to the remote server for processing to detect traffic events and prepare warnings for vehicle safety and instructions for route planning. Typically, each vehicle unicasts traffic updates to the remote server or TIS over the Internet through the LTE network. Another way of FCD uploading is cooperative uploading by exploiting V2V communication to form clusters; only the CHs are allowed to collect and upload data. Data collection and aggregation schemes developed so far are divided into two types, namely, reactive (event-driven) and proactive (periodic). If vehicles report their parameters to the server periodically, the proactive data collection scheme is considered. If vehicles report their parameters to the server or TMC upon demand, then this is the reactive type of data collection.

Most known proactive schemes, such as the periodic FCD collection scheme, are centralized. Prominent (Drira et al., 2016) event-driven schemes are distributive, centralized, selective, and RSU-based relaying. Event-driven schemes, such as distributed learning, are distributed, and centralized schemes are server-assisted. The important features of these schemes are outlined in Table 2.11.

Table 2.11: Comparative features of data collection and aggregation schemes of LTE-based TMSs

Paper	Architecture	Method	Scheduling	Type	Purpose
(Terroso-Sáenz et al., 2012)	Distributive learning	Distributive	Reinforcement learning, localized view	Reactive	Data collection
(Remy et al., 2011)	Centralized	Integrated	Multiple parameters	Reactive	Data aggregation
(Taleb & Benslimane, 2010)	Decentralized	Periodic	Multiple parameters	Proactive	Data collection
(Płaczek, 2012)	Selective	Uncertainty calculation	Fuzzy logic	Event driven	Data aggregation
(Cherif et al., 2010)	Distributive	Relaying	Store and forward	Event-driven	Data collection and aggregation

The underlying data collection and dissemination schemes discussed in this section vary from solution to solution. These schemes are developed mostly from safety and content downloading aspects. In the case of traffic flow efficiency applications, both data upload and download are involved simultaneously. Out of the discussed data download schemes our focus is on the following schemes.

2.4.5 Game Theoretic Schemes

Game theory is the model of strategies and related payoffs between rational players (decision makers). It is being used widely in economics and computer science to calculate the behavioral aspects and decision making in algorithms. Game theory is being used to analyze ad hoc networks and related application scenarios(Ficco et al., 2018; Roughgarden, 2010; Srivastava et al., 2005). One of the important solutions (Junior et al., 2018)is used for content downloading from a remote server for vehicles within the cluster. A CH is selected that downloads the content usually large infotainment files form Intenet and share with other CMs.

After the analysis of data downloading and dissemination schemes in current LTE-based TMSs, we came to know that the game-theoretic method has already been used in clustering for content downloading in infotainment class of applications to motivate vehicles such as (Gerla, Wu, et al., 2014). We used it in our scenario to achieve the cooperation behavior which is essential when cost is involved in the clustering process.

2.4.6 Location Calculation Schemes

Addition to the discussed literature the schemes that are related to the location calculation of the vehicles for various purposes are focused in our work. Mostly vehicles in VANET calculate their location or position with the help of GPS by finding out the coordinates. Usually, each vehicle propagates location to each other to take cooperative decision regarding road safety and traffic efficiency that is a built-in feature of DSRC based communication. There are TMSs those utilize and make use of the other vehicle position to take better decision regarding route planning and driving assistance(Rana et al., 2018). In the absence of GPS for the vehicles to find out its position is difficult which create hurdle in communication within the cluster. A geometry-based scheme (Kaiwartya et al., 2018)is introduced that is cooperative GPS assisted localization mechanism works on mathematical calculation of location. There are other localization schemes (Sobehy et al., 2018) those work with GPS and graph theory to know own position on the road. Global navigation satellite system (GNSS) (Hasan et al., 2018) enables precise timing information that is the primary means for vehicle positioning and velocity determination in VANETs.

2.4.7 Potential Research Issues and Challenges

It is worth mentioning that vehicle mobility, and resource heterogeneity is the main cause of other issues in vehicular network and should be considered when developing solutions. As for as VANET–LTE-based applications face the challenges of incurred cost, non- cooperation, instability and LTE resource usage within VANET, among others such as QoS requirements for road traffic management, and scalability.

2.4.7.1 Road Traffic Management and QoS requirements

The focus of researchers is on safety and infotainment applications, that is, content downloading and FCD uploading, as shown in Tables 2 and 3 and presented in Figure 2.12. These two types of applications have their own QoS parameters. However, the third category, which is traffic flow efficiency or traffic management, requires QoS parameters to lie between safety and infotainment. The latency requirement of traffic flow control applications approximates that of safety applications. In the case of the amount of data to be uploaded and downloaded, traffic flow control applications approximate infotainment applications. Therefore, a different type of solution is required for driver assistance, navigational applications, and route planning-related applications.

2.4.7.2 Scalability

Vehicles produced by different vendors have different types of resources available to them. Also, the number and type of resources in VANETs are always changing because which, where, and when a vehicle leaves or joins the VANET cannot be predicted and controlled. Scalability is an issue because aggregation, coordination, and control of sensing, computation, and communication resources do not exist. The number of vehicles involved in a VANET depends on the type of service required by a particular vehicle and application. If the number of vehicles cannot be handled by aggregation and coordination, complex schemes are required to handle it.

2.4.7.3 Non-cooperation

Various ICTs have enabled smart cities objects to interact with each other by providing and ensuring network connectivity. However, the coexistence of thousands of devices brings about several problems. The use of LTE and LTE-A also cannot provide reliable and seamless connectivity. Even, Device-to-device (D2D) communication (Bagheri et al., 2017) capability of fifth generation (5G) facing the problem of frequency interference and uncooperative participation of devices. For instance cooperation among vehicles is necessary for all developed solutions. One of the proposed solutions is the use of cloud computing in vehicular networks (known as VCC) (Ahmad et al., 2017; Iftikhar Ahmad, 2016; Whaiduzzaman et al., 2014). Cooperation among clouds may extend the capabilities of cloud computing and increase cooperation. Another option is cooperative clustering enforcing cooperation among the interested vehicles to participate in the cluster and share resources, information and incurred cost burden as well.

2.4.7.4 Resource Utilization

As far as TIS are concerned, the underlying telecommunication network resources(spectrum and data) usage should be controlled because the cost has to pay to access the Internet-based servers for desired information. These resources are limited such as for LTE; network capacity cannot be increased within the cell (ETSI, 2012). ETSI estimated how many numbers of vehicles can be connected within LTE cell at various delay time and also the downlink resource usage per number of vehicles, and incidents happen on the road. The resource utilization should be at a minimum level to reduce cost.

2.4.7.5 Fair Use

In vehicular clustering for TIS information access and sharing, only CH has to pay for Internet use. So, the tendency of the vehicle as a free rider within the cluster should have been controlled. To make it sure, not only one vehicle within cluster always selected as CH and pay the cost, a fair use policy should also be adapted to fairly share the cost of use and data.

2.4.7.6 Stable Clustering

In VANET traditional constraints always cause link breakage that has a negative impact on the performance of the network. Instability factor should be taken care to share data at the right time and place for effective road traffic management. When it comes to heterogeneous networks stable connection to 3G/LTE network is essential for the proper functioning of TMSs. There are a variety of methods (D. Zhang et al., 2018)have been proposed to make the cluster stable, but each method has their pros and cons when it comes to our scenario of TIS.

2.4.8 Outlines of V2-LTE based TMSs

One of the objectives of this study is to provide an overview of state-of-the-art V2-LTE technologies and the support they could provide to road traffic management. We investigated V2-LTE technology and applications to determine their viability and usefulness under current scenarios of network infrastructure and demands. We classified current V2-LTE TMSs into three main classes by data, and network dependency of applications as LTE-assisted, LTE-dependent, and V2V exploited systems.

A comparative and qualitative analysis of the usage of LTE in road traffic management applications by parameters, such as LTE spectral utilization, data usage, and effect on the QoS of traditional LTE users is provided. A taxonomy of proposed mechanisms for LTE utilization in road traffic management applications was established to categorize underlying data collection and dissemination schemes.

An increasing number of vehicular users, data-greedy applications, smartphones, and autonomous vehicles increase the data traffic demands on LTE networks. Also, vehicular application parametric requirements necessitate the development of a solution that incorporates emerging technologies and utilizes resources efficiently. Hence, smart city traffic requires a smart solution to handle traffic flow control in congested situations.

2.5 Conclusion

The study of literature review indicates that increasing use of LTE for vehicular applications places stress on the capacity of LTE networks. Few studies based on clustering of vehicles are conducted to solve this issue but when it comes to road traffic efficiency applications such as driving assistance and route planning special consideration are there to be a focus on. The first consideration is road traffic efficiency applications have their loco-temporal requirements (data rate and delay sensitivity). The second consideration is the cost of use because data is to be accessed from a remote server over the internet via LTE network that involves cost. A third consideration is who and why one should pay the cost, for this cooperation is required among the participating vehicles in the cluster. Last but not least is instability due to VANET tradition constraints of high speed and rapid topology changes.

After an in-depth review of the literature, we came to know that a new solution is required to be developed to manage road traffic flow by utilizing minimum resources and by providing stability to vehicular clusters. A heterogeneous architecture that incorporates VANET with cellular technologies posing a challenge on, how to utilize the network's infrastructure in a manner to give stability to the clusters to increase the performance of the network. In other words, a smart heterogeneous vehicular network-based solution to manage and control the road traffic smartly is needed to be developed instead of VCC based solution. So, we proposed a novel solution to provide cluster stability based on the cooperative exchange of information with the aim of utilizing minimum LTE network resources that are described in detail in chapter 5.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter is about the research methodology adapted to achieve the research aim and objectives. The research is completed in three main phases. Literature review and problem analysis phase is described in section 3.2. The design and development of VANET–LTE-based heterogeneous clustering framework phase is described in section 3.3. Section 3.4 presents the third phase named as verification and validation phase. Summary of the discussion is provided in section 3.5. The proposed research methodology with important contents and flow is presented in Figure 3.1

3.2 Literature Review and Problem Analysis

This phase is concerned with understanding the heterogeneous VANET and problem of LTE resource utilization. First, we studied the state-of-the-art in existing TMSs especially related to road traffic efficiency. We focused on two types of existing TMSs; the first type is those are based on VCC and the second type is those incorporates LTE with DSRC. A taxonomy of VCC based TMSs is proposed that categorized the existing solutions, and comparative analysis is made to highlight issues.

A thorough investigation of VANET–LTE-based existing approaches is also carried out, and a qualitative comparison is made which helped to find a research gap. The existing literature is categorized into LTE dependent, LTE assisted, and V2V exploited. Most of the literature deals with content downloading for infotainment services within vehicles and FCD for road safety purposes. The literature related to road traffic efficiency class of applications is infancy, and there is a need of V2V exploited VANET–LTE-based end-user solution. We also came to know that existing related applications lacking in catering instability of cluster caused by the high mobility of vehicles.

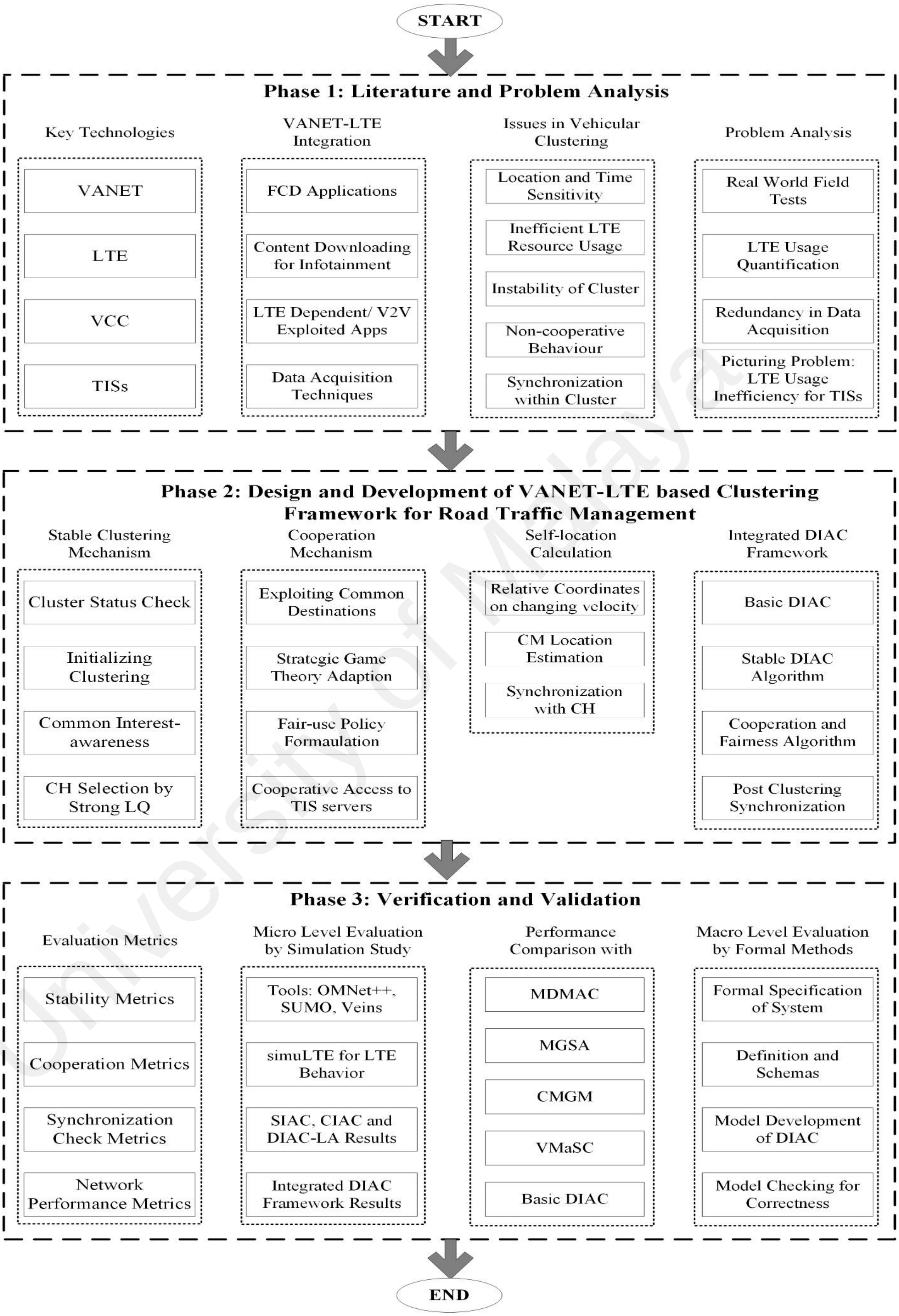

Figure 3.1: Research Methodology Flow Chart

Moreover, when it comes to applications utilizing LTE network resources to access remote server data, a cost factor is involved that must be considered while developing a solution. A detail discussion is provided in chapter 2. Hence, while developing a solution instability of cluster, cooperation in accessing and sharing costly data among other vehicles must be considered comprehensively. The most important of this part of phase one is reported in published work by the author (Ahmad et al., 2017).

Secondly, real-world field experiments are carried out to investigate and calculate LTE data usage by vehicular applications while driving on the road. The data usage is quantified and data rate per travel time of vehicles is calculated to generalize the results. The experiments are completed in the urban city of Kuala Lumpur, Malaysia, and Cambridge UK, by using the latest navigational and route planning applications such as Waze and Google Map within the cars. It is found that there is redundancy in the data acquisition from the remote server when some of the vehicles have an interest in the same data such as vehicles traveling toward the same destination nearby. Each has a dedicated connection to the remote server via the LTE network that can be reduced by clustering vehicles (details are provided in chapter 4). The impact of the identified gap is also quantified after taking and summarizing real-world data within the partial scope of the study.

3.3 Design and Development of VANET–LTE-based Clustering Framework

After the study of both types of literature, we came up with a solution which better suits the context of the identified problem(s). We proposed a VANET–LTE-based heterogeneous clustering framework named as a DIAC for driving assistance and route planning applications aiming to minimize the LTE spectrum usage and resulting cost. DIAC enables cooperative access to TIS data and minimizes the instability of connections not only among CMs (vehicles) but also between vehicle and LTE network base station. A unique clustering criterion is used with CH selection process and to achieve cooperation among CMs an SGT algorithm is applied.

Further that a fair-use policy is incorporated within game theory to control the behavior of CMs, in addition to this, an SLCA is developed to enhance synchronization of CMs with CH which extends the lifetime of the cluster further. The sub-mechanisms are designed and developed first with the intention to cater to each outlined issue one by one. First, a SIAC mechanism is developed exploiting common interest, LTE signal strength and average speed of the vehicles. SIAC is based on CH selection process. Secondly, a CIAC mechanism is developed by exploiting common destination and interest of the vehicles. CIAC incorporates SGT to promote/enforce vehicles participation in the cluster and share the cost of the use of the internet. A fair –use policy is also developed to tackle free-riders within the cluster. This cooperative access mechanism reduces the non-cooperative behavior and increases the participation rate of the vehicle in cluster formation. Third, SLCA is designed based on CH relative coordinates which increase the level of synchronization among CMs and CH, resulting in the increased lifetime of the cluster. Lastly, all algorithms from sub-mechanisms are taken and modified to incorporate in DIAC framework which we named as integrated DIAC clustering framework aiming to utilize LTE resources at minimum (details are given in chapter 5). The research output of phase two has already been published by the author as a technical paper (Ahmad et al., 2018) in a prestigious journal.

3.4 Verification and Validation

To check and validate the performance of proposed mechanisms, first, we implemented each submodule of integrated DIAC framework separately such as SIAC clustering mechanism, CIAC based SGT and self-location mechanisms respectively. Secondly, integrated DIAC clustering framework is implemented to check the performance. Four types of performance metrics are defined namely, metric to check the stability of cluster, metric to check the co-operational behavior of the cluster, metric to check the increase in the synchronization of the cluster and the metric to check overall performance of the heterogeneous clustering network infrastructure. The quantitative results are acquired by low-level modeling of the proposed solution using simulations. We used well-known simulation tool specifically developed for vehicular networks such as SUMO(Krajzewicz et al., 2012a), Veins, SimuLTE over the OMNeT++ network simulator (Hagenauer et al., 2014) and the maps of road infrastructures are accessed from OpenStreetMap.

To further verify the working and functionalities of the integrated DIAC framework, we formulate the mathematical modeling of the proposed system using the formal language "Z" or Zee notations. Macro-Level testing of the system model is done using a formal testing technique known as model checking. A system model is first developed by defining states and properties then desired properties are checked for validity. The properties such as cluster formation success, CH selection and accept/reject responses are checked for correctness. The developed model of the framework holds all the desired properties. Hence the system is verified and validated.

3.5 Conclusion

Starting from the literature review, state-of-the-art literature chosen for investigation. Our literature is of two types. First VCC based road TMSs are studied, taxonomies are developed, and comparative analysis is made to outline the current issue. Secondly, we studied VANET–LTE-based heterogeneous based existing solutions, literature is classified, and taxonomies are developed by considering key parameters, and issues of inefficient LTE usage when used in TIS, other related issues of instability in clusters, the non-cooperative behavior of the CMs are identified. Problem is then analyzed through real-world field tests, where quantification and verification of the existence of the problem are done. For the design and development of the solution, we flow step by step approach by first developing stable clustering mechanism, cooperation mechanism, self-location mechanism and finally incorporating all mechanisms to develop a framework over VANET–LTE heterogeneous network infrastructure for vehicular clustering. The important features are the common interest and destination awareness, incorporation of Game theoretic approach and SLCA based on CH GPS coordinates.

To verify and validate our framework, micro, and macro level evaluation is done through a simulation study and formal verification methods respectively. The important feature of simulation study is the incorporation of SimuLTE tools for LTE behavior in VANET and other tools such as SUMO and Veins. The use of well-known open source simulation tools is important because testing through real VANET testbeds is expensive and vehicles with such capabilities are not available. Further, it is easy to repeat the tests over simulation tools for confident results. To further validate our framework, mathematical modeling is done using formal verification methods to check the functionality and operation correctness of the system. A model of our framework is formally developed and checked for correctness. The technical work related to our thesis has already been published refer to paper 1, 2 and paper 3, and a part of the literature review has also been published refer to paper 4, in the list of publications mentioned following the reference section of this thesis.

CHAPTER 4: PROBLEM ANALYSIS

4.1 Introduction

In-depth analysis of related literature indicates that no comprehensive solution addresses the efficient use of LTE for vehicular applications, especially for road traffic management based on TIS. Few studies based on clustering of vehicles have been conducted to solve this issue, but they have ignored road traffic efficiency applications, such as driving assistance and route planning. Therefore, we conduct a real-world field test to verify and quantify the inefficiency in the use of LTE for road traffic management applications. Real-world field test must be used to assess the trends, the type of mobile data traffic must be identified, and quantification must be performed to determine the effect of data traffic growth prior to developing the related solution.

This chapter reports the field tests (preliminary investigation) conducted and summarized results. This chapter is divided into five sections. The background of the research investigation is discussed in Section 4.2. Section 4.3 presents the experimental setup, TIS data usage trends, and redundancy in TIS data usage among proximate vehicles. Findings of the field experiments are discussed in Section 4.4. Section 4.5 concludes the discussion in this chapter.

4.2 Background of the Investigations

LTE technology is critical for the envisioned usage scenarios in IoVs. An important usage scenario is TIS for VANETs that depend on LTE for the delivery of non-safety information to vehicles. TISs are centralized data warehouses that collect and process traffic information and subsequently allow vehicles to receive such information before and during a road trip. Considering the extensive deployment of VANETs, the LTE demand for TIS is expected to increase. Therefore, we explore and quantify the inefficiency of LTE when used in TIS. By envisioning basic test case scenarios, we establish the trends of data usage while commuting and provide insights into the effect of LTE usage in TIS on the inefficient use of available wireless spectrum during road trips. We also examine the common interest of vehicles traveling in proximity to the accessed information from the remote TIS server and investigate the redundancy in the acquisition of TIS information.

Data-greedy applications bring difficulty for telecommunication networks in meeting the capacity and spectrum planning needs of users. The use of mobile data is dramatically increasing (Shim et al., 2016). Vehicle users contribute significantly to this growth. The proportion of vehicular user data traffic also increases by 8.62 times (from 2012 to 2015) of the overall data traffic growth of 3.04 for the same period (Shim et al., 2016). The vehicle is the third place (following home and office) where modern people spend most of their time. Autonomous cars, public transport, and commercial taxis connect wirelessly to one another and traffic management authorities. Nearly all connections are implemented using cellular Internet via 3G/LTE networks. Such connections increase the load on LTE networks, and this increase affects (Uppoor & Fiore, 2015) the QoS provided to traditional LTE users.

Vehicles generate large amounts of traffic data, which are sent to a remote data processing server known as a TIS. TIS information is disseminated back to vehicles for road traffic flow control and route planning. Vehicular data traffic poses a significant challenge to telecommunication operators because it demonstrates high mobility and low delay and requires frequent access. These unique characteristics of vehicular data traffic should be understood well when conducting capacity planning for networks, especially in urban areas where LTE networks are under extreme pressure. Vehicles use cellular Internet, which is costly, to upload and download traffic data.

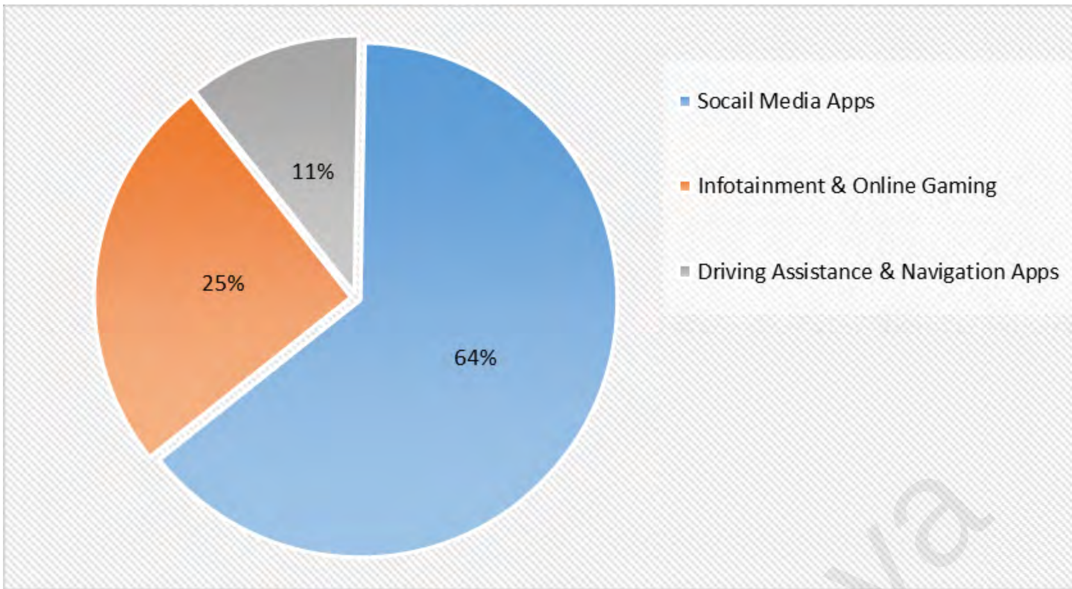

Figure 4.1 Data consumption ratio

Therefore, the capacity of an LTE network to handle the current increase in vehicular data should be addressed to obtain a comprehensive solution that can meet the increasing demands of mobile data traffic.

The average data consumption ratio of different vehicular applications in real-world tests shows that approximately 11% of vehicular data traffic is attributed to driving assistance and navigational applications (Figure 4.1). The trend shown in Figure 4.1 is the average of data usage of regular taxi drivers (10) and commuters (2) by installing applications on their mobile phones while on the move. Through the data manager installed in each driver's mobile device, each application category named as social media applications, infotainment, and online gaming is calculated with the average taken for subsequent analysis. Afterwards, the data usage ratio out of total data package purchased at the beginning of the experiment for each category is calculated. The data usage of driving assistance and route planning applications contributes significantly to the overall data usage of cellular networks. The prices of different data packages offered by a telecommunication operator in Kuala Lumpur, Malaysia range from 30 RM to 120 RM (8 USD to 30 USD). For the lowest-priced data package, a vehicle user may consume at least 338 MB of data for driving assistance applications per month. The estimated cost of these applications per month per vehicle is around 4 RM (1 USD). Regarding TIS data, redundancy exists in the data acquisition of vehicles. Redundancy removal can reduce data consumption and thus relieve the burden on LTE networks and the costs incurred. Therefore, data usage trends should be studied to determine the inefficiency in data usage and identify a comprehensive solution such as hybrid VANET–LTE architecture (Ahmad et al., 2017). In this architecture, WAVE is integrated with cellular 3G/LTE networks to provide seamless data access to vehicles for addressing road traffic issues but with the cost incurred. Some solutions (K. Liu et al., 2015; Ucar et al., 2016; Shen Wang et al., 2015; C. Wu et al., 2015) focus on reducing the number of connections and bandwidth utilization but are insufficiently stable and limited in providing data needed by the traffic flow control applications (with different data rate and latency requirements).

We design real-world test case scenarios to measure and quantify the amount of data consumed by a vehicle for navigation and route planning (assistance) while traveling. Our case study is an urban region in Kuala Lumpur and Cambridge. We use My Data Manager, Waze, and Google Map applications in our case study to analyze cellular data usage trends and redundancy in TIS data usage. Our study covers a part of the overall data consumption of current vehicular data-greedy applications. We only analyze road traffic efficiency applications, which also play a pivotal role in vehicular safety and infotainment applications (Zheng et al., 2015). We calculate and investigate four aspects of vehicular traffic data consumption. First, we measure the trends of data volume consumption by vehicle users while on the move by using applications such as Waze and Google Map. Second, we quantify the data traffic volume consumed and identify the redundancy in TIS data usage for driving assistance and navigational applications. Third, we investigate the literature on the similar kind of existing solutions (K. Liu et al., 2015; Ucar et al., 2016; Chuchu Wu et al., 2015) and find that cluster stability is fundamental while developing a solution in this regard. Fourth, we establish redundancy and secondary problems in a diagrammatic form.

Hybrid VANETs integrate WAVE with cellular 3G/LTE networks to provide seamless data access to vehicles for addressing road traffic issues (Ahmad et al., 2017). TIS involved in this integrated VANET–LTE network infrastructure consists of a 3G/LTE network, the Internet, a traffic management center, and remote data processing servers. This system also involves a GP, RSUs, and roadside sensors (cameras and inductive loops). Data are collected from vehicles (and related sensors) in small amounts but frequently and transmitted to remote servers over the Internet via LTE networks. In the data warehouse, the data are continuously processed to determine trends in road traffic flow. This information is transmitted back to vehicles, where it is handled by route planning and driving assistance applications to generate instructions (alerts and alarms) accordingly. TIS data are time and location sensitive and should be transmitted within the given time frame and location. Otherwise, the data will no longer be useful.

Internet-based servers collect information from vehicles moving on the roads continuously, analyze, and send alerts and notifications back to vehicles to assist them in driving. Each vehicle usually unicasts its data back to the server and obtains information. In the same way, this procedure requires individual 3G/LTE connection for each vehicle and introduces additional load on the network (Shim et al., 2016).

When a vehicle needs information for driving assistance and route planning during the journey, it either connects to the Internet via 3G/LTE network, or it can acquire such information from the neighboring vehicles. Given that connecting to the Internet is costly, acquiring information from the neighboring vehicle is a good choice with minimum cost. To achieve the latter, a stable cluster of moving vehicles on the road is required. In the cluster formation, which type of information is to be transferred to whom, when, and how is decided. The primary consideration is the type of information to be accessed and the distribution of such information. It depends on the purpose of the application being developed because functional and parametric requirements of different applications (safety, traffic efficiency, or infotainment) differ. The secondary consideration is CH selection, which controls and decides who can access and share information. It also determines how the communication of information takes place among CMs and to and from the cluster.

4.3 Trends in TIS Data Usage

We conduct real-world field tests to determine TIS data usage trends. The details of the experimental setup and measurement of data usage are discussed as follows.

4.3.1 Experimental Setup

We investigate data download of vehicles to determine trends in data consumption over the specified route through field experiments. We calculate and record the data consumption of a typical navigational application used for driving assistance and route planning. Field tests were conducted in July 2017 in Kuala Lumpur (Figure 4.2) and August 2017 in Kuala Lumpur and Cambridge (Figure 4.3 and Table 4.1). In the tests, only one car is used for 30 days to determine average data download at different times of the day. The amount of data download for one car is used to determine the difference between the data download of a group of 3 to 5 vehicles. The android navigational app Waze, which relies on mobile phone GPS and community-based traffic updates, is used as a tool for driving assistance. The data download through cellular Internet is dependent on the number of community-based updates and warning generated by the Waze server regarding the particular route.

According to the Google support portal, Waze is free to download and can be used by everyone; however, phone and carrier data rates continue to apply. A mobile data plan with a mobile service provider is strongly encouraged to use Waze on the go because

Waze receives and delivers real-time road information related to the target route. Continuous usage can entail a vast amount of data. The amount of data used by Waze may differ from one device to another. The amount depends on the route taken and its length, map(s) downloaded, time of the day, the day of the week, number of reports, and traffic, among other factors. For the experiments, the preceding factors are considered. Regular taxi drivers, who have already utilized known route and passenger assistance, Grab car Android applications, are recruited.

Table 4.1 Experimental environment

Month	**July 2017**	**August 2017**	**August 2017**
Location	Kuala Lumpur, Malaysia	Kuala Lumpur, Malaysia	Peterborough to Cambridge, UK
Experimental period	30 days	30 days	15 days
Driving Period	15-20 mint drive along the route once each day	Regular Taxi drivers, having 3-5 hour's drive daily within the city	The regular Taxi driver, 1-2 hours' drive 3-4 times each day
Drive timing	Morning (rush time), noon	Any time	Morning, noon, evening
Participant vehicles	one	Ten	One
Cellular Technology	LTE	LTE	LTE
Measurement applications	My data manager, Waze	My data manager, Grab car, Waze	My data manager, Waze

Figure 4.2 Common route between Pantai Hill Park and FSKTM, University Malaya

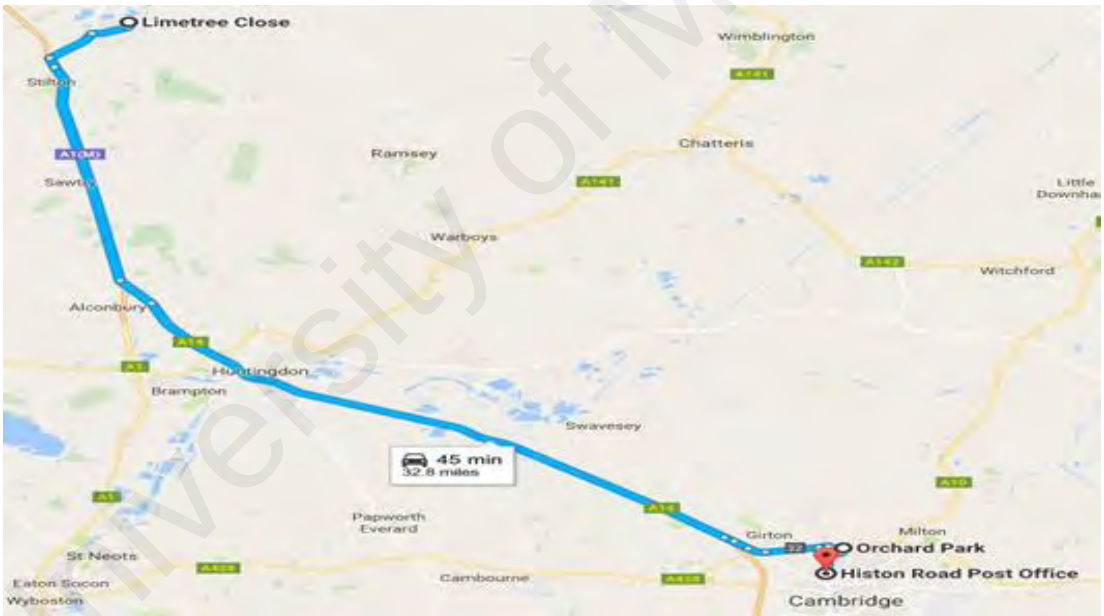

Figure 4.3 Common route between multiple destinations at Peterborough and Cambridge, UK

Some of the glimpses of readings taken during the field test experiments are presented in Tables 4.2 and 4.3 for the test set 1 (conducted in Kuala Lumpur) and test set 2 (conducted in the UK).

Table 4.2 Some of the readings of field test set 1 in Kuala Lumpur, Malaysia

Date	Time	Reading	Route
12-72017	10:30	3.74MB	-From Pantai Hill-park to Wisma R &D UM.
13-7-2017	6:12	3.64MB	-From Pantai Hill-park to Wisma R &D UM.
15-7-2017	10:35	2.04MB	-From Pantai Hill-park to Wisma R &D UM.
18-7-2017	10:42	1.34MB	-From Pantai Hill-park to Wisma R &D UM.
22-7-2017	9:55	1.34 MB	-From Pantai Hill-park to Wisma R &D UM.
25-7-2017	10:38	1.34MB	-From Pantai Hill-park to Wisma R &D UM.
26-7-2017	10:10	2.24MB	-From Pantai Hill-park to Wisma R &D UM.
29-7-2017	9:22	5.48MB	-From Pantai Hill-park to Wisma R &D UM.
01-8-2017	10:10	2.27MB	-From Pantai Hill-park to Wisma R &D UM.

Table 4.2 shows only some of the indifferent readings recorded on a short route during the whole month of the experiment.

Table 4.3 Some of the readings of field test set 2 in the UK

Test	Reading	From	To
Trip 1	8.74MB	Northfield Road, Peterborough PE1 3QE, UK	Orchard Park, Cambridge, UK
	1.64MB	Budgens, 6, Adkins Corner, Perne Road, Cambridge CB1 3RU, United Kingdom	Nuns Way, Cambridge CB4 2NT, UK
	1.04MB	Shelly Garden, Cambridge CB3 0BT, UK	Station Road, Cambridge CB1 2JB, UK
	7.34MB	Cambridge (City Centre), United Kingdom	Lime tree Avenue, Peterborough PE7 3WP, UK
Total	**18.76 MB**	**Using google map (this is average taken after repeating tests 5 times, once in consecutive 5 days)**	
Trip 2	16.34 MB	Northfield Road, Peterborough PE1 3QE, UK	Orchard Park, Cambridge, UK
	2.21MB	Bugden, 6, Adkins Corner, Perne Road, Cambridge CB1 3RU, United Kingdom	Nuns Way, Cambridge CB4 2NT, UK
	2.39MB	Shelly Garden, Cambridge CB3 0BT, UK	Station Road, Cambridge CB1 2JB, UK
	12.48MB	Cambridge (City Centre), United Kingdom	Lime tree Avenue, Peterborough PE7 3WP, UK
Total	**33.42MB**	By using Waze (this is average taken after repeating tests 5 times, once in consecutive 5 days)	

The readings are recorded by a regular taxi driver whenever he passes through the road segments mentioned in Table 4.3.

4.3.2 Data Usage Measurements

We measure data download on different routes ranging from short (5 km to 12 km) to medium (15 km to 30 km) and long (15 km to 65 km) in a metropolitan city at different times and days.

4.3.2.1 Results of Test Set 1

The average data download is around 2.49 MB for a short route, and the amount depends on the rush on the roads. After extending our route range from 15 km to 65 km, data download is calculated. The data download involved is presented in a comparative form in Figure 4.4 against a number of trips. A trip indicates traveling of a vehicle on a particular road at a particular time of the day. Our ultimate target is to calculate the data consumption rate per travel time of a vehicle to obtain generalized results.

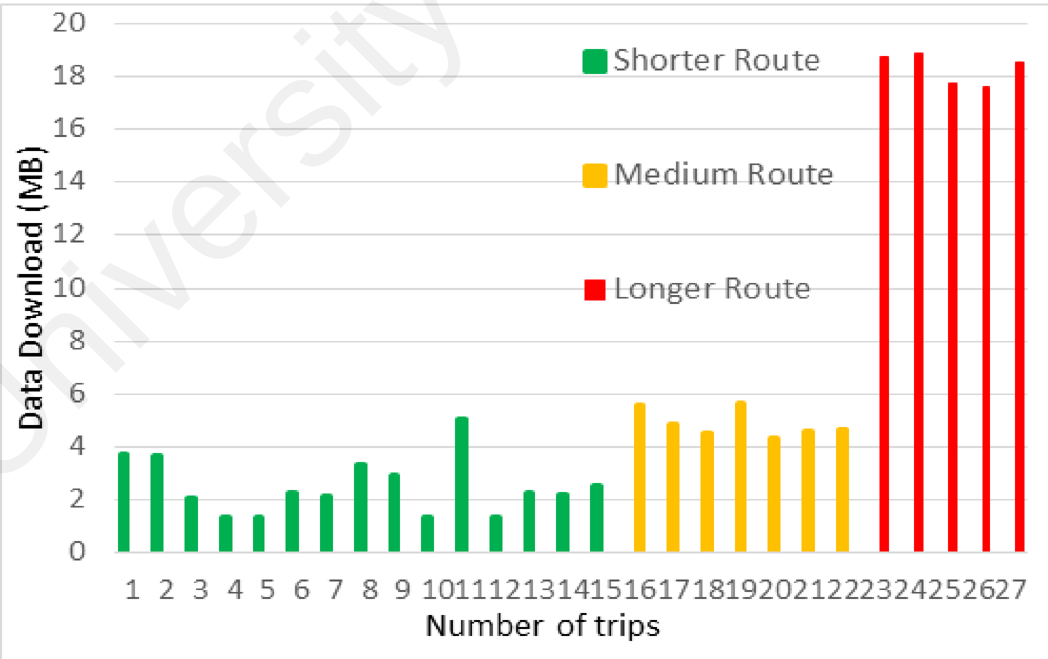

Figure 4.4 Data download for short to long routes

We conduct these tests at various times of the day and days of the week to ensure the generalizability of our findings. The data consumption of these applications is related to traffic intensity, which is the number of cars on the road at a particular time of the day.

Traffic intensity directly affects the travel time of vehicles. Intense rush indicates increased travel time. The number of alerts generated in such situations increases the data download from the Internet.

We calculate data consumption per hour using Equation 4.1 to calculate the data consumption per travel time of a vehicle.

$$D_c = \frac{\frac{\sum_{n=1}^{x} D_{sn}}{x} + \frac{\sum_{n=1}^{y} D_{mn}}{y} + \frac{\sum_{n=1}^{z} D_{ln}}{z}}{\left(\frac{\sum_{n=1}^{x} T_{sn}}{x} + \frac{\sum_{n=1}^{y} T_{mn}}{y} + \frac{\sum_{n=1}^{z} T_{ln}}{z}\right)/60}, \quad (4.1)$$

where D_c represents data consumption per travel time of 1 h of the vehicle; D_{sn}, D_{mn}, and D_{ln} are data downloads for short, medium, and long routes, respectively; *x, y*, and *z* represent the number of times that these particular tests are repeated for short, medium, and long routes, respectively; and T_{sn}, T_{mn}, and T_{ln} represent travel for short, medium, and long routes, respectively.

According to our field tests, the average amount of data consumed for a short route D_{sn} is 2.49 MB for the driving time T_{sn} averaged at 18 min. The amount of data consumed for a medium route D_{mn} is 4.88 MB for the driving time T_{mn} averaged at 55 min. The amount of data consumed for a long route D_{ln} is 18.33 MB for the driving time T_{ln} averaged at 2 hour. Thus, D_c of field tests is calculated using Equation 4.1 as follows:

$$D_c = \frac{2.49 + 4.88 + 18.33}{(18 + 55 + 120)/60} = 7.9641\ MB. \qquad (4.2)$$

Equation 4.2 reveals that the data consumption rate of a vehicle per hour is around 8 MB. These calculations represent the actual quantity of data download of the available driving assistance and navigational applications.

4.3.2.2 Results of Test Set 2

We repeat our experiments in Cambridge, UK as per experiment setting mentioned in Table 4.1 for medium to long routes. Figure 4.5 indicates that data download in Cambridge, UK using Waze has a large number of community-based alerts.

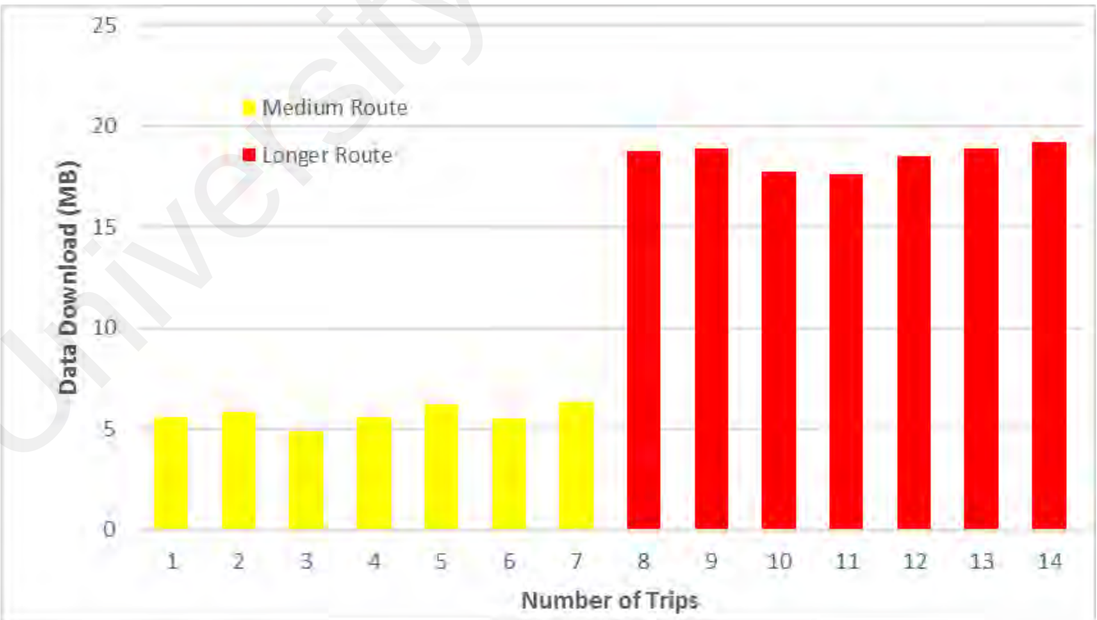

Figure 4.5 Data download for medium to long routes in Cambridge, UK

The average data downloads for the medium and long routes are 5.73 and around 18.55 MB, respectively. These values generally agree with our records for Kuala

Lumpur, Malaysia, which are also approximately 5 and 18 MB for medium and long routes, respectively.

4.3.3 Redundant TIS Data among Proximate Vehicles

Cellular technology provides good coverage and sufficient security but is relatively costly. Technologies, such as LTE, must be used efficiently especially in urban areas to minimize spectrum usage and cost. We take an urban highway where several vehicles are moving toward a common destination as an example (Figure 4.6). This example has also been endorsed in Figure 4.5, in which a common route is identified among multiple routes. The traffic on this common route follows the same route up to a common destination. The number of vehicles depends on traffic density at a particular time of the day. Vehicles need to communicate with TIS for driving assistance and route planning at runtime. Moreover, vehicles continuously send and receive traffic-related information to and from remote servers (TIS) over the Internet via LTE networks.

Through a high-order descriptive language, we formulate the problem of high bandwidth utilization and data redundancy. In Figure 4.6, we assume that x is the number of vehicles that travel in the same direction. The same scenarios are identified during our field tests, and an example of an identified scenario is shown in Figure 4.5. This scenario requires all vehicles to have individual LTE connections to acquire TIS information. We refer to this acquired information as redundant because multiple vehicles travel in the same direction and require the same type of information for driving assistance and route planning. Similar to GPS, a map constantly updates with the movement of vehicles to assist drivers in taking actions, such as taking a turn and slowing down, well before the set time. With the increase in the number of vehicles, the data rate, number of connections to LTE, and redundancy of information increase. Such increases consume high LTE spectrum bandwidth.

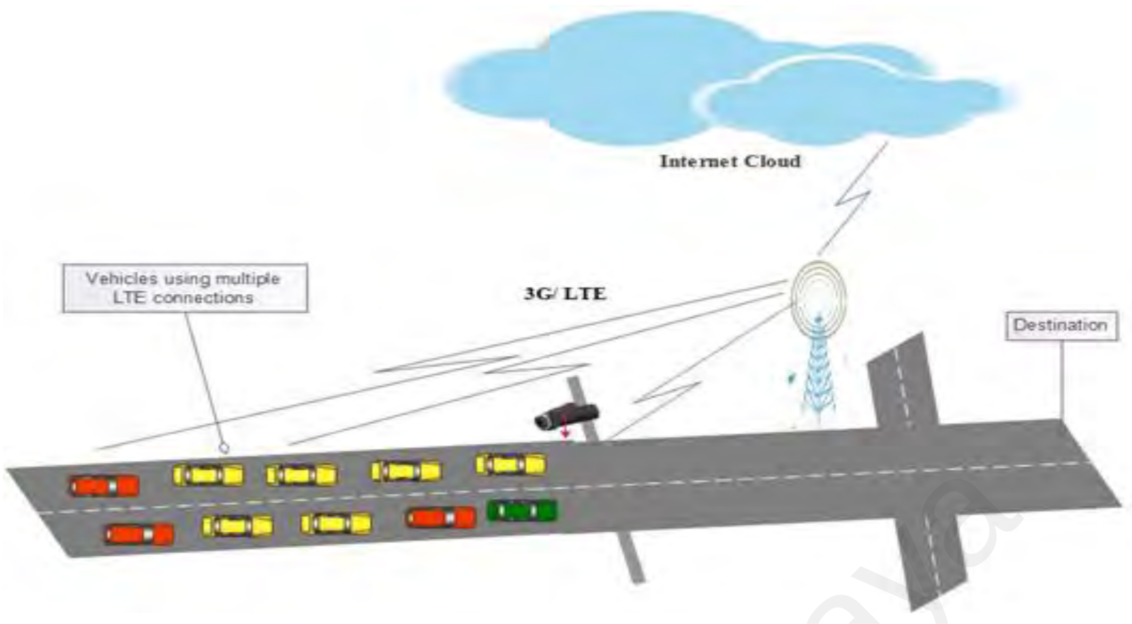

Figure 4.6 Road traffic scenario

4.3.3.1 Quantifying Redundancy

After calculating the amount of data, we find that driving assistance and route planning applications consume a similar type of data. In other words, vehicles in proximity have interest in common information, that is, the common interest of vehicles. A common interest in our case is the type of information that vehicles are interested in for their driving assistance and route planning. This information is TIS data that must be received at the right time and place for the proper functioning of route planning and driving assistance applications. We rent five cars and record the data usage of these applications. Each car downloads nearly the same amount of data because the cars receive the same type of alerts regarding movement on the roads. Cars in proximity receive and individually download a similar type of information; thus, redundancy in downloading the information exists.

Next, we consider only simple navigation and GPS data and exclude a considerable amount of remaining information that a full-fledged driving assistance application is required to download. We assume that x number of vehicles travel in the same direction for y number of kilometers for time t. The amount of existing redundant data is calculated.

Average data download as per field test: D = 2.49 MB for a short route. Thus, calculating redundancy as per Equation 4.3 is shown as follows:

$$\text{Redundancy} = D * (x-1). \qquad (4.3)$$

In our case, x is 5. Thus, the results are shown as follows:

$$D * (5-1) = 9.96 \text{ MB}.$$

This scenario indicates that, if five cars travel in the same direction in proximity in an urban area (e.g., from Pantai Hill Park to Wisma R&D in Kuala Lumpur as shown in Figure 4.2), then the redundancy in downloaded data is around 10 MB. The preceding calculation is only for a single trip. The average data usage per month according to our field measurements is approximately 338 MB. In this case, the redundancy is significant (1.35 GB of data). Notably, these values are calculated using the lowest data plan and taking the simplest route and driving assistance applications. The redundancy in the case of a full-fledged application is expected to be high. The redundancy increases as the number of vehicles increases. A solution should be provided to solve these potential issues and reduce spectrum usage and cost.

4.4 Findings

Our findings are summarized as follows. Statistically, the rate of data consumption of driving assistance applications is around 7 MB per hour. Driving assistance and navigational applications consume approximately 11% of the total data plan purchased by regular taxi drivers. The estimated cost of these applications per month per vehicle is around 4 RM. The costs incurred by these applications are small but are non-negligible.

The cost involved increases as the travel time of vehicles increases, especially in urban areas during rush hours.

4.4.1 Spectrum and Network Resources Withheld by Vehicle Users

As the number of vehicles increases, Internet connection via LTE networks intensifies, and the number of channels occupied by vehicles moving on the road increases. The capacity of telecommunication networks is limited and depends on numerous factors (Drira et al., 2016). Thus, telecommunication operators cannot increase their capacity on the run. As mentioned earlier, a capacity of only 1200 channels/user per sector (for upload only) is provided by a cell site; anything that exceeds this capacity leads to connection failures and quality degradation (ETSI, 2012). A large number of users indicate low data rate per user because the bandwidth in LTE networks is shared. For example, the average capacity of a 10 MHz LTE cell is 5 Mbps, which has to be shared by all users. If 20 active users are present, each user will have an average throughput of 250 Kbps (Singh et al., 2014).

4.4.2 Cost of Internet Download

According to the scenario in Section 6, each vehicle has to pay the cost of data download from the Internet because Internet downloads are costly. High usage indicates high payment for Internet connection.

Therefore, if data redundancy can be decreased by minimizing the number of connections to LTE, then the cost and dependency on the Internet can also be minimized. A solution is necessary to solve these potential issues for reducing spectrum usage and cost. Doing so can be beneficial for VANET application users and LTE networks.

4.4.3 Paving the Way Toward 5G

Although the introduction of emerging 5G technology is expected to be a good candidate for vehicular networks and applications, the cost factor has not been fully realized and modeled typically for D2D communication. Issues such as inter-cell inference are also present. The problems identified in our work are the potential issues expected to be addressed through full penetration of 5G technology (Liu et al., 2017). However, a solution at the end-user side can be proposed to address the identified issues in the use of LTE that may also support the changing network dynamics of emerging 5G infrastructure.

The concepts in our findings give insight into changing the paradigm from 4G to the 5G network infrastructure. For example, data offloading and clustering of users (especially cars via DSRC) in 4G can be realized as network offloading (via D2D) and network slicing. Considerable work still needs to be conducted for the full realization of 5G, and a short-term solution within existing telecommunication and VANET technologies is useful in addressing the identified issues.

A specific solution for reducing the data usage of driving assistance applications can significantly reduce the overall contribution of vehicular users to LTE resource utilization. Doing so will assist in controlling traffic flow on roads with minimum use of LTE resources and cost. An efficient solution should be established for the end user (VANET level) without involving resource and capacity planning for LTE networks. A solution to address the findings is proposed in Chapter 5.

4.5 Conclusion

Current cellular networks are under pressure imposed by data traffic demand. This scenario necessitates the development of new schemes to relieve cellular network traffic, especially in urban areas. Contents need to be downloaded in an effective manner to avoid overburdening the network and in consideration of the cost factor. Furthermore, the impact on traditional LTE application users should not worsen with the presence of heavy traffic, which creates an immense load (Zheng et al., 2014). To resolve such problems, the capacity of LTE to handle increasing demands should be analyzed first. Second, the type of mobile data traffic must be identified, and quantification must be performed to determine the impact of data traffic growth on the QoS requirement. Finally, the changing aspects of vehicular data traffic must be established to propose efficient solutions. Thus, we propose a novel cooperative heterogeneous solution (Chapter 5) to provide cluster stability for utilizing minimum LTE network resources to save cost.

CHAPTER 5: VANET–LTE-BASED HETEROGENEOUS CLUSTERING FRAMEWORK

5.1 Introduction

This chapter presents the proposed solutions for addressing the research gaps identified during the literature review and verified through problem analysis. The literature review and investigation through real-world field tests motivate and advocate the development of a solution. A new solution for road traffic management especially for driving assistance and route planning is proposed to utilize a small amount of LTE resources for avoiding instability and non-cooperative behavior within the cluster and increasing the level of synchronization among participating vehicles.

This chapter reports the methods and procedures for solving the problems found in existing applications developed for road traffic management. Section 5.2 presents the essentials of heterogeneous vehicular clustering process, clustering procedure, and clustering criterion delineation. A novel, stable, interest-aware clustering mechanism is discussed in Section 5.3. A cooperation mechanism that incorporates SGT approach is presented in Section 5.4. Section 5.5 presents the SLCA, which enables CMs to calculate their respective location coordinates even in the absence of GPS signals. Section 5.6 presents a detailed discussion of the integrated DIAC framework, which is based on destination and interest-aware vehicular clustering mechanism. The framework comprises three phases: cluster status check, formation, and maintenance. The algorithms developed for the mechanisms discussed in Sections 5.4 and 5.5 are incorporated within the DIAC framework for a conclusive solution. Section 5.7 presents the block diagram of the workflow of the integrated DIAC framework, and Section 5.8 concludes the discussion on the proposed solution.

5.2 Vehicular Clustering Process

This section presents the lists of the acronyms used (Table 5.1) in cluster formation, procedure, and parameter delineation.

The cluster formation process starts with basic clustering scheme adapted from MDMAC, in which vehicles are grouped to form a cluster. We extend and develop a clustering scheme with up-to-date methods for communication of vehicles and information sharing for the primary purpose of road traffic management. Along with basic clustering criteria, the new criterion is defined in consideration of the issues that need to solve in this research.

Table 5.1 Acronyms used in the clustering process

Acronym	Meaning	Acronym	Meaning
C_v	Cluster of vehicles	**Pr (t)**	Received power at time t
f_i	Member match requirements	**ΔT**	Change in time
θ	Direction of vehicle	**dBm**	Power ratio in decibels per mW
S_a	Average speed	**VID**	Vehicle ID
L_v	Location of vehicle	**SV**	Source vehicle
GƆ	Destination	**CM**	Cluster member
LQ	Link quality	**CH**	Cluster head
S_r	Relative speed	**eNodeB**	
S_v	Speed of vehicle	**LQcm**	LQ of CM
t	time	**LQsv**	LQ of SV
d_s	Standard deviation of speed	**R**	Counts rejected offers
ΔS_{thr}	Speed difference threshold	**A**	Counts accepted offers
β	Weighing factor of Λv	**C**	Variation as per SGTA
Λv	Aggregated mobility metric	**ACK**	Acknowledgment
σ	Variance in speed of vehicles	**Notify**	Multi-cast to several vehicles
RSS	Received signal strength	**CHID**	CH identification
ΔSc	Change in speed of CH	**ΔSm**	Change in speed of CM
ΔLi	Initial difference in location coordinates of CH and CM	**COc_i**	Initial coordinates of CH
Com_i	Initial coordinates of CM	**CCOc**	Current coordinates of CH
CCO_m	Current coordinates of CM		

Few aspects of cluster formation are considered beforehand. For example, the type of information to be accessed and its distribution are considered because the functional and parametric requirements of applications vary. Another consideration is CH selection, which controls and decides who can access and share information. The CH also determines the criteria for communication among the CMs.

Each vehicle in VANET is equipped with multiple communication interfaces nowadays, thereby managing to communicate with one another and with other available access networks, such as 3G/LTE.

Vehicles traveling at the same speed help prolong the cluster lifetime, thereby reducing the network overhead. An unstable cluster requires re-clustering, which increases network overhead and causes delays.

A milestone is an intermediate location before the destination where most of the vehicles are expected to pass. Vehicles that travel toward the same destination or milestone participate in the cluster formation process to become CMs.

Another important consideration is a common interest among vehicles. Interest represents common information desired by vehicles from Internet-based servers, such as information and alerts required for driving assistance and route planning.

5.2.1 Procedure of Clustering

Each vehicle maintains a list of its immediate connected neighbors. This list consists of vehicle identification (VID), direction (θ), average speed (S_a), and location (L_v) of neighboring vehicles. At the start of the journey, a vehicle broadcasts its status, which consists of θ, S_a, L_v, VID, destination or milestone to be reached (denoted as Ꝺ), and LTE link quality (LQ). This list is continuously updated as each vehicle shares status information periodically.

The mechanism of vehicular cluster C_v can be represented as Equation 5.1.

$$C_v = \{f_i \in [\theta \,|S_a\,|\,L_v\,|\,\text{GƆ}\,|\,LQ], \text{ --------------------- } (5.1)$$

where f_i is any member of cluster C_v that meets the requirement of cluster formation. All other vehicles within the range receive this broadcast message. Vehicles travel in the same direction with an average speed close to that of source vehicle (SV) and with the same milestone reply to this broadcast.

5.2.2 Clustering Parameter Delineation

Neighboring vehicles share their status information along with 3G/LTE network signal LQ and GƆ with SV as a response. SV selects a vehicle with a high LQ value of the signal from the eNodeB of the LTE network as CH. The selected CH connects to the Internet to access the remote server and obtain the required information, which is then shared with CMs. The CH controls the communication among the CMs and keeps a record of members' information, such as VIDs, initial speed, LQ, and location.

Here, the clustering parameters are defined and explained as a reference for use in the subsequent section. Each vehicle shares speed information with its neighbors. Thus, every vehicle calculates the average of speeds periodically. If n is the number of vehicles and exchanged speed information S with vehicle V in time interval t, then average speed S_a is as shown in Equation 5.2.

$$S_a = \frac{\sum_{i=1}^{n} S}{n} \text{ . ---------------------------- } (5.2)$$

Vehicles compute their relative speed (S_r) as shown in Equation 5.3.

$$S_r = (S_v - S_a) = d_s, \text{ ---------------------- } (5.3)$$

where S_v is the speed of vehicle v and d_s is the standard deviation of the speed of its neighbors. After a vehicle receives a cluster formation request, it compares its calculated S_a with the value of the speed in the received request message. If these values are similar (the difference should be less than the defined threshold value ΔS_{thr}), then the vehicle responds positively to the requesting vehicle. A threshold is defined on the basis of the findings in (Kakkasageri & Manvi, 2012; May, 1990; Rawashdeh & Mahmud, 2012) and configured as a function of the standard deviation (e.g., $\Delta S_{thr} = \beta\sigma$), where β is the weighting factor of the aggregated mobility metric Λv and σ is the variance in the speed of vehicles.

We use received signal strength (RSS) (H. Liu et al., 2015) to measure the LQ of the connection between the vehicle and the LTE-based station or the eNodeB. As vehicles move away from eNodeB, the RSS decreases. In 3G networks, the RSS ranges between −50 and −140 dBm. Values close to 0 indicate high signal strength.

The exact measurement of RSS differs from one vendor to another and depends on the hardware used by manufacturers. According to (Deblauwe, 2008), user equipment connected to cellular networks monitors broadcast channels continuously to search for a good channel and regularly makes RSS measurements, which can be defined as shown in Equation 5.4;

$$\text{RSS} = \left| \frac{1}{\Delta T} \int_{t}^{t+\Delta T} 10 \log_{10}\left(\frac{\Pr(t)}{0.001}\right) . dt \right| \text{.------------ (5.4)}$$

Here, Pr (t) is the received power at time t, expressed in watts and normalized against 1 mW. By obtaining $\log_{10}$, the value is converted to dBm. To calculate the average value, the integration over time interval ΔT is performed. Then, the absolute of the resulted value is regarded as RSS. This process illustrates how signal power is measured in the form of RSS at 3G/LTE reference devices (at receiving devices). The direction and destination or milestone is set by each vehicle at the start of their journeys to obtain assistance from online servers (TIS) in route planning and driving across particular road segments.

5.3 SIAC Mechanism (First Mechanism)

We propose a clustering mechanism called SIAC, as shown in the block diagram in Figure 5.1, to achieve cluster stability and utilize 3G/LTE network resources at a minimum level. SIAC consists of three phases: cluster status check, formation, and maintenance. In cluster status check, vehicles broadcast hello packets to check for existing clusters around them. If any cluster already exists in the proximity of the vehicles, then cluster formation phase starts. We define clustering parameters such as average speed (S_a), direction (Θ) and LTE LQ along with location updates of vehicles to select CH during the cluster formation phase. A flow diagram of the CH selection process in SIAC is presented in Figure 5.2.

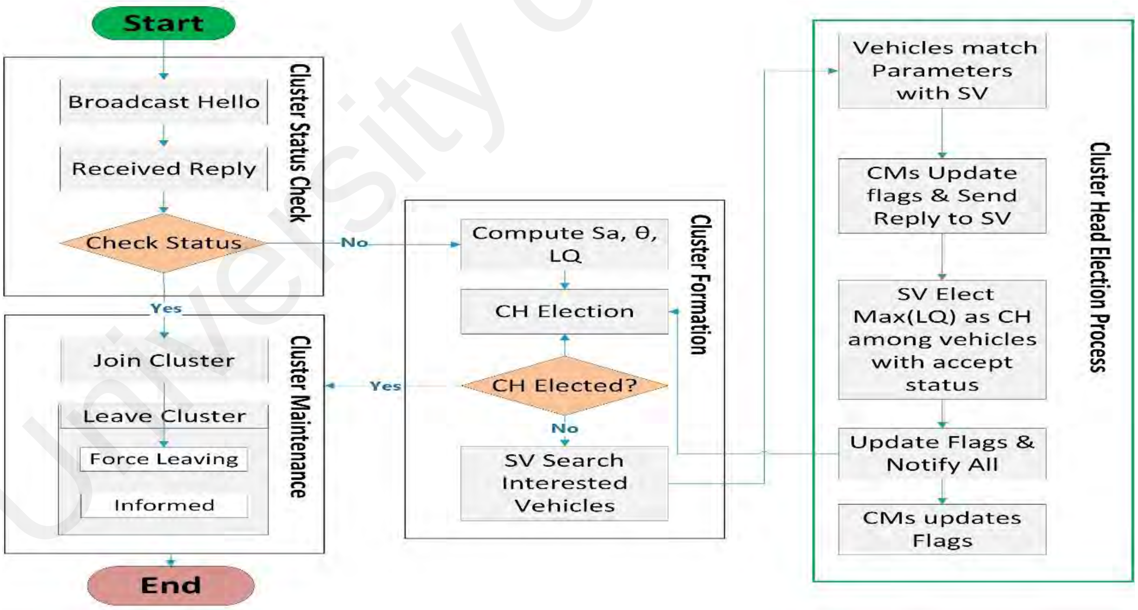

Figure 5.1 Interest-aware clustering mechanism

The clustering process starts when a vehicle in a particular road network attempts to form a cluster, that is, status check phase. In the status check phase, the vehicle first checks the current status (whether a cluster already exists around it) by broadcasting the status check message. If the vehicle founds a cluster nearby, then it starts the cluster maintenance phase and joins an existing cluster; otherwise, it begins the cluster formation process. The vehicle that begins the cluster formation is called SV, and its parameters S_a, ϴ, and LQ are computed.

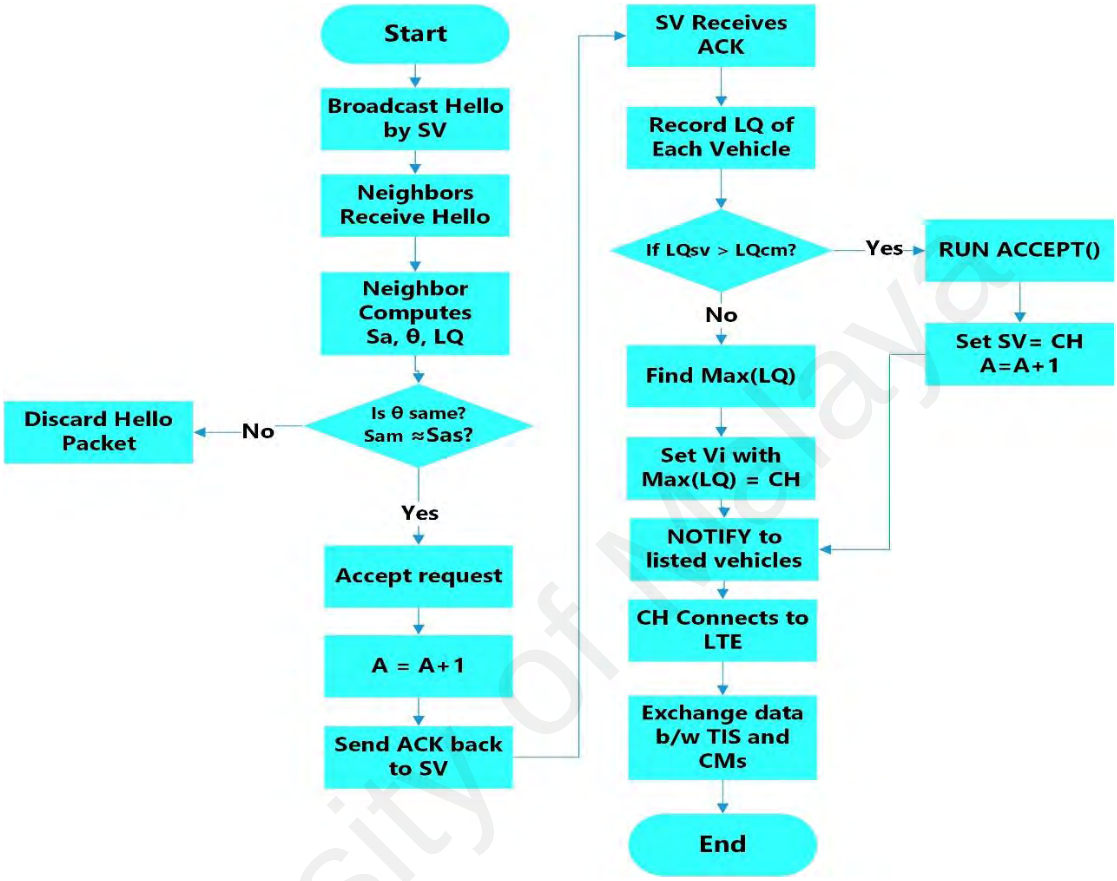

Figure 5.2 Flow diagram of CH election process

SV starts the CH election process and broadcasts hello packets with the above-mentioned parameters to its single-hop neighbor vehicles to find interesting vehicles. Interested vehicles are those that want to acquire information for driving assistance and route planning from neighbors without connecting directly to the Internet and have parameters that match with SV hello packet parameters. Only vehicles with matching parameters (average speed of CM (Sam) approximately equals to an average speed of SV (Sas)) and are interested in being part of the cluster update their flags and send a reply back to SV. The flags count and store information regarding the number of times a particular vehicle accepts to be part of the cluster and the number of times it has been selected as CH. If this time is not the first a particular vehicle receives a request for cluster formation, then the vehicle will check its own flag value and decide to accept or reject the request. Upon receiving replies from neighbors, SV elects a vehicle among vehicles with an accept status as CH with a maximum LQ. SV updates its flags and notifies all listed vehicles about a particular VID that is selected as CH. In this way, a cluster with a CH is formed, and then CH starts the cluster maintenance phase. In the maintenance phase, CH handles new CMs through cluster joining and leaving procedures. In our mechanism, cluster leaving has two types: one is forced leaving, and the other is informed leaving. Force leaving is conducted by CH when it receives no periodic updates from a CM for particular periods. Informed leaving is when a CM that wants to leave the cluster will inform the CH and the CH will remove that CM from the list such that no further updates are sent.

LQ is calculated by each vehicle because we assume that each modern vehicle has multiple interfaces and can connect to available access network at the same time. Each vehicle has at least two antennas: one for IEEE802.11p-type communication that works at a frequency of 5.9 GHz, and the other for 3G/LTE networks to connect to Internet-based servers. The LTE interface always looks for better signal strength and has a built-in feature to check the RSS (H. Liu et al., 2015) for measuring LQ periodically; we use this information for clustering criteria. The average speed and direction are calculated by each vehicle while traveling on the road. The critical feature of SIAC is to maintain a strong connection to the Internet by opting for good LTE LQ during the formation of the cluster. Clustering parameters such as average speed and direction provide stability to the cluster by allowing and enabling only those vehicles with average speed close to SV to participate in the cluster. In this way, SIAC not only enables stability within the CMs but also opts for strong LTE LQ, thereby affecting the performance of the cluster network for road traffic management. Our solution is based on the assumption that "do serve others, you will be served soon." Here, we assume that vehicles agree to share the data accessed from the Internet by paying the cost.

5.4 CIAC (Second Mechanism)

The non-cooperative behavior of vehicles is critical when paying the cost of the use of the Internet for accessed information, and a useful solution cannot be developed without ensuring the stability of the cluster. For stable clustering, Mvs are first selected among the vehicles on the road on the basis of clustering criteria such as location, speed, direction, and LQ. Then, a game theoretic approach is incorporated in it to enforce them to be selected as a CH. We name our proposed mechanism as CIAC. The location, speed, and direction information are exchanged periodically among vehicles, and LQ is measured through LTE device (i.e., its default behavior to opt for stronger signal strength level). A vehicle SV (the vehicle that initiates the process) starts the clustering process by sending a message inquiring about who is around, who has matching clustering criteria, and who wants to be part of the cluster and consequently willing to be CH. The interested vehicles use SGT algorithm (SGTA) to decide whether to participate with the will of being elected as CH. The SV also starts SGTA over the responses gathered from neighbors to select a CH among them, and that CH is going to bear the cost of connecting to the Internet via LTE network. The vehicles will opt for strategic choice against one another, that is, maximum benefit/payoff, which is the motive to participate in the cluster. The values of different flags in this mechanism are used to control bias over the selection of the same vehicle repeatedly in repetitive clustering. Detailed description of the SGT algorithm is presented in Section 5.6.5.

In SGT, each player (a vehicle in our case) has a set of choices (accept or reject to be a CH in our case), and each choice offers with some benefits or loss. Therefore, actions are named as a strategy, as shown in Table 5.2. Each player intends to go for a strategy with a maximum payoff or at least a minimum loss against the strategy chosen by another player. The choice of player one is related to the choice of player two. Thus, the player goes typically for a strategy in which the risk of loss is minimum and chances of benefit are maximum. Such strategy is called dominant strategy. In our case, players are vehicles that play against one another for free access to the information from neighbors. Sometimes, players adopt the same strategy in which players have similar benefits or loss; this situation is called equilibrium. A block diagram of SGT-based clustering mechanism is presented in Figure 5.3.

Table 5.2 Game theoretic strategies and payoffs

		Member Vehicle	
		Reject	**Accept**
Source Vehicle	**Reject**	-1, -1	-2, 3
	Accept	3, -2	1, 1

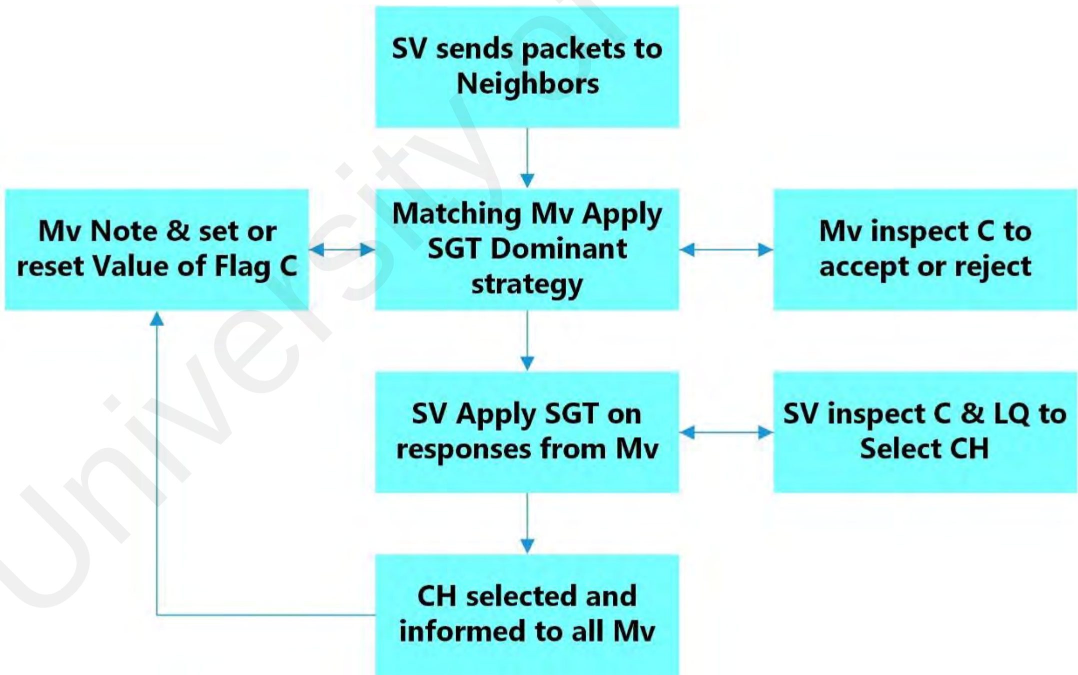

Figure 5.3 SGT-based CIAC mechanism

Table 5.2 shows that, if SV and Mv reject the request, then both players will obtain a payoff of −1. If SV rejects but Mv accepts, then SV will obtain the minimum payoff of −2, whereas Mv will obtain the maximum payoff of 3. If SV accepts but Mv rejects, then SV obtains the maximum payoff of 3, whereas Mv will obtain the minimum payoff of −2. Moreover, if SV and Mv accept, then both will obtain a payoff of 1, which is also a good choice. As per game theoretic properties, each player will opt for a dominant strategy (the accept strategy in our case).

Joining a cluster indicates obtaining free access to data acquired by a chosen CH; otherwise, the cost for Internet connection via LTE must be paid. Being part of a cluster is preferable to enjoy free data for route planning and driving assistance. If selected as CH, then the vehicle will have no problem because the next possible CH will be some other vehicles, and someone else from the rest of the participants will serve this vehicle. This benefit is the motive for the participation in a cluster. A fair-use policy is incorporated within STGA using control flags to control overuse of the same vehicle as CH.

The Mv maintains a queue to store the value of C flag. During the clustering, the vehicle looks its value whether to accept or reject the offer of being selected as CH or not. C flag is a special flag, and its value changes with the strategy adopted by vehicles. In the fair-use policy, if the value of C is greater than or equal to 5 then the vehicles will have no other option but to accept. Upon acceptance, 3 will be added to C flag; otherwise, 2 will be subtracted from the value of C. The values of C flag will be decreased by 1 if all vehicles reject the offer and increased by 1 if all vehicles accept the offer. According to game theory, vehicle payoffs are interrelated to each vehicle's decisions of acceptance and rejection. The value of C flag will be set as per Table 5.2 with the condition that SV dominates in decision making and choose a vehicle with the highest LQ value among the multiple vehicles that accept offers. When clustering is repeated with the assumption that same vehicles participate in the clustering process, some other vehicles will be chosen as CH. The primary players are SV and Mv with the strongest LQ value. The algorithm behavior for fair-use policy is also controlled in a way that the dominant strategy opted by SGT is overruled through flags to ensure the same vehicle is not selected as CH again in a new turn of the clustering process.

We execute our game strategies on GAMBIT software (Fallucchi et al., 2017) to check the correctness of our outcomes and find that the dominant strategy (accept) we explored in our case is correct. GAMBIT is a software package developed by the researcher to check and test the validity and correctness of game plan and strategies opted. “Gambit is an open-source collection of tools for doing the computation in game theory.” Our game theoretic algorithm enforces players to participate to obtain high payoffs. The fair-use policy controls and rewards the vehicles for becoming CH. We assume that three vehicles that travel in the same direction form a cluster to share the TIS information. In the case of our algorithm, if they repeat cluster formation 9 times, then each of the three vehicles would have been selected as CH for at least 3 times. A balance should be maintained between the number of times the vehicle serves as CH and the number of times some other vehicles serve it. After the selection of CH, data and status updates are exchanged between CH and Mv.

5.5 Self-Location Calculation Mechanism (Third Mechanism)

The successful exchange of status information among vehicles in the cluster prolongs the CM and cluster life. In urban topography, GPS signals are weakened or disappear because of reflection and refraction due to high-rise buildings and structures. In this situation, all vehicles within the cluster do not receive GPS signals. Thus, their locations cannot be calculated and sent back to CH. Accordingly, SLCA is initiated by the CMs to calculate the position by utilizing CH location updates, as presented in Figure 5.4. We incorporate SLCA within DIAC to provide them with stability.

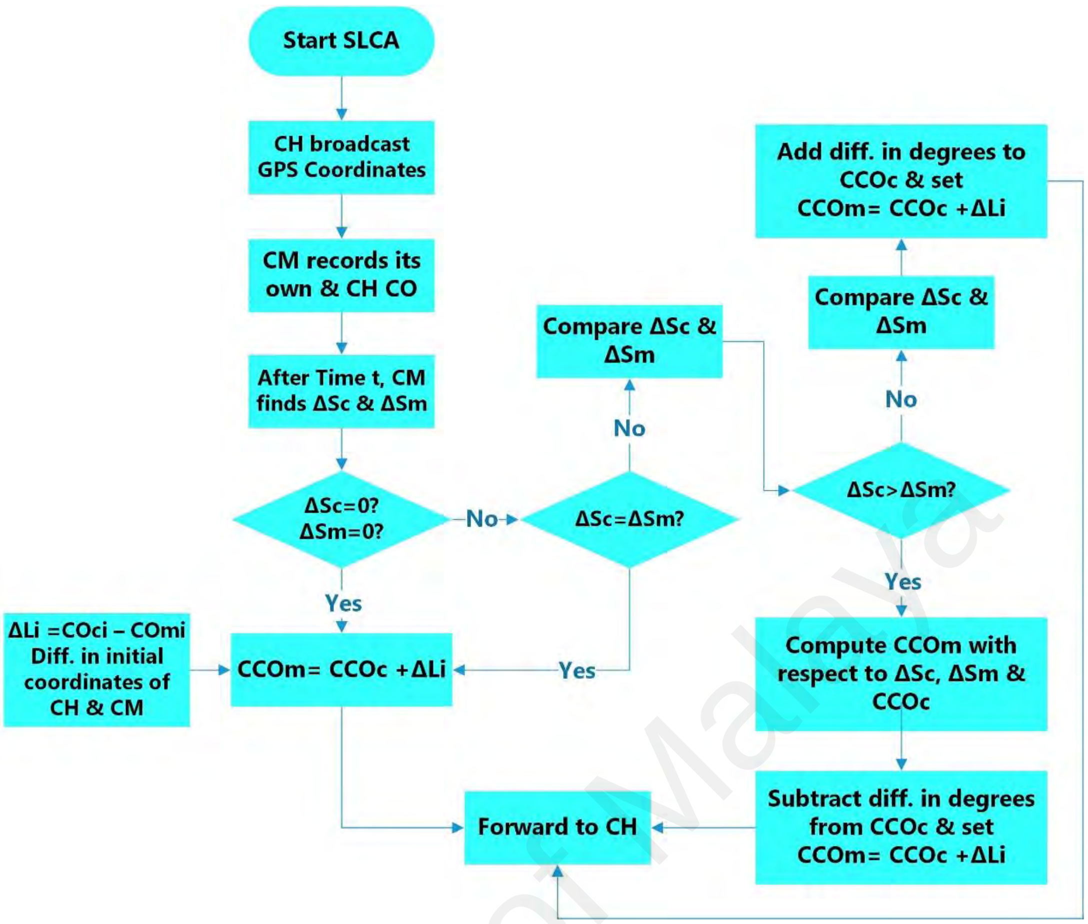

Figure 5.4 Flow diagram of self-location calculation mechanism

This mechanism uses the relative change in velocity of vehicles (i.e., SV and CM). If no difference is found or the difference is the same, then the initial difference in the coordinates of the CH and those of the CM, which are calculated initially during CH selection, are added to the current coordinates of the CH. Otherwise, the initial difference in the coordinates of CH and CM is subtracted from the current coordinates of the CH. This process provides members with their coordinates.

Meanwhile, Mvs update their location coordinates while traveling. SLCA aims to continue the sending of status updates to the CH to maintain a long-lasting, stable link. As per our cluster maintenance algorithm (Algorithm 5.4 [cluster leaving process]), the CH uses the leaving algorithm to forcibly remove a CM that does not send status updates up to a threshold time from the cluster. In this regard, SLCA plays an important role by enabling CMs to be part of the cluster longer than usual, thereby resulting in extended CM life. As a result, the stability of the cluster increases.

5.6 Integrated DIAC Framework

Integrated DIAC framework consists of a DIAC clustering mechanism (a simple destination and interest-aware mechanism for VANET) and is extended to VANET–LTE-based heterogeneous clustering. VANET–LTE-based heterogeneous DIAC is extended further by incorporating SGT-based cooperation algorithm and SLCA. The algorithms from the mechanisms discussed in Sections 5.3, 5.4, and 5.5 are amended to be incorporated within our integrated DIAC framework.

5.6.1 Organization of DIAC Mechanism

Our cluster formation process is unified as the CH selection algorithm. The merging of cluster formation with CH selection is unique and critical to enforcing cooperative behavior among the participating vehicles. The merge includes a mechanism in which every vehicle is provided the choice of whether to participate in a cluster. If a vehicle chooses to be part of a cluster, then the vehicle can be selected as CH and cooperate with other CMs. We use such parameters as destination/milestone and RSS values of connections between vehicles and eNodeB (as LQ) in addition to direction and average speed.

DIAC cluster formation process comprises three main phases: cluster status check, formation, and maintenance, as elaborated in Figure 5.5. The detail of each phase is provided in Sections 5.6.2–5.6.4. The elaboration in Figure 5.5 shows the steps and flow of the clustering process, status of flag variables, and incorporation of sub-algorithms.

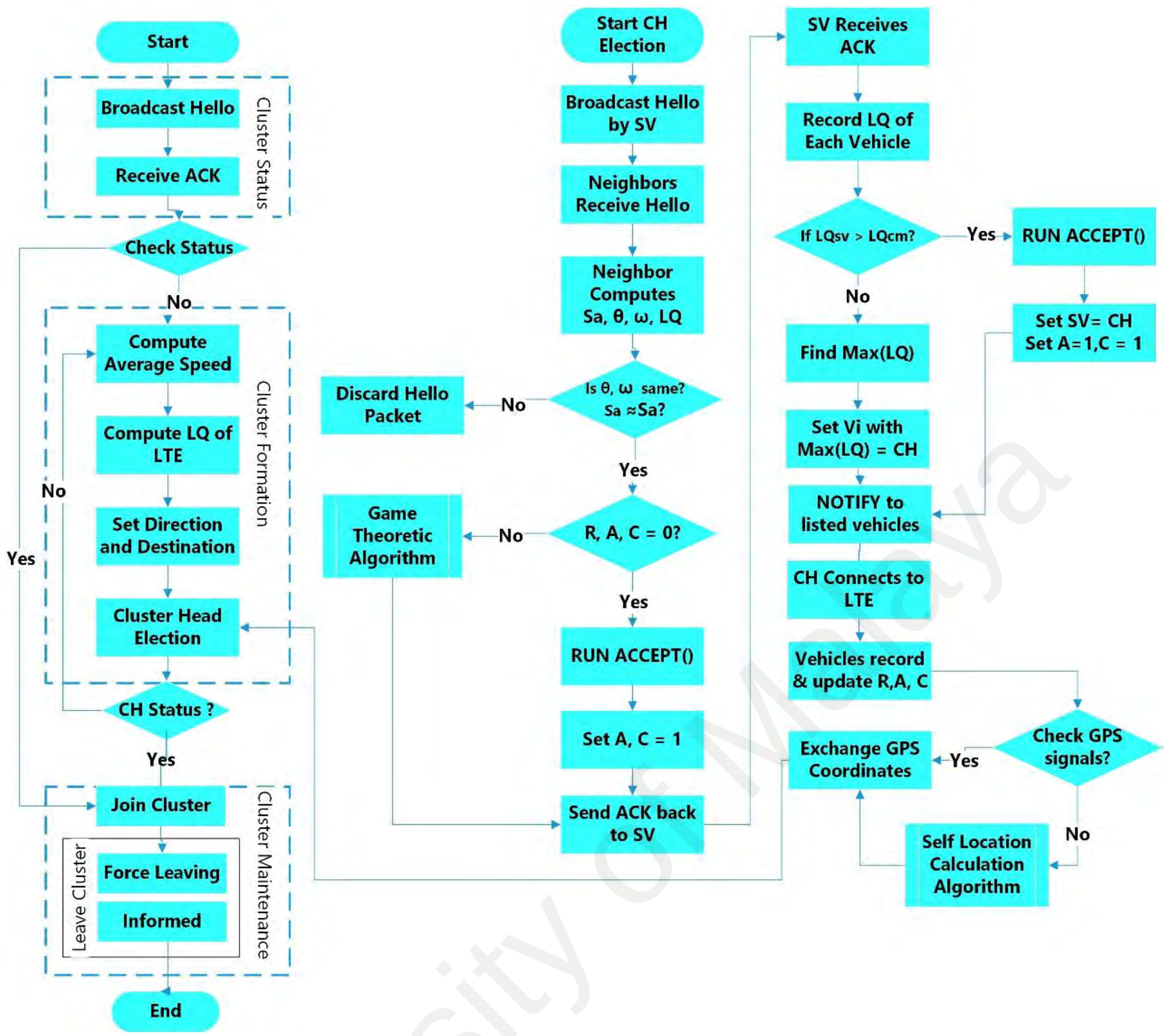

Figure 5.5 Elaboration of DIAC Process

5.6.2 Cluster Status Check

During a journey, vehicles exchange status information with other vehicles. Such information usually comprises speed, location, and direction. In our case, set vehicle parameters are sent via a hello packet that also has a destination and link quality information. First, vehicles broadcast hello packets to check for existing clusters around them. All neighboring vehicles receive hello packets and send acknowledgment (ACK) back to SV. If neighbors do not answer up to a certain time t, then SV resends the hello packets. If neighbors still do not reply, then the vehicles connect to the Internet directly to access a remote server, and no cluster is formed. After SV receives ACKs, it checks whether a CH is already selected among the vehicles. An ACK packet with a CH identification (CHID) must exist among the replies from the neighbors. SV sends a join request to the existing CH, which then accepts the request. Subsequently, vehicles start communicating with the CH by executing the cluster joining algorithm. The steps for cluster status check and joining are presented in Algorithm 5.1. If no CH exists, then Algorithm 5.2 is initiated by SV.

Algorithm 5.1 *Cluster Status Check and Joining Process*

1. SV **Initiate** Hello **packet**
2. Broadcast Hello **to neighbors**
3. Received ACKs **from Neighbors**
4. Check status IF **cluster is there (receives** CHID**)?**
5. IF STATUS = YES
6. Record CHID, S_a, LQ, **GƆ, and** θ **of Cluster exists**
7. **Send** JOIN **request to existing** CH
8. **Existing CH accepts joining request**
9. **CH records ID, S_a, LQ, GƆ, and θ of new member**
10. **CH inform other members**

5.6.3 Cluster Formation Process

If vehicles do not find a CH during the first phase, then they begin the cluster formation process. SV starts the CH selection process by initiating the CH selection algorithm, which is presented in Algorithm 5.2.

SV broadcasts a hello packet to its single-hop neighbors. Neighboring vehicles receive the hello packet and compute Sa, θ, GƆ, and LQ. The vehicles compare their destination, Sa, and θ with the parameters of the received hello packet. If the parameter values do not match, then the hello packet is discarded; otherwise, the values of R, A, and C flags in the queue of the vehicles are checked. Each vehicle maintains a queue to store the respective values of R, A, and C flags. Table 5.3 shows the initial status of the flags, which aim to record the number of times cluster formation requests are rejected, accepted, and selected as CH by the vehicles. If the values of R, A, and C are not 0, then the vehicles may accept, reject, or select themselves as CH by examining the respective values of the flags. If the values of R, A, and C are all 0, then any neighboring vehicle can accept the request and set the values of A and C flags to 1. Neighboring vehicles send an ACK back to SV.

Table 5.3 Initial status of flags

R	A	C
0	0	0

Upon receipt of ACK from neighboring vehicles at the SV side, the only option is re-clustering in the worst case scenario that all vehicles reject the offer to be CH. Otherwise, SV records the respective values of LQs of all vehicles in a queue. SV checks whether its LQ value (LQsv) is higher than those of the vehicles with the accepted state (LQcm). If LQsv is greater than LQcm, then SV accepts its cluster formation request and sets its status as CH. SV also sets the values of A and C to equal to 1 and multicasts NOTIFY to the vehicles listed in the queue. The neighboring vehicles note this information and update their flags depending on the criteria set by game theory. SV then connects to the 3G/LTE transceiver and starts sharing the information with the CMs.

If LQsv is not greater than LQcm, then SV finds the maximum value of LQ and selects the vehicle with the identified maximum LQ value as the CH. SV sends NOTIFY to all vehicles regarding the CH selection. The CMs update their status and flags as per Algorithm 5.3. The vehicle selected as CH sets its status as CH, and all the other vehicles update their flags accordingly. Vehicle Vi (any vehicle selected as CH) now connects to the 3G/LTE network to access the remote server and starts sharing TIS information among the CMs. Thus, a CH is selected, which forms a cluster of cooperative vehicles. Details of the enforcement of cooperation are explained in the game theoretic algorithm.

Algorithm 5.2 *CH Selection Process*

1. IF STATUS = NO
2. SV **Initiate** Hello **packet parameters**
3. Assign **S_a, θ, ω, LQ, the values computed as per equations 1,2,3**
4. Broadcast Hello **packet to** ALL **one-hop neighbors**
5. **Neighbors receive** Hello **from** SV
6. Compute S_a, θ, ω, LQ **values as per equations 1, 2, 3**
7. COMPARE **with** SV **values in** Hello **packet**
8. IF S_a, θ **of** CM $\neq$ S_a, θ **of** SV then
9. DISCARD **the packet**
10. ELSE **check values of Flags** R, A, C =0?
11. IF False **Apply S**GTA
12. ELSE RUN ACCEPT() **(ready to be a** CH**)**
13. **Set flags** A=1, C **=** 1
14. SEND **reply to** SV
15. Receive **Reply from members**
16. Record **values of S_a, θ, ω, LQ of each member**
17. IF **$LQ_{sv} \geq LQ_{cm}$ then**
18. Set SV as CH
19. Set flags A=1, C=1
20. ELSE Find Max(LQ_{cm})
21. Set VID **of vehicle having** Max(LQ_{cm}) **as** CH
22. NOTIFY **all listed members**

Algorithm 5.3 *Receives NOTIFY by CM*

1. CM **receives** NOTIFY
2. IF VID = CH {
3. **Set itself as** CH
4. **Update flags** R, A, C
5. Connect **to Internet via** LTE/LTE-A**}**
6. ELSE {
7. **Note** VID **of** CH
8. UPDATE **flags }**
9. COMPUTE **Location coordinates**
10. **Exchange data with** CH

5.6.4 Cluster Maintenance

If a cluster is formulated and a CH is selected successfully after the cluster formation phase, then cluster maintenance starts; otherwise, the cluster formation process is repeated. A formed cluster needs maintenance in the sense that new members join or existing members leave the cluster. The algorithm for leaving the cluster before reaching the destination or milestone is presented in Algorithm 5.4. If all vehicles leave the CH or the CH leaves the cluster, then any vehicle that wants a cluster formation starts a new clustering process.

Algorithm 5.4 *Cluster Leaving Process*

1. **Member (vehicle) send** LEAVING **request**
2. CH **receive request**
3. REMOVE **member** VID **from the (routing) table**
4. SEND **update to members**

OR

5. No **status updates from CM**
6. IF **time t elapses**
7. REMOVE **member** ID **from the (routing) table**
8. **SEND updates to members**

During the CH selection process, CMs receive a hello packet. SGTA decides whether to participate in a cluster and whether to accept or reject becoming a CH. The working mechanism and algorithm of SGT are explained in Section 5.6.5.

5.6.5 Incorporation of Cooperation Mechanism

In SGT, players (vehicles in this case) have a set of choices (actions). Each choice offers certain benefits or losses. Actions are named strategy. In our case, the strategies are to accept or reject the request. Table 5.4 shows that a payoff (benefit/loss) exists in the form of numerical values against each strategy. Each player intends to implement a strategy that provides the maximum payoff or at least has the minimum loss against the strategy selected by another player. The choice of player one is related to the choice of player two. Thus, the player typically chooses a strategy with the minimum risk of loss and maximum chances of benefit. This strategy is called dominant strategy. In our case, vehicles play against one another for free access to the information from neighbors. Sometimes, players adopt the same strategy in which they have similar benefits or losses. This situation is called equilibrium. A flow diagram of SGT algorithm is presented in Figure 5.6. Algorithms 5.5 and 5.6 describe the step-by-step process for SV and CM, respectively.

In Table 5.4, we assign the row player as SV and the column player as CM. The payoffs for each entry in the strategic game table correspond to those for the situation in which the row player plays the strategy specified in that row for it, and column player plays the strategy specified in that column for it. The strategies are accepting or rejecting the hello packet, which indicates participating in the cluster and opting to be CH or not. In each case, the related payoffs are already set. The table shows that, if SV and CM reject, then both players obtain a payoff of −1. If SV rejects but CM accepts, then SV obtains the minimum payoff of −2, whereas CM obtains the maximum payoff of 3. If SV accepts but CM rejects, then SV obtains the maximum payoff of 3, whereas CM obtains the minimum payoff of −2.

Moreover, if SV and CM accept, they both obtain a payoff of 1, which is also a good choice. As per game theoretic properties, each player opts for a dominant strategy, which is the acceptance strategy in our case. Table 5.4 shows that the payoff for the acceptance strategy, which corresponds to the possible strategy of opponent players, is high.

Table 5.4 Game theoretic strategies and payoffs

		CM	
		Reject	**Accept**
Source Vehicle	**Reject**	−1, −1	−2, 3
	Accept	3, −2	1, 1

5.6.5.1 Strategy Choices

The dominant strategy is to accept the request to be part of a cluster and be selected as CH, as presented in Algorithm 5.5. Lines 1 to 10 of Algorithm 5.5 are defined to choose the dominant strategy among the possible choices by a neighboring vehicle. The reason is that each vehicle aims to acquire data while incurring the minimum cost from neighbors instead of having a direct connection to the LTE network. Therefore, accepting the request to become CM and exploit free data acquisition is the ideal choice. A vehicle chosen to be CH must bear the cost of the LTE connection.

Algorithm 5.5 *Strategic Game Theoretic Process at Neighbor*

1. Neighbor receives HELLO **packet**
2. Apply Game theory **to decide to participate or not**
3. Set strategies **and** related payoffs
4. SWITCH: Max(Vipayoff) {
5. S=> IF Vi = accept **and** SV = accept then Vipayoff = 1
6. S=> IF Vi = accept **and** SV = rejects then Vipayoff = 3
7. S=> IF Vi = reject **and** SV = accept then Vipayoff = -2
8. S=> IF Vi = reject **and** SV = accept then Vipayoff = -1}
9. Set S AS dominant strategy WHERE
10. Vipayoff = Max (Vipayoff)
11. IF R=A=C $\neq$ 0 AND C>5 **then Overrule dominant strategy and reject** HELLO **packet**
12. RUN reject-set () {
13. Set R=R+1, C=C -1, sstate= 0 (**sstate is opt strategy**)}
14. ELSE **apply the dominant strategy**
15. RUN accept-set(){
16. Set A=A+1, C=C+1, sstate= 1}
17. Send ACK **back to** SV
18. SV **select** CH **and Send** NOTIFY
19. CM **receives** NOTIFY
20. IF CHID=VID (VID **is any vehicle ID) then**
21. C=C+2, VID=CH
22. ELSE IF sstate=1 **then**
23. C=C=0
24. ELSE C=C-1
25. Note CHID **and start a conversation**

This vehicle is rewarded soon when another vehicle serves as CH. In this manner, game theory encourages each vehicle that is interested in data acquisition to participate and become CH. Meanwhile, the fair-use policy controls the CH selection criteria through control flags and prevents the same vehicle from being selected as CH repeatedly.

Algorithm 5.6 *Strategic Game Theoretic Process at SV*

1. SV **receives** ACK **from neighbors**
2. IF sstate =1 {
3. Record LQs **of each neighbor**
4. Find Max(LQ**) of vehicles including** SV **with sstate=1**
5. IF LQsv = Max(LQ) AND C>= 5 {**then overrule dominant strategy**
6. **Set** R=R+1, C=C-2
7. Find Max(LQ) **of only vehicles with sstate=1**
8. SELECT Vi of Max(LQ) **as a** CH}
9. IF LQsv = Max(LQ) AND C< 5 **then apply dominant strategy {**
10. Set A=A+1, C=C+3
11. **Set** SV **as** CH}
12. IF LQsv ≠ Max(LQ) AND C< 5 **{then accept**
13. **Set** C = C +1, A = A +1
14. **Find** Max(LQ) **of only vehicles with sstate=1**
15. SELECT Vi of Max(LQ) **as a CH}**
16. IF LQsv ≠ Max(LQ) AND C>= 5 **{then reject**
17. **Set** C = C -1, R = R +1
18. **Find** Max(LQ) **of only vehicles with sstate=1**
19. SELECT Vi of Max(LQ**) as a CH}**
20. NOTIFY **all**
21. ELSE **Resend** HELLO **packet**

Each vehicle maintains a queue to store the respective values of R, A, and C flags to enforce the fair-use policy. If the values of R, A, and C are not 0, then the vehicles run the game theoretic algorithm and accept or reject the request depending on the strategies set in game theory. In our case, all vehicles that wish to participate in the cluster set their action strategies and related payoffs in accordance with SGT in a tabular form, as shown in Table 5.4.

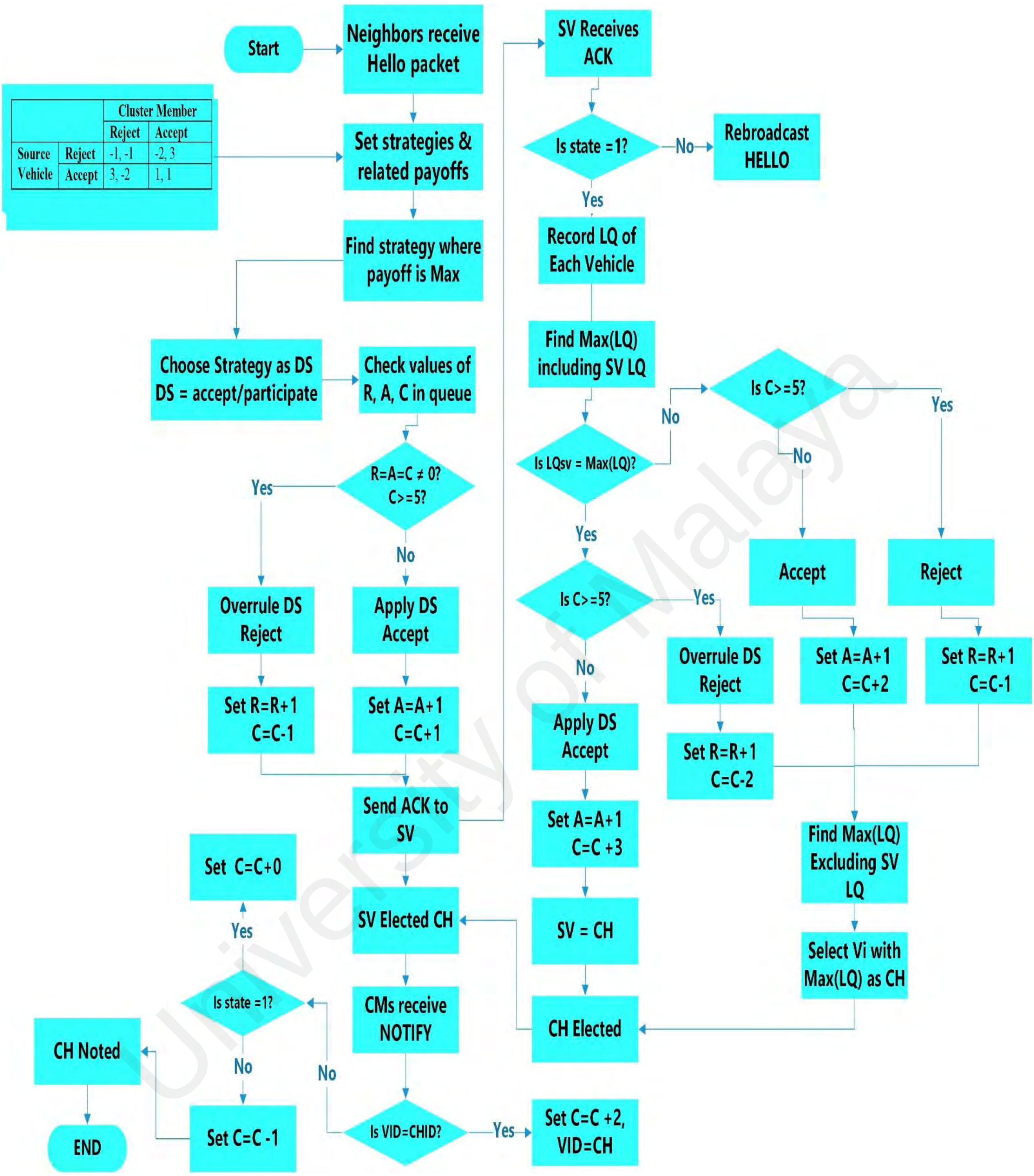

Figure 5.6 Flow diagram of SGTA

SV dominates in choosing a vehicle with the most robust LQ value as CH initially. The primary players in our game are SV and CM (the vehicles nearest SV) with large LQ values.

5.6.5.2 Correctness

We execute our game strategies on GAMBIT software (Fallucchi et al., 2017) to check the correctness of our outcomes. "Gambit is an open-source collection of tools for doing the computation in game theory" and was developed to check and test the validity and correctness of games planned and strategies opted. We find that the dominant strategy (accepts) we explored in our case is correct. Figures 5.7 and 5.8 show a snapshot of GAMBIT when we analyzed our strategic game to find equilibrium and dominant strategies.

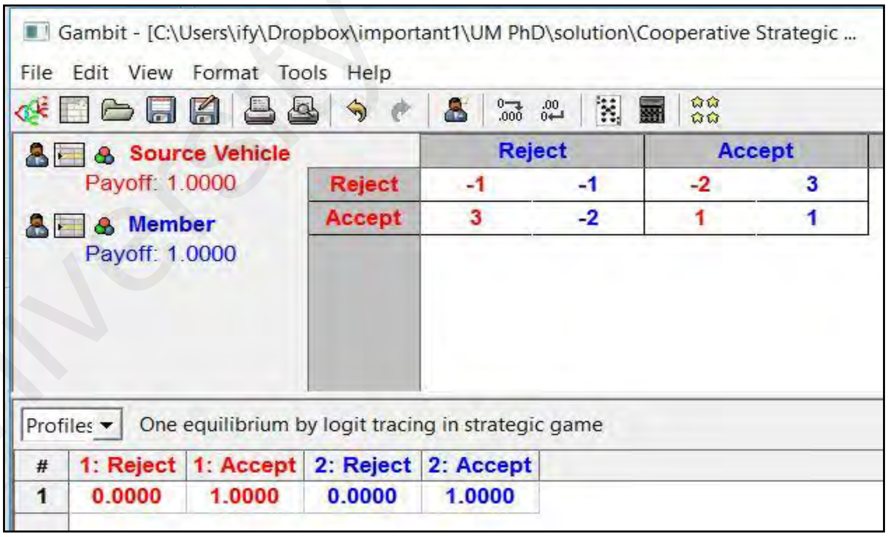

Figure 5.7 Equilibrium state analyzed by software GAMBIT

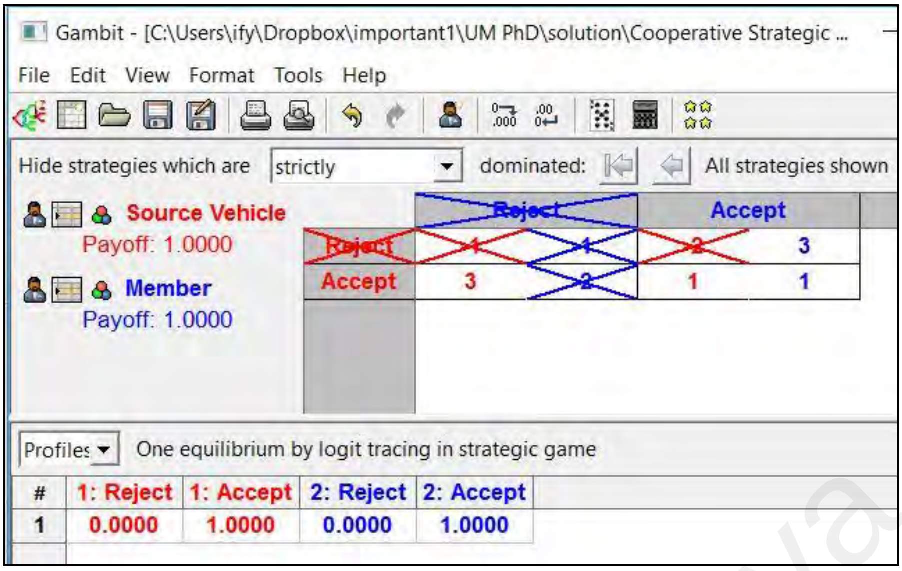

Figure 5.8 Dominant strategy analyzed by software GAMBIT

When relevant strategies are set, neighboring vehicles (CMs) check the values of R, A, and C flags in the queue, as depicted in Figure 4.6. If the value of C is greater than or equal to 5 (C > = 5), then the CMs overrule the dominant strategy; otherwise, the vehicles apply the dominant strategy and accept the request to be CH. Algorithms 5.5 and 5.6 and Figure 5.6 explain the step-by-step process, the selection of strategies, and the setting and resetting of flag values before and after the selection of a CH.

The process repeats whenever a cluster needs to be formed by vehicles moving on a road segment. C flag is a special flag, and its value changes with the strategy adopted by the vehicles. It controls the fair-use policy among CMs because vehicles selected as CH must pay the charges for the Internet data plan. Our game theoretic algorithm enforces these vehicles to participate for obtaining high payoffs. The fair-use policy controls and rewards vehicles for becoming CHs. For example, three vehicles travel in the same direction toward the same destination and thus form a cluster to share the TIS information. In the case of our algorithm, if these vehicles repeat cluster formation 9 times, then each vehicle is selected as CH at least 3 times. A balance must be established between the number of times a vehicle serves as CH and the number of times the said vehicle is served by another vehicle.

A vehicle seldom meets the same vehicle again on the road. The idea of maintaining equilibrium in the usage of the Internet by the vehicles cannot be generalized. This notion can only be conducted by assuming that the same vehicles travel on the same road segment in a particular timeframe. The assumption that vehicles belonging to the same destination have a great chance of meeting again on the roads strengthens our idea. However, our idea is to serve others and then you will be served in response sooner or later up to a certain extent. Our approach posits that, if you have been served by others 3 times, then you must serve others for at least 3 times.

After the selection of a CH, data and status updates are exchanged between the CH and CMs. If any CM does not receive GPS signal while on the move due to high-rise buildings or weak signals, then SLCA is initiated, as explained in Section 5.6.6.

5.6.6 Incorporation of Self-Location Calculation Mechanism

Each vehicle receives the coordinates of the CH, calculates its position from these coordinates, and keeps a record of its own and CH location coordinates. When no signal from GPS is received, the CMs start SLCA, as described in Algorithm 5.7.

The CMs first calculate the following. The current CH speed is subtracted from the initial CH speed. Specifically, the CH periodically sends its speed and location to the members, who continuously calculate the speed difference between themselves and the CH speed. Current CM speed is subtracted from the initial CM speed. The difference between the change in speed of the CH and that of the CMs is then determined.

Algorithm 5.7 *Self-Location Calculation Process*

1. CH **propagate GPS coordinates**
2. **CM record its own and** CH **location coordinates**
3. **After time** t, CM **calculates** ΔSc & ΔSm
4. **IF** $\Delta Sc = 0$ AND $\Delta Sm = 0$ AND $\Delta Sc = \Delta Sm$
5. DO $\Delta Li = COci - Comi$
6. DO $CCOm = CCOc + \Delta Li$
7. ELSE IF $\Delta Sc > \Delta Sm$
8. Compute CCOm **concerning** ΔSc, ΔSm, **and** CCOc

9. Do $CCOm = CCOc - \Delta li$
10. ELSE DO $CCOm = CCOc + \Delta Li$
11. CM **send location back to** CH

If no difference is found or the difference is the same, then the initial difference in the coordinates of the CH and the CM, which are calculated initially during CH selection, are added to the current coordinates of the CH. Otherwise, the initial difference in the coordinates of CH and CM is subtracted from the current coordinates of the CH. This process provides members with their coordinates. Mvs update their location coordinates while traveling. SLCA aims to continue the sending of status updates to the CH to maintain a long-lasting, stable link. As per our cluster maintenance algorithm (Algorithm 5.4 [cluster leaving process]), the CH uses the leaving algorithm to forcibly remove a CM that does not send status updates within a threshold time from the cluster. In this regard, SLCA plays an important role by enabling CMs to be part of the cluster longer than usual, thereby resulting in extended CM life. Thus, the stability of the cluster increases.

5.7 Work Flow Diagram of Integrated DIAC Framework

We integrate our clustering mechanism DIAC with SGT mechanism and SLC mechanism into one framework called stable and cooperative DIAC, as shown in Figure 5.9.

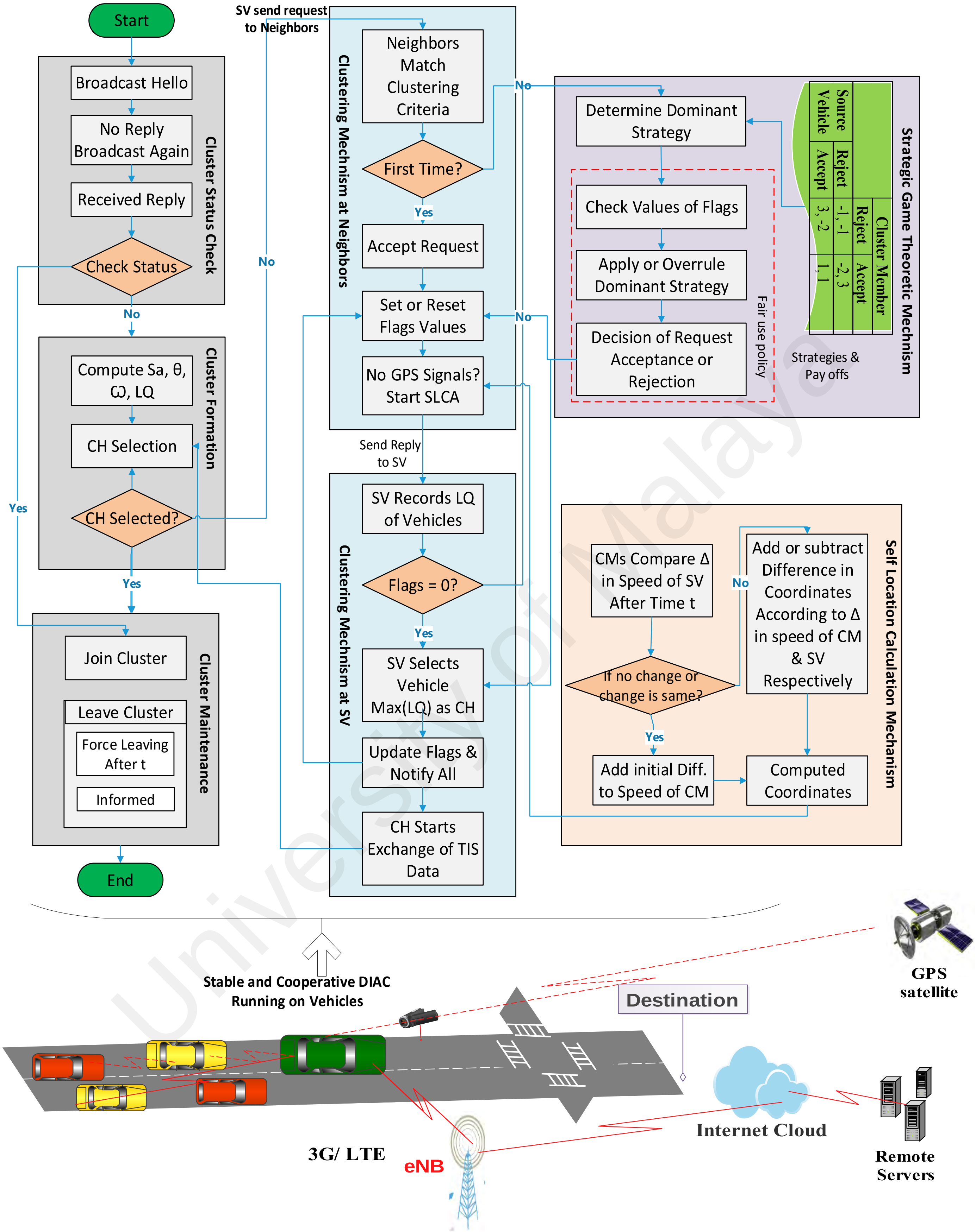

Figure 5.9 Cooperative Integrated DIAC Framework

The workflow of all mechanisms within a stable and cooperative DIAC-integrated framework is depicted in Figure 4.9. This represents a VANET–LTE-based heterogeneous vehicular clustering developed for driving assistance and route planning applications. The details and step-by-step workflow of the proposed framework have already been provided from Sections 5.6.1 to 5.6.6.

5.8 Conclusion

To develop a vehicular clustering-based solution for driving assistance and route planning applications, first, a stable clustering mechanism SIAC is formulated for the vehicles with a common interest (TIS data), which reduces the direct number of connections to the LTE for the access of remote TIS server. Second, a cooperative clustering mechanism CIAC is developed to motivate cooperation among the neighboring vehicles to participate and agree to be selected as CH. Third, self location calculation mechanism is formulated to increase the interaction duration of CM with CH. The important algorithms from the three mechanisms are extracted and combined to formulate an integrated framework for the vehicles traveling toward the same destination. This framework is called stable and cooperative DIAC.

CHAPTER 6: IMPLEMENTATION AND RESULTS

6.1 Introduction

This chapter reports the implementation and results of the proposed integrated DIAC framework at the micro level through a simulation study. The tools used for testing the proposed solution, data collection, and statistical analysis are also discussed. This chapter is divided into eight sections. Section 6.2 describes the micro-level implementation and evaluation of the proposed solution by a simulation. This section also discusses the simulation tools used, simulation framework setup, simulation parameters, performance metrics, and outline of the performance comparison of each proposed mechanism. Section 6.3, 6.4, and 6.5 present the results and discussion of our first mechanism (SIAC), second mechanism (CIAC), and third mechanism (SLCA), respectively. The expanded results of the DIAC algorithm at VANET-level comparison are presented in Section 6.6. Section 6.7 shows the results of the integrated DIAC heterogeneous clustering framework and comparative analysis with existing popular approaches. Section 6.8 concludes the discussion in this chapter.

6.2 Micro-Level Evaluation

Micro-level evaluation is conducted through a simulation study, and quantitative results are acquired by modeling low-level abstraction of the proposed solution by using simulation framework of OMNeT++ for network simulations. This section discusses the simulation tools used for implementation, simulation setup, performance metrics, baseline approaches, and analysis of results for each of our proposed mechanisms, namely, SIAC, CIAC, SLCA, DIAC, and integrated DIAC framework.

6.2.1 Simulation Tools for Implementation

Implementation of vehicular communication in real-world test beds involves high cost and is not scalable in most circumstances (Mussa et al., 2015; Stanica et al., 2011). This situation is mainly due to the low distribution of vehicles with VANET communication capabilities on the roads. The vehicles with OBUs that support V2V and V2I communications are very few, and having such vehicles is costly at this level. Therefore, previous researchers have recommended the use of popular simulation tools to model and evaluate the performance of new algorithms for vehicular networks (Sommer et al., 2015). Network simulators are computer software tools that model the real-world network systems to provide analysis that validates and verifies protocols or a specific aspect of the network algorithms before implementing them in the real working environment. Mobility generators are used to generate realistic vehicle behavior in VANET environment, capture roadmaps and scenarios, and provide mobility trace that is used as input to network simulators. The choice of a simulation tool is based on requirements regarding behavior that needs to be simulated and modules or software packages incorporated by the tool. In our case, we need a network environment, mobility traces, and LTE integration for our heterogeneous VANET–LTE-based network infrastructure development.

Open-source software that suits the implementation of our work and is available with a free license for the general public is selected. Open-source network simulators allow anyone to use the software and modify the source code without any legal implication from the distributors. Open-source software is not developed by a single distributor, mostly involves various research communities, and can further be modified by other researchers. In the beginning, open-source software is a good choice for testing of new algorithms because it can easily modify existing code to determine the behavior of the proposed algorithms. Many open-source network simulation tools support VANET simulation (Hagenauer et al., 2014), but similar works have mostly used OMNeT++ to simulate VANET with SUMO and Veins.

6.2.1.1 OMNeT++

Objective Modular Network Testbed in C++ (OMNeT++) is a modular open-source simulation framework architecture based on C++ library that provides a base for building network simulators. For OMNeT++, the network is considered in a wide sense to incorporate wireless and wired networks, queuing networks, on-chip networks, and ad hoc networks (Varga). Simulators to simulate these networks are provided by independent researchers as an add-on to the OMNeT++ framework. OMNeT++ network modules are developed in C++ libraries and are assembled into larger components and modules using the NEtwork Description language. The modular approach enables component and module reuse for the research community. The main module that is considered standard protocol model library of OMNeT++ is INET framework. This framework is composed of models that are used to simulate Internet stack and link layer protocols for wireless and wired networks. This framework also supports mobility for MANET protocols.

6.2.1.2 SimuLTE

One of the important modules developed to run over OMNeT++ is SimuLTE for simulating LTE and LTE-A networks (Virdis et al., 2015). SimuLTE is a project of the Computer Networking Group of the University of Pisa, Italy. It is written in C++ and is fully customizable, thereby enabling easy development of new modules for new algorithms and protocols. SimuLTE can also work with Veins to simulate LTE-capable vehicular networks. The integration of Veins into SimuLTE enables simulating cellular communications in vehicular networks.

6.2.1.3 Vehicles in Network Simulation (Veins)

Veins is used to facilitate the simulation of vehicular communication in OMNeT++ (Sommer et al., 2015). Veins is an event-based network simulator for inter-vehicular communication that incorporates road traffic and microscopic simulation models. The simulator implements full detailed models of WAVE/IEEE802.11p standard protocol, which is important for VANET.

6.2.1.4 Simulation of Urban MObility (SUMO)

SUMO is an open-source, discrete microscopic road traffic mobility generation simulation tool that is developed to handle large road networks (Krajzewicz et al., 2012b). It is highly portable and widely used by research communities. Its features include collision-free movement of vehicles, different types of vehicles, individual vehicle routing, and hierarchical junction type with right-hand rule routing. SUMO is an active community support-based software tool, which is implemented in C++ with some graphical user interface.

The major component of SUMO is developed by the Institute of Transportation System at the German Aerospace Center. Nevertheless, SUMO is open source and permits other researchers worldwide to contribute many features under the general public license. SUMO supports explicit modeling of vehicles at individual-level movement through the network. Furthermore, SUMO supports simulation of large road networks with different features, such as speed limits on the roads, traffic light, different types of vehicles, and various junction layouts. SUMO supports importing real-world maps (i.e., OpenStreetMap) into the simulation environment. The list of tools used for the implementation of our work is presented in Table 6.1, and the setup of these tools is shown in Figure 6.1.

Table 6.1 Tools used for simulation

Tool	Description	Reference
OMNeT++	4.6 version for the simulation network of VANET	(Hagenauer et al., 2014)
SUMO	Version sumo-0.19.0 to simulate mobility of vehicles	(Krajzewicz et al., 2012a)
Veins	To incorporate the behavior of cars on the roads	(Sommer, 2015)
SimuLTE	To integrate LTE with VANET	(Virdis et al., 2015)

6.2.2 Simulation Setup

We perform vehicular network simulations over a realistic urban environment by taking road network infrastructure of the urban city of Kuala Lumpur, Malaysia. The hybrid architecture is built using these algorithms, single-hop broadcast type is used for dissemination of messages, and other parameters are set for VANET and LTE as shown in Table 6.2. The simulation is repeated for various velocities of vehicles ranging from 10 m/s to 35 m/s. To increase the confidence level, simulation is repeated 3 times at each velocity of vehicles, and average is taken for comparative analysis in a graphical form. The simulation tools are set up as presented in Figure 6.1.

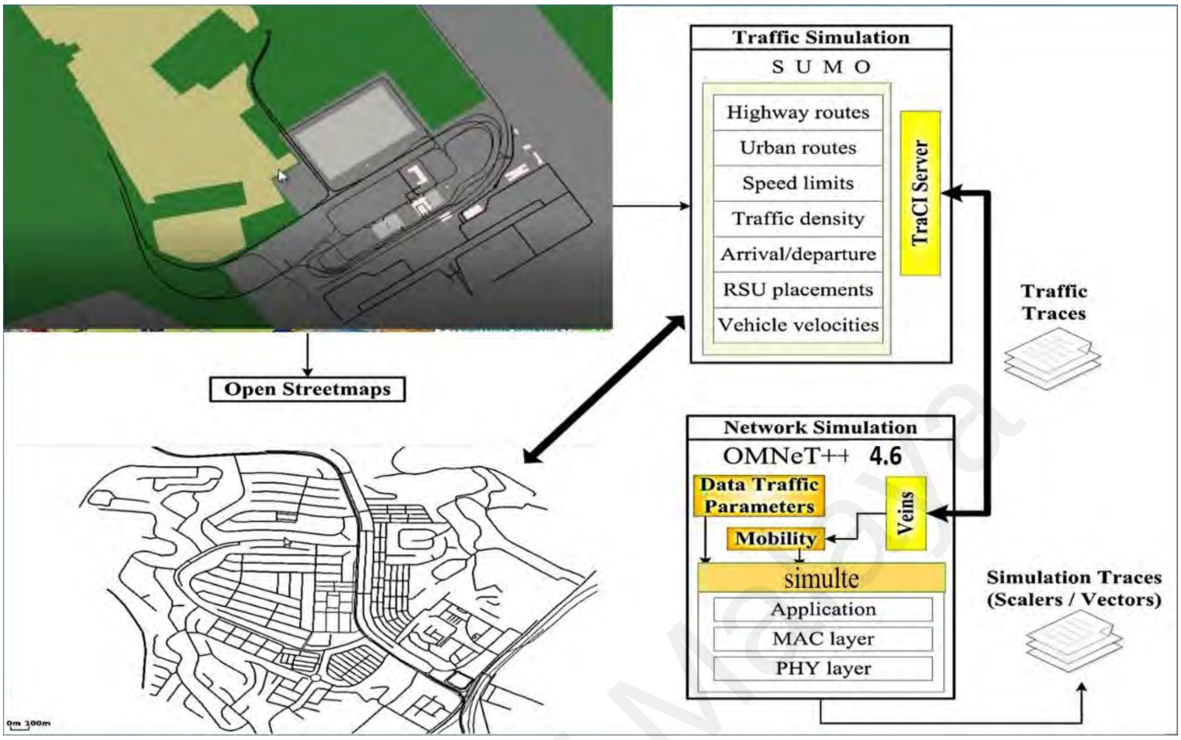

Figure 6.1: Simulation and evaluation setup

Table 6.2 Simulation parameters

Parameters	Values	Parameters	Values	Parameters	Values
Simulation area	3 km × 3 km	RSU antenna type	Sector directional (16 dBi)	ENodeB TxPower	45 dBm
IEEE 802.11p (frequency/BW)	5.89 GHz/10 MHz	OBU vehicle antenna type	Omni-directional (8 dBi)	Number of vehicles	100
Data rate	6 Mbps	OBU height	1.5 m	Resource blocks	100
TxPower	26 dBm	RSU height	10 m	Guard subcarriers	423
Header packet size	256 B	LTE (frequency/BW)	2.1 GHz/20 MHz	Control subcarriers	500
Beacon interval	25 ms	UE TxPower	20 dBm	No. of subcarriers per RB	12
Maximum velocity	10- 35 m/s	LTE BS antenna type	3-sector directional (16 dBi)	LTE vehicles antenna type	Omni-directional (8 dBi/6 dBi)
Base station height	18 m	Vehicle height	1.5 m	Simulation Time	300 s

6.2.3 Performance Comparison and Benchmarking

The performance of each proposed mechanism and integrated DIAC framework is compared after presenting simulation results in a graphical form. The details of the results and discussion are described in Sections 6.3 to 6.7. The outline of proposed mechanisms with their benchmarking approaches, underlying network infrastructure, and performance metrics is presented in Table 6.3.

Table 6.3 Outline of simulation work and benchmarking

Proposed Mechanism	Bench Marking with	Network Infrastructure	Performance Metrics
SIAC	• MDMAC (Wolny, 2008) • CMGM (Benslimane et al., 2011)	VANET–LTE (heterogeneous)	• CH Duration • CM Duration • CH Changing Rate • Clustering Overhead • Packet Delivery Ratio • Data Download
CIAC	• MDMAC • VMaSC (Ucar et al., 2016) • NCIAC (a version of CIAC with no cooperation)	VANET–LTE (heterogeneous)	• Participation rate • Utility • Percentage of vehicles act as CH
SLCA based DIAC	• VMaSC • MGSA(Benslimane et al., 2011) • DIAC	VANET–LTE (heterogeneous)	• CM Duration • Number of CMs per cluster • % of forced leaving CMs • Packet Delivery Ratio • Clustering Overhead
DIAC	• MDMAC • CMGM • VMaSC • MGSA	VANET	• CH Duration • CM Duration • CH Changing Rate • Clustering Overhead • Packet Delivery Ratio
DIAC Integrated framework	• MDMAC • CMGM • VMaSC	VANET–LTE (heterogeneous)	• CH Duration • CM Duration • CH Changing Rate • Clustering Overhead • Packet Delivery Ratio • Average Delay • LTE Cost

6.3 SIAC Results and Discussion

After the implementation of our first proposed mechanism (SIAC), first, the results are compared with MDMAC (Wolny, 2008) and CMGM (Benslimane et al., 2011) in terms of the performance metrics displayed in Table 6.4.

Table 6.4 Performance metrics

Parameter	Definition
CH Duration	It is the time duration of CH for each cluster of vehicles
CM Duration	It is the time for which a vehicle remains a member of the particular cluster. Time from joining a cluster to leaving.
CH Changing Rate	Number of status changes by a vehicle from CH to CMs
Clustering Overhead	It is the ratio of the control packets to the total data packets transmitted within the given cluster for the set simulation time
Packet Delivery Ratio	It is a percentage of the total packets received by the destination vehicles to the total packets transmitted within the network
Data Download	It is data download by each CH during the simulation time

We define these performance metrics primarily to check the stability of cluster and CH because the time duration of the cluster, CH, and CMs reflects the stability of a particular cluster. Second, data download is measured to estimate cost.

6.3.1 Result Discussion

The implementation results for our SIAC are presented in this section. We present the output of the simulation in a graphical form by taking the maximum velocity of vehicles along the X-axis and CH duration, CM duration, clustering overhead, CH changing rate, packet delivery ratio (PDR), and data download on the Y-axis.

First, CH durations of SIAC, CMGM, and MDMAC are calculated and represented in a graphical form as illustrated in Figure 6.2. The average CH duration of SIAC is higher than those of both existing algorithms because of the efficient cluster formation and maintenance mechanism of SIAC. CH duration generally decreases with the increase in the velocity of vehicles because high velocity increases topology changes, thereby possibly resulting in link breakage and opt for re-clustering.

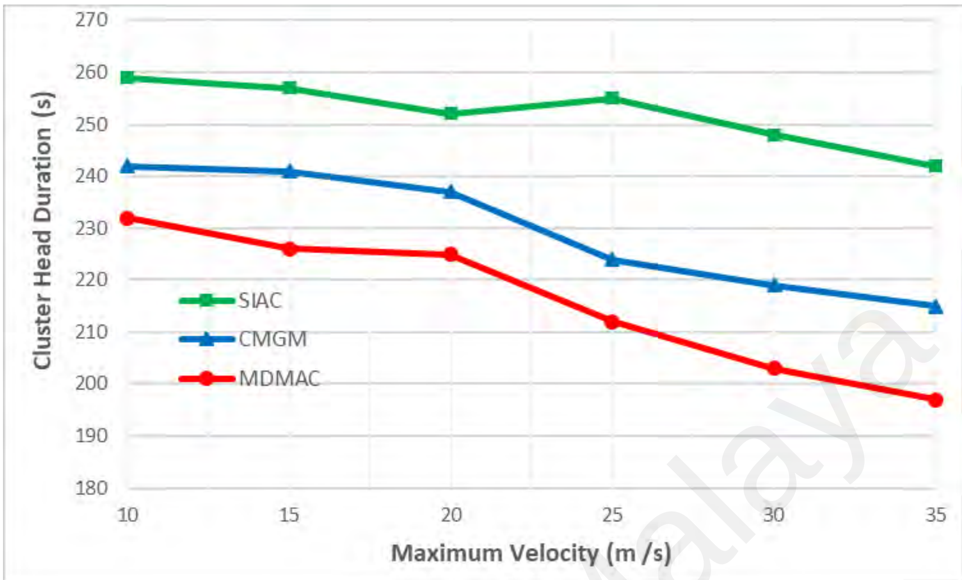

Figure 6.2: CH duration comparison of SIAC, CMGM, and MDMAC

Another reason is that SIAC always opts for strong LTE LQ, which also increases the CH duration whenever CH loses connection to the Internet. As a result, clustering process is repeated to select new CH. MDMAC ignores LTE link stability, and CMGM has poor performance in this sense.

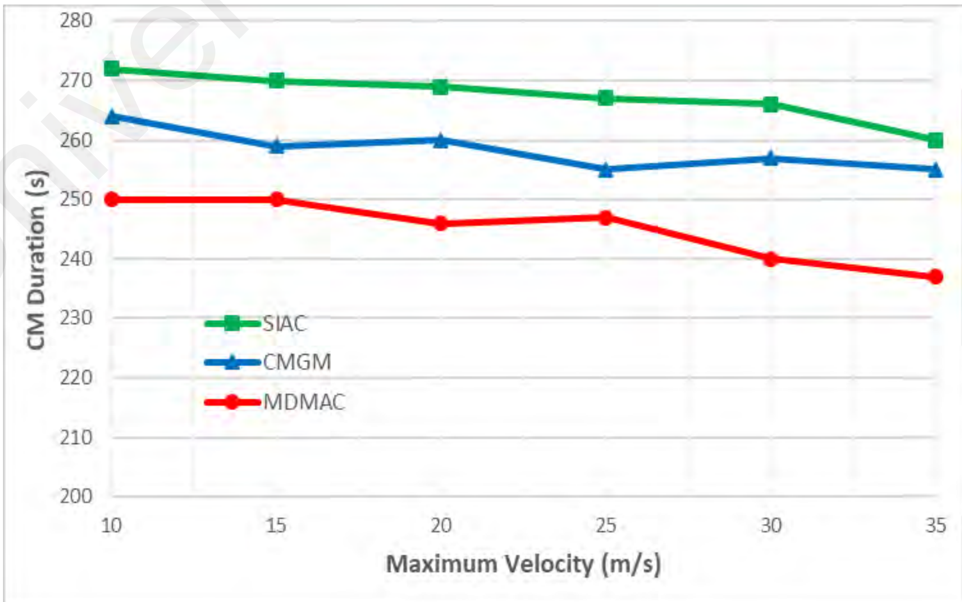

Figure 6.3: CM duration against various velocities

The CH duration of SIAC ranges from 18 s to 30 s, which is higher than that of CMGM.

We calculate CM duration from the time of joining a cluster to the time of leaving, as shown in Figure 6.3. The CM duration of SIAC is higher than those of the two other existing algorithms under a single-hop broadcast condition because of low delay in cluster joining. Overall, CM duration decreases with the increase in the velocity of vehicles. Our proposed mechanism does not show fluctuation in CM duration for the velocity between 10 m/s to 20 m/s. The variation in durations for CH and CM is nearly similar.

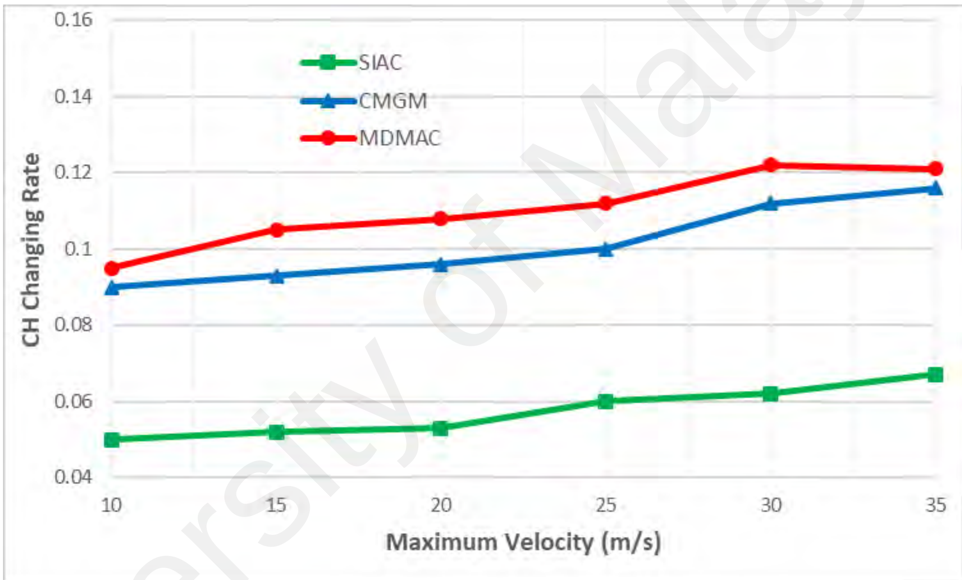

Figure 6.4: CH change rate per second against various velocities of vehicles

The third factor is the CH change rate, which is also crucial for the measurement of cluster stability. CH change rate is also measured against different velocities of vehicles as presented in Figure 6.4. The CH change rate of SIAC is lower than those of CMGM and MDMAC. This result again confirms the stability of our proposed protocol. The reason is that CMGM and MDMAC use periodic clustering and unnecessarily change CH in the network, which is not the case with SIAC. Few times of re-clustering also result in a small amount of cluster overheads. The CH change rate of all protocols generally increases with the increase in the velocity of vehicles. When CH is selected by considering the strongest LQ value, chances of link instability decrease. In our case, the CH duration is increased and CH changing rate is decreased. This condition shows link stability between vehicle and LTE network.

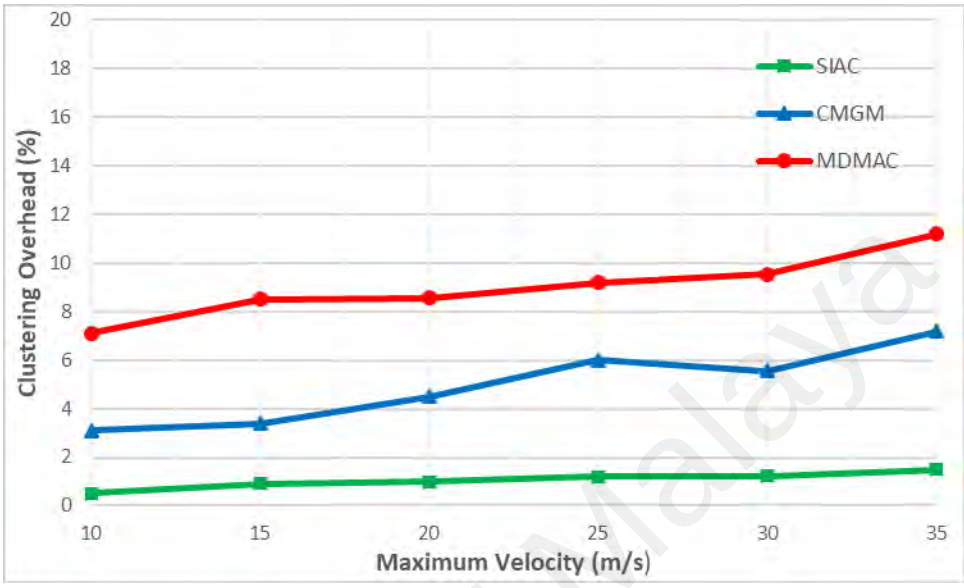

Figure 6.5: Clustering overhead of protocols against various velocities of vehicles

Figure 6.5 shows the clustering overhead of SIAC, CMGM, and MDMAC protocols. The clustering overhead of SIAC is smaller than those of the two other protocols because of its high cluster stability. The clustering overhead of SIAC is approximately 2% lesser than that of CMGM at the velocity of vehicles of 10 m/s and nearly 5% lesser than that of CMGM at the velocity of vehicles of 35 m/s. Low CH changing rate decreases the number of control packets in the network. Overall, the curve of SIAC in Figure 6.5 is less steep than those of CMGM and MDMAC as the velocities of vehicles increase. This finding shows the stability of SIAC under high speed.

To check the performance regarding data packets, we compare the data PDR of protocols as shown in Figure 6.6. The PDR of SIAC is greater than those of the two other protocols. Specifically, the ratio is around 95% at the velocity of vehicles of 10 m/s and remains nearly consistent up to 90% at velocities ranging from 15 m/s to 25 m/s. Overall, the PDRs of CMGM and MDMAC are low and decrease further with the increase in velocities of vehicles. The PDR of SIAC improves by approximately 10%–15% compared with that of its close competitor (CMGM). The first reason for this improvement in the PDR of the SIAC is its stability and long connection duration with the LTE eNodeB of the respective cluster. The second reason is the low CH and CM changing rate, which enable SIAC to exchange a large number of packets among CMs.

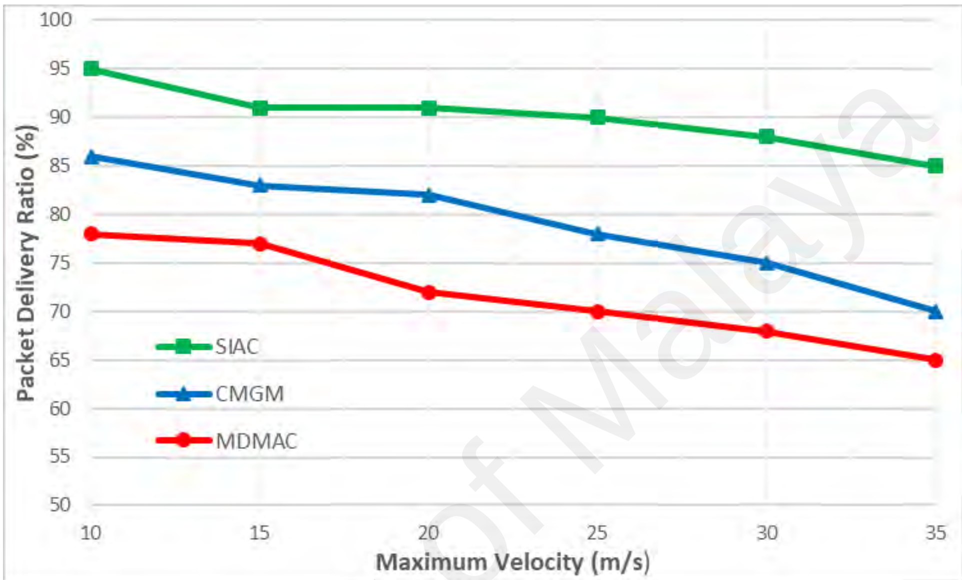

Figure 6.6: PDR of protocols against various velocities of vehicles

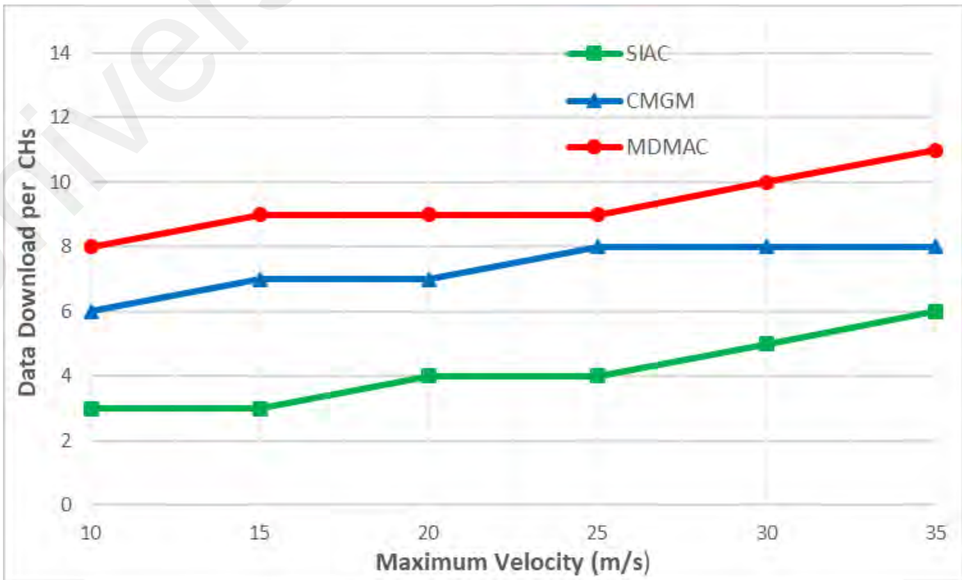

Figure 6.7: Data download against various vehicle velocities

Figure 6.7 shows the data download of networks against various velocities of vehicles. The cost of using LTE infrastructure is measured on the basis of the number of CHs because each CH is connected to the LTE access network to obtain the required information from Internet-based servers. In our case, a large number of CHs indicate large data download and thus high cost. The number of CHs depends on the traffic density and velocities of vehicles. It also depends on the CH changing rate of the different algorithms because high CH changing rate indicates high cost. In our case, if a CH losses connection to the Internet, then it will not work as CH anymore. As a result, the stability of cluster positively affects not only other performance parameters but also the cost of the Internet.

Our simulations show that around 1 MB of data is received by each CH from LTE network, and data download is directly proportional to some receivers (CH) in the network. Thus, a large number of CHs indicate high data download of vehicles. A highly stable cluster indicates a small number of CHs within a given density of vehicles (vehicles per meter of the simulated geographical area). Few times of re-clustering are done, thereby reducing not only network overhead but also cost.

The improvements in CH duration, CM duration, and CH changing rate primarily indicate the improvement in cluster stability. The improvement in parameters such as clustering overhead and PDR indicates overall network performance. The parameter of data download per CH shows the reduction in the data demand of vehicles, the increase in CH duration, and the decrease in CH changing rate. This condition further reduces data download and number of connections.

The cluster size of CMGM is larger (given that CMGM is multi-hop) than that of SIAC (SIAC is a single hop with a transmission range of up to 300 m). As a result, the number of CHs is decreased for CMGM at the point of simulation, but instability breaks large clusters after a few seconds. Ultimately, clustering overhead becomes large. Regarding MDMAC, any vehicle becomes CH regardless whether it has high or low LQ value. Moreover, link breaks very often, thereby resulting in a large number of CHs and low CH duration.

Our proposed SIAC shows better performance in all parameters than CMGM and MDMAC. Therefore, SIAC is a stable clustering protocol for vehicular networks, which is important for improved network performance. A high CH duration indicates stable and long-lasting LTE connection, which is the strength of transferring data to and from Internet-based servers. In our case, only the CH connects to the LTE network because the Internet reduces the data demand of vehicles by reducing the number of connections to the LTE network. A stable CH collects and disseminates data among CMs at the right place and time, which is an essential requirement of the road traffic management application. Small CH fluctuation reduces the usage of LTE spectrum and cost of the use of the Internet.

SIAC increases the life of the cluster, reduces network overhead, and decreases the data demand of vehicles for driving assistance and route planning. Our protocol minimizes the cost and LTE network utilization by reducing the number of connections to LTE. It also provides transmission path stability, which increases the PDR of the network and decreases clustering overhead. Our proposed mechanism SIAC performs better than existing approaches.

6.4 CIAC Results and Discussion

The CIAC protocol is compared with MDMAC, VMaSC, and NCIAC (a version of CIAC with no cooperation) in terms of the performance metrics displayed in Table 6.4. We define these performance metrics primarily to check the utility of Mv and CH in the cluster and vehicle participation in clustering to increase node (vehicle) participation and balance the use of every node within the cluster as CH.

Table 6.4 Performance metrics

Parameter	Definition
Participation rate	It is the percentage of the vehicles participating in the cluster out of total interesting vehicles. More participation means cooperation algorithms performance is good.
Utility	It is the probability of use of vehicle both as CH and Mv against a various number of interesting vehicles after iterating clustering several times.
Percentage of vehicles act as CH	It is the percentage of vehicles out of total interested vehicles that act as CH after various iterations. An increasing number of percentage after each iteration means not only a few vehicles always act as CH every time. The new vehicle is chosen in new iteration shows balance in use of CH and cost-incurring.

6.4.1 Analysis of CIAC Results

The implementation results for CIAC are presented in this section. The output after the simulation is displayed in a graphical form by taking the maximum velocity of vehicles and maximum interested vehicles at different clustering iterations along the X-axis, the percentage of vehicles that act as CH, the utility of vehicles as CH or Mv, and the participation rate of vehicles in clustering on the Y-axis.

Figure 6.8 compares the percentage of vehicles that act as CH against different maximum interested vehicles for NCIAC, CIAC (proposed mechanism labeled in green color in Figures 6.8 to 6.10), MDMAC, and VMaSC. The graph represents the number of vehicles that act as CH out of the total interested vehicles after the first iteration of clustering. When the number of vehicles is small, the participation of vehicles as CH is the same. As the number of vehicles increases, the participation rate decreases. The number of CHs reflects the number of clusters formed out of total vehicles. When 25 vehicles are available, only 8% of them act as CH for VMaSC. This value is the lowest among others. The reason is that VMaSC allows vehicles to connect to CH through intermediate vehicles, thereby increasing cluster size and scale. The performance of

CIAC and non-cooperative version of our CIAC (NCIAC) is the same against various numbers of vehicles.

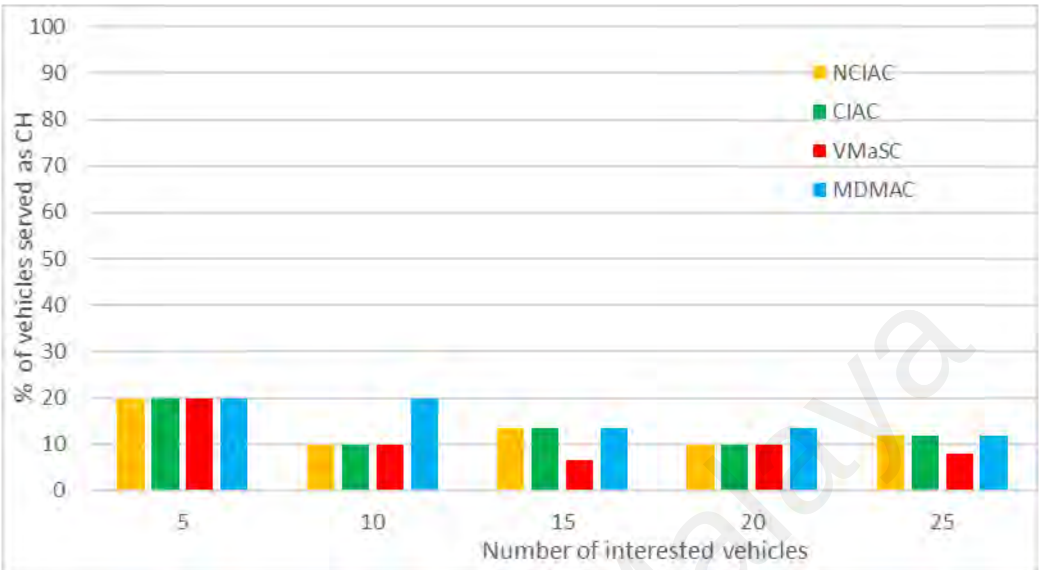

Figure 6.8: CH against different maximum interested vehicles

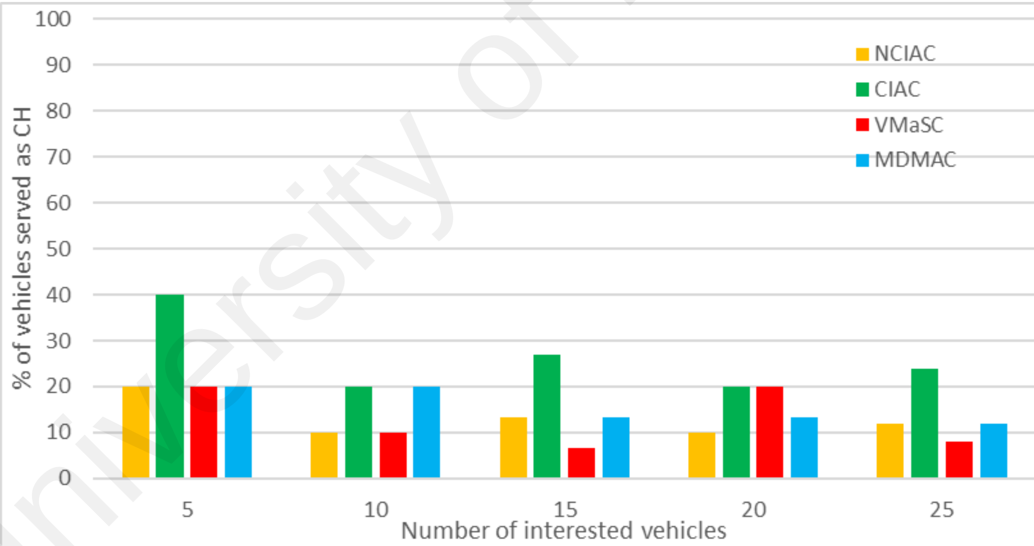

Figure 6.9: Total of CHs versus interested vehicles after second iteration

Figure 6.9 compares the percentage of vehicles that act as CH against different maximum interested vehicles for NCIAC, CIAC, MDMAC, and VMaSC after the second iteration. Figure 6.9 shows that the percentage of vehicles that act as CH in CIAC is more than those in MDMAC, VMaSC, and NCIAC. The percentage for our CIAC also decreases with the increase in the number of vehicles but is still higher than those of other approaches.

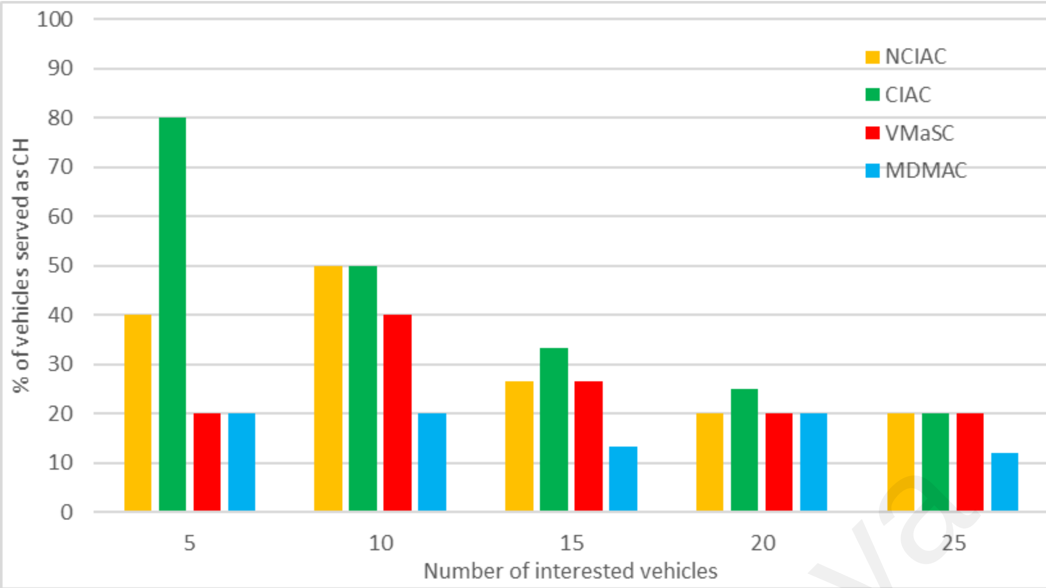

Figure 6.10: Total of CHs versus interested vehicles after the fifth iteration

The values after the fifth iteration as depicted in Figure 6.10 indicate that the value of CIAC is considerably high at 80% when the number of vehicles involved in clustering is small. The value of NCIAC is around 40% under the same condition. The percentage of vehicles that act as CH out of the total number of vehicles decreases with the increase in the number of vehicles. MDMAC has the lowest values among all methods. When 25 vehicles are available, the percentage of the remaining three methods is the same. After multiple repetitions of clustering process for CIAC, nearly every vehicle acts as CH, which shows a balance in use as CH. As a result, the cost of use is balanced for CH who is paying the cost for the access of information from the Internet via LTE. This result shows that a typical road segment with vehicles in proximity will have a fair balance in the cost of use due to the fair-use policy of our protocol incorporated in CIAC.

Figure 6.11 shows the utility of vehicles as CH, Mv, or free rider for CIAC and NCIAC against various numbers of vehicles. With the increase in the number of vehicles, the utility of vehicles as CH increases, whereas the utility of vehicles as Mv decreases. The utility of CIAC is the maximum at a number of vehicles of 5. That of NCIAC is also the maximum when the numbers of vehicles are 10 and 25. The probability that vehicles will remain a free rider is very low when the number of vehicles is small. If the number of vehicles increases, then the utility of vehicles as free rider also increases. The probability of vehicles that can remain as free rider in CIAC is lower than that in NCIAC but is the same when the number of vehicles is large. The reason is that CIAC does not select the same vehicle as CH repeatedly due to the fair-use policy of SGTA. After clustering is repeated 5 times, we check the number of vehicles that serve as CH and remain as free rider.

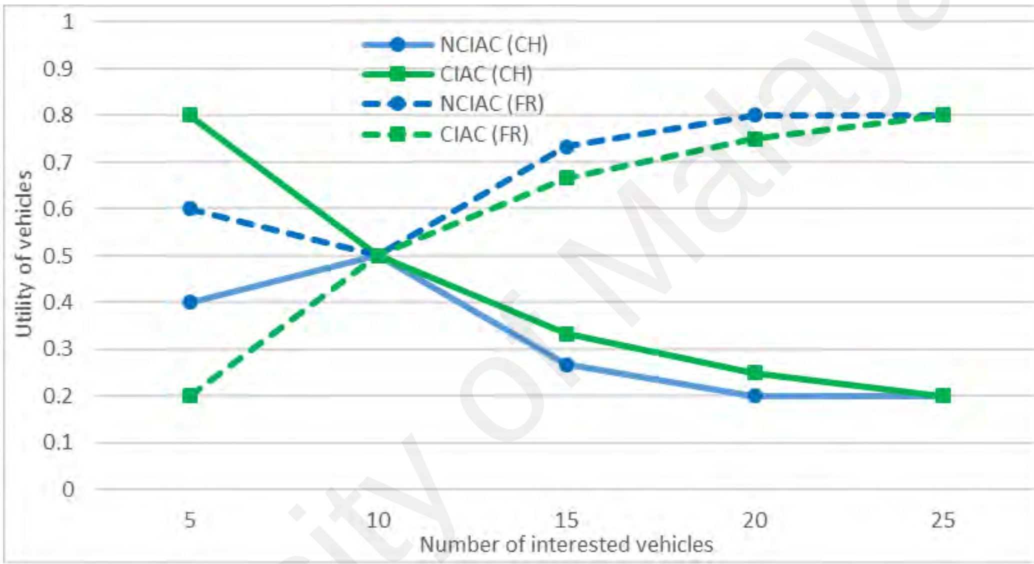

Figure 6.11: Utility of vehicles as CH and free rider against interested vehicles after 5 times of iteration

We check the participation rate of vehicles in the cluster by setting the total number of vehicles in the simulation environment the same but changing the velocities of vehicles.

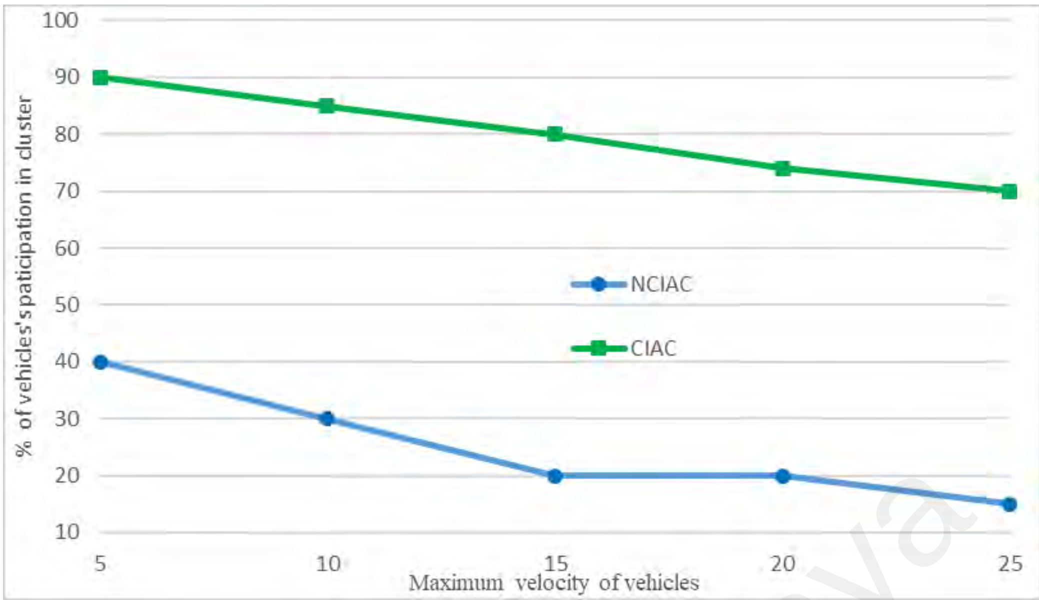

Figure 6.12: Vehicle participation in clustering at various velocities

Figure 6.12 presents the participation rate of vehicles in the cluster for CIAC and NCIAC against various velocities of vehicles. The participation rate of vehicles in CIAC is much higher than that in NCIAC at all maximum velocities of vehicles. Although the rate decreases with the increase in the velocities of vehicles in CIAC, it remains considerably high. The increase in vehicle participation in clustering reduces the direct links to LTE networks, thereby resulting in significant decreases in data download from Internet-based servers and cost.

The incorporation of SGTA in CIAC increases the participation of vehicles in clustering and balances the utility of vehicles as CH out of the participating vehicles. Our proposed mechanism performs better than the other approaches because it not only reduces the cost of use but also shows improved performance for route planning and driving assistance applications.

A solution such as our CIAC is a good choice for clustering among vehicles that are interested in accessing TIS information from remote servers over the Internet. CIAC motivates vehicles to participate in the clustering process and controls the CH selection procedure with balanced use of vehicles as CH to share the accessed information and cost.

6.5 SLCA Results and Discussion

Some obstacles, such as high-rise buildings, are introduced in the simulation. Underpasses with GPS signal interruptions are also simulated. We test by introducing interruption pauses during our simulation deliberately and check the performance of SLCA. The performance of SLCA-based DIAC (DIAC-LA) is compared with simple DIAC, VMaSC, and MGSA in terms of metrics such as CM duration, number of CMs per cluster, CMs that forcefully left per cluster, PDR, and clustering overhead. The comparison results are shown in Figures 6.13–6.17.

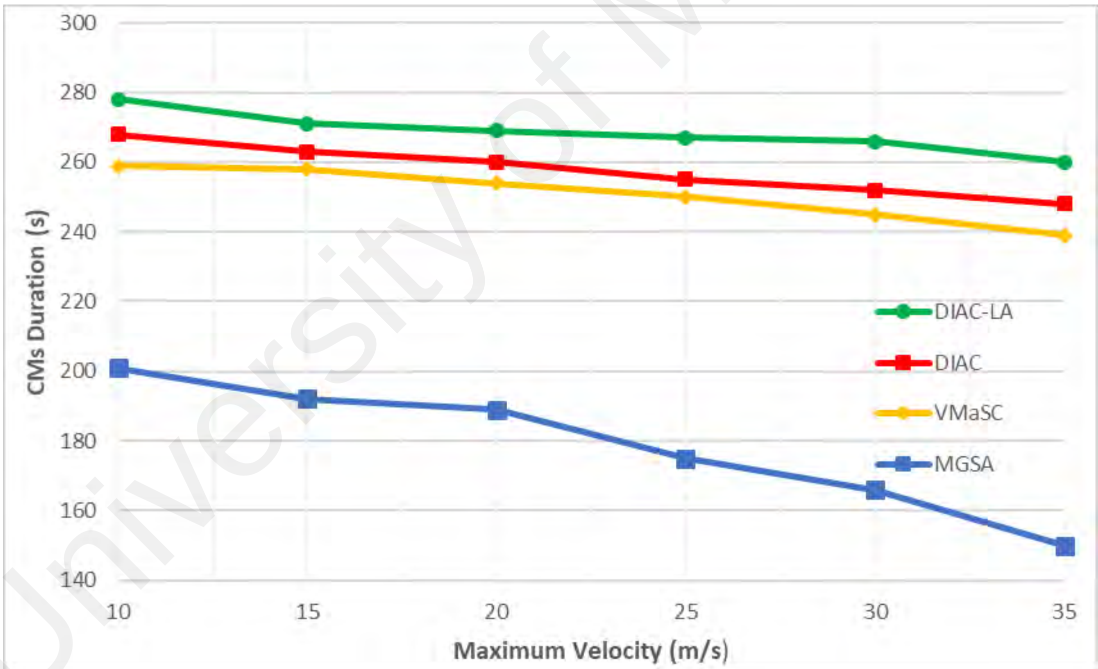

Figure 6.13: Comparison of DIAC with and without SLCA

Figure 6.13 shows that the CM duration of DIAC-LA is greater than those of all other approaches at various velocities of vehicles. The reason is that SLCA running at CM sides increases the synchronization between the CMs and CH, which reduces the chances of CMs leaving from the cluster. The difference between red and green lines in

Figure 6.13 shows the increase in CM duration when SLCA is incorporated within DIAC.

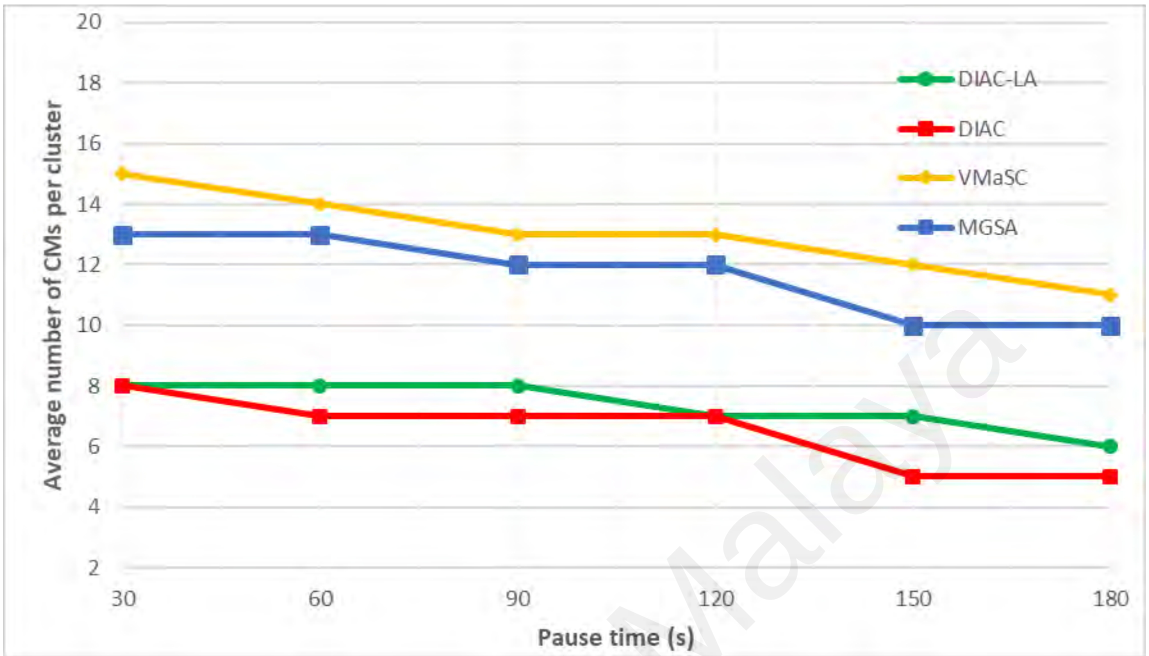

Figure 6.14: Number of CMs per cluster at different pause times of simulation

Figure 6.14 shows the average number of CMs per cluster at various pause times of simulation. The number of CMs per cluster for VMaSC and MGSA are higher than those for DIAC and DIAC-LA. The reason is that VMaSC allows multi-hop clustering and has different clustering criteria. However, the number of CMs per cluster for DIAC-LA is higher than that for simple DIAC, which shows an increase in the number of CMs within the cluster. At various pause times, a large number of CMs remain with CH in DIAC-LA. Therefore, the incorporation of SLCA provides sustainability to CMs within the cluster.

Figure 6.15 shows the percentage of vehicles forced to leave per cluster at various velocities of vehicles. The percentage for DIAC-LA is lower than that for DIAC. The reason is that, when CMs can calculate their locations in the absence of GPS signals, their synchronization with CH increases, and the frequency of CHs applying forced leaving procedure to CMs decreases. When CH is not hearing from a CM for a period, it forcefully removes that CM from the cluster. In our case, SLCA allows CMs to calculate their location and coordinate with CH for a long period even in the absence of GPS signals. The forced leaving increases with the increase in the speed of vehicles. However, DIAC-LA is still more synchronized than DIAC.

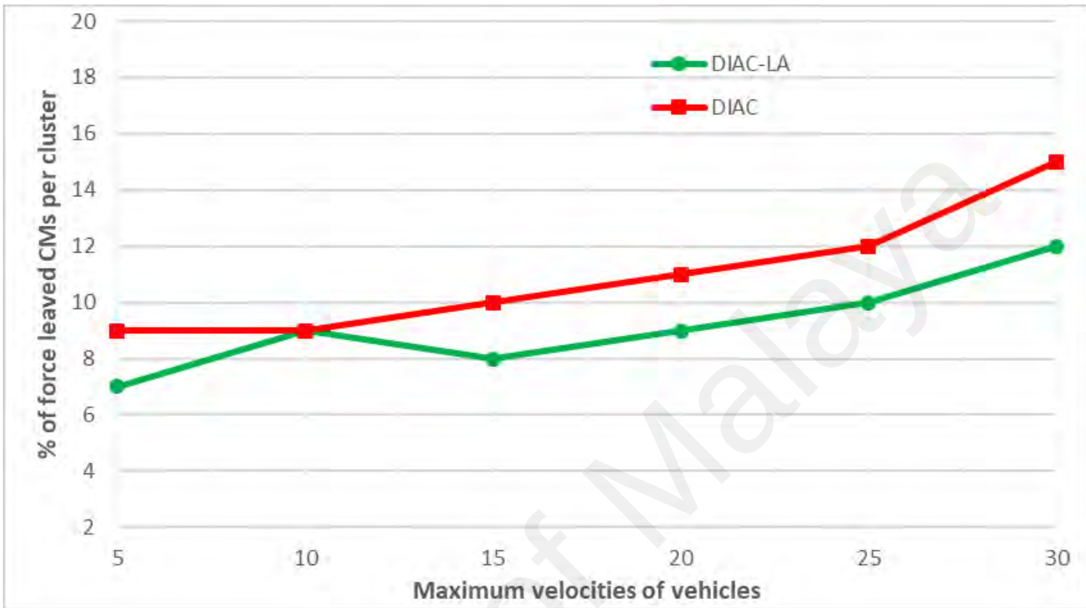

Figure 6.15: Percentage of vehicles that forcefully leave per cluster at various velocities of vehicles

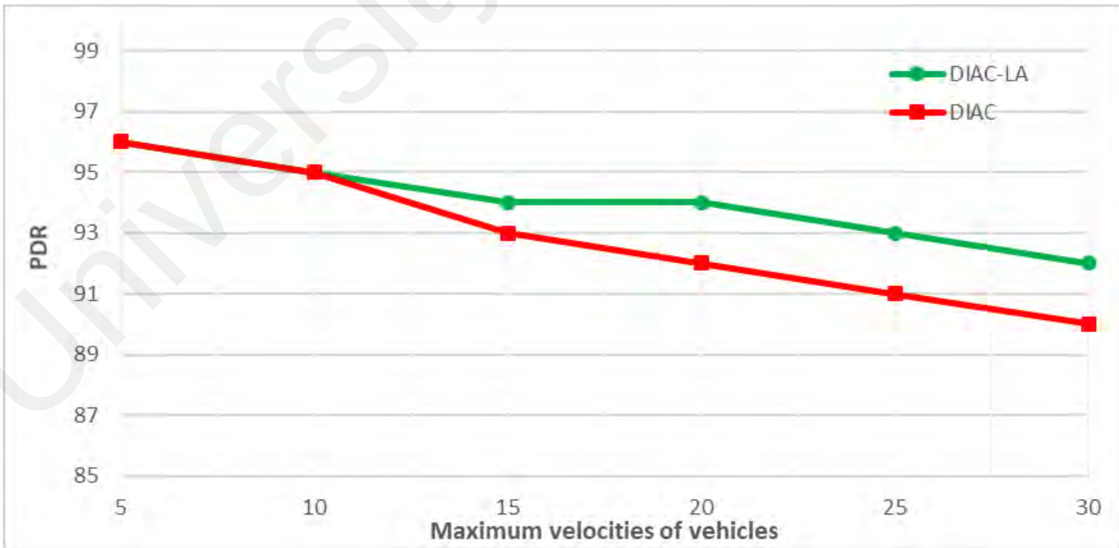

Figure 6.16: Difference in PDR at maximum velocities of vehicles

The PDR of DIAC-LA is greater than that of simple DIAC, and it remains higher at various velocities of vehicles, as shown in Figure 6.16. DIAC-LA has a longer connection with CH than DIAC, which is the reason for higher PDR of the latter than the former. At velocities of vehicles of 5 and 10, PDR remains the same for both mechanisms and is high for DIAC-LA under the rest of the velocities.

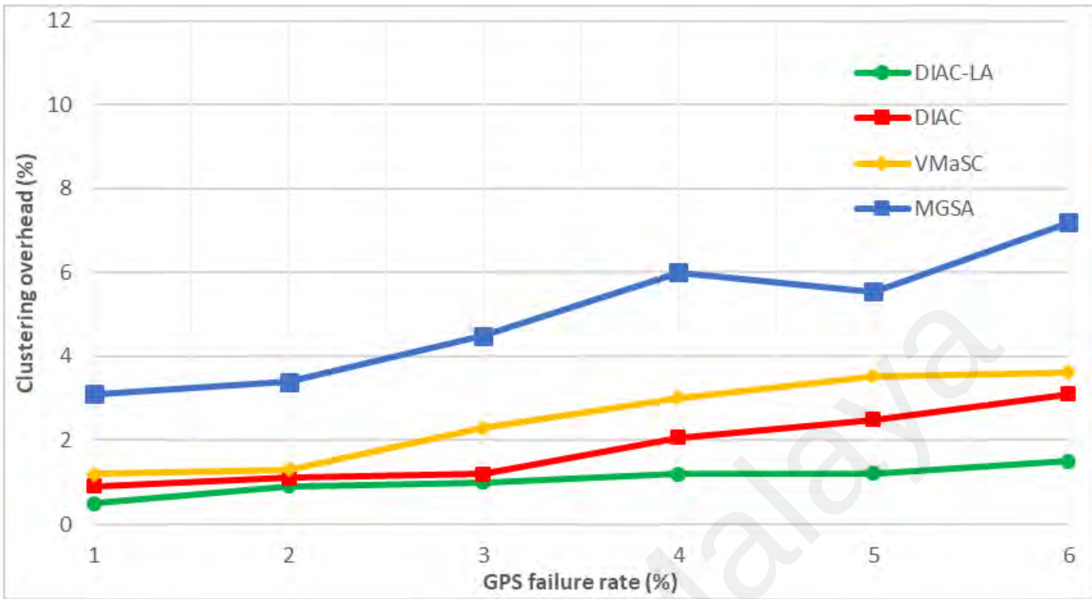

Figure 6.17: Clustering overhead against preset GPS failure rate

Regarding clustering overhead, the DIAC-LA has lower values than other approaches at various velocities of vehicles, as shown in Figure 6.17. This result is due to the small fluctuation of CMs in the cluster, which causes stability and few times of re-clustering.

In all performance comparisons, DIAC-LA shows better results than VMaSC, MGSA, and especially DIAC. These improve results validate the increase in the synchronization of CMs with CH, which increases the overall cluster life.

6.6 Comparison of DIAC with VANET Clustering Algorithms

We compare our simple DIAC clustering algorithm with existing VANET-based clustering algorithms but not with heterogeneous VANET–LTE-based network in terms of performance metrics such as CH duration, CM duration, CH changing rate, and PDR. The VANET-level comparison is made to further increase the performance of the proposed solution at various levels of network infrastructure. Our simple DIAC is compared with VANET version of approaches, namely, MGSA, MDMAC, CMGM, and VMaSC, to check the performance at VANET level.

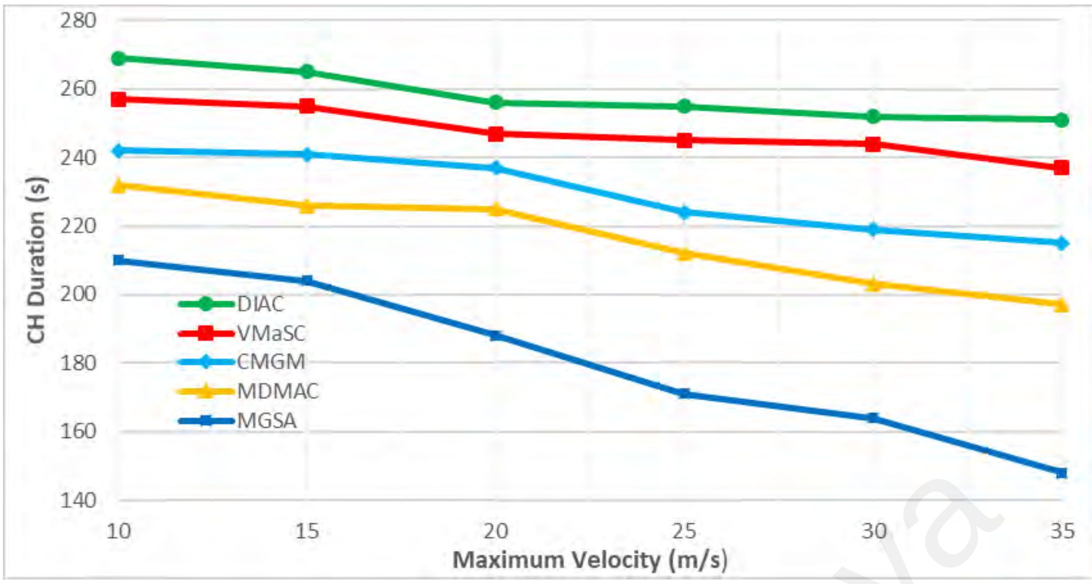

Figure 6.18: CH duration against various velocities of vehicles

At VANET level, DIAC has large CH duration at various velocities of vehicles, as shown in Figure 6.18, which is even better than those of the most recently proposed VMaSC. This result shows the stability of DIAC due to its criteria of same destination and common interests.

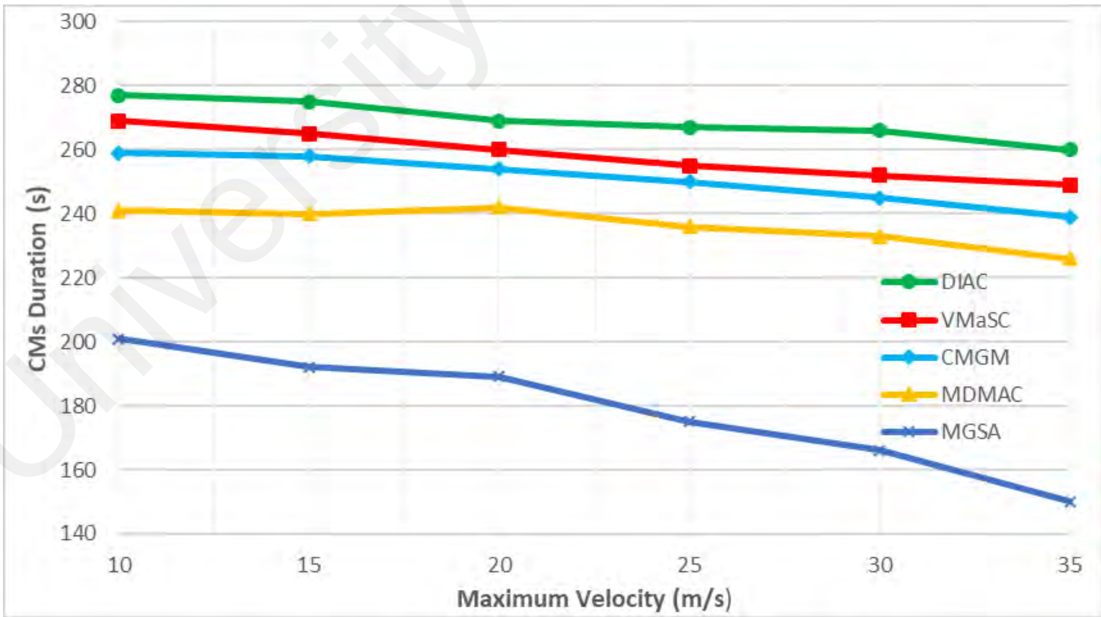

Figure 6.19: CM duration against various velocities of vehicles

CM duration within the cluster of DIAC is also greater than those of other approaches at various velocities of vehicles, as shown in Figure 6.19. The CH changing rate of DIAC is lowest among those of all other approaches, as shown in Figure 6.20.

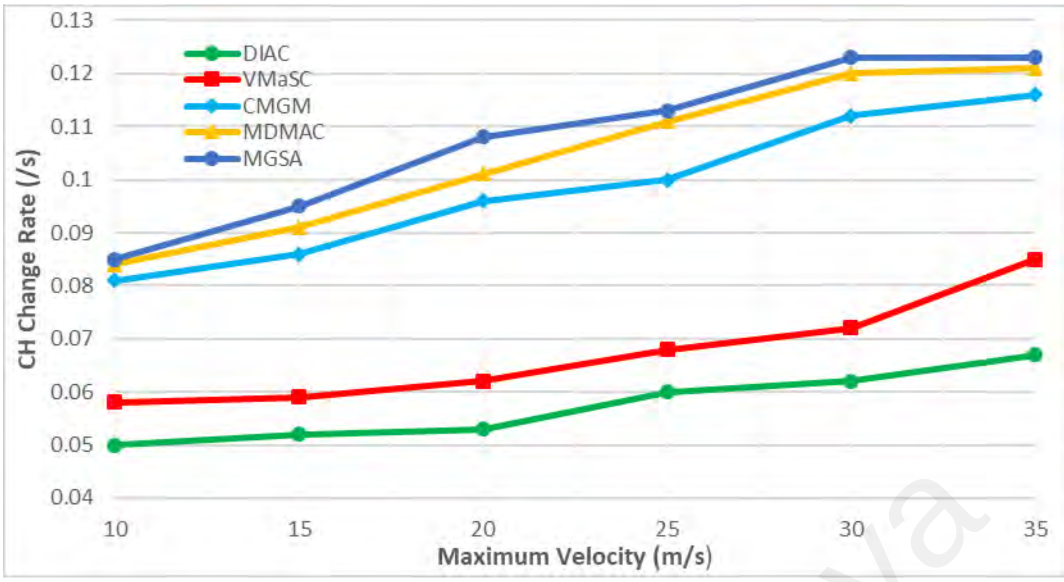

Figure 6.20: CH changing rate against various velocities of vehicles

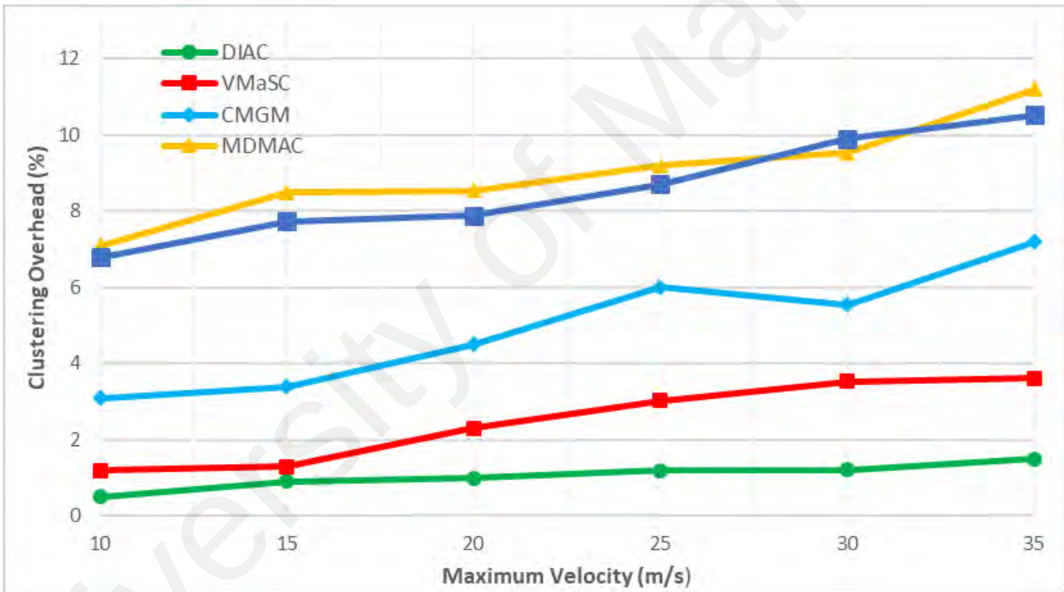

Figure 6.21: Clustering overhead against various velocities

The cluster breakup in DIAC is less because it considers the strongest connection to LTE while selecting CH. Thus, the clustering overhead of DIAC is lower than those of others, as shown in Figure 6.21.

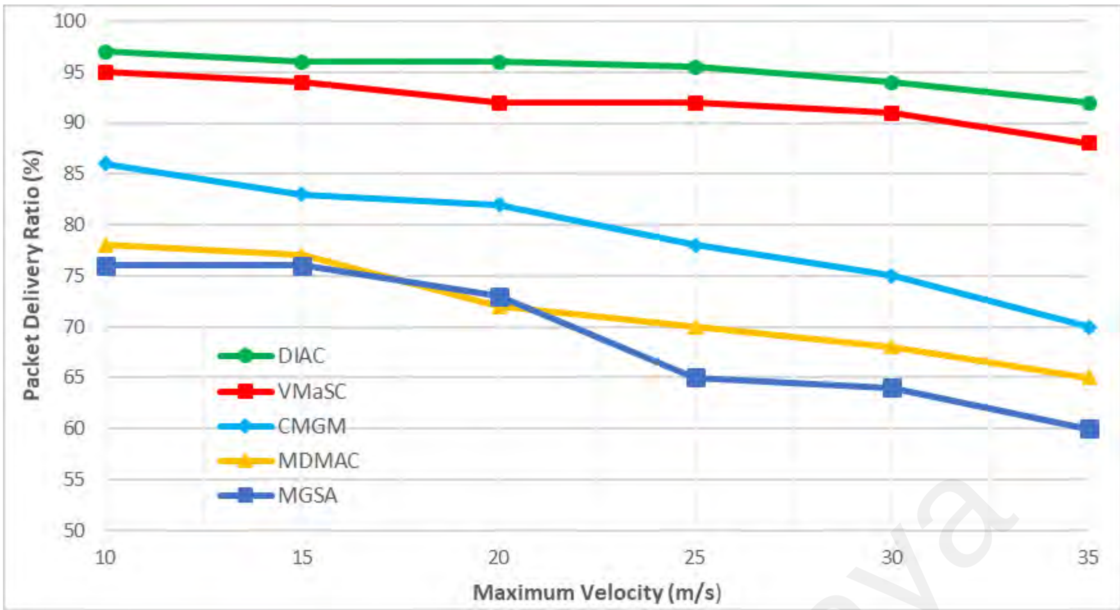

Figure 6.22: PDR versus various velocities of vehicles

The percentage of PDR of DIAC is greater than those of others when compared at different speeds of vehicles, as depicted in Figure 6.22. In all metrics, DIAC shows better performance than other existing popular approaches. Therefore, DIAC is good at VANET level clustering as well.

6.7 Results and Discussion of Integrated DIAC Framework

We integrate all our algorithms, namely, DIAC, SGTA, and SLCA, for heterogeneous VANET–LTE architecture to form the integrated DIAC framework for inclusive results and compare it with similar existing approaches.

The integrated DIAC framework is compared with the VANET–LTE-based heterogeneous architectures of MDMAC, CMGM, and VMaSC in terms of the performance metrics displayed in Table 6.5. We define these performance metrics primarily to check cluster and CH stability because the duration of the cluster, the CH, and the CMs reflect the stability of a cluster. To analyze the overall performance, we define such parameters as clustering overhead, PDR, and average delay. Moreover, we define data download to measure the LTE data download of each protocol and assess the cost of LTE network usage.

Table 6.5 Performance metrics

Parameter	Definition
CH Duration	The time duration of CH for each cluster of vehicles
CM Duration	The time that a vehicle remains a member of a particular cluster Time from joining a cluster to leaving it
CH Changing Rate	Number of status changes by vehicles from CH to CM
Clustering Overhead	The ratio of the total control packets for clustering to the number of packets generated in the network
Packet Delivery Ratio	The ratio of the total number of the data packets generated by the vehicles and the total number of packets received by the vehicles successfully
Average Delay	The average latency of the data packets traveling from source to destination
LTE Cost	The number of connections to the LTE network; that is, the number of CHs selected by the protocol in a given time and area of simulation

6.7.1 Analysis of Results

The implementation results for integrated DIAC framework are presented in this section. The output after the simulation is displayed in a graphical form by obtaining the maximum velocity of the vehicles along the X-axis. CH and CM duration, CH changing rate, clustering overhead, PDR, average delay, and data download are plotted on the Y-axis.

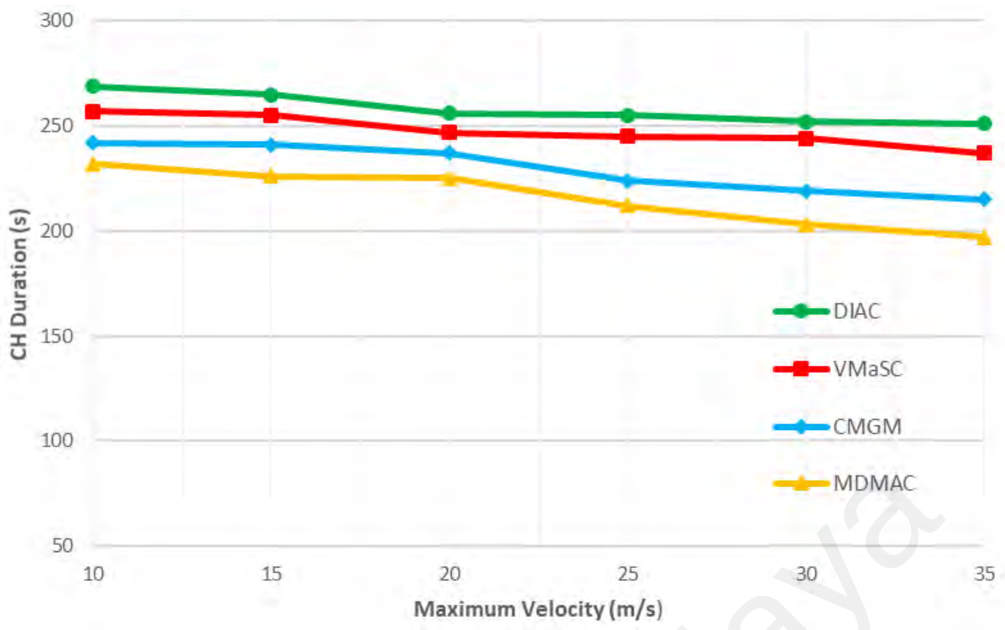

Figure 6.23: CH duration comparison of DIAC with VMaSC, CMGM, and MDMAC

The CH durations of DIAC, MDMAC, CMGM, and VMaSC are calculated and represented in a graphical form, as illustrated in Figure 6.23. CH duration is measured against the various maximum velocities of vehicles ranging from 10 m/s to 35 m/s.

The average CH duration of DIAC is higher than those of the three existing approaches due to the efficient cluster formation and maintenance mechanism of DIAC. In general, CH duration decreases as the velocity of vehicles increases because high velocity rapidly changes topology. Such change may result in link breakage and need for re-clustering.

Another reason is that DIAC always opts for a strong LTE LQ, which also increases the CH duration because re-clustering is required to select a new CH whenever a CH loses Internet connection. MDMAC ignores LTE link stability, and CMGM has poor performance in this sense. VMaSC displays good results, which are not better than those of DIAC.

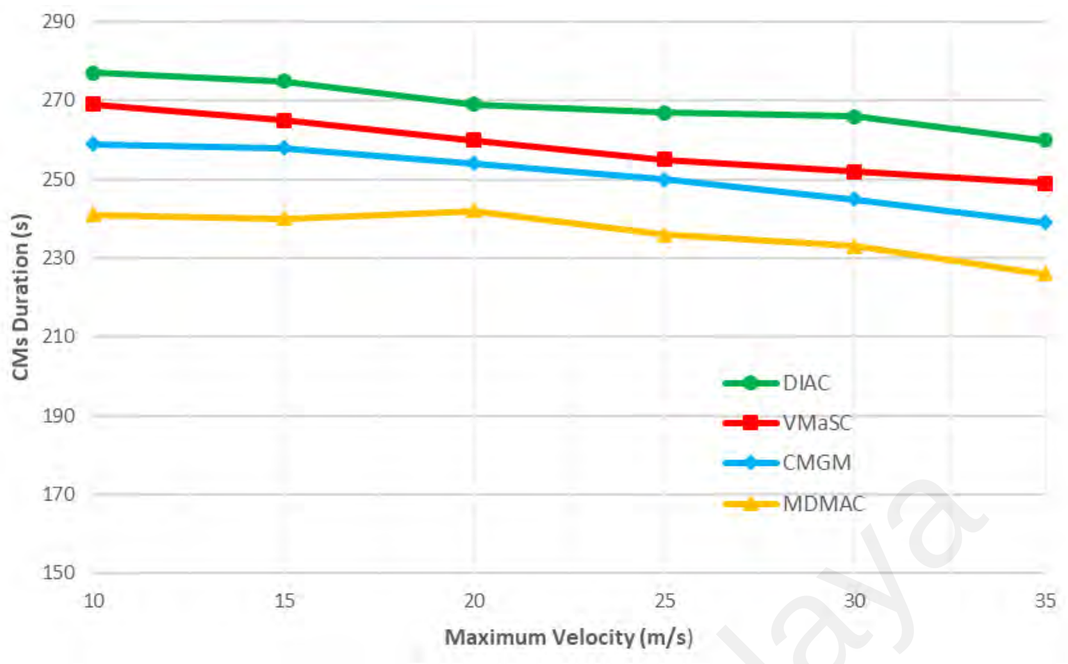

Figure 6.24: CM duration against multiple velocities

We calculate CM duration as the time between joining and leaving a cluster, as shown in Figure 6.24. The CM duration of DIAC is higher than that of existing algorithms under a single-hop broadcast condition because of the small delay in joining a cluster. Overall, CM duration decreases as the velocity of vehicles increases. Regarding our proposed mechanism, no fluctuation is found in CM duration for velocities ranging from 10 m/s to 20 m/s. The variation in durations for CH and CM is nearly similar.

The third factor is the CH change rate, which is also crucial for the measurement of cluster stability. CH change rate is also measured against different maximum velocities of vehicles, as presented in Figure 6.25. The CH change rate of DIAC is lower than those of CMGM, MDMAC, and VMaSC. This result indicates the stability of our proposed protocol. The reason is that CMGM and MDMAC use periodic clustering and unnecessarily change CH in the network. This situation does not happen in DIAC. VMaSC is unsuitable for single-hop clustering because its true essence lies in multi-hopping and joining of CMs indirectly to the CH. This condition does not happen in our work. Few times of re-clustering result in decreased cluster overhead. In general, the CH change rates of all protocols increase as the velocity of vehicles increases.

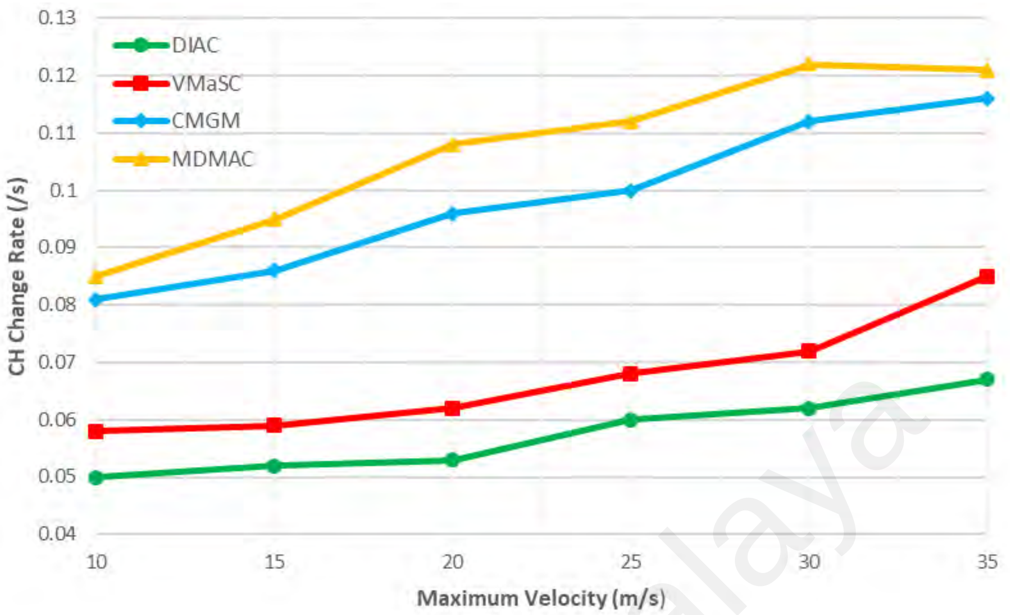

Figure 6.25: CH change rate per second against various velocities of vehicles

Clustering overhead is directly related to the stability and overall performance of the network. A large number of disconnections in the network indicate that a large number of control packets must be transmitted again to re-cluster. The clustering overhead of DIAC is smaller than those of other protocols because it involves only vehicles that are interested and traveling toward the same destination. The important difference between our protocol and existing ones is that it increases network life by providing link stability.

Figure 6.26 displays the clustering overhead of the related protocols as a function of maximum vehicle velocities. The performance of VMaSC is close to that of DIAC because VMaSC eliminates periodic updates and replaces them with timer-based cluster maintenance. Overall, the clustering overhead of all protocols increases as vehicle velocities increase, but DIAC shows a smaller increase than the others, which indicates stability.

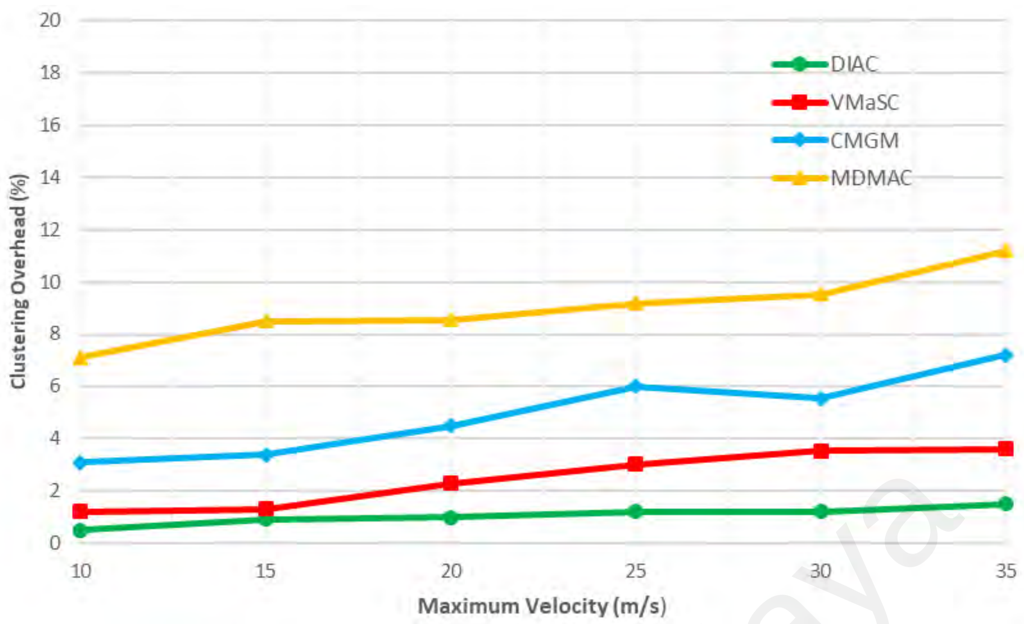

Figure 6.26: Clustering overhead at various velocities

Figure 6.27 shows the PDRs of different algorithms at different maximum velocities of vehicles. The PDR of DIAC is higher than those of the other algorithms at all maximum vehicle velocities. The reason for the improved PDR is good stability, reduced overhead, and strong LQ with LTE and among vehicles. DIAC opts for vehicles with strong LQ to the LTE network for access to information from Internet-based servers. Other important reasons are the cooperative nature of clustering and smooth periodic updates regarding vehicle locations, which decrease the number of forced leaving from the cluster. Moreover, reduced clustering overhead decreases medium access contention, thereby increasing the chances of successful transmissions.

The PDR of DIAC does not change rapidly and is smooth because no considerable change occurs in a curve with the change in the maximum velocities of vehicles, which shows the stability of DIAC under the dynamicity of the network.

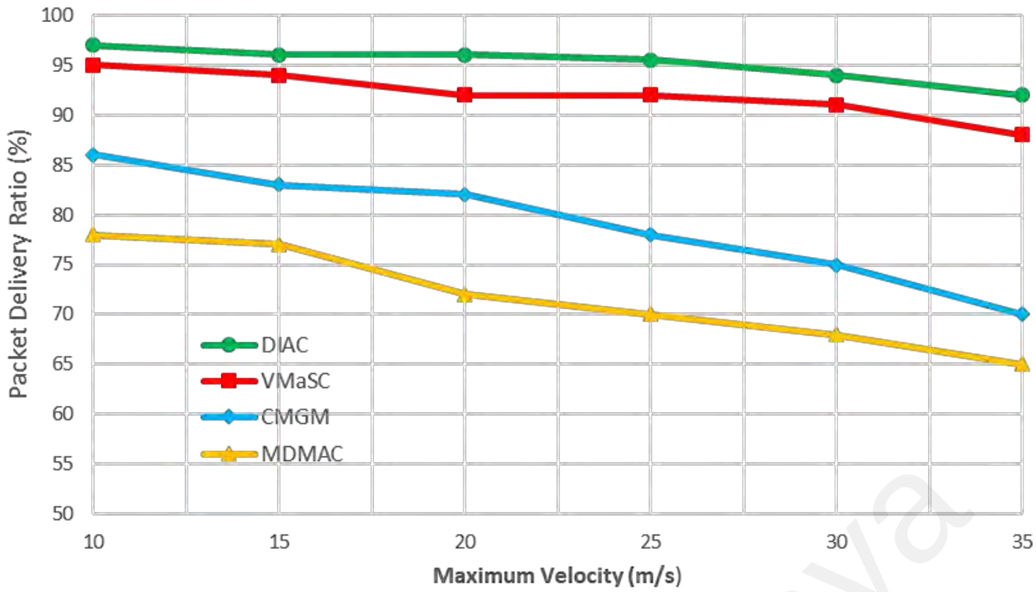

Figure 6.27: PDR against various vehicle velocities

Figure 6.28 shows the average delays of the different algorithms at varying maximum velocities of vehicles. The performance of DIAC is good because it is more stable than the other protocols. The average delay of VMaSC is close to that of DIAC at velocities of 15 and 20 m/s.

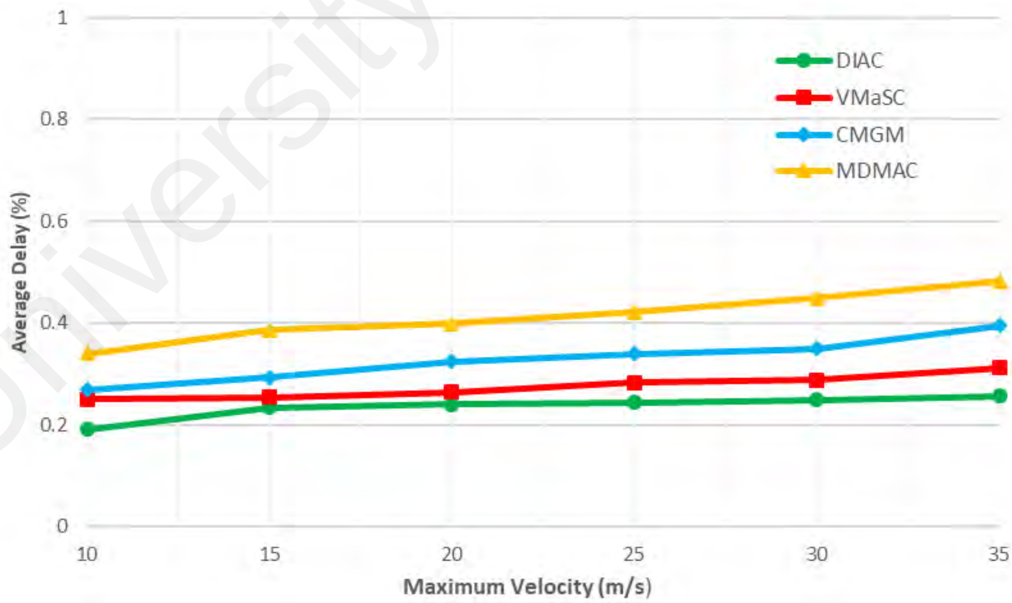

Figure 6.28: Average delays of algorithms at various velocities

The delay of the flooding algorithm is usually less than that of the others, but the clustering algorithm shows a small delay and a high PDR.

Figure 6.29 shows the data download of networks against various velocities of vehicles. The cost of using the LTE infrastructure is measured given the number of CHs because each CH is connected to the LTE access network to obtain the required information from Internet-based servers.

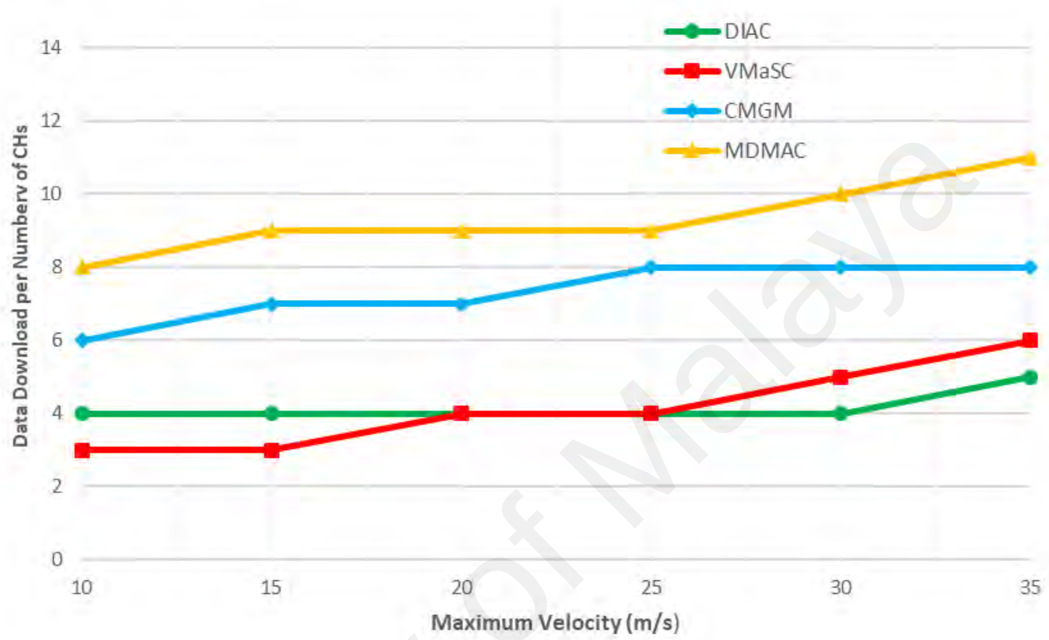

Figure 6.29: Data download of each CH

In our case, a large number of CHs indicate high data download and additional cost. The number of CHs depends on the traffic density and velocities of vehicles. It also depends on the CH changing rate of the different algorithms because a high CH changing rate implies added cost. In this work, if a CH loses Internet connection, then it cannot work as a CH anymore.

According to our simulations, approximately 1 MB of data is received by each CH from the LTE network, and data download is directly proportional to certain receivers (CH) in the network. Thus, a large number of CHs indicate a larger amount of data than normal are downloaded by vehicles. Highly stable cluster implies a small number of CHs within a given vehicle density (vehicles per meter of the simulated geographical area). Few times of re-clustering are performed, thereby reducing network overhead and cost. With a small number of CHs and low data download at vehicle velocities ranging from 10 m/s to 15 m/s and from 20 m/s to 25 m/s, VMaSC and DIAC have the same number of CHs. However, at velocities of 30 and 35 m/s, DIAC has only a few CHs. Overall, DIAC performs better than the other algorithms.

According to extensive simulations performed in OMNeT++ by integrating SUMO, Veins, and Sumlte and by using the OpenStreetMap of Kuala Lumpur, Malaysia, our proposed DIAC protocol shows superior performance over previously proposed architectures and alternative clustering-based protocols, such as MDMAC. The PDR of the simple clustering algorithms is poor at high velocities due to disconnected networks and broadcast storm. VANET–LTE-based VMaSC architecture eliminates broadcast storm by elevating periodic updates but still does not perform well at high vehicle velocities. The decrease in the number of CMs reduces PDR by up to 100% because of the decrease in contention delay and overhead within IEEE 802.11p-based networks. DIAC performs well under a heterogeneous network environment, and this performance can be further improved by reducing the number of CMs and creating additional CHs but at the cost of further LTE utilization under application scenarios, such as road traffic flow control (driving assistance and route planning applications). In all performance parameters, DIAC shows better performance than the existing CMGM and MDMAC and the recently introduced VMaSC.

6.8 Conclusion

The integrated DIAC framework reduces the frequency of link failures not only among vehicles but also between vehicles and the 3G/LTE network. It also considers vehicle mobility and LTE LQ. DIAC exploits common interests among vehicles in the cluster formation phase, thereby improving cluster network life. SGTA enforces and enables vehicles to participate and cooperate in cluster formation and CH selection. SGTA also implements a fair-use policy among the CMs by preventing the repeated election of the same vehicle as CH under a road traffic scenario. SLCA allows CMs to work and calculate their location coordinates in the absence of GPS under an urban topography, where various high-rise buildings may interfere with GPS signals.

Three proposed mechanisms and integrated DIAC framework are simulated and compared with related state-of-the-art protocols to investigate their performance. The results show that our protocol performs better in all performance metrics than the other algorithms. Therefore, DIAC is a suitable protocol for heterogeneous (VANET–LTE) network-based road traffic management applications, especially for driving assistance and route planning applications. DIAC is also a good addition to ITSs that enable good road traffic management.

CHAPTER 7: VALIDATION

7.1 Introduction

This chapter reports the evaluation of the proposed integrated DIAC framework at the macro level. The definitions, schemas, system modeling, and model checking techniques are also discussed. This chapter is divided into five sections. Section 7.2 presents the macro-level evaluation and describes the formal evaluation process, formal specification and definitions, and schemas for the development of mathematical modeling of the proposed system (framework). Section 7.3 presents a formal model of the system at two levels (accept/reject). Section 7.4 presents a model checking technique and proof of the formal verification of the system by mapping the desired properties of the system via CLTs. Section 7.5 concludes the discussion in this chapter.

7.2 Macro-Level Evaluation

A system analysis technique is required to check and increase the reliability of the system analysis with mathematical proofs. One important technique is formal verification in which a mathematical model of a given system is developed to formally verify that the model meets the specified properties of intended behavior. Formal methods enable verifying the system properties and provide a conceptual understanding of the system or protocols (Qadir & Hasan, 2015).

Formal evaluation is completed in two steps:

1. Model specification is written using Z specification.
2. Formal verification is carried out using a model checker.

Our formal evaluation has three purposes:

1) To represent clarity through high-level abstraction of the proposed framework DIAC
2) To capture the system states that involve vehicle connectivity and participation of the distributed vehicular communications
3) Performance evaluation of the model using system performance metrics
   - Formation success
   - CH selection success
   - Accept/Reject control

7.2.1 Formal Evaluation Process

Formal verification verifies that a system design has the intended functionality. Formal verification uses static analysis without any stimulus to prove design functionality. Formal methods are applied in different areas of computer science, such as software engineering, information security, databases, and computer networks (Qadir & Hasan, 2015). Formal verification consists of formal methods (a mathematical method) with two important parts: one is formal model, and the other is formal analysis. A formal model has a well-defined syntax and clear mathematical semantics. Formal analysis has three types: deductive methods, model checking, and abstract and symbolic execution.

In our work, we perform system analysis through model checking (Clarke et al., 1986), and such a model system is called a transformational system. This kind of modeling consists of pre and post conditions and specification language such as “Z.” Model checking is the application of formal methods in which a set of assertions for system design is created against a set of conditions that must happen or not happen. A model is designed with a defined set of states of the system, and changes in these states are triggered by binary logic (true or false basis) (Baier & Katoen, 2008). The workflow of the formal evaluation process of our system is presented in Figure 7.1.

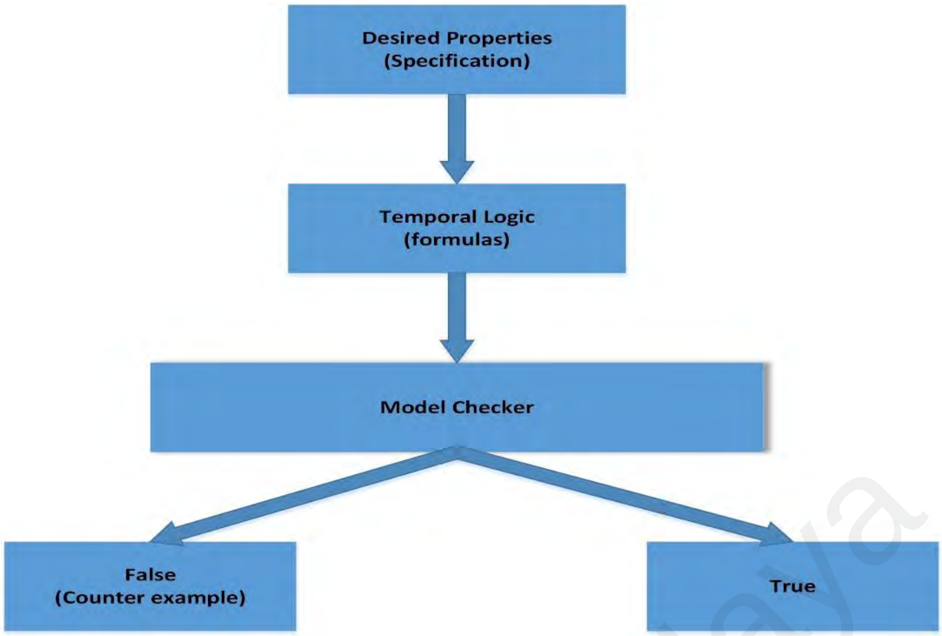

Figure 7.1: Work flow of the formal evaluation process

7.2.2 Formal Specification of System

Z language consists of Z notations based on set theory and mathematical logic. Mathematical logic is a first-order predicate calculus and makes a language when integrated with set theory. The beauty of the Z is how mathematics can be constructed. Mathematical objects and their properties are incorporated in schemas with a pattern of declaration and constraints. The schema describes the state of the system and the change in states. Z notations are also used to describe system properties and logical reasoning related to refinement.

7.2.3 Definitions and Schemas of DIAC

First, we define terminologies of our system and develop different schemas. DIAC is the name of the schema, and the schema signatures within the first part of container are Vi: ℙ VEHICLE, CVsit: VEHICLE ⇸ SPEED. The second part contains the schema predicates. The schema predicates are always true and refer only to elements in the signature of the schema. The Z notations and symbols used in definitions and schemas are presented in Table 7.1.

Table 7.1 Symbols and notations

Symbol	Definition	Symbol	Definition
$\mathbb{P}$	Subset	$\rightarrow\!\!\!\!\!+$	Partial function
$\subseteq$	Is a subset or equal to	$\in$	Element belongs to set
$\emptyset$	Empty set	Δ	Change in value
$\wedge$	AND	$\vee$	OR
$'$	Prime	$\forall$	For all
$\bullet$	Predicate whose value is true	A?	Input to an operation
$\cup$	Union	$\neg$a	Negation of predicate 'a'
$\rightarrow$	Total function		

Our first schema called DIAC is the state space schema that shows the contents in its signature, and its predicates are defined as follows.

DIAC

Vi: $\mathbb{P}$ VEHICLE
CVsit : VEHICLE ⇸ SPEED
CVxit : VEHICLE ⇸ X
CVyit : VEHICLE ⇸ Y
CVDxit : VEHICLE ⇸ Dx
CVDyit : VEHICLE ⇸ Dy
CVDir : VEHICLE ⇸ DIRECTION
CLUSTER : $\mathbb{P}$ VEHICLE
LQ : VEHICLE ⇸ LINK QUALITY

(*CLUSTER j* ⊆ $\mathbb{P}$*VEHICLE*) &
(*CLUSTER F* = { *Vi* | *Vi* ∈ *V* & *CVDirit* (*Vi*) = *F* & *d* (*Vi*, *CLUSTER j*) ≤ 300 }to &
(*CVDxit* (*Vi*) = *CVDyit*(*CLUSTER j*))
(*CLUSTER B* = { *Vi* | *Vi* ∈ *V* & *CVDirit* (*Vi*) = *B* & *d* (*Vi*, *CLUSTER j*) ≤ 300 } &
(*CVDxit* (*Vi*) = *CVDyit*(*CLUSTER j*))

The second schema called *DIAC initialization* presents an initial form of signature, and predicates are defined as follows.

DIAC Initialization

Δ*DIAC*

CLUSTER j = ∅
CLUSTER F = ∅
CLUSTER B = ∅
CLUSTER G = ∅

Our third schema called *SERAC* is related to the control procedure within SGT and changes in R, A, and C flags.

SERAC

Δ *DIAC*

∀ *Vj* (∈ *Vc*(*Vj*) > 5 ∧ *Offer* = *Reject* ∧
r' = *r*+ 1 ∧ *c'* = *c* – 1)
∨(*C* (∈ *Vc*(*Vj*) ≤ 5 ∧ *Offer* = *Accept*
a' = *a*+ 1 ∧ *c'* = *c* + 1)

The fourth schema called *selection-of-clusterhead* shows the selection of CH.

Selection-of -clusterhead

Δ *DIAC*

∀ *CLUSTER j* ∈*CLUSTER* •
Ch j = { *V* | *Vj* ∈ *CLUSTER j* & *offer* = *Accept*
LQ (*Vj*) = *Max* (∀ *LQj* ∈ *LQ* | *Vj* ∈ *CLUSTER j*)} ∧ *c'* = *c* + 2

The fifth schema called *add-vehicle-to-cluster* represents change within DIAC and input to DIAC. Predicates represent the main clustering criteria.

Add-Vehicle-to-Cluster

Δ *DIAC*
Vj? : *V*

CLUSTERj' = *CLUSTERj* ∪ *Vj*
∀*CLUSTER j* ∈ *CLUSTER*•
(*d* (*Vj*, *CLUSTERj*) ≤ 300 &
(*Direction* (*Vj*) = *Direction* (*CLUSTERj*)) &
(*Dx* (*Vj*) = *Dx* (*CLUSTERj*) &

After defining the schemas using Z notations, the formal model of the system is developed and described in detail in Section 7.3.

7.3 Formal Modeling of the System

A system model of our solution is developed, and its verification and analysis are done through model checking. First, we develop an abstract-level model (0 levels) of the proposed solution. Second, we expand it to a one-level model and present additional details in the form of properties and states.

7.3.1 Abstract Model of Proposed Solution

Our system has five defined states as presented in Figure 7.2. Before booting, the state of the system has the properties of not started, not selected, and no error. After booting, the system gets into a new state with properties of started, not selected, and no error. After the system is started, a hello message is broadcasted with information regarding the average speed of the vehicle, direction, location, and destination coordinates.

In another state of the system, it has the properties of started, CH is selected, and no error. At this stage, if the CH loses LTE connection, then the system is triggered into a state in which it has properties of started, selected, and with an error. The system waits for a certain time before gets into a state with properties of started, CH is not selected, and with an error. At this stage, if the LTE connection is established again within the specified time, then the system returns to the state in which it has properties of started, selected, and no error. Otherwise, the system returns to the state in which it has properties of started, not selected, and no error.

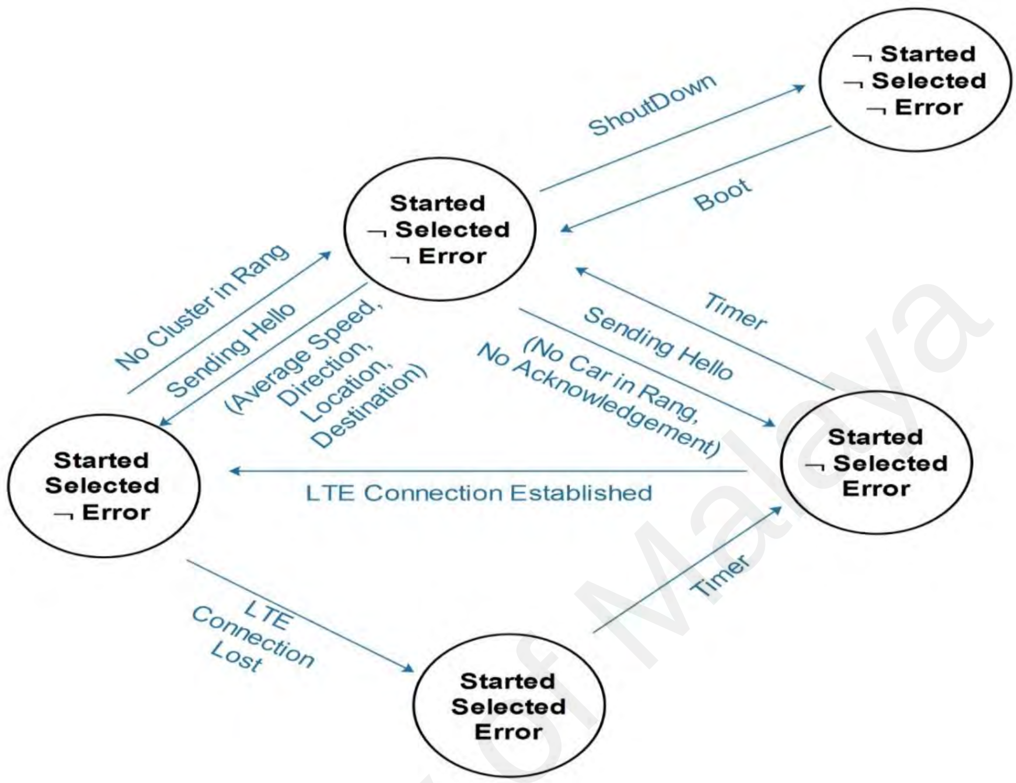

Figure 7.2: Abstract model (system)

After sending a hello message again, if no car is in range or no ACK is received within the specified time, then the system is triggered into the state with properties of started, not selected, and with an error. Under the most desired state in which the system has properties of started, selected, and no error, if communication with all CMs is lost, then the system returns to the initial stage in which it has properties of started, not selected, and no error for re-clustering. From this stage, the system can be shut down to the very initial stage.

7.3.2 Expanded Model

Our expanded model consists of six different states with two properties, namely, ACK and wait, as presented in Figure 7.3. The first state is a very initial state in which all defined properties of the system hold negative. After booting, the system is started, but the remaining properties such as selected, error, ACK, and wait do not hold.

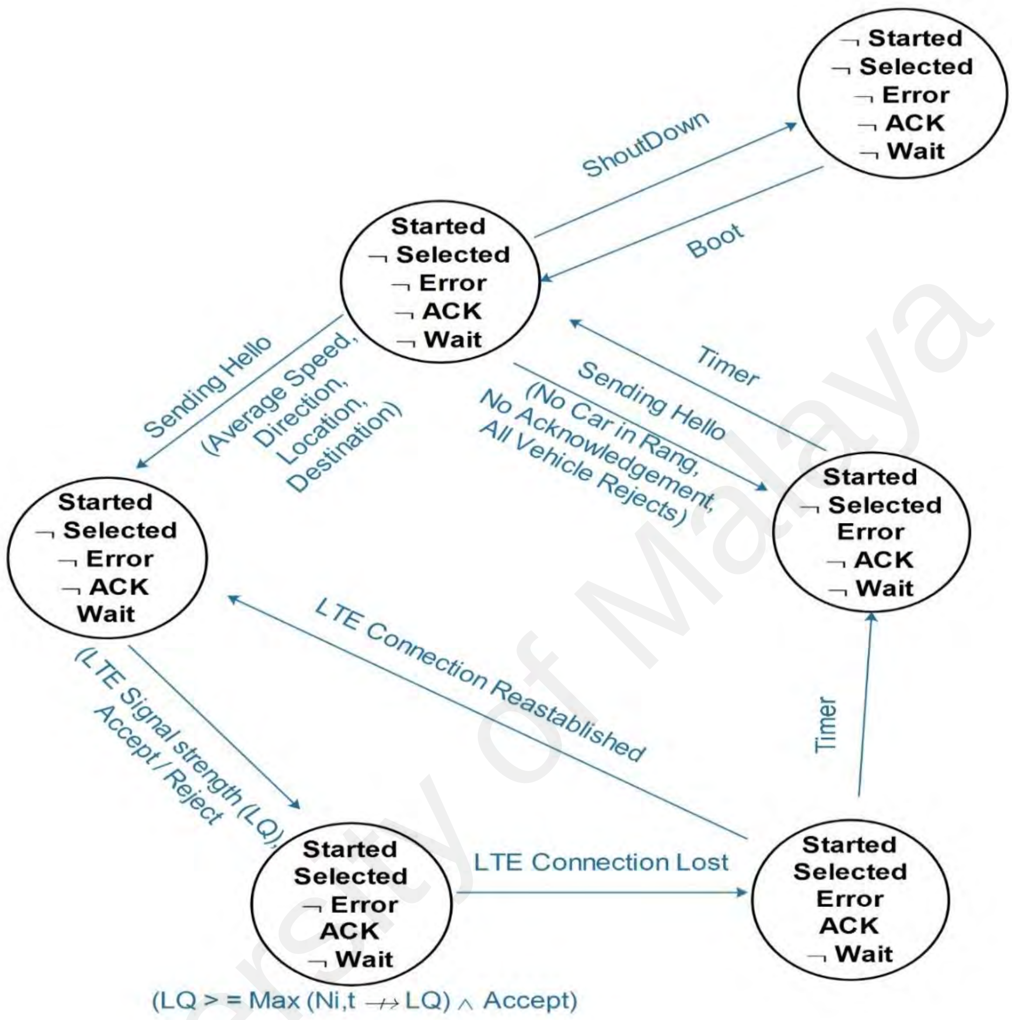

Figure 7.3: Expanded system model

When the system is started, it sends a hello message and waits for the response. If the system receives ACKs, then it finds a vehicle with maximum LQ value and selects that vehicle as CH. In this state, only properties of error and wait hold. If connection is lost in this state, then the system gets into a state in which all properties hold except wait.

At this stage, the system can get to two states. If the connection to LTE is re-established, then the system gets to a state in which only properties of started and wait hold; if the connection to LTE is not reestablished within the specified time, then the system is started and has an error. From here, the system returns to a state in which only the property of started holds. The system will again send a hello message. If no vehicle is in the range, no ACK, or all vehicle reject the offer to be selected as CH, then the system gets into a state in which properties of started and error hold, and the rest is false.

7.3.3 Accept/Reject Decision Model

We present an accept/reject decision model that is incorporated into a system model, as shown in Figure 7.4. Accept decision model consists of five states, and each state reflects the status of our flag variables within the SGT. These flags control the default behavior of game theory, which motivates vehicles to accept the offer of being selected as CH. The first state represents R, A, and C initial statuses; if the value of C is greater than 5, then the decision system gets into a state in which the property of accept does not hold, and statuses of C and R change.

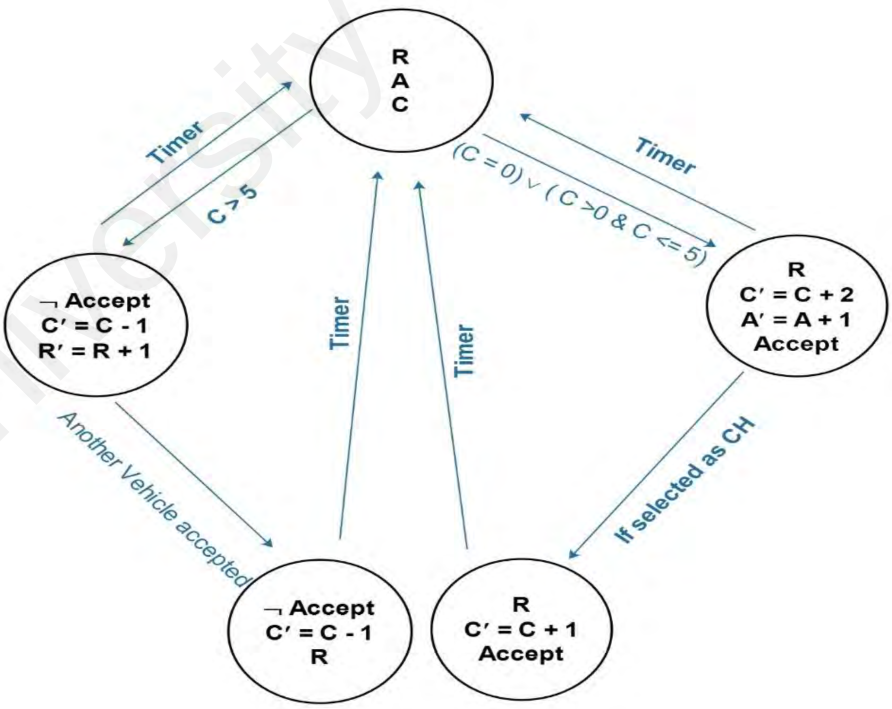

Figure 7.4: Accept/Reject decision model

From this state, if any of the other vehicles accept the offer, then the state changes to a new state in which only the value of C decreases by 1. From here, the system is triggered to its initial state but with new values of flags; from the initial state, if the value of C is greater than 0 and less than or equal to 5, then the system gets into a new state. At this state, the property of accept is true and the values of A and C change. The value of R remains the same. At this stage, if CH is selected, then the system gets into a new state in which only the status of C changes. From this state, the system returns to the initial state again.

7.4 Model Checking of the Temporal Logic

In model checking, users produce system model and some logical formulas that describe the properties. If the system is complex, then the model checking algorithm is used to determine whether the system satisfies the desired properties (logical formulas). If the properties are not satisfied, then a counterexample is produced. Model checking is based on the state specifications that describe all possible behaviors of the system. In the system model (graph), nodes are states, and transactions of the system are edges of the graph. For model checking, a model must be closed. Model checking has three steps:

1- Modeling: system → Model

2- Specification: natural language specification → properties in formal logic

3- Verification: algorithm checks whether desired system properties are met

Our system is inconsiderably complex and has few states. Thus, this system can be checked by simply traversing the graph using CTL. In CTL, the model is unwind to show all possible computational paths. Then, the number of computational paths that indicate (hold) the desired property is checked.

7.4.1 Desired Properties of the System

The CTL is explored in our case to check the temporal logic. The computational tree is made from a model transition diagram by unwinding into an infinite tree routed at the initial state. Paths in the tree represent all possible computations of the system being modeled. The examples of computational paths are shown in Figures 7.5–7.7.

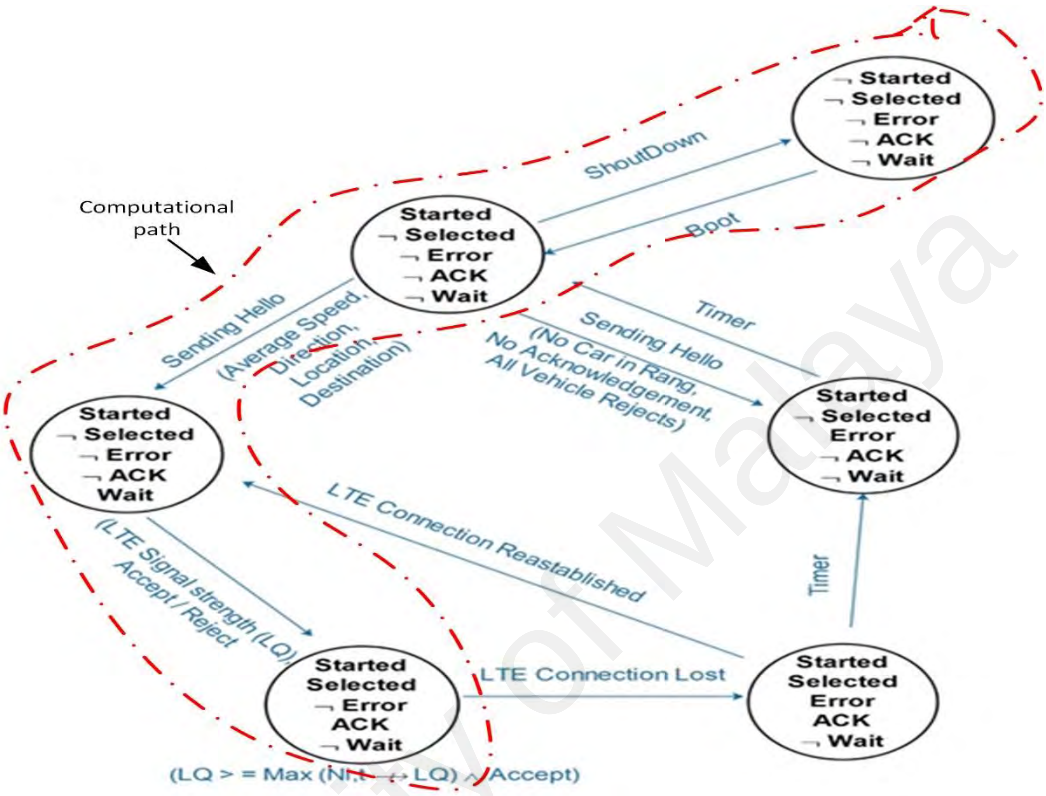

Figure 7.5: One of the computation paths in the system (graph)

We define some desired properties of the system as those intended to be TRUE or FALSE.

1) First desired property: ***CH will eventually be selected***

AF (Started → Selected) TRUE

For all computation paths (AF) within the closed graph, the following properties hold. Figure 7.5 shows that one of the computational paths in dotted red lines has at least one state in which the property of selected is positive.

2) Second desired property: ***The same vehicle is not selected as CH every time***

EF (Started → Accept) TRUE

For some computation paths (EF) within the closed graph, the above-mentioned properties hold. Figure 7.6 shows that one of the computational paths in dotted red lines has states in which the property of not accepted holds. When one vehicle is not in an accept state, another one is chosen. Thus, the property holds.

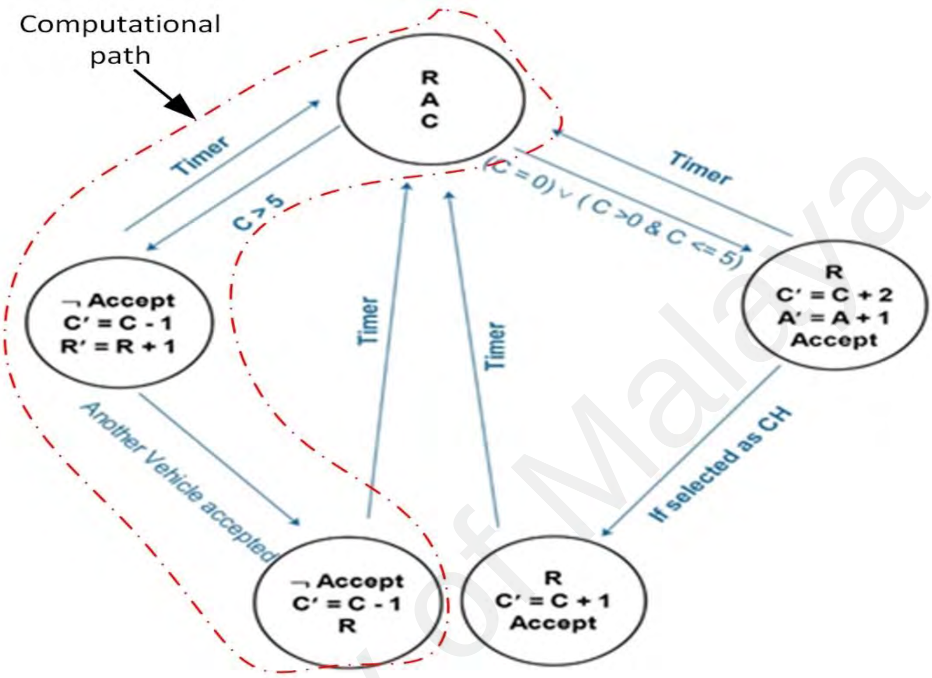

Figure 7.6: Computational path that indicates the same vehicle is not selected as CH every time

3) Third desired property: ***The CH is not selected every time***

EF (Selected ⇸ Reject) TRUE

The computational path in Figure 7.7 shows that the system starts properly in some cases, but no cars are around, cars are not meeting criteria for CH selection, or all cars reject being selected. The system is thus in the state of not selected.

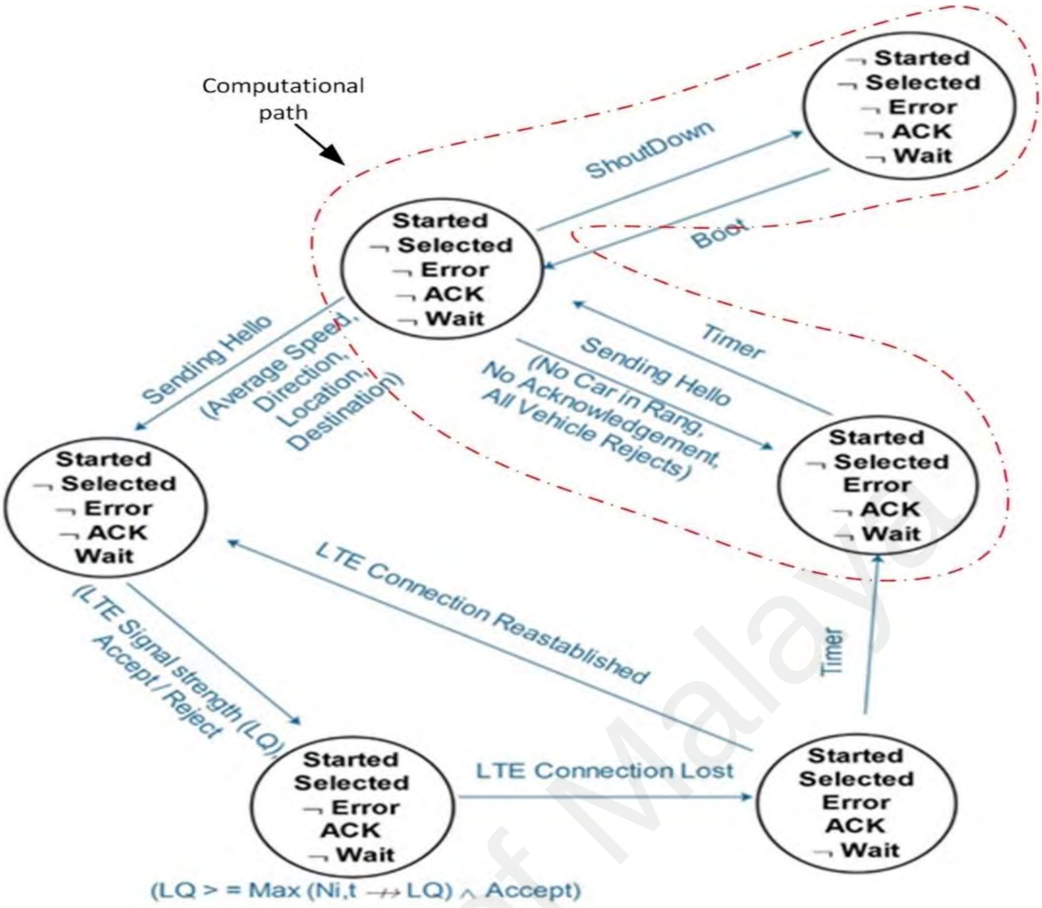

Figure 7.7: One of the computational paths shows the state is not selected

Main desired properties (intended behavior) of our system hold, which shows the correctness of our model. Formal verification proves that the design and behavior of DIAC are correct. To further validate our system, a state transition table depicting the operation of our system (with a small cluster size) is formulated as an example, as shown in Appendix A.

7.5 Conclusion

In the macro-level evaluation, the integrated DIAC framework is checked for correctness and completeness through formal verification methods. Specification, modeling, and verification are done. The results show that DIAC meets the desired properties set to evaluate its performance. Therefore, the integrated DIAC framework is formally verified.

CHAPTER 8: CONCLUSION

8.1 Introduction

This chapter concludes and re-evaluates the objectives of this research, presents the major contributions, discusses the scope and limitations, and presents future directions. This chapter is organized into five sections. Sections 8.2 and 8.3 discuss the reappraisal of the objective of the research and major contributions, respectively. Section 8.4 presents the scope of the research. Section 8.5 discusses the future work.

8.2 Reappraisal of Objective Achievement

This research investigates the problem of redundancy in the acquisition of TIS data by vehicles while moving on the road from the remote server over the Internet. Existing TMSs are first investigated. Then, a new solution is developed, which not only addresses limitations of existing popular approaches but also introduces new features. The four major objectives of this research that are highlighted in Section 1.5 are achieved as follows:

For reviewing the state-of-the-art traffic efficiency related to TMSs and analyzing research problem through real-world field tests, first, we study state of the arts to determine issues in existing TMSs that are related to road traffic efficiency. State of the arts are studied from web databases and online digital libraries (ACM, IEEE, Springer, and ISI web of knowledge). We review the latest and relevant literature regarding road TMSs. We focus on two types of existing TMSs: those based on VCC and those that incorporate LTE with DSRC. A taxonomy of VCC-based TMSs that categorizes the existing solutions is produced, and comparative analysis is performed to highlight issues (Section 2.3). A thorough investigation of VANET–LTE-based existing approaches is carried out, and a qualitative comparison is made (Section 2.4). A functional design-based taxonomy is developed to gain insight into underlying data collection and dissemination techniques of existing approaches (Section 2.4.4).

Second, we analyze the research problem by quantifying the rate of cellular data used by real-world navigational and route planning. The primary purpose is to verify and quantify the research problem through real-world field tests. These tests are performed in the urban city of Kuala Lumpur, Malaysia and Cambridge, UK by hiring cars and regular taxi drivers for a specific period and by using Waze and Google map applications. Tests are conducted over selected short to long road segment routes, and data are collected to find the trends regarding the use of LTE while cars move on the roads (Section 4.2). The average data rate per travel time of vehicles is estimated by analyzing results in a mathematical form (Section 4.3). We quantify the redundancy in data acquisition from the remote server accessed by vehicles for driving assistance and route planning applications (Waze and Google Map) (Section 4.3.3). Finally, the outlined problem is highlighted in a diagrammatic form, and other findings are concluded (Section 4.4).

To achieve the second research objective, a stable interest-aware vehicular clustering mechanism is developed for road traffic efficiency (Section 5.3). The target is to achieve cluster stability and utilize 3G/LTE network resources at a minimum level. The detail description of the developed mechanism is provided in Figures 5.1 and 5.2. After the development, we implement our mechanism over OMNeT++ for simulation study. The results are calculated and compared with those of existing popular approaches. From the discussion, we conclude that the developed mechanism is stable while consuming a small amount of LTE resources, as presented in Section 6.3.1. To further improve the stability by enhancing synchronization of vehicles with CH, an SLCA that works on CMs in the absence of a GPS signal when integrated within DIAC

(Section 5.5) is developed. Simulation of DIAC-LA and comparison of its results demonstrate its improved synchronization with CH. Thus, this method increases the CM life within the cluster, as discussed in Section 6.5.

Our third objective is achieved by developing a cooperative interest-aware mechanism for vehicular clustering, as described in detail in Section 6.4. The CIAC is first developed as a standalone mechanism, as represented in Figure 5.3. Then, simulation study is carried out to compare its performance against existing solutions. The comparative results in Section 6.4 show the superiority of CIAC over others.

To achieve the fourth objective, an integrated DIAC framework is developed by incorporating all mechanisms, as described in Section 5.6. An elaboration of integrated DIAC framework is presented in Figure 5.5, and all its algorithms are pseudo coded in Algorithms 1, 2, 3, 4, 5, 6, and 7. The main DIAC and incorporation of sub-mechanisms, namely, cooperation mechanism and self-location mechanism, are presented in Sections 5.6.1, 5.6.5, and 5.6.6. The workflow block diagram of an integrated DIAC framework is presented in Section 5.7 after the development of our integrated framework, which is first evaluated at macro level by formal verification methods. A formal system model is built, and formal verification using model checking technique is carried out to check the correctness of the developed system, as presented in Sections 7.2, 7.3, and 7.4. The system model is checked against the desired properties, and it is found to hold all properties. Second, a simulation study is done for micro-level evaluation, and the results are benchmarked against popular existing approaches, as presented in Section 6.7 of Chapter 6. The results show that our integrated DIAC performs better in all performance metrics than the other approaches. Therefore, DIAC is a suitable protocol for heterogeneous (VANET–LTE) network-based applications, especially for driving assistance and route planning applications. DIAC is also a good addition to ITSs that enable good road traffic management.

8.3 Contribution of the Research

This research redirects existing efforts in acquiring TIS information toward a novel perception, that is, designing a stable V2-LTE heterogeneous communication framework for cooperative data access to remote servers to minimize network usage and cost. This research produces several contributions to the body of knowledge as follows:

8.3.1 Taxonomies

Some taxonomies that help analyze critical aspects of existing road TMSs are produced. An abstraction of vehicular cloud integration and cloud-centric computing is provided for visualizing the device- and communication-level infrastructure. These implementations help explore and generalize the VCC process.

A taxonomy of vehicular clouds that defines the cloud formation, integration types, and services is presented in Figure 2.7. A taxonomy of vehicular cloud services is presented in Figure 2.8 for exploring the object types involved and their positions within the vehicular cloud. Thus, comparative analysis of current state-of-the-art VCC-based TMSs in terms of network infrastructure, traffic flow control, and emerging services is provided.

Regarding VANET–LTE-based network and applications, a taxonomy of LTE-based vehicular application is produced (Figure 2.11) and helps in providing an overview of state-of-the-art V2-LTE technologies and the support they can provide to road traffic management. A taxonomy presented in Figure 2.12 provides insight into V2-LTE technology and applications to determine their viability and usefulness under current scenarios of network infrastructure and demands. The classification of current V2-LTE TMSs and comparative and qualitative analysis of the usage of LTE in road traffic management applications provide direction regarding the development of the new solution. Therefore, these taxonomies can help researchers in the related area in quick categorization and comparative analysis of literature to determine the direction for the new potential solution.

8.3.2 Quantification of LTE Usage in Vehicular Applications

We quantify the LTE usage in vehicular applications especially in driving assistance and route planning applications through real-world field tests. By conducting a campaign for one month, we collect data from cars during their trips on different road segments and arrive at generalized results by finding data usage per travel time of vehicles. This process helps in not only finding inefficiency in the usage of LTE for vehicular applications but also assessing the development of a future end-user oriented solution for telecommunication network planning. Therefore, these field tests and outcomes are major contributions to the body of knowledge.

8.3.3 Development of Stable and Cooperative Heterogeneous Clustering Framework

The major contribution of this research to the body of knowledge is the proposition, design, and development of a stable and cooperative VANET–LTE-based heterogeneous vehicular clustering framework for road traffic management. First, a SIAC mechanism is developed to mitigate the traditional VANET constraints, and its performance is checked through a simulation study. Second, a cooperative mechanism based on game theory is developed, and its correctness is checked via open-source software. The simulation results are compared to determine its cooperativeness. Third, a self-location mechanism is developed and incorporated in DIAC. The implementation shows increased synchronization of vehicles with CH. Finally, an integrated VANET–LTE-based heterogeneous framework is developed by incorporating all three mechanisms. The integrated framework is evaluated at macro and micro levels.

Another contribution of this research is the development of a system model and its verification through formal verification methods. First, system schemas and definitions are specified using Z specification language. Then, a model is developed. This model is checked for desired properties using model checking technique, and the results find that all properties hold.

Another contribution is the evaluation of the proposed framework at micro level by modeling low-level details of the system using popular simulation tools such as OMNeT++, SUMO, Veins, and SimuLTE. Real scenarios are reproduced in the simulation environment to check the validity of the proposed framework. The evaluation of the proposed framework confirms its suitability for cooperative access to TIS server through VANET–LTE-based heterogeneous vehicular clustering for driving assistance and route planning applications.

8.4 Research Scope and Limitations

The scope of this research is limited to analyzing the problem of identification of issue of inefficiency in the utilization of LTE resources in existing road traffic management applications related to the driving assistance and route planning and proposing stable VANET–LTE-based heterogeneous vehicular clustering framework for cooperative access to TIS information for road traffic management. This research covers only the network and lower layers and ignores the other layers in the protocol stack. Issues related to the performance evaluation of routing algorithms for intra-cluster communication are not discussed. The transmission of data not related to traffic management class of applications cannot be segregated while clustering network is in function. During the real-world field experiments, the telecommunication network fluctuates between LTE and 3G network due to the type of services provided by the telecommunication operators.

8.5 Future Work

This research focuses on the development of heterogeneous clustering framework for cooperative access to TIS servers to minimize the utilization of LTE resources. Each mechanism is developed to cater to a specific challenge while considering the performance and parametric requirement of traffic efficiency class of applications. Thus, this research emphasizes not only data download cost but also the stability of the cluster and cooperation in the formation of vehicle cluster. However, this research can be extended in the following aspects:

- The developed framework can be transformed into a prototype for real-world implementation considering that OBU with LTE capability is costly and APIs within cars are very costly.
- Some of the real-world experiments are carried out using 5 GHz devices and can further be analyzed at 5.9 GHz frequency. This condition shows no difference in our data gathering campaigns, which are conducted to investigate the trends in data usage. The amount of data required to be accessed by an application does not depends on the type of network provided. Thus, the data rate and latency must be guaranteed.
- The research done can easily be transformed to operate on emerging 5G telecommunication networks because this solution is end-user oriented. If the telecommunication network provides high data rate, then the operational efficiency will increase.

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List of Publications and Papers Presented

The published works and papers presented at a seminar about the research topic of the thesis are listed as follows:

1- **Iftikhar Ahmad,** Rafidah Md Noor, and Muhammad Reza Z'aba, et al., "A Cooperative Heterogeneous Vehicular Clustering Mechanism for Road Traffic Management," International Journal of Parallel Programming, 2019, pp. 1-20 **(Q3) (Published)**

2- Iftikhar Ahmad, Rafidah Md Noor, and Muhammad Reza Z'aba, "LTE Efficiency When Used in Traffic Information Systems: A Stable Interest-Aware Clustering," International Journal of Communication Systems **(Q2) (Published)**

3- Iftikhar Ahmad, Rafidah Md Noor, Ismail Ahmedy, et al. (2018), "VANET–LTE-based Heterogeneous Vehicular Clustering for Driving Assistance and Route Planning Applications," **Computer Networks (Q1) (Published)**

4- Iftikhar Ahmad, Rafidah Md Noor Ali I, Imran M, Vasilakos A (2017), "Characterizing the Role of Vehicular Cloud Computing in Road Traffic Management," International Journal of Distributed Sensor Networks 13 (5):1550147717708728 **(Q2) (published)**

5- Iftikhar Ahmad, Rafidah Md Noor Ali I, Qureshi MA, "The Role of Vehicular Cloud Computing in Road Traffic Management: A Survey," International **Conference** on Future Intelligent Vehicular Technologies, 2016. Springer, pp 123-131 **(published)**