Performance analysis of vehicular networks for motorway scenario.

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Performance Analysis of Vehicular Networks for Motorway Scenario

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DECLARATION

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I dedicate this thesis to my husband Vijay and my parents, and am especially grateful to them for their belief and confidence in me. I would like to say a special thanks to my uncle Das and aunt Renate who initiated this whole process

And… saving the best for the last, to the Almighty, for giving me an opportunity to learn the skills and to have made it possible, to Him be the Glory.

Chapter 1
Introduction

In recent years, there has been steady growth in communications and networking. The demand for ubiquitous personal communications and for supporting multimedia services has resulted in to the rapid development of wireless communication technologies and applications. Recent advances in wireless ad hoc networks have further pushed the state-of-the-art for the technologies supporting our desire of seamless mobility [1]. We have also seen a major paradigm shift for mobile personal communications where cellular and other mobile devices are increasingly being used with multimedia applications, replacing the more traditional voice communications and text messaging. The wired communication technologies have incrementally adapted to the need to support multimedia traffic, although, for the wireless communications, it has remained more challenging to provide the required quality of service.

The need to communicate anywhere at any time has led to intensive research and development in vehicular networks. This rapid change in technology has not only changed the way we live and communicate, but has also put greater demands on the ways we organise and manage our day-to-day life. Intelligent transport systems (ITS) have evolved substantially in the recent years with the increase of the range of applications and with the fast expansion of the technologies [2]. The ITS system integrates the information and communication technology which includes data storage and processing equipment, global positioning systems and sensors. The technologies are integrated into communication systems to give the ITS capabilities of road safety, minimize traffic congestion, monitor traffic and provide public safety [3-6]. There are organisations such as Car 2 Car Consortium [7] aiming to standardise the optimal communication between vehicles and projects such as CVIS – "Co-operative Vehicle Infrastructure Systems" [8] , SAFESPOT – "Smart Vehicles on Smart Roads" [9], NOW – "Network on Wheels" [10] shows the current research activity undertaken in vehicle to vehicle (V2V) communication. The objectives of these projects are road safety combined with comfort, transport efficiency and environment concerns.

Vehicular applications are classified as safety applications and comfort applications. With cost reduction of wireless technologies, ITS is finding favour in comfort applications such as data transfer, maps downloading, file sharing, email access, infotainment services like web browsing, games, music data updates, video downloads, discovering local services, tourist information etc [6]. These applications pose a host of completely new set of requirements such as maintaining end to end connectivity, packet routing, and reliable communication for internet access while on the move.

One of the biggest challenges in vehicular networks is provision of Quality of Service (QoS) while handling the topology changes. In a highly mobile network, the communication links become inconsistent thereby unsuitable for the standard protocol requirements [11]. In addition, standard protocols are not fast reconfigurable. Hence protocols should be designed to cope with faster changes and support scalability. The wireless network should have robust and reliable links. The main requirements for comfort applications are high data rate and providing reliable and robust wireless links.

There are two types of traditional vehicular networks used for the above applications. They are vehicle to roadside communication (V2R) – a wired backbone with a wireless last hop and vehicle to vehicle communication (V2V) – infrastructure-less and vehicles forming adhoc network for communication [12].

In vehicular networks, vehicles are installed with on board diagnostics managed by radio devices allowing them to communicate with the other equipped vehicles within their transmission range or the road side infrastructure. The vehicles exchange information about the local traffic scenarios which results in formation of vehicular ad hoc networks (VANET). This information is used to improve the safety for drivers and pedestrians [13-15]. This infrastructure-less setup of the vehicles provides the benefit of low cost and easy deployment for scenarios such as left turn, blind merge, sign violation, co-operative forward collision warning, lane change warning and emerging electronic brake light.

The advantages for V2R communication are reliable links and high data rate [16, 17], while the disadvantages are high power consumption (low energy efficiency), low spectral efficiency, presence of dead zones and delays in request process due to high contention. On the other hand, the advantages for V2V communication are high data rate, short links and energy efficient and the disadvantages are rapid changes in network topology, unreliable links and packet loss due to contentions [18-20].

The vehicular network applications also require a medium access control (MAC) protocol which is fair and efficient. Protocols such as IEEE 802.11 standard use Request to Send (RTS)/Clear to Send (CTS) to avoid collisions from hidden terminals. But the packet delay and data congestion increase rapidly with the number of vehicles contending for the channel in the network. The MAC protocols need to be adjusted to handle the topological changes and provide a good QoS [21-25]. The adaptation of wireless links with respect to the various physical constraints such as path loss, signal to noise ratio, longevity of the links needs to be taken into account.

As the key requirement for comfort applications is to provide reliable data links with high data rate, a solution is proposed where the two vehicular networks are combined to provide a hybrid network (V2V+V2R). The hybrid network uses V2V communication that does not rely on the fixed infrastructure but can utilise it for improved performance and functionality. The hybrid network combines both the systems advantages and thereby eliminates the disadvantages of the individual networks to a certain degree. The advantages for the proposed hybrid network are higher capacity, improved spectral efficiency, reduction of dead zones, energy efficiency, lower costs and reduced delays and packet losses. However, the high mobile nature of the network still exists along with the possibility of the odd dead zones making the communication between vehicles challenging.

The communication protocols in vehicular ad-hoc networks (VANET) use broadcast technique [26,27], single hop and multi-hop communication, or hierarchical architecture for data dissemination [28]. The broadcasting technique is a straight forward method but has the drawbacks of increased data congestion and bandwidth consumption. For single hop and multi-hop techniques, hidden node problems, packet collisions and delays need to be addressed. Finally, the hierarchical clustering architecture is considered as it is an efficient method to reduce data congestion, optimise communication and improve network stability.

A hierarchical clustering system is used for grouping the vehicles and a head is selected for the group based on various constraints. The cluster head is intended to act as a point of the communication between vehicles in a cluster and also between vehicles and the roadside base station. The vehicle clustering is periodically updated to reflect the topological changes and vehicle movements. The clustering should operate fast to minimise the time lost and feature low cluster head changes for the stability of the network. Hence, a good clustering algorithm would reduce the fast reconfigurable condition of the dynamic network ensuring a better performance of the MAC protocols [29-31]. A hybrid network with an efficient clustering algorithm for V2V communication should be able to improve the network stability and exhibit good performance results for MAC protocols in a fast moving vehicular environment.

A seamless service is required for comfort applications in a vastly mobile environment where there is a high density of users trying to share the system resources. To satisfy multiple users with different service requests, the system should be capable of providing the services with different QoS requirements. The resources are shared based on the decision of scheduling algorithms [32, 33] in such a way that the system resource is utilised efficiently and in a fair manner. There are two main objectives for a scheduling algorithm – 1.To optimise the resource utilisation and 2.To achieve fairness between users. As part of this research, the scheduling algorithms for V2R communication with the clustering algorithm are studied. A cluster based scheduling algorithm is proposed and compared with the round robin scheduling algorithm.

A realistic mobility model is required in attaining consistent results as the vehicular environment and movement can have a major impact on the communication layer [34]. Therefore an understanding of key traffic parameters obtained from the inductive loops on the M4 motorway is required. This will enable us to derive an accurate vehicular traffic model which can be used in study of the proposed clustering algorithm while ensuring the Qos is maintained. A detailed analysis of the important vehicular traffic parameters such as vehicular flow, arrivals per lane, average speed etc is carried out to study the traffic patterns. Based on the study, we have designed a motorway vehicular simulator which uses the vehicular data as input while integrating the clustering algorithm, protocols and scheduling algorithms as part of the system.

1.1. Research Objectives

The main objectives for this research work are as follows: -

- To identify and study the suitable applications, technologies, clustering and scheduling algorithms and MAC protocols apt for vehicular environment.
- To develop an accurate data traffic model as they are pivotal in assessing the algorithms and protocols.
- To comprehend the important traffic parameters such as vehicular arrivals and speed measured on the M4 motorway and using them to derive a mobility model for vehicular traffic.
- To design a bespoke motorway simulator which uses the traffic parameters as the input and evaluates the performance of the clustering algorithm and communication protocols.

- To propose a new clustering algorithm based on physical constraints for V2V communication.
- To build a hybrid network consisting of group of clusters communicating to the base station through cluster heads.
- To investigate the performance of MAC protocols (Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) and Dual Busy Tone Multiple Access (DBTMA)) with the clustering algorithm for vehicle to vehicle communication.
- To investigate the performance of Round Robin and Cluster based scheduling algorithms for vehicle to road side communication.

1.2. Original Contributions

The author in this thesis has:

a. Carried out a detailed analysis of the M4 motorway vehicular traffic profiles to understand the service requirements for different hours of the day.

b. Designed and developed a motorway traffic simulator based on the vehicular traffic model obtained from the M4 traffic patterns. The motorway simulator is extended to integrate the vehicular models, clustering algorithm, MAC protocols and scheduling algorithms to evaluate useful and practical scenarios.

c. Proposed a novel clustering algorithm based on minimal path loss ratio (MPLR). The performance of the algorithm is measured in terms of a rate of change of cluster heads, average size of a cluster and average number of clusters. A mathematical model is derived for rate of change of cluster head and is compared with simulation results.

d. Integrated and studied the performance of two MAC protocols – Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and Dual Busy Tone Multiple Access (DBTMA) with the clustering algorithm for V2V communication.

e. Proposed a scheduling algorithm based on the clustering properties and compared with the performance of round robin scheduling algorithm for V2R communication.

These contributions are supported by the following publications:

1. **Y Harikrishnan** and T O Farrell, "Novel Clustering Algorithm based on Minimal Path Loss Ratio for Medium Access Control in Vehicle-to-Vehicle Communication System," *in Proceedings of London Communication Symposium* (*LCS*), London, UK, September 2009.
2. B Qazi, **Y Harikrishnan**, R Mehmood, J M H Elmirghani and H Dass, "A mobile diverse heterogeneous ad hoc network for city management," *in Proceedings of the World Congress on Intelligent Transport Systems* (*ITS 2006*), London, UK, October 8-12, 2006.

1.3. Organisation of thesis

Following the introduction in chapter 1, the rest of the thesis is organised as follows.

In Chapter 2, a review about the different technologies and standards related to the area of work are discussed. The frequency spectrum, data rates, area of coverage, modulation techniques etc are outlined. The different mobility models such as macroscopic model, mesoscopic model and microscopic model for vehicular traffic are explained and justification for selecting microscopic model is given. The MAC protocols for V2V communication – CSMA/CA and DBTMA are explained in detail.

In Chapter 3, state of the art review of V2V and V2R networks are explained and existing hierarchical clustering algorithms are discussed. The mechanisms of the existing clustering algorithms, their advantages and drawbacks are explained and a hypothesis is drawn from the above study.

Chapter 4 describes the analysis of the empirical vehicular traffic profiles and development of the motorway simulator. An in-depth analysis of experimental vehicular traffic profiles on M4 motorway was carried out. Key characteristics such as average arrivals, speed and inter-arrival times are analysed and are used to define the motorway traffic patterns which helps in estimating the bandwidth requirements at different times of the day. The bespoke motorway simulator is designed and developed. The vehicular arrival models obtained from the M4 data is used an input to the motorway simulator to simulate realistic mobility patterns.

Chapter 5 proposes a new clustering algorithm based on minimal path loss ratio (MPLR). The chapter explains the clustering technique and characteristics of the cluster. It also looks into the cluster creation and cluster head nomination rules based on path loss and interference between vehicles. The clustering algorithm metrics in terms of rate of change of cluster head, average cluster size and average number of clusters are evaluated. A mathematical model is proposed for the rate of change of cluster head. There is a brief introduction about the classes used in designing the system simulator. Event driven simulation is described and also the traffic generation phase is explained in detail. Algorithms and flowcharts are given describing the flow of the system simulator. This chapter draws comparison of the analytical results derived from the mathematical model for rate of change of cluster head metric with the simulated results. The clustering performance metrics average number of clusters and average cluster size are derived from the simulator. Two popular clustering algorithms are studied and compared with the proposed MPLR algorithm for rate of change of cluster head. A hybrid (V2V+V2R) motorway scenario is proposed as the system setup and is compared to a pure V2R system in terms of throughput, average access delay and packet dropping probability.

Chapter 6 has two parts – the first section analyses and compares the performance of the clustering algorithm with MAC protocols CSMA/CA and DBTMA for vehicle to vehicle communication. The performance is evaluated in terms of throughput, average access delay and packet collision ratio. The second section presents the scheduling algorithms for resources allocation. The performance of the algorithms are measured in terms of throughput, average access delay and packet dropping probability.

Chapter 7 summaries the thesis and delves into the related areas for future work.

Chapter 2

BACKGROUND

2.1. Introduction

There are two main types of applications emerging for Intelligent Transport Systems (ITS) [35]:- public safety related and comfort based applications. These applications require timely delivery of data packets, high reliability and low delays. For applications requiring minimal latency the communication should be direct between vehicles without an infrastructure and for applications requiring high data rate, vehicle to road side communication will be advantageous. However, the high mobile nature of the vehicular network makes the traditional wireless systems unsuitable. Hence, there is a need for a new set of standards or technologies for vehicular communication.

The motivation for Dedicated Short Range Communication (DSRC) development came from a consortium formed by a group of electronic toll suppliers and other stake holders. The IEEE has released a set of draft standards called Wireless Access in Vehicular Environment (WAVE) which is a standardised DSRC technology and also to help in the development of vehicle to vehicle communication systems. Some of the commonly used applications for vehicle to vehicle (V2V) communication include toll collection, road condition warning and co-operative vehicle systems. For vehicle to roadside (V2R) communications, applications targeted are on demand or real time video and high speed internet access. These applications require large bandwidth and high data rates. Mobile WiMax (802.16e), High Speed Packet Access (HSPA) and the evolving, Long Term Evolution (LTE) are some of the widely known wireless metropolitan area networks (WMAN). The technologies use centralised control, support handover between cells and use the Internet Protocol (IP) for end to end addressing.

The applications for ITS are driven by the requirement for high reliability and low delay. These parameters are dependant on the Medium Access Control (MAC) protocols and mobility conditions for vehicular traffic. There are three different approaches to model the vehicular traffic mobility condition. They are macroscopic modeling, mesoscopic modeling and microscopic modeling. The models simulate the realistic movement of vehicles. The protocols considered for vehicular communication are Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) and Dual Busy Tone Multiple Access (DBTMA).

The following sections give a detailed background description of the different technologies, vehicular mobility models and MAC protocols, used in this work

2.2. Standards and Technologies

This research focuses on combining V2V and V2R networks to form a hybrid network. The objective of the hybrid network is to provide high data rate, good spectral efficiency, low latency and efficient data dissemination. The fast changing and harsh vehicular environment pose a new set of requirements with respect to channel modelling, modulation, novel network configuration, effective medium access control (MAC) protocols, robust routing and efficient congestion schemes.

Several standards and technologies have been proposed for the V2V communication. Of the many standards, DSRC/WAVE is the most commonly studied system. WAVE technology is the currently evolving next generation DSRC system and is used in this research for V2V networks. The WAVE system comprises of IEEE 802.11p standards for lower layers and IEEE 1609 standards for upper layers.

Comfort applications require the presence of internet access and hence need robust links supporting high data rate. The technology selected for V2R communication should be able to meet the demands rising from the vehicles grouped together as clusters, improved spectral efficiency, reduced round trip delays, sustaining the high mobile nature and should provide a reliable environment. LTE is in the process of standardisation and is being developed with the above performance requirements set as targets. This research work considers using LTE for vehicle to roadside communication.

2.2.1. Dedicated Short Range Communication (DSRC)

DSRC uses a technology based on the 802.11 Wireless Local Area Network (WLAN) Medium Access Control and 802.11a physical layer specifications [36-38]. The primary goal of DSRC is to provide short to medium range communication between vehicles, and between vehicles and roadside equipment. It supports both public safety [39] and private operations for communication. DSRC is often used for its high data rates, low latency in communication links and isolation of small communication zones. The technology is currently operating in the 5.9 GHz band in the USA and 5.8 GHz band in Europe and Japan. The envisaged applications were designed to improve safety. Different parts of the world have their own standards for DSRC (e.g., Europe, Korea, US, Japan).

In Japan, the Association of Radio Industries and Businesses (ARIB) is responsible for the development of standards for DSRC and referred to as ARIB T55 [40,41]. This includes a physical layer, a data link layer and an application layer. It uses the 5.8 GHz band with a data rate of 1 to 4 Mbps. Though DSRC is used for multiple applications such as parking management, gas station payments, logistics management and information providing, its main application is Electronic Toll Collection (ETC). In 2004, a new Application Aublayer (DSRC –ASL) was developed by ARIB (ARIB STD-T88) to interface with other communication system such as TCP/IP stack. The protocol stack is shown in the Fig. 2.1.

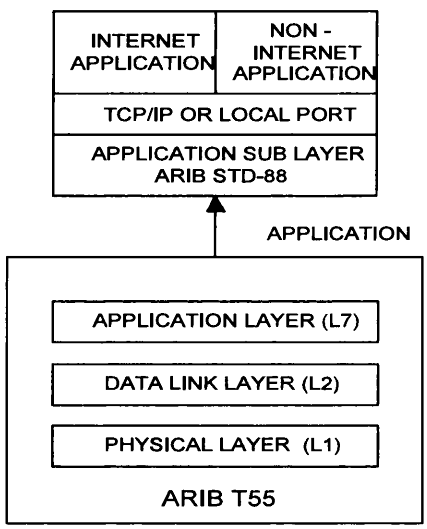

Fig 2.1 Japanese DSRC protocol stack

The technology works at 5.8 GHz frequency and has a bandwidth of 80 MHz with 7 channels allocated for both uplink and downlink. The data rate achieved is between 1 to 4 Mbps and has a coverage range of 30 m. The DSRC system consists of onboard units (OBU) and roadside units (RSU). The vehicular network is a combination of one RSU and one or multiple OBUs. The communication for OBU is half duplex whereas for RSU is full duplex.

In North America, the American Society for Testing and Materials (ASTM) was selected by the Federal Highway Administration (FHWA) to propose a system for Electronic Toll Collection in 1999. It was decided to make use of wireless local area network standards as a basis for the new DSRC standard. In 2003, specifications were developed based on the 802.11a standard. The application layer was standardised by the IEEE. The protocol stack for the North American DSRC standards is shown in Fig.2.2.

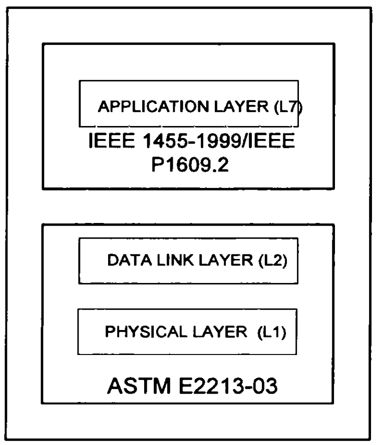

Fig 2.2 North American DSRC protocol stack

As mentioned earlier, DSRC standards are based on IEEE 802.11a and modified to adapt to the high speed environments. The Federal Communication Commission (FCC) has allocated 75 MHz of bandwidth between 5.850 and 5.925 GHz. The PHY uses 10 MHz wide channels as opposed to 20 MHz as specified in 802.11a. The data rates are half of 802.11a data rates – 3, 4.5,6,9,12,18,24,27 Mbps. The coverage range is 1000 m and the maximum transmission power supported for 1000m range is 28.5 dBm. The vehicular system network consists of OBU and RSU and they both are half duplex. There is a list of planned applications for DSRC pertaining to both public safety and private usage. With respect to public safety, the applications are collision warning, toll collection, probe data collection, in-vehicle signing, intersection collision avoidance, emergency vehicle preemption etc. For private applications, parking lot payment, drive through payment, data transfer, and fleet management are some of the applications which are finding a lot of demand.

DSRC systems are used in many of the European countries [42] but the compatibility between the systems is questionable. Hence standardisation of the systems has become essential. The base standards of DSRC were developed by the European Committee for Standardization (CEN). The CEN in co-operation with the International Organization for Standardization (ISO) established the DSRC standards as shown in the protocol stack in Fig. 2.3.

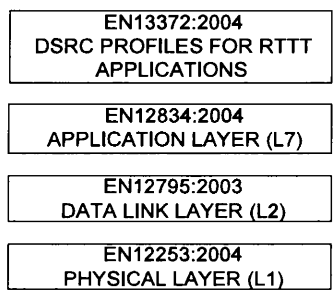

Fig.2.3 European DSRC protocol stack

In the European DSRC standard, a 10 MHz band is used in the allocated frequency of 5.8 GHz and this is followed in most of the European countries. The band comprises a downlink channel with a bit rate of 500 Kbps and uplink channel with a bit rate of 250 Kbps. The applications targeted are similar to Japan and North American DSRC applications.

2.2.2 Wireless Access in Vehicular Environment (WAVE)

802.11 standards group made an effort to standardize the different DSRC specifications existing in different parts of the world and now within the IEEE, the DSRC technology is referred to as 802.11p WAVE systems [43, 44]. Wireless Access in Vehicular Environments (WAVE) technology operates at 5.850 – 5.925 GHz and is divided into 7 channels each of 10 MHz bandwidth It uses OFDM with data rates varying between 3 and 27 Mbps and a coverage range of up to 1000m. These IEEE 802.11p is a draft amendment to the IEEE 802.11 standard to incorporate support for wireless access in a high speed setting. The physical and data link layers are addressed by the 802.11p module while the higher layers are based on the IEEE P1609 series of standards. The vehicular system components comprise of roadside units (RSU), onboard units (OBU) and the WAVE interface [45].

The physical layer of 802.11p is based on 802.11a and data rates are same as the DSRC technology. The modulation used is OFDM with a symbol duration of 8 μs, forward error correction (FEC) convolutional coding with constraint length K=7 and a guard period of 1.6 μs. The table (Table 2.1) summarises the different modulation techniques, coding rates, coded bits per sub-carrier, coded bits per OFDM symbol and data bits per OFDM symbol used for different data rates [46].

Data rate in Mbps	**Modulation**	**Coding rate**	**Coded bits per sub carrier**	**Coded bits per OFDM symbol**	**Data bits per OFDM symbol**
3	BPSK	½	1	48	24
4.5	BPSK	¾	1	48	36
6	QPSK	½	2	96	48
9	QPSK	¾	2	96	72
12	16-QAM	½	4	192	96
18	16-QAM	¾	4	192	144
24	64-QAM	2/3	6	288	192
27	64-QAM	¾	6	288	216

Table 2.1 Parameters of 802.11p physical layer

The MAC layer for 802.11p is based on CSMA/CA with the Distributed Co-ordinated Function (DCF). In DCF mode all stations compete for channel access. Before sending the data, the station senses the channel to determine whether the medium is free or not. On detecting the channel to be free for a specified time interval known as the distributed inter-frame spacing (DIFS), the station starts transmitting the data. If the medium is sensed as busy, the station defers the transmission for a random back-off time before it reinitiates the transmission. The back off time is based on the specified slot time multiplied by a random number, uniformly distributed between [0, CW] where CW stands for Contention Window. The value of CW is doubled for every attempt to retransmit a packet from its initial value CW_{min} and reaches a maximum of CW_{max}. The value for CW_{min} is 15 and CW_{max} is 1023. On a successful transmission of a packet, the value of the CW is reset to its initial value and if the value of CW exceeds the maximum limit, then the packet is dropped.

The MAC in 802.11p uses the Enhanced Distributed Channel Access (EDCA) mechanism based on 802.11e for prioritization of channel access. Different Arbitration Inter-frame Space (AIFS) and Contention Window sizes are chosen for different application categories (AC). There are four queues which represent levels of priority – background traffic, best effort traffic, voice traffic and video traffic where voice traffic has the highest priority. Each station in an 802.11p network contains these four queues and the queue with the highest priority will wait for the shortest period before it initiates transmission. By assigning priorities, stations having low priority traffic will wait the longest, for the medium to be free. Collisions between packets of the same priority traffic are still possible and are handled by the back off procedure [47-49].

The IEEE P1609 series of standards are responsible for upper layers in protocol stack of WAVE systems and they comprise of a) IEEE P1609.1 which defines the resource management operations, b) IEEE P1609.2 specifies the security services for applications and management messages, c) IEEE P1609.3 describes the services for the network and transport layers in support of wireless access between OBUs and between OBU and RSU and finally d) IEEE P1609.4 defines the enhancements to the 802.11 MAC to support the WAVE system.

As mentioned earlier, the spectrum is divided into 7 channels each of 10 MHz bandwidth. Channel 178 is the control channel and this is to relay safety and high priority messages. The type of communication is broadcast. The other channels are service channels and have two way communication between the RSU and OBU and between OBUs. They are used for applications such as tolling, internet access etc. Thus in a fast evolving vehicular environment, different applications can make use of the service channels whilst giving priority to safety applications in the control channel.

Due to the dynamic nature of the vehicular network, the communication between the vehicles follows an opportunistic data exchange in a limited period of communication time. It cannot afford the time for authentication and authorisation. Therefore it is essential for all the 802.11p radios to be tuned into the same channel and configured with the same base station ID to enable safety communications.

Hence, the Basic Service Set (BSS) of a traditional IEEE 802.11 system is referred to as the WAVE BSS (WBSS). In the WBSS system, there is no authentication or association required between the OBU and RSU communication. A WAVE device can take a role of service provider or service user. It is the responsibility of the service provider to periodically broadcast information of services that are being offered to the surrounding neighbours. The service profile, channel number and routing information are encapsulated as service information known as WAVE Service Advertisement (WSA). This is carried by the WAVE Announcement (WA) frame and it is periodically broadcast on the Control Channel (CCH). At the service user side, when the service user receives a WSA in the CCH and if the service matches the requirement, the service user will locally decide to join the WBSS. After joining the WBSS, the user will switch to the dedicated Service Channel (SCH), as specified in the WSA to use the service. When a user leaves the WBSS, there is no explicit termination process required in WAVE systems. The purpose of WBSS in WAVE systems is to reduce the management overhead and to endure the high mobility of vehicles in the system.

2.2.3 Long Term Evolution (LTE)

Long Term Evolution (LTE) is a step forward in the evolution of third generation cellular services. Though 3G networks have been commercialised and leading providers/operators have deployed High Speed Packet Access (HSPA), there is still an ever growing interest to investigate 4G technologies. To ensure the competitiveness of 3G systems, Long Term Evolution (LTE) of the 3rd Generation Partnership Project (3GPP) access technology first version is specified in the Release 8 of the 3GPP standard [52, 53]. LTE is a promising technology as it allows backwards compatibility and has higher and better performance compared to the other 3G technologies. LTE has further enhanced highly demanding applications such as interactive TV, mobile video blogging, advanced games or professional services. The feasibility study for 3G

LTE started in December 2004 and the key requirements established were increased service provisioning, reduced cost, flexibility of use of bandwidth, open interfaces and minimal power consumption.

LTE provides a peak data rate of up to 300 Mbps for downlink and 75 Mbps for uplink. In addition, the Radio Access Network (RAN) round trip times will be less than 10 ms thereby satisfying a key 4G requirement of significantly reduced latency time. LTE supports flexible bandwidths selectable from 1.4 MHz up to 20 MHz with sub-carrier spacing of 15 KHz. LTE supports both FDD (Frequency Division Duplex) and TDD (Time Division Duplex).Fifteen paired and eight unpaired spectrum ranges have been identified so far by the 3GPP (February 2009) and more bands could be introduced later. Also, LTE radio network products will have a number of features such as plug and play, self-configuration and self-optimisation, thereby reducing the complexity of building and management of next generation networks. LTE is deployed in parallel with IP-based core and transport networks which are simple and easy to build and maintain. Since LTE supports handovers and roaming to existing mobile networks such as GSM/UMTS/GPRS, devices like mobile phones, notebooks, gaming devices and cameras can have mobile broadband coverage over a wide geographic range [54].

LTE uses OFDMA for the downlink and Single Carrier Frequency Division Multiple Access (SC-FDMA) for the uplink. The OFDMA helps in achieving high data rates and SC-FDMA due to its lower Peak to Average Power Ratio (PAPR), improves the power efficiency and consequently increases the battery life [120]. The LTE downlink and uplink are composed of physical channels and physical signals. Physical channels carry user data information and control information from the higher layers. Physical signals are used for cell search and channel estimation. LTE uses Multiple Input Multiple Output (MIMO) to increase the throughput and spectral efficiency. For LTE, 3GPP is defining an IP based flat network architecture. This architecture is part of the System Architecture Evolution (SAE) effort. The LTE-SAE architecture and concepts are designed to support usage of any IP-based service. The architecture is based on the enhancements made to the existing GSM/WCDMA core network with simplified operations and cost-efficient deployment. Essentially the architecture is a flat network and this helps in reducing the latency time and the data can be routed more directly to its destination [55]. There are two components in this SAE architecture: - the LTE base station and the SAE Gateway. The LTE base stations are connected to the Core Network using the Core Network – RAN interface S1. This type of architecture minimises the number of involved nodes in the connections. The basic purpose is to provide support for a heterogeneous type of access network in terms of mobility and service continuity [55].

The following table (Table 2.2) lists the key parameters used in building LTE and also compares it with HSPA.

Parameters	**HSPA**	**LTE**
Frequency Band	2000 MHz	2000 MHz
Duplex	FDD	FDD and TDD
Channel Bandwidth	2 x 5 MHz	Up to 20 MHz
Multiple Access Method DL:UL	WCDMA	SC-FDMA : OFMDA
Peak Data Rate DL:UL	14.5/5.7 Mbps	300/75 Mbps
Spectral Efficiency	2.88/1.15 bps/Hz	5/2.5 bps/Hz
Modulation	QPSK,16 QAM	QPSK ,16QAM,64QAM
Coding	1/3,1/2,3/4	1/2 , 3/4

Table 2.2 Comparison of key parameters for LTE and HSPA

3GPP Release 5 and Release 6 of HSPA were deployed in 2006/07. It can be concluded that in the developed world, major UMTS/HSPA service providers will naturally evolve to 3GPP LTE and is expected to be deployed in 2011 [56,57].

2.3 Mobility models for vehicular traffic

The applications for ITS require a clear understanding of traffic flow operations such as the cause and time of congestion, location of vehicles, density of the flow and propagation of information through the system. Mathematical models are required to predict the patterns of vehicular arrivals, traffic flow in the system and thereby characterise the behaviour of the entire system [58]. There are wide ranges of traffic flow theories and models to predict the behaviour of complex traffic flow systems and to get a better perspective on the behaviour of the traffic flows. The models are classified according to the level of details required for description, scale of independent variables (continuous or discrete), representation of the process (deterministic or stochastic), mode of operation (analytical or simulation) and scale of application (indicates the area of application of the model). Based on the level of details with which they present the traffic system, they are divided into 3 categories: - macroscopic models, mesoscopic models and microscopic & sub-microscopic models.

2.3.1 Macroscopic models

The main focus lies in the description of the traffic flow without distinguishing its constituent parts. The behaviour of the aggregated traffic is simulated. Individual vehicle manoeuvres, such as lane changing, are not explicitly represented. The model may assume that the traffic stream is allocated to the roadway lanes accurately and employ an approximation to this end. Models are developed in analogy of the traffic flow in fluid dynamics. This leads to a set of partial differential equations which are easy to manipulate and represent characteristics such as flow-rate, density and velocity. The independent variables for macroscopic models are location x and time instant t. There are three types of macroscopic models: - a) Ligthill – Whitham – Richards model, describing the density of the flow , b) Payne – type model, describing both density and velocity , and c) Hebing- type model, with dynamic equations for density, velocity and velocity variance [59].

2.3.2 Mesoscopic models

Mesoscopic models depict behaviour of the individuals in probabilistic terms but does not distinguish or trace individual vehicles [60]. Vehicles and driver behaviour are clearly distinguished but rather in more aggregate terms (probabilistic functions). However behaviour rules are described at the individual level. For example, a gas kinetic model describes velocity distributions at specific locations and time instants. The dynamics of these distributions are generally governed by various processes such as acceleration, interaction between vehicles and lane changing, describing the individual driver's behaviour. There are three well known representations for mesoscopic model- headway distribution model, cluster model and gas kinetic model.

2.3.3 Microscopic and sub-microscopic models

Microscopic models describe both the time-space behaviour of drivers under the influence of the vehicles in their proximity as well as their interactions at a high level detail. For instance, a lane changing movement for each vehicle is described as a detailed chain of driver's decisions. Traffic is simulated by describing and tracing single vehicles. In sub-microscopic models, apart from providing a description of the characteristics of individual vehicles in the traffic stream, it also gives a detailed description of driving behaviour and vehicle control behaviour [61,62]

Existing microscopic models can be categorised into time-continuous and time-discrete models. Time-continuous models are those similar to car-following models where there is restriction imposed by physical objects or by legal rules such a speed limits. Safe-distance models, Stimulus Response models and Psycho spacing models fall under the car following models. These models are all based on differential equations and have to be solved.

The other approach is the time-discrete model which updates the velocity in discrete time steps called as Cellular Automaton (CA) or particle hopping models [63]. A well known representation of this model is the Nagel and Schreckenberg model based in cellular automaton. CA model is described as a one dimensional lattice composed of individual cells with open or periodic boundary condition. Each can be either empty or is occupied exactly by one vehicle. Each vehicle has an integer velocity with values between 0 and v_{max}. At any instant of time t, the model consists of the four following consecutive steps for each update of the system. These series of steps are updated in parallel for all the vehicles in the system. The steps are as follows:

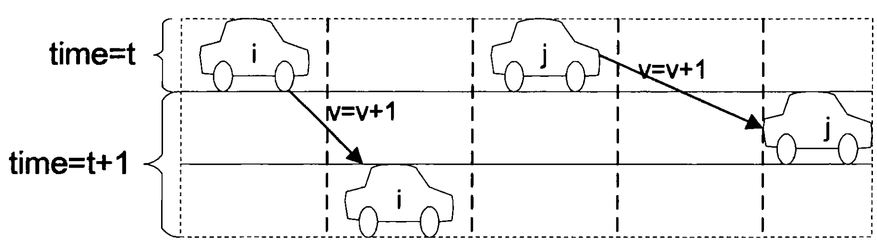

Fig 2.4 Schematic diagram of traffic cellular automaton

a) Acceleration – If velocity v of the vehicle is < v_{max} and the if the distance to the next car ahead is > $v+1$, then the velocity is incremented by one $[v \rightarrow v+1]$;

b) Deceleration – If a vehicle in cell i sees the vehicle at cell $i+j$ with $j \leq v$, the speed is reduced to one [$v \longrightarrow j$ -1];

c) Randomisation – With a probability P, the velocity of each vehicle (if greater than 0) is reduced by one [$v \longrightarrow v$-1];

d) Car motion – Each vehicle is advanced to v cells;

The CA model is very fast as a minimal set of driving rules is used. This model can be used to simulate traffic movements on large scale motorway networks, traffic assignment and traffic forecasting purposes. The CA models have been verified on German and American motorways and urban traffic networks. The results obtained are fairly realistic. The motorway simulator developed in this thesis uses the basic principles of microscopic model and the traffic movements are simulated in a similar way to the CA model.

2.4 MAC protocols for vehicular communication

In a highly mobile vehicular environment, maintaining the quality of service is very challenging. The protocols need to be configured to handle the fast topological changes. It will be of interest to observe the performance of the MAC protocols in this environment. The MAC protocols considered for vehicular communications are Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) and Dual Busy Tone Multiple Access (DBTMA) [70].

2.4.1 Carrier Sense Multiple Access (CSMA/CA)

In protocols like pure and slotted ALOHA, the users transmit messages on to the channel as soon as a message is ready for transmission. The user never senses the channel before transmitting the messages. By listening to the channel before engaging in transmission CSMA protocols achieve greater efficiencies. CSMA protocols are based on the fact that each user senses the channel before they transmit. If the channel is detected idle (i.e., no carrier is detected), then the user transmits the information based on a particular algorithm which is common to all the users in the network which ensures fairness [64].

There exist several variations of the CSMA strategy [65]

- 1 – persistent CSMA – The terminal listens to the channel and waits till the channel is idle. As soon as it senses the channel to be idle, the terminal transmits a packet with probability one.
- non-persistent CSMA – In this type, the terminal waits for a random time after receiving a negative acknowledgment, before it retransmits the packet. This technique is quite often used in wireless LANs.
- p-persistent CSMA – This is applicable to slotted channels. When a channel is found to be idle, the packet is transmitted in the first available slot with probability *p* or in the next slot with probability *1-p*.

For vehicle to vehicle communication, non-persistent CSMA/CA is used and it includes listen before talk (LBT) and a random back-off. The back-off consists of a fixed and a random waiting time. The fixed waiting time is the slot duration, for example in 802.11p, a fixed waiting time of 13 μs is used. The random waiting time is a factor of the number of slots drawn from a Contention Window (CW). The CW has a minimum and a maximum value. Each time a transmission attempt fails, the value of CW is doubled until it reaches the maximum value of CW. After reaching the maximum value of CW and if a re-transmit attempt fails, the packet is dropped. In a high mobile vehicular environment, there is a short span of time for communication and in order to be efficient, communication overhead should be minimal. Thus no frame exchange for authorisation and authentication is required before the actual data transmission [66-69]

2.4.2 Dual Busy Tone Multiple Access (DBTMA)

In CSMA/CA, the nodes sense the channel before packet transmission and in order to avoid collision between packets, however collisions are still frequent due to hidden terminal problems. Hidden terminals are the nodes in the range of the receiver and out of the range of the transmitter. In this instance, the collisions occur at the receiver end and sensing the channel before attempting packet transmission will not eliminate packet collisions. The exposed terminal problem occurs when nodes are in the range of the transmitter but not the receiver. In the case of exposed terminal problem, the node in the range of transmitter, senses the channel as busy and avoids sending packets to the other nodes. In the regular channel sensing mechanism, the exposed terminals will defer from accessing the shared channel thereby under-utilising the channel. Due to the exposed and hidden terminal problems, CSMA/CA does not suffice to achieve high network utilisation in vehicular ad-hoc networks. Other MAC protocols such as Multiple Access with Collisions Avoidance (MACA) and Multiple Access with Collision Avoidance for Wireless (MACAW) have been proposed attempting to address the hidden and exposed terminal problems but they have not been highly successful in eliminating the problems.

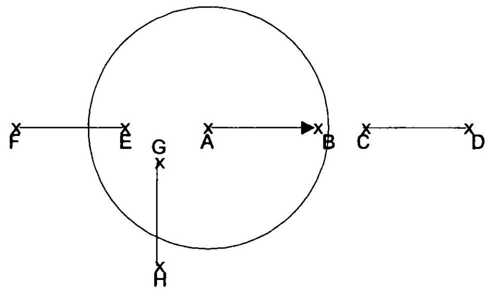

Fig 2.5. Diagram for hidden and exposed terminal problems

In the DBTMA protocol [70-72], two out-of-band busy tones, namely the transmit busy tone (BT_t) and the receive busy tone (BT_r), are used to protect the request to send (RTS) packets and data packets. The RTS packet initiates the channel request and sets the transmit busy tone as in fig.2.6. At the end of an RTS transmission, the transmitter resets the transmit busy tone. On the receiving side, the receiver acknowledges the RTS packet by setting the receive busy tone and provides continuous protection for the in-coming data packets. Nodes sensing busy tones in any of the channels defer from sending their RTS packets.

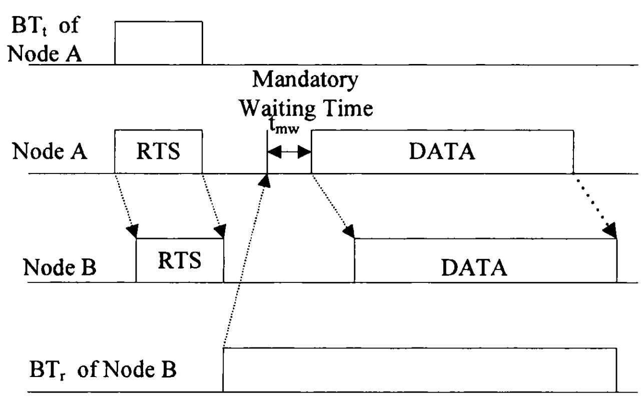

Fig 2.6 Timing Diagram for DBTMA [70]

There are total of 7 states in the finite state machine (FSM) of the DBTMA protocol as shown in fig.2.7.

- *IDLE*- A node with no packets to send remains in this state.

- *CONTEND*- A node with a packet ready to be sent but is not allowed to sent a RTS packet, stays in this state.
- *S_RTS*- A node transmitting RTS packets will be in this state.
- *S_DATA*- A node transmitting data packets will be in this state.
- *WF-BTR*- The node sending the RTS packets waits for the acknowledgement from its receiver in this state.
- *WF_DATA*- The receiving node waits for the data packet while waiting in this data.
- *WAIT*- The node sending the data packet waits for a mandatory period of time in this state. This mandatory period is meant to allow all the ongoing RTS transmissions in the range of the receiver to be aborted.

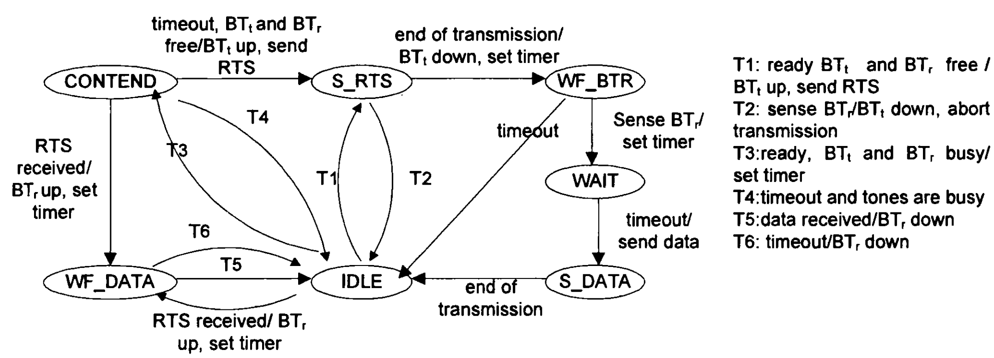

Fig.2.7 Finite state diagram for DBTMA [70]

2.5 Summary

This chapter summarises the different technologies and standards for vehicle to vehicle communications and vehicle to infrastructure communication. Different flavours of DSRC and the WAVE standards proposed for vehicle to vehicle communication were described. DSRC systems are based on IEEE 802.11a and different countries have their own standards for DSRC systems. In order to have a global standard, WAVE systems are being developed. The WAVE systems use the 802.11p PHY and MAC layer. The MAC layer in WAVE is identical to 802.11e Enhanced Distributed Channel Access (EDCA) Quality of Service extension. The application layer is defined by IEEE P1609 standards. For vehicle to infrastructure communication, technologies providing large data rates in a highly mobile environment and covering large ranges were presented. LTE belonging to the 3GPP family could possibly meet the requirements demanded by the vehicle to infrastructure communication systems was described [12]. The conventional mobility models for vehicular traffic were discussed. Among the three mobility models, microscopic mobility model present the interaction and behaviour of the vehicular system in detail, mesoscopic model focuses on behaviour of individual in probabilistic terms and the macroscopic model describes the behaviour of aggregated traffic. MAC protocols like CSMA/CA and DBTMA are proposed. To overcome the problems of hidden and exposed terminals, DBTMA is suggested. The following chapter will present the review of literatures with respect to vehicular communications and protocols.

Chapter 3

Literature Review

3.1 Introduction

Vehicular networks have received wide attention due to increased demand of communication anywhere at anytime. The vehicular networks possess specific characteristics [11,23] such as 1) intelligent computing and sensing abilities; 2) high mobility but regular and predictable patterns due to the pre-existing motorway geometry; 3) dynamic network topology and vehicular density; 4) tendency to form groups where the vehicles follow each other with similar speeds; and 5) large scale networks. There are two types of applications for vehicular networks – the real time applications such as safety messages, video data and the non-real comfort applications such as road traffic, weather conditions, parking, toll service, travel information support. The two key requirements in vehicular networks for safety and comfort applications are data reliability and low latency. The applications require wireless exchange of various types of data between vehicles. Different types of data have different requirements and hence it is necessary to distinguish between real time data with low latency such as safety messages and video data and non real time data such as road traffic information, weather conditions, parking and toll services and travel information support. Both vehicle to vehicle (V2V) and vehicle to roadside (V2R) communication systems are used for the different telematics applications. There are two main factors to be considered while building a communication system – costs and performance tradeoffs. V2V is preferred for economical reasons due to absence of infrastructure. However, V2V is also very challenging since it requires intelligent design algorithms to support various data requirements in different traffic conditions, to sustain rapid topological changes and minimised packet losses due to disruption prone links. A pure vehicle to vehicle (V2V) network as a standalone system cannot be deployed as it requires access to online resources such as the Internet for the applications [24]. On the other hand, vehicle to roadside (V2R) communication provides reliable data links and high data rates but the infrastructure installation can be expensive. To overcome the shortcomings of both networks and to maximise the performance, a hybrid network combining both V2V and V2R is proposed in this thesis. In a hybrid network multiple wireless technologies can co-exist in an area.

The vehicular network applications also require a medium access control protocol which is fair and efficient. Protocols such as CSMA/CA slotted ALOHA experience high packet delay and data congestion as the number of vehicles contending for the channel in the network becomes large. Therefore to aid these MAC protocols clustering of vehicles is considered in order to enhance the communication reliability and improve the network stability between the vehicular nodes. This thesis proposes to use a hierarchical clustering system with a cluster head selected for the group based on various constraints. The cluster head acts as a point of communication between vehicles in a cluster and also between the cluster and roadside communication infrastructure. The topological changes and vehicular movements will be updated at regular intervals. The formation and de-formation of clusters should be fast to minimise the time lost to clustering and should have few cluster head changes to enhance the stability of the network. The medium access control protocol combined with a good clustering technique can overcome the drawbacks of using a broadcast transmission, reduce data congestion and thus increase the probability of success of delivery of safety and comfort message types.

This chapter provides a critical review of the open literature on V2V and V2R networks and focuses on various clustering techniques studied for vehicular adhoc networks.

3.2 Vehicular Networks

3.2.1 Vehicle to vehicle (V2V) communication networks

Vehicle to vehicle (V2V) communication was originally used for transmitting safety messages. Recent research activities have shown a lot of interest in comfort driven applications. The applications include navigational driver assistance, road information services and infotainment applications such as games, file downloads, video on demand, web browsing, email access, file sharing etc. V2V networks can be an attractive choice in rural areas or developing countries with poor coverage or limited infrastructure facility. The deployment of V2V networks are cheaper and also avoids the fast fading, short connectivity and high frequency handoffs caused by the relative high speed difference between the vehicles and stationary roadside infrastructure. However, the system poses challenges in terms of rapidly changing environment due to high mobility, regular disruption to the network, frequent updating of routing table with the position information and poor reliability due to the interruption in the link topology. Vehicular mobility patterns can be used to propagate information from one network partition to another [73]. As a result of fast movements, well studied structures such as clusters, trees and grids for efficient data dissemination could be very difficult to set up. Flooding the network with data can result in heavy congestions as the node density will be high in rush hours or traffic jams. Therefore localised algorithms are preferred and techniques such as data replication and diversity can be utilised to improve the performance of the V2V networks

As the authors in [20] points out, the main challenges in vehicle to vehicle communication are – 1) lack of centralized management, 2) high mobility, 3) hidden terminal problem, 4) channel congestion, 5) unfavourable radio channel characteristics and 5) transmission power and link layer de-synchronization. It is shown for different vehicular ad-hoc network (VANET) message types such as the broadcast of periodic messages, flooding and unicast communication, a realistic communication model is still required to counter act some of the issues in V2V communication. The authors suggest probabilistic models in dealing with all trade off situations while designing robust protocols for V2V communication.

In [6], the authors present the requirements for the communication system in V2V technology. Effective data propagation, good data rate and low latency are key parameters which defines quality of service (QoS). The paper also highlights the security aspects for the messages and considers tamper proof hardware. The authors conclude by saying that topology awareness is a crucial factor for V2V communication. They propose building blocks for mechanisms and strategies which constitute the architecture of the communication system. But, a practical implementation and simulation are required to prove the performance of their proposed system.

The QoS routing solutions discussed in [21] considers two routing techniques based on local state information and imprecise knowledge of global information. The routing mechanisms detect broken routes and they either repair the routes or detect alternate routes with desired QoS. Redundant routes are also used to support the provisioning of QoS. However, authors conclude that in a fast moving network, guarantee of QoS with their proposed routing techniques may not always be efficient. The other QoS solution discussed in [74] calculates the bandwidth and slot reservation for multihop networks as a part of the routing protocol. The results show distinct advantages with the routing protocol however the performance of the proposed QoS solution in a vehicular network is still unexplored.

In [75], the authors have conducted extensive experiments for determining the performance of video transmission in V2V scenario. The experiments were carried out to show the effect of speed and distance on the quality of video packet transmission. The results showed that the path loss was slightly higher in a highway than city scenario. Noise level remained the same for both city and highway regardless of speed and distance. The various results such as packet losses, jitter, and quality of the video were collected and intended for characterisation of VANET networks.

In [76], experiments were conducted to prove the feasibility and characterisation of VANET. The results concluded that a good signal to noise ratio (SNR) is a must factor for highway scenario, large packets with lower bit rate yield better throughput and finally the link is more readily available in highway scenarios. However, the deployment for the VANET was done using static routing and the future work proposed include comparing the experimental results with position based routing and topology based routing.

3.2.2 Vehicle to roadside (V2R) communication networks

Although vehicle to vehicle communication has progressed rapidly in the past few years, it has predominantly been used for direct exchange of short safety messages. For comfort applications listed in the previous section, access to the World Wide Web is generally required. To provide the link to the internet, roadside infrastructure could be installed along the major roads across the country. In spite of considerable research work done in V2V, the introduction and wide scale deployment of V2V communication may take some more years to come. In a pure V2V system without any roadside infrastructure, a minimum market penetration of equipped vehicles is required for full fledged functioning of services. As this requirement can be difficult to be satisfied in scenarios with lower vehicular density or in the remote areas, V2R networks could be an intermediate solution. However V2R have certain limitations such as fast fading, shorter residence time and the high costs incurred for the set-up,

In [77], the authors use roadside wireless sensor networks (WSN) as an alternative to roadside infrastructure to maintain the cost efficiency. The scheme uses 802.15.4 technology for sensor nodes. The authors propose to use WSN on the road surface or at road boundaries to measure the physical data such as temperature, humidity, light or track the vehicle movements. The authors have used a hybrid architecture combining both vehicle to vehicle and vehicle to roadside sensor communication and have mainly considered it using in accident prevention and post accident investigation.

The authors in [78] investigate the usability of wireless local area network (WLAN) infrastructure for vehicle to roadside access. Cellular networks such as GSM, GPRS and UMTS are unsuitable for V2R communication as they are expensive to build and maintain, have high subscriber cost and limited bandwidth availability. Also, with cellular networks, there is the additional overhead of connection authentication and configuration. This overhead is not affordable in the vehicular networks due to short link durations. The proposal is to use WLAN hotspots for connectivity along the road and provide an internet service. The communication characteristics were observed with different measurement configuration using Transport Control Protocol (TCP) and User Datagram Protocol (UDP) as transport protocols. The measurements show at least ten seconds connectivity for vehicles driving at 180 km/h from a single access point. A major set back is that in order to connect several access points along the road to extend the reach of connectivity is complex and requires a large distance of separation between the access points. A maximum data volume of 9 Mbytes was transmitted while crossing a single access point. On analysing the network characteristics, the authors found the behaviour of TCP in terms of the connectivity phase, packet losses and throughput is better compared to UDP in spite of the abruptly changing network characteristics but applicable only in topologically close systems with no handovers. The results The drawback with this system is for applications requiring continuous connectivity such as IP telephony, database access or file access, it is unable to provide persistent connectivity and hence unsuitable in the present state.

The authors in [79] show that environmental awareness of the position of the vehicle on the road can help to reduce packet losses, resulting in increase of throughput. It was found that at high speeds, the performance of the protocols was significantly reduced. The constraints such as delayed connection set up procedure, lengthy duration taken for roadside access point selection, MAC timeouts attributed to the poor performance of the protocols. The protocols performance could be improved by being aware of the surrounding environment. In a fast moving vehicle scenarios using wireless technologies, there is bound to be dead spots and interference causing high packet losses. It is shown by the authors that the system behaves poorly in marginal coverage areas.

3.3 Clustering Techniques

Vehicular networks are characterised by frequent changes in network topology and link path connectivity. The rapid changes may cause paths to be disconnected even before they can be utilised. Emerging comfort based applications such as internet access, high data rate downloads, drive through payments, discovering local services, tourist information etc, pose a host of completely new requirements in terms of traffic control and mobility management. These applications in contrary to the safety related applications are bandwidth sensitive than delay sensitive.

Comfort applications rely on V2R communication as they require high data rate wireless links. However for a fast moving vehicle crossing the road side unit, the duration of communication is limited and with the presence of dead spots, where the vehicle is out of the transmission range of the road side unit, the system performance degrades swiftly. The limited communication duration is quite challenging for the medium access layer as it has to ensure the availability of a channel, quality of service, efficient bandwidth allocation, and contention resolution whilst tracking the topology changes [21-25].

An alternative to this problem is to introduce a hierarchical structure [30, 31] in V2V networks and have a hybrid architecture combining V2V and V2R systems for access to the online resources. The hierarchical infrastructure is proposed, as the flat routing techniques does not always address the issue of scalability and may not yield the expected results [80]. The hierarchical technique reduces the overhead caused by maintenance and frequent updates of the routing tables. It partitions a large network in to several smaller groups and internal changes within the cluster are not required to be notified to the entire network. The communication reliability and network stability between nodes is enhanced by avoiding flooding of data in the network [26, 27]. Clustering can help with the conservation of bandwidth since the interactions between the inter-cluster takes place through the cluster head and avoids the redundant exchange of messages. It can also help in stabilising the network topology and reduces the topology maintenance overhead. Clustering technique helps to overcome the scalability problem by spatial resource reuse and hence allows the nodes in a cluster separated far apart to reuse the same frequency [27]. Clusters are formed by the nodes which share similar characteristics such as speed, location and direction [81]. The hybrid network has the following advantages such as higher capacity, improved spectral efficiency, reduced dead zones, lower cost and helps to reduce delays and packet losses. A hybrid vehicular network with a good clustering algorithm could ensure network stability leading to a better performance of the MAC protocols in vehicular environment.

Several clustering algorithms have been proposed to choose the cluster heads in both mobile ad-hoc network (MANET) [29] and vehicular ad-hoc network (VANET) [82,83]. Although some of the MANET algorithms can be reused for VANET but the performance degrades due to vehicular network characteristics. The algorithms proposed for the networks use different data replication techniques to forward the data. Some of the clustering algorithms are the Lowest ID Cluster Algorithm (LIC), highest connectivity cluster algorithm, associativity based clustering protocol, weight based algorithm, and position aware clustering protocol.

The authors in [84, 85] focussed on efficient network organisation which resulted in reliable and stable network structure in highly mobile conditions. This self organisation was done without employing any centralized controller. Also, another basic requirement according to the authors was to identify the need for conflict resolution capability. The network is arranged into a group of nodes called cluster where each node belongs to at least one cluster. A cluster head (CH) is elected which acts as the local controller of the cluster and it is grouped with the rest of the CHs to form a backbone network. The aim of the proposed algorithm, known as the Lowest ID Cluster Algorithm (LIC), for the cluster head selection is to group the clusters such that a CH is directly linked to the rest of the nodes in the cluster. The main objectives of LIC are direct communication with the nodes in the cluster to maximise network connectivity, to avoid hidden terminal problems and robust to topology changes and node losses [86]. The network is organised as cluster of nodes. Each node in the cluster is assigned a distinct ID and the node with the lowest ID is selected as the cluster head (CH). The nodes in the radius of the CH transmission range become the neighbour nodes. Each node belongs to at least one cluster. Thus the IDs of the neighbour nodes will be higher than that of the cluster head. From among the nodes, not in the first cluster, the node with the lowest ID becomes the second cluster head and neighbours of the second cluster head not in the range of the first cluster head would join the second cluster. The procedure is repeated till every node is a member of at least one cluster and has its own cluster head. Initially the node broadcasts its ID and listens to the transmission of other nodes. In the next round, the node broadcast the set of neighbours which are 1-hop and 2-hops away. The CH acts as the local controller of the cluster and it is grouped with the rest of the CHs to form a backbone network. There are two main drawbacks of the LIC algorithm. One is the node ids are arbitrarily assigned numbers without considering any other qualifications of a node for election as a cluster head. And the second drawback is nodes are susceptible to power drain due to serving of cluster head for longer periods of time.

The highest connectivity (degree) algorithm is proposed in [87, 88]. The algorithm is based on the number of neighbour nodes with which it can communicate and the node with the maximum number of neighbours (connectivity) becomes the CH. Each node broadcasts the list of nodes that it can hear. A node without a CH is called as an uncovered node and the node with a CH is called as a covered node. A node is made a CH if it has the most number of neighbour nodes which are not associated to any cluster head. In case if there are two nodes with the highest number of connectivity, the lowest ID algorithm prevails. The disadvantages with this algorithm are creation of unstable clusters and no upper bound restriction on the number of nodes in the cluster thereby resulting in low throughput.

The authors in [89] proposed the associativity based clustering protocol. This protocol uses the concept of spatial-associativity of the nodes with respect to a virtual cluster. The idea of a virtual cluster is of a geographical area divided into equal regions of circular shapes and each node will be able to identify the circle it resides in, provided the location information is readily available. Based on the geographical location, each virtual cluster is assigned an ID which can be calculated using a publicly known hash-function. Each node should be aware of the location of its respective virtual cluster and centre of the cluster. The main criticism for this clustering technique is there will be superfluous location updates flooding by every node which increases the signalling traffic causing overhead.

The authors in [90] use a weighted clustering algorithm (WCA) based on degree of connectivity, transmission power, mobility and battery power. The WCA algorithm effectively combines each of the above mentioned system parameters with certain weighing factors selected according to the system needs. The algorithm is not performed periodically and hence the communication overhead is avoided. The cluster head election procedure is invoked based on node mobility and when the current dominant rules are not capable of covering of all nodes. As the weighing factors could be changed based on need, this algorithm is quite flexible and can be used for various networks. The disadvantage with this algorithm is that it is quite complex to gather all the system information for all the nodes before clustering and this process takes a long time.

In [91], an efficient flooding mechanism is introduced for clustering in vehicular communication. Clusters are formed without exchange of protocol-specific messages before the actual data transmission. This helps in reducing the packet redundancy and routing overheads. However, this method is unsuitable for vehicular communication with a highly mobile network and large number of active communication nodes.

The algorithm given by the authors in [92,93] is based on Cluster Based Location Routing (CBLR) algorithm. The basic idea behind CBLR is that all nodes know their position and the position of the destination node. This makes the routing of the packets easy and improves the routing efficiency as the packet can be forwarded directly to the destination node. The formation of clusters is based on regular transmission of "HELLO" messages. The frequency of these messages depends on the state of the node (CH, member or a gateway node). A CH sends the HELLO messages on a higher frequency as its existence has to be notified to new nodes as early as possible. Member and gateway nodes send HELLO messages on request by the CH to ensure the topology is updated in case of any changes.

Due to the dynamic nature of the VANET, CBLR must track the changes in the topology and change the states of the nodes depending on the situation. In the algorithm in [93], each node has tables – one for all nodes it can hear (neighbour table) and one for the adjacent clusters (cluster table). The neighbour and cluster tables are used to decide on changes in the states of the nodes based on topological changes. In the case, when there are two CHs that are in range of one other, one of them has to give up their status. This decision is based on a weighted factor such as connectivity, mobility and distance to the neighbours.

In [94], each node is assigned a distinct ID which is greater than zero. For clustering purposes, each node maintains information about itself and about its neighbour nodes. On a periodic basis, this information is broadcast within the cluster and is denoted by a 5 tuple (i, h, g, iN, p), where i: node ID; h: cluster head ID; g: node geographic location; iN : ID of the next node along the path from the node to its cluster head; p:

node priority. The cluster head is elected based on the priority. A node with the highest priority among its one hop neighbourhood and in multi-hop neighbourhood becomes the CH.

In [95], the proposed clustering algorithm consists of 3 core protocols. They are the cluster configuration protocol, cluster communication protocol and intra-cluster co-ordination and communication protocol. In the cluster configuration protocol, the vehicles in the same direction are grouped into clusters containing a cluster head (CH). This is appropriate as the vehicles flowing in the same direction share similar speeds and moving patterns governed by the traffic rules and road infrastructures. This results in a relatively stable cluster topology. In this algorithm, each vehicle node is equipped with two sets of transceivers which operate simultaneously on different channels. The vehicles in the transmission range of each other form a cluster and a cluster head is elected. Each vehicle operates under one of the four states at any given time: a) Cluster head (CH), b) Quasi Cluster head (QCH), c) Cluster Member (CM) and d) Quasi Cluster member (QCM). The main objective of the cluster configuration protocol is to control the transitions between the states. A QCH has the same functionalities as a CH except for the ability to form clusters. The function of a QCM is to guarantee that the cluster member can receive messages even if it looses temporary contact with the CH or a malfunction occurs at the CH.

On initiating, the vehicle is in a QCH status and waits for an invite to join (ITJ) advertisement message from the nearby CH vehicles. A CH broadcasts ITJ messages periodically for every t_j time units. On receiving the ITJ, the QCH checks the signal strength to see if it is greater than a predefined threshold. On receiving a valid ITJ message, the vehicle sends a request to join (RTJ) message to the CH including the vehicle's id and network address. After the CH receives RTJ, it sends an ACK and adds the requesting vehicle to its cluster member list. A node is elected as a CH if it doesn't receive an invite to join (ITJ) advertisement messages within the t_j time units. As mentioned before, the CH periodically sends the ITJ messages to all its cluster members and if a vehicle doesn't receive a valid ITJ message, it is considered to be out of the transmission range of the CH and elects itself as the CH.

3.4 Summary

This chapter summarises the relevant work done in the field of V2V, V2R communication and also looked into different clustering techniques used. By clustering the V2V network, it facilitates the spatial reuse of resources thereby increasing the capacity of the system. The hierarchical architecture reduces the generation and propagation of routing information and fewer topology updates are required. Different clustering techniques were studied and drawbacks analysed which motivates the research work in this thesis.

Chapter 4

Analysis of vehicular traffic profiles and design of motorway simulator

4.1 Introduction

The traffic flow models are classified into three categories as explained in Chapter 2. These models can be used to depict the vehicular traffic dynamics and can help in getting a better outlook on the traffic flow. Most of the vehicular simulation models follow the microscopic model. Different models, described in various literatures [96] base their vehicular traffic flow on assumptions. In this thesis, the vehicular traffic profiles are based on the real time data measured on the M4. The results measured on M4 exhibit rich vehicular traffic dynamics capturing parameters that are functions of time, space, control flow measures, regular repairs and refurbishment work. It is difficult to capture these dynamics in the existing modelling tools and hence there is a requirement to design and develop an experimental motorway vehicular simulator which can accurately model the dynamic nature of vehicular traffic.

A lot of time was spent in validating and checking the simulator operations. It is important to note that all simulations ran for a time long enough to reach a steady-state. The simulator has also been validated by comparing the raw data with the simulation data for vehicular arrivals measured for every hour. The results obtained from the simulator are in good correlation with the real data indicating the competence of the simulator. Therefore, the simulator designed can be considered to be a reliable tool that has modelled the proposed network.

This chapter comprises of 2 sections. Section 4.2 deals with the vehicular traffic models obtained from TrafficWales M4 data which will used as an input for the motorway simulator. Section 4.3 describes the motorway vehicular simulator. The motorway simulator forms the basis for the all simulations carried out in the thesis.

4.2. Vehicular Traffic Models

Accurate models for vehicular traffic are required to implement clustering dynamics more accurately. For this purpose in this section, an in-depth analysis of real vehicular data to understand key traffic characteristics such as traffic flow rate, average speeds, lane behaviour and study the impact of different vehicular traffic densities on the base station for multimedia communications in a motorway scenario. The main objective of this section is to propose a realistic mobility model of the vehicular traffic flow depicting the real world which can facilitate the application of the clustering algorithm.

The vehicular arrival model is derived from the Traffic Wales data and is fed into the simulator. The motorway traffic simulator uses this model as an input and simulates vehicular movements based on time-discrete microscopic traffic model.

4.2.1. Raw vehicular data collection and data pre-processing for motorways

Motorways are part of a nation's transportation infrastructure and it is specifically designed for high speed vehicular traffic. Different countries have different conventions for motorways but have common characteristics such as junctions, round about, lane indicators, and hazard and information boards [12]. Also, cameras stationed in the stretch of the motorway and inductive loops record vehicular statistical data such as number of vehicles, types of vehicles and average vehicles speed over different time durations. These features of the motorway aim to improve the traffic flow, safety such as collision avoidance, relay of poor weather conditions, co-operative driving and infotainment. There has been a marked rise in the development of motorways in UK [97] and it can been seen in the increased refurbishment works on the motorways such as increasing the number of lanes, widening the lanes, changes in the round about and junctions. The traffic flows on the motorways vary according to the time and day of the week, weather conditions and accidents [98].

Different distributions are used to describe the vehicular arrivals for situations such as low, medium and congested traffic flow [12]. These distribution models can be deployed in scenarios where there is not enough data to predict the traffic flow. Discrete distributions such as Poisson (for low density traffic), negative binomial (for varying flow) and binomial distribution (for congested flow) can be deployed to predict the traffic flow patterns. There is not sufficient literature describing the dynamics of the vehicular flow in the motorways of UK and hence, the following sections will elucidate in detail the nature of the motorway vehicular arrival profiles specific to UK.

Traffic Wales, responsible for traffic management in Wales UK have provided traffic profiles on the M4 motorway for the past 5 years to help in research for implementing an accurate vehicular traffic model. The data set comprises of data obtained from the inductive loops in M4 between Swansea and London. There are 585 inductive loops in the stretch each spaced 500m apart. A map of the stretch is given below in Figure 4.1.The raw data set provided by Traffic Wales comprises of inductive loop id, lane, average speed, traffic flow in each lane, average vehicle time headway, traffic occupancy and time.

Fig.4.1 M4 stretch between Swansea and London

4.2.2. Vehicular Arrival Model

Traditional traffic flow models for vehicles follow vehicle traffic flow theory [99,100]. There are three main parameters characterising the traffic flow. They are flow q (vehicles/hour), speed v (km/h) and density d (vehicles/km). The basic traffic stream model is expressed by [99,100]

$$v = \frac{q}{d} \tag{4.1}$$

Statistical analysis was done on the M4 data to derive an accurate vehicular arrival and speed models. These models are used as an input to the vehicular simulator for simulating realistic vehicular traffic. Further studies were carried out on data for different inductive loop ids and similar trends were observed. The mathematical analysis presented in this thesis is based on the data recorded by the inductive loop id 2198 for different days in May 2002 from 00:00 to 23:50 consecutively for 24 hours. The data provided was in minutes rather than seconds and in some rare cases, the data was missing. So the values have been averaged to carry on with the analysis. Fig.4.2

shows the average vehicular arrival rate for every 5 minute interval for all the three lanes obtained from the M4 data.

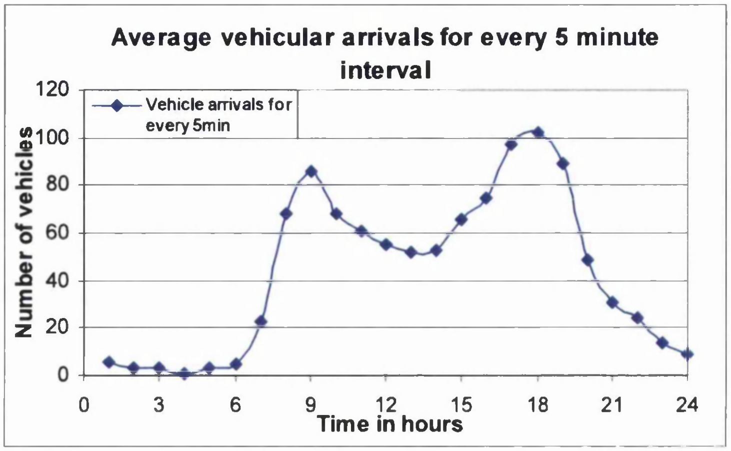

Fig 4.2 Average vehicular arrivals obtained from Traffic Wales data

A 2 peak Gaussian distribution for multiple peaks is used to fit the data [101]. The chi square test (X^2) is performed which yields a value of 0.064759. A low value of X^2 indicates the level of independence. Fig.4.3 shows that a good agreement exists between the real and fitted data thereby predicting the vehicular arrival model to follow a 2 peak Gaussian distribution.

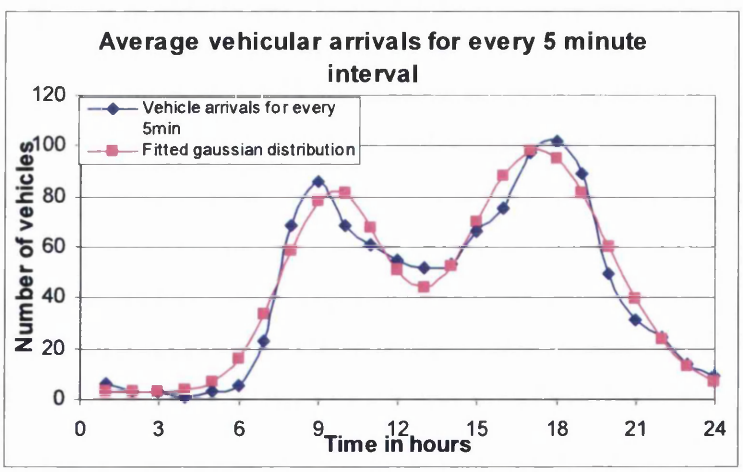

Fig.4.3 Collected traffic flow data vs fitted data

Another important parameter is the traffic intensity per lane. Fig. 4.4 shows the number of vehicles in different lanes in the motorway. It can be seen that in the early hours of the morning, lane 1 has the highest number of vehicles. The reason for this is a large number of heavy good vehicles (HGVs) travel at that time as compared to the other vehicles and also HGVs normally travel in lane 1 unless and until they have to overtake any other vehicle or an obstacle. However, after 6:00am lane 2 exhibits an increasing number of vehicles arriving at the motorway due to business traffic before 09:00am and subsequently in the evening lane 2 and lane 3 have a much higher number of vehicles as compared to lane 1.

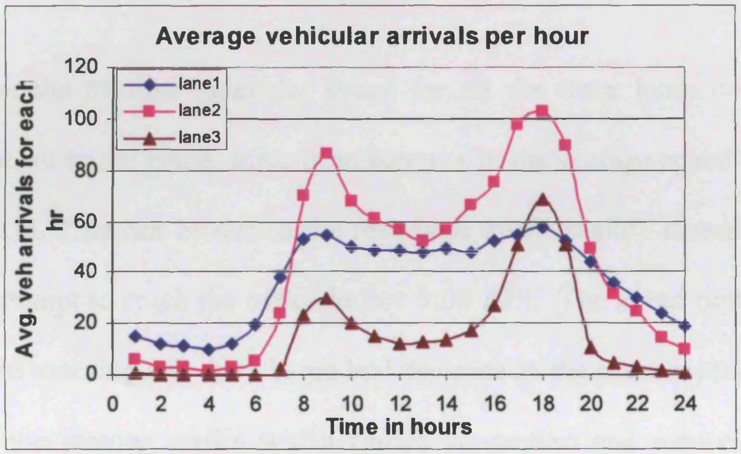

Fig.4.4 Average vehicular arrivals per hour for the 3 lanes

4.2.3. Average vehicular speed analysis

The vehicular speed is averaged for all the three lanes, for a 24 hour period and the probability density function is given in fig.4.5. It can be seen from the graph, the average speed for the vehicles is around 30m/s (metres/sec) (108km/h, 67 miles/h) and in some cases it can reach a maximum speed of 35 m/s and a minimum speed of 15m/s.

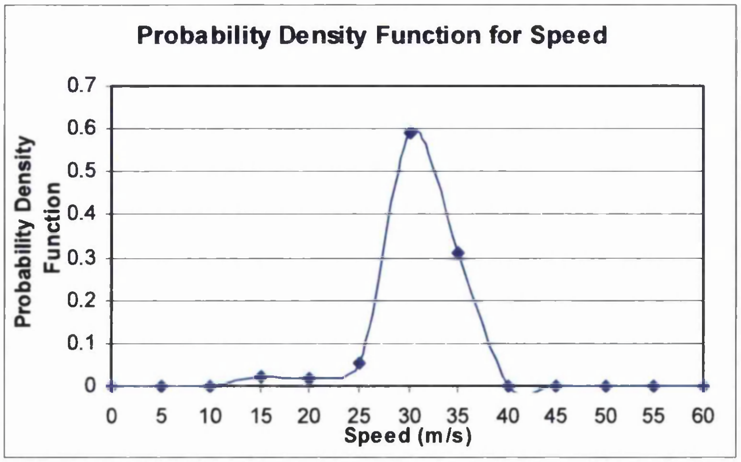

Fig.4.5 Probability density function for average vehicular speed in m/s for the 3 lanes

Fig.4.6 shows the average vehicular speed for all the three lanes over 24 hour's period. As shown in the graph, there is an increase in the average speed between 6:00 AM – 8:00 AM. This can be due to the rush hour traffic mainly consisting of office goers in an attempt to reach the office before 9:00 AM. The speed remains constant for most of the morning and there is gradual decrease as the noon approaches. This is attributed to the moving traffic which causes congestion and reduces the average speed.

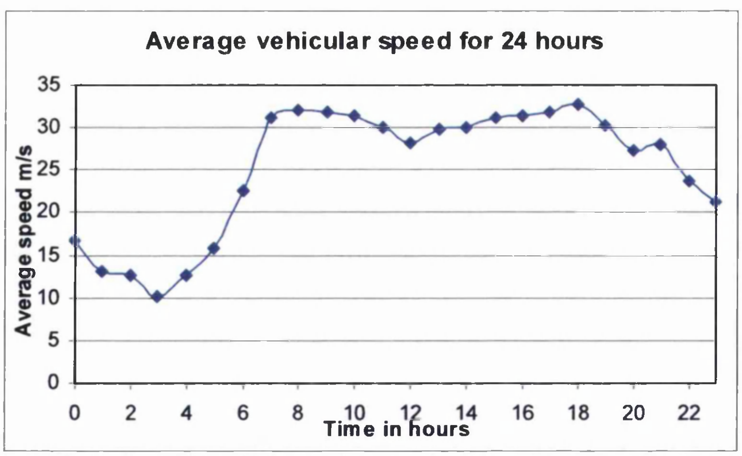

Fig.4.6 Average vehicular speed in m/s for the 3 lanes

4.2.4. Vehicular inter-arrival times

Fig.4.7 represents the Probability Density Function (PDF) of the inter-arrival times. The figure shows the inter-arrival times for majority of vehicles are between 25-75 seconds. These values are based on the traffic for all the 3 lanes and for the whole 24 hours.

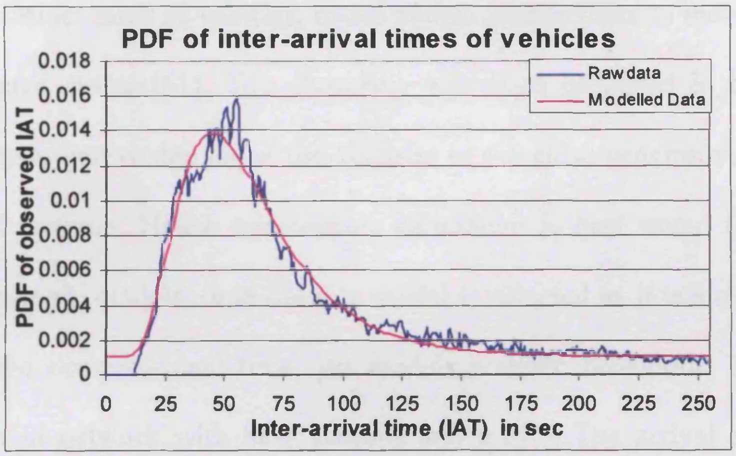

Fig. 4.7 Probability Density Function (PDF) of inter-arrival times

The motorway simulator explained in the next section uses the above models to generate the traffic flow per hour.

4.3. Design and implementation of the motorway vehicular simulator

The motorway vehicular simulator was designed to implement the dynamic traffic flow parameters measured from the M4 data. Initial assumptions are required to build a simulator and the assumptions are listed as follows:-

1) 3 lanes unidirectional motorway is considered. Lane width is 3.65m (highway agency quotes) [102]

2) Vehicle arrival times and speed are obtained from the model derived from Traffic Wales data. The Traffic Wales data set comprises of data obtained from the inductive loops in M4. There are about 585 inductive loops in this stretch each spaced 500m

apart. The data is the measure of vehicle speed in a particular lane crossing the inductive loop at a particular time and this is measured for a series of inductive loops in M4.

For the simulator, the time-discrete microscopic model is used. Microscopic models represent all entities such as vehicles, round about, intersections as individual objects in the simulated system[61]. The clustering algorithm proposed in this thesis, is expected to have knowledge about the vehicles in the close proximity, their speeds, direction and position. Hence microscopic simulation is best suited for this setup. Within microscopic models, time discrete model is selected as it is simple and helps in reducing the computational time, yet models realistic behaviour. The simulator models the road network with base stations and traffic. The arrival pattern of the vehicles into the road network must be realistic because the evaluation depends on the validity of the traffic used within the simulations.

In the simulation, each lane in the motorway is divided into boxes of 2m size as shown in fig.4.8. The reasoning behind selecting 2m as the size of each box is, this thesis proposal considers vehicles with an average length of 4m which is an average length of a car. The value is obtained from the official Highway Code. As the study covers different vehicle classes such as coaches, trucks etc, for which the length varies from 12m to 16 m according to the Department of Transport. The box size of 2m is easier for representing all vehicles and help in the discrete movement of the vehicles based on the speed.

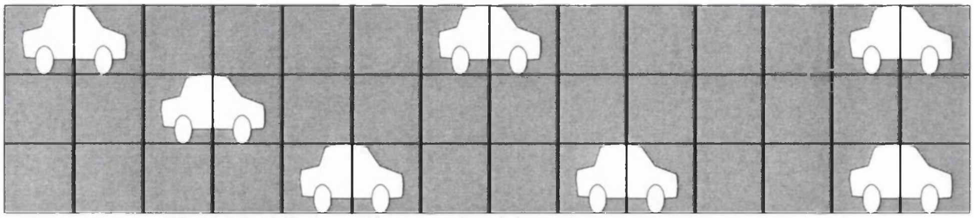

Fig.4.8.Depiction of lanes and vehicle placements in motorway

A partial motorway stretch of 5km length is considered for this study and as the simulator is flexible the length can be increased or decreased. The vehicular arrivals and speed model are fed into the simulator. Upon arrival of each vehicle, the speed and lane are assigned.

There are other important variables defined to control the flow of the simulator. The variable *TotalBoxes* represents an array of 2m boxes dividing the entire stretch of the motorway length and this array variable can be changed according to the requirement. The variable *sysTimer* is a global timer which is used to generate and update the events for vehicular movements. The variable *ArrVehnos* keeps a count of arrived vehicles. The function *StepIncrements* takes care of updating the location of the vehicles. The function *SpeedCalc* calculates the position of the vehicle based on the speed.

Fig.4.9. shows the operation of the motorway simulator. The vehicles entering the motorway are assigned speed and lane based on the vehicular traffic models derived from the previous sections. For every increment of the global timer *sysTimer*, the function *StepIncrements* is used to update the position of the vehicle based on the function *SpeedCalc* output. The function *SpeedCalc* checks the distance of the vehicle ahead. In case, there is no vehicle, the vehicle remains in the same lane maintaining the same speed. The new position is updated based on the current speed.

But if there is vehicle ahead in the same lane and there is not enough space for the vehicle to maintain the original speed, the function is left with two options, either to change lanes provided there is space in the adjacent lane or reduce the speed. If the vehicle changes lanes or reduces speed, the vehicle will continually monitor for space to shift to its initial lane and initial speed. Once the vehicles reach the end of the motorway stretch, it is fed back into the simulator. This is done to achieve a steady state where the birth and death rate of the vehicles are same. The simulator is run for a 24 hour period after which it stops.

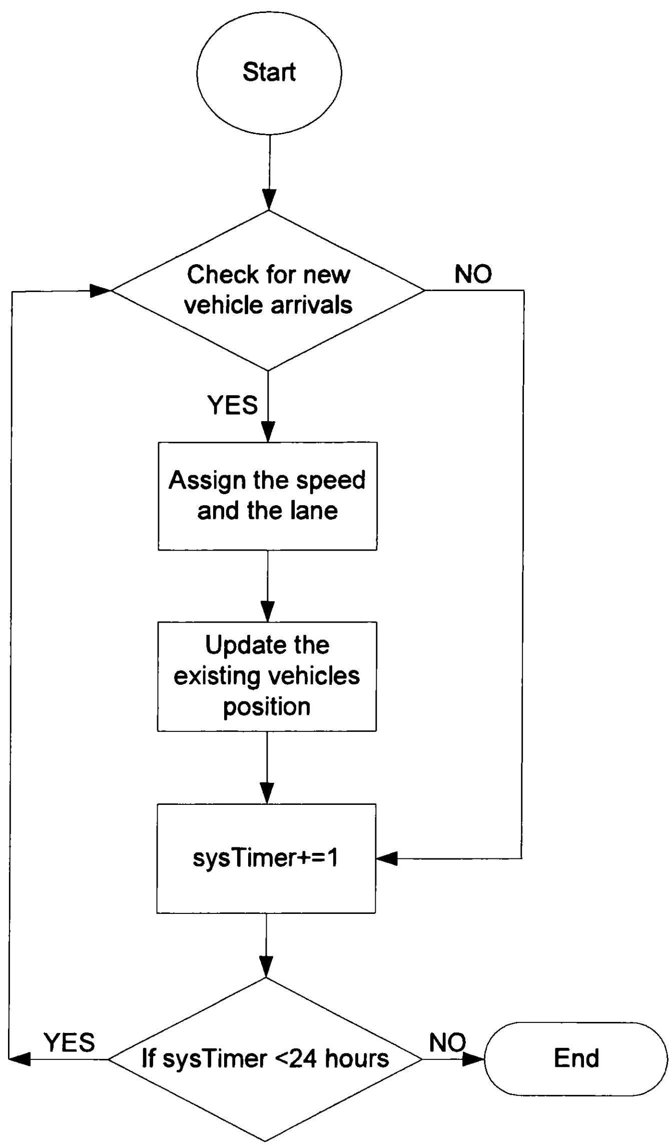

Fig.4.9 Flowchart for the motorway vehicular simulator

The motorway vehicular simulator has been designed in a logical and a consistent fashion with all the mechanisms for motorway vehicular movements incorporated and an attempt has been made to make it error free and accurate. The simulator does not require huge computing resources to provide results and independent of operating system and machine.

In order to prove the competence of the designed simulator, it is validated by generating vehicular arrivals for each hour on the motorway according to the 2 peak Gaussian distribution whose parameters are extracted at 5 minute intervals from the measured data as shown in Fig. 4.3. Fig.4.10 demonstrates that both the real traffic flow data and simulated vehicular arrivals based on the modelled data are in good agreement. Consequently, these figures show that the arrival of vehicles at a base station on the M4 follows a 2 peak Gaussian distribution, and illustrates the accuracy of the simulator.

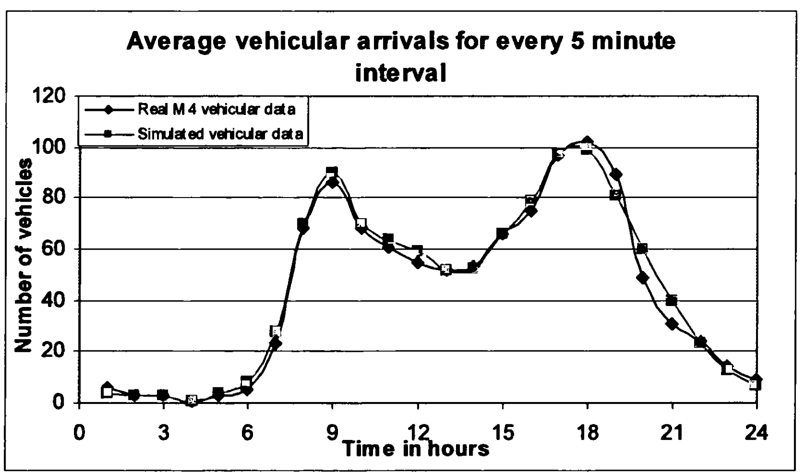

Fig.4.10 Collected vehicular arrivals vs simulated vehicular arrivals for every 5 minute interval

4.4. Summary

This chapter presented the vehicular traffic model and implementation of an experimental motorway vehicular simulator. The vehicular traffic model was obtained from the Traffic Wales data set. A 2 peak Gaussian distribution was fitted for the vehicular arrival model. Different statistical analysis was carried out for vehicular speed and vehicular-inter arrivals times. These traffic flow parameters are used as inputs to the motorway simulator used to simulate the vehicle movements. The simulator used event driven simulation and discrete microscopic model for vehicular movemnts. The simulator is further extended in the Chapter 5 to integrate the proposed clustering algorithm.

Chapter 5

Design and performance evaluation for Minimal Path Loss Ratio (MPLR) clustering algorithm

5.1. Introduction

The popular clustering algorithms and vehicular networks (both V2V and V2R) were compared in Chapter 3 as part of literature review. Though different clustering algorithms were studied, there is still a need to study these algorithms for vehicular networks. Vehicular networks possess dynamic network conditions and hence the performance of these algorithms in fast moving environment has to be studied. The vehicular network used for performance analysis of the algorithms will be a hybrid type network combining both V2V and V2R networks. The hybrid vehicular network has several advantages such as improved spectral efficiency; capacity etc. over a pure V2R system. For a hybrid system to function efficiently, the V2V tier of the hybrid network should be able to offer stability with fewer topological changes. The V2V network employs hierarchical architecture for communicating between vehicles. In a hierarchical clustering system vehicles are grouped to form a cluster and a cluster head is selected for the group based on various criteria. The cluster head is intended to act as a relay point of the communication between vehicles in a cluster and also between vehicles and the roadside base station. The vehicle clustering is periodically updated to reflect the topological changes and vehicle movements. The clustering should operate fast to minimise the time lost in organisation of the wireless links and minimize the cluster head changes for the stability of the network. Hence, a good clustering algorithm should reduce the adverse impact of dynamic network topology changes and ensure a better performance of the MAC protocols. This chapter proposes a novel clustering algorithm which takes into consideration the above mentioned factors for network stability.

Clustering algorithms can have significant impact on the communication performance of the vehicular networks e.g. network throughput, message delivery delay and collision ratio. On the other hand, the dynamics of clustering algorithm can also affect the stability of the network. Therefore the proposed clustering algorithm is to be evaluated and compared from two aspects: 1) comparison with a pure V2R system; 2) comparison with other clustering algorithms for the robustness of the algorithm.

The chapter comprises of 8 sections. Section 5.2 concentrates on explaining the proposed clustering algorithm, the rules for cluster creations and the performance metrics. Section 5.3 describes the mathematical model for the algorithm. Section 5.4 presents the system setup. The performance metrics for the clustering algorithm are obtained from the simulator and are explained in detail in section 5.5. Section 5.6 looks into the comparison of the change of cluster head metric with other popular clustering algorithms. Finally section 5.7 compares the hybrid system (V2V+V2R) to a pure V2R system in terms of throughput, average access delay and PDP.

5.2. Clustering algorithm based on physical constraints

In hierarchical clustering architecture, a cluster head (CH) is selected to act as the co-ordinator for data exchanges within the cluster and also between the cluster and the base station. Although the cluster head acts as the controller of the cluster, it is different from base station, in that it does not require special hardware. The vehicles in transmission range of each other are grouped together to form a cluster and the cluster head is dynamically selected from this group of adjacent vehicles. The cluster head is selected using an algorithm. Different algorithms base their cluster head election on different factors. For example, the lowest id clustering algorithm nominates a node with the least id value as a cluster head and for a highest degree algorithm, the cluster head is elected depending on the degree of connectivity within the group.

This thesis proposes a clustering algorithm with two main objectives- a) the network should be fairly stable with lower cluster head changes and b) the elected cluster head should have good signal strength as they will act as a point of relay between the vehicles and base station. Hence the proposed algorithm is based on the two main physical constraints - a) path loss which is characterised by the distance between the vehicle and base station and b) interference between vehicles for communication.

5.2.1. Cluster creation rules

Clusters are created according to a set of factors such as the size of cluster, cluster head nomination, and single cluster creation. These factors are described in detail as follows:

1. **Cluster Size:** This is determined by the coverage range, the data flow, channel availability and also by traffic demands (service requests). The coverage range is limited by transmitter/receiver device.
2. **Cluster head nomination:** This is an important rule for the cluster creation and is based on physical constraints such as distance (associated with loss), environment noise (reflections due to terrain conditions/ infra structure and interference with other vehicles) and antenna/base station position (also

features such as height). Cluster heads are selected based on distance parameter between the vehicle and base station. The other physical constraints will be part of the future work.

3. **Single cluster formation:** The rules for a vehicle to form a cluster with a single vehicular node are as follows:-
    a) This can happen when a vehicle is isolated i.e., there are no vehicles within its transmission range.
    b) The nearest cluster is fully loaded i.e. it will not be able to service any more requests and long delays are expected.
    c) The next to nearest cluster cannot provision good signal quality.

There is an increase in the cost factor with formation of a single vehicle cluster but it can be compensated for long anticipated delays and poor signal quality.

5.2.2. Clustering technique

The clustering technique is identified by a set of key events in the system. The cluster head is selected based on the physical constraints such as distance (associated with loss), environment noise (reflections due to terrain conditions/ infra structure and interference with other vehicles) and antenna/base station position (also features such as height). Loss and Attenuation are both related to distance factor while fading is related to terrain conditions and physical obstacles such as buildings. This thesis selects the cluster head based on the path loss factor and the other constraints will be considered for the future work. Path loss is influenced by the terrain conditions, distance between the transmitter and receiver and the height and location of the antennas. For the motorway scenario, the terrain conditions and the location of the antennas will not make a huge impact to the path loss. Therefore the varying factor influencing the path loss is defined by the distance between the vehicle and the roadside infrastructure. Hence a longer distance of separation between the vehicle and roadside infrastructure has a higher path loss which implies a drop in the signal strength. A vehicle with minimal path loss is a good candidate for the cluster head. Fig.5.1 shows a finite state diagram for selecting a cluster head.

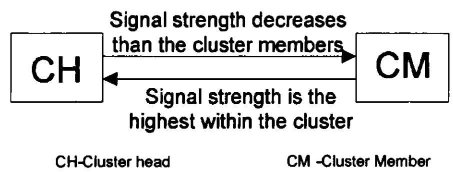

Fig 5.1 Finite state diagram for selecting a cluster head

The vehicle within a cluster can experience interference from the neighbouring clusters. Hence the communication between the cluster members and the cluster head is affected by the interference from the surrounding vehicles. The vehicles in an overlapping cluster experience high interference and this has to be considered in the clustering algorithm. The vehicles in the overlapping regions refrain from transmitting on the channel if it hears an ongoing transmission from the vehicle in the overlapping clusters. Fig.5.2 depicts overlapping clusters with cluster heads CH1 and CH2. Node C and E are in range of each other and hence experience interference when any one of them transmit to their cluster. In the fig 5.2, while node E is transmitting to CH2, node C doesn't transmit or receive from CH1. The dotted line between node C and node E shows that they are in range of each other's transmission.

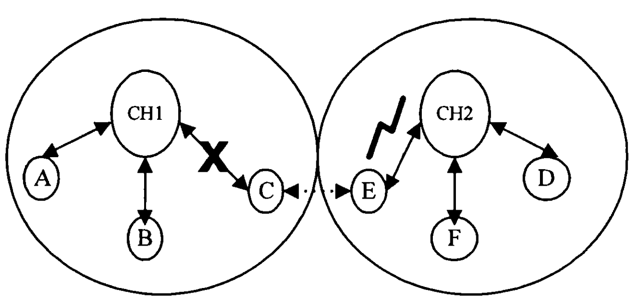

Fig 5.2 Overlapping clusters

The key events which characterise the clustering algorithm are – a) cluster head nomination for a new vehicle joining the motorway; b) the cluster head changes due to the signal strength variation; c) the cluster head moving out of range of cluster; d) a cluster member moving out of range of cluster head; e) meeting of two clusters and finally f) single cluster formation.

The algorithm for electing the cluster head has the following procedures:-

1) Node entering the motorway looks for any existing cluster heads within its transmission range. If there is a cluster head already present, the newly arrived node checks its distance from the base station and compares it with the distance between the existing cluster head and base station. Based on the shortest distance to the base station the cluster head is selected. This is a standard procedure for selecting a cluster head.
2) When cluster head moves out of range of cluster, it performs the standard procedure for selecting the cluster head. If there are no other cluster heads near by, it becomes its own cluster head.
3) When a cluster member is moving out of range of the cluster, it tries to look for a cluster head within its transmission range and if unable to find a cluster head nearby, it becomes its own cluster head.
4) When two clusters come in the proximity range of each other, a new cluster head is selected based on shortest distance between the node and the base station.
5) Single cluster formation is influenced by 3 cases; first case, when the vehicle is isolated from the rest of the vehicles with no vehicles within the transmission range, second case, the nearest cluster will not be able to service more requests and in the third case, the next to nearest cluster doesn't have good signal quality.

5.2.3. Performance metrics for clustering

The performance of the algorithm is measured by three metrics to ensure network stability and robustness with respect to V2V communication. They are rate of change of cluster head, average cluster size and average number of clusters supported by a single base station.

a) Rate of change of cluster head: There is a need to assess the number of cluster head changes in the network in order to have an idea about the average life time of a cluster head. The average cluster head lifetime combined with rate of change of cluster heads measures the mobility of the network i.e., tells about the reconfiguration speed of the network. This will assess the robustness of the algorithm. A mathematical analysis in section 5.3 is presented for the rate of change of cluster heads.

b) Average cluster size: This gives an average capacity of a cluster. This metric is useful in determining the average number of service requests that can emerge from a cluster and this information can be used during the cluster head to base station communication.

c) Average number of clusters supported by base station: A base station can support a number of clusters. Knowledge about the maximum number of clusters will help in the efficient bandwidth allocation and communication relay of both cluster head –base station and intra cluster communication. This metric places a limitation on cluster creation.

5.3. Mathematical analysis for rate of change of cluster heads

Of the three main performance metrics described in section 5.2.3, the rate of change of cluster heads i.e. the number of cluster head changer per time unit, will measure the network stability and robustness of the algorithm. A lower number of changes of the cluster head imply a better stability of the network. A mathematical model is derived to define the rate of change of cluster head and will be verified and compared with simulation results later in the section.

The main rule for a cluster head change is based on the path loss associated with the distance of the vehicular node to the base station. The vehicular node closer to the base station is elected as the cluster head for a cluster. The mathematical expressions for rate of change of cluster head are derived for 1 lane and 2 lanes scenarios leading to three lanes motorway. The lane width is taken from the Department of Transport and is given as 1.75m.

Hypothesis for the model

A cluster is formed when there is a new vehicle entering the motorway. A new mid point N or I is formed between the vehicle already in the motorway and vehicle just entering the motorway, provided they are within the transmission range of each other. The mathematical analysis is structured in three subsections for 1 lane, 2 lanes and 3 lanes, respectively. Assumptions and notations for each section will be listed along with mathematical derivation of rate of change of cluster heads for the different lane numbers and for both constant and variable speeds.

5.3.1. Mathematical derivation for rate of change of cluster heads for one lane

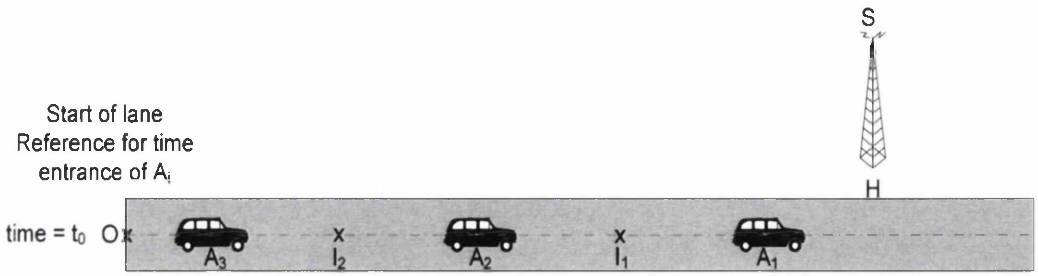

Fig 5.3 Change of cluster head for single lane

Fig.5.3 demonstrates a setup where all the vehicles A_1, A_2 and A_3 following each other with a base station or roadside infrastructure (SH) positioned by the side of the lane. The point O denotes of the start of the lane which is used as a reference for the time of entrance for the vehicles. The vehicle closest to the base station becomes the cluster head.

Notations:

The table 5.1 gives the notations used in the fig.5.3 and the derivations.

A_1	Cluster head
A_2	Immediate cluster member – defined as the cluster member following the cluster head and closest to the cluster head.
$A_i A_{i+1}$	Distance between the cluster head A_i and immediate cluster member A_{i+1}
I_i	Middle point of the segment A_iA_{i+1} (imaginary point and travelling at the same speed as A_i& A_{i+1})
$I_i I_{i+1}$	Distance between the imaginary middle points I_i and I_{i+1}
SH	Distance of the base station to the lane. (SH is perpendicular to $A_i A_{i+1}$)

Table 5.1 Notations for change of cluster head for single lane

The rate of change of cluster head is derived for two scenarios of constant and variable speeds. Case (a) and case (b) will derive generalised expressions for rate of change of cluster heads for constant and variable speeds.

1. At time t_0, A_1 is the cluster head and it forms an imaginary mid point I_1 with the cluster member A_2 immediately following A_1.
2. At time t_1, A_1 crosses the base station position SH and when I_1 meets the point H ($I_1 \equiv H$; $\equiv$ implies coincides), there is the first change in cluster head from A_1 to A_2 as A_2 is closer to the base station and it is given by

$$t_1 = \Delta t_0 = \frac{HI_1}{v(I_1)}$$

   Where HI_1 is the distance between the point H and the imaginary mid point I_1 and v (I_1) denotes the speed of the I_1.

3. At time t_2, there is another change in cluster head A_2 to A_3 as I_2 coincides with the point H.

$$t_2 = t_1 + \Delta t$$

$$\Delta t_1 = \frac{d}{v} = \frac{I_1 I_2}{v}$$

   Where v is speed of the vehicle and the mid point I_i travels at the same speed as v

4. The rate of change of cluster head (ΔCH) is given by :

$$(\Delta \text{CH}) = \frac{1}{\Delta t_1}$$

Case a - Single lane but constant speed for all vehicles

The rule for cluster head change from A_i to A_{i+1} is when I_i crosses H. The Δt_1 and Δt_2 are given

$$\Delta t_1 = \frac{I_1 I_2}{v};\ \Delta t_2 = \frac{I_2 I_3}{v}$$

Where v is the speed of the vehicle,

$I_i I_{i+1}$ is the distance between the two middle points, Therefore average time period for cluster change can be generalised as:

$$\langle \Delta t \rangle = \frac{\sum_{i=1}^{n} \frac{I_i I_{i+1}}{v}}{n-1} \tag{5.1}$$

Where n is the number of participating vehicles.

The average rate of change of cluster head (ΔCH) = $\frac{1}{\langle \Delta t \rangle}$

$$\Delta CH = \frac{n-1}{\sum_{i=1}^{n} \frac{I_i I_{i+1}}{v}} \tag{5.2}$$

Case b - Single lane and different speeds for different vehicles

The notations and diagrams are the same as in case (a) except that A_i & A_{i+1} are travelling in different speeds. A_i is faster than A_{i+1} and distance A_iA_{i+1} varies which implies I_i speed is variable as well.

The rule for cluster head change is when I_i crosses H, cluster head changes from A_i to A_{i+1} with speed of I_i which is a variable.

At t_1, H≡ I_1 (≡ implies I_1 is at the same position as H)

$$\Delta t_1 = \frac{I_1 I_2(t_1)}{v(I_2)} = \frac{HI_2(t_1)}{v(I_2)}; \quad \Delta t_2 = \frac{HI_3(t_2)}{v(I_3)}$$

As I_1 is at the same position as H, I_1I_2 can be represented as HI_2.

On generalising the above expression,

$$\Delta t_i = \frac{HI_i(t_i)}{v(I_i)}$$

Where

- v (I_i) is given by the speed of the vehicle and is given by average of the speeds of two successive vehicles A_{2n+1} and $A_{2(n+1)}$: $v(I_i)=\frac{v(A_{2n+1})+v(A_{2(n+1)})}{2}$

- HI_i is the distance between the base station and middle point I_i, and is given by:- $HI_i = OH - OI_i(t_{i-1})$

  Where OH is the distance from base station H and the starting point of the motorway assumed to be O and OI is the distance from the middle point I_i to the starting point of the motorway.

The average time period for cluster change:

$$\langle \Delta t \rangle = \frac{\sum_{i=1}^{n} \Delta t_i}{n-1} = \frac{\sum_{i=1}^{n} \frac{OH - OI_i(t_{i-1})}{v(I_i)}}{n-1} \tag{5.3}$$

Where n is the number of participating vehicles.

Average rate of change of cluster head ΔCH $= \frac{1}{\langle \Delta t \rangle}$

$$\Delta CH = \frac{n-1}{\sum_{i=1}^{n} \frac{OH - OI_i(t_{i-1})}{v(I_i)}} \tag{5.4}$$

5.3.2. Mathematical derivation for rate of change of cluster heads for two lanes

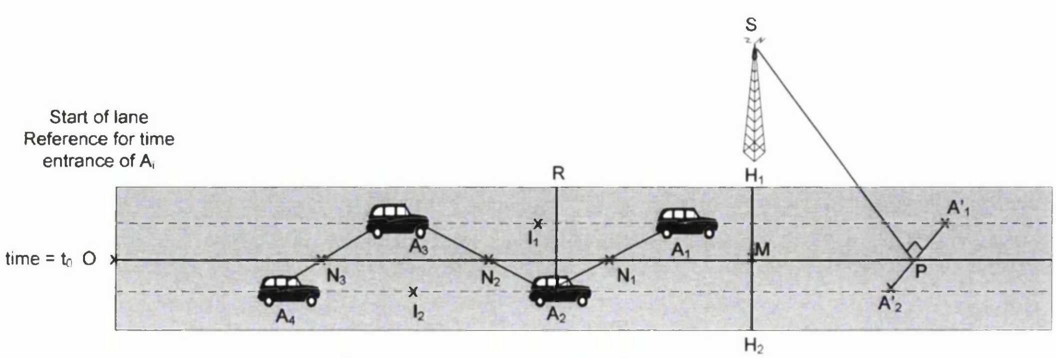

Fig 5.4 Change of cluster head for two lanes

Fig.5.4 demonstrates a setup where all the vehicles A_1, A_2, A_3 and A_4 are travelling in two lanes. A_1 and A_3 travel in one lane with A_3 following A_1. A_2 and A_4 travel in the second lane with A_4 following A_2. The base station or the roadside infrastructure (SH) is positioned by the side of the lane. The point O denotes of the start of the motorway lanes which is used as a reference for the time of entrance for the vehicles. The vehicle closest to the base station becomes the cluster head. In the first instance, A_1 is the cluster head.

Notations:

The table 5.2 gives the notations used in the fig.5.4 and in the following derivations.

A_1	Cluster head
A_2, A_3	Immediate cluster members
I_1	Middle point of the segment A_1A_3 (imaginary point and travelling at the same speed as A_1& A_3)
SH_1	Distance of the base station to the lane
H_1H_2	Lane width (1.75m)
N_i	Mid point of A_{2i+1} and $A_{2(i+1)}$ and is moving.
P_i	Imaginary static point
M	Mid point of H_1H_2

Table 5.2 Notations for change of cluster head for 2 lane motorway

For a vehicles travelling with the same speed, the vehicles A_{2i+1} and $A_{2(i+1)}$ will be moving at a same speed. In the case of they are moving at different speeds, A_{2i+1} & $A_{2(i+1)}$ are travelling at different speeds. The distance $A_{2i+1}A_{2(i+1)}$ will vary when the speeds vary which implies I_i speed and N_i speed is variable.

Mathematical Expressions for the four scenarios

There are 4 different scenarios for the two lanes setup. The scenarios are explained followed by the mathematical derivation for rate of change of cluster heads.

Scenarios:

1) The first scenario takes places when the vehicles A_1, A_2, A_3 and A_4 are moving at the same speed. If A_1A_3 and A_2A_4 are aligned as in the diagram fig.5.5, the rate of change of cluster heads is same as in case (a) for one lane scenario.

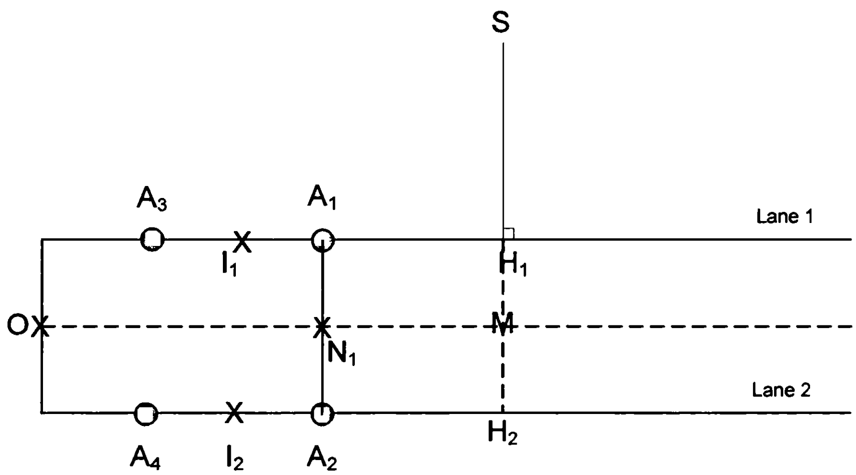

Fig 5.5 Change of cluster head for variable distance and constant speed in two lanes

2) In second scenario, the vehicles A_1, A_2, A_3 and A_4 are moving at different speeds. A_1 is the cluster head as it enters the motorway first. A_1 and A_3 are moving in one lane while A_2 and A_4 are moving in the second lane. The position of A_2 is between A_1 and A_3 and the projection of A_2 on A_1A_3 is given by R as in the fig.5.6. N_i is the mid point formed between the vehicles in different lanes (for e.g.N_1 is the imaginary mid point between A_1 and A_2). The cluster head will change from A_1 to A_2 after the point N_1 coincides with point P_1 with $P_1A'_1=P_1A'_2$. SP_i is orthogonal to $A'_1A'_2$, where A'_1 and A'_2 are the expected positions of A_1 and A_2 at Δt_0. SP intersects MN_i.

The distance MP_i is given as: $$MP_i = \frac{SM}{\tan\left(a\cos\left(\frac{H_1H_2}{A_{2n+1}A_{2(n+1)}}\right)\right)} \quad (5.5)$$

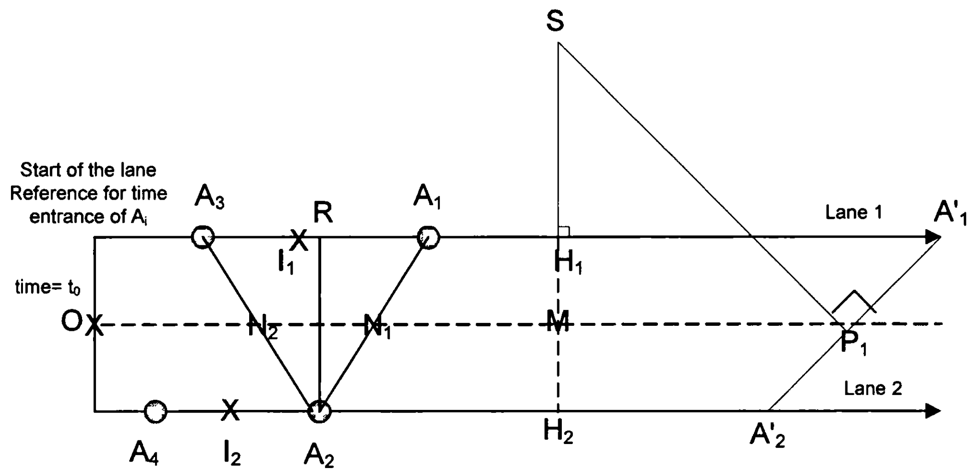

Fig 5.6 Change of cluster head for variable distance and constant speed in two lanes

The cluster head change will follow A_1->A_2->A_3->A_4 sequence.

At time t_1, the cluster head changes from A_1 to A_2 when N_1 crosses the static point P_1.

Therefore, the time it takes to change is given by

$$\Delta t_0 = \frac{N_1 P_1(t_0)}{v(N_1)}$$

Where N_1P_1 gives the distance between the mid point N_1 and the imaginary static point P_1

$v(N_1)$ gives the speed of the N_1 and is the average of speed of vehicles A_1 and A_2

At time $t_2 = t_1 + \Delta t_1$, the cluster head changes from A_2 and A_3.

$$\Delta t_1 = \frac{N_2 P_2(t_1)}{v(N_2)}$$

At time $t_3 = t_2 + \Delta t_2$, the cluster head changes from A_3 and A_4.

$$\Delta t_2 = \frac{N_3 P_3(t_2)}{v(N_3)}$$

On generalising the above expressions:

$$n \in N : \Delta t_{2n} = \frac{N_{2n+1}P_{2n+1}(t_{2n})}{v(N_{2n+1})} \qquad (5.6)$$

$$n \in N : \Delta t_{2n+1} = \frac{N_{2(n+1)}P_{2(n+1)}(t_{2n+1})}{v(N_{2(n+1)})} \qquad (5.7)$$

In lane 1, A_i (odd numbered vehicle) is entering the lane, i.e., A_{2n+1} entering at time T_{2n+1} for all $n \in N$. Hence for n=0: A_1, $T_1=0$

In lane 2, A_i (even numbered vehicle) is entering the lane, i.e., $A_{2(n+1)}$ entering at time $T_{2(n+1)}$ for all $n \in N$.

- ON_{2n+1} with N_{2n+1} middle of $[A_{2n+1}A_{2(n+1)}]$ is formed at time $T_{2(n+1)}$ i.e., when vehicle $A_{2(n+1)}$ enters the motorway.
- $ON_{2(n+1)}$ with $N_{2(n+1)}$ middle of $[A_{2(n+1)}\ A_{2(n+1)+1}]$ is formed at time $T_{2(n+1)+1}$ i.e., when vehicle $A_{2(n+1)+1}$ enters the motorway

The distance between the start of the motorway O to the mid point N_i at the time when a new vehicle enters the motorway is given by:

For vehicles in lane 1 (odd numbered vehicles),

$$ON_{2n+1}(T_{2(n+1)}) = \frac{OA_{2n+1}(T_{2(n+1)})}{2} = \frac{v(A_{2n+1}) * (T_{2(n+1)} - T_{2n+1})}{2} \qquad (5.8)$$

For vehicles in lane 2 (even numbered vehicles),

$$ON_{2(n+1)}(T_{2(n+1)+1}) = \frac{OA_{2(n+1)}(T_{2(n+1)+1})}{2} = \frac{v(A_{2(n+1)}) * (T_{2(n+1)+1} - T_{2(n+1)})}{2} \qquad (5.9)$$

A change in cluster head will take place at time t_{2n} as given by equation (5.6) and the distance $N_{2n+1}P_{2n+1}$ at time t_{2n} is given by:

$$N_{2n+1}P_{2n+1}(t_{2n}) = OP_{2n+1} - ON_{2n+1} = OM - ON_{2n+1}(t_{2n}) + MP_{2n+1} \qquad (5.10)$$

Where $ON_{2n+1}(t_{2n}) = v(N_{2n+1}) * (t_{2n} - T_{2(n+1)}) + ON_{2n+1}(T_{2(n+1)})$

$$MP_{2n+1} = \frac{SM}{\tan\left[a\cos\left(\frac{H_1H_2}{A_{2n+1}A_{2(n+1)}}\right)\right]}$$

$$A_{2n+1}A_{2(n+1)} = \sqrt{(OA_{2n+1}(t_i) - OA_{2(n+1)}(t_i))^2 + (H_1H_2)^2}$$

$$OA_i(t_i) = v(A_i) * t_i$$

A change in cluster head will take place at time t_{2n+1} as given by equation (5.7) and the distance $N_{2(n+1)}P_{2(n+1)}$ at time t_{2n+1} is given by:

$$N_{2(n+1)}P_{2(n+1)}(t_{2n+1}) = OM - ON_{2(n+1)}(t_{2n+1}) + MP_{2(n+1)} \qquad (5.11)$$

Where $ON_{2(n+1)}(t_{2n+1}) = v(N_{2(n+1)}) * (t_{2n+1} - T_{2(n+1)+1}) + ON_{2(n+1)}(T_{2(n+1)+1})$,

$$MP_{2(n+1)} = \frac{SM}{\tan\left[a\cos\left(\frac{H_1H_2}{A_{2(n+1)}A_{2(n+1)+1}}\right)\right]}$$

$$A_{2(n+1)}A_{2(n+1)+1} = \sqrt{(OA_{2(n+1)}(t_i) - OA_{2(n+1)+1}(t_i))^2 + (H_1H_2)^2}$$

$$OA_i(t_i) = v(A_i) * t_i$$

Speed of mid point N_i is given as

$$v(N_i) = \frac{v(A_{2i+1}) + v(A_{2i})}{2} \qquad (5.12)$$

Hence $v(N_{2n+1})$ and $v(N_{2(n+1)})$ is given by

$$\therefore \quad v(N_{2n+1}) = \frac{v(A_{2n+1}) + v(A_{2(n+1)})}{2} \quad , \quad v(N_{2(n+1)}) = \frac{v(A_{2(n+1)}) + v(A_{2(n+1)+1})}{2}$$

Average rate of change of cluster head for 2 lane motorway at time t_{2n} is given by :

$$\Delta \text{CH} = \frac{v(A_{2n+1}) + v(A_{2(n+1)})}{2(OM - v(N_{2n+1}) * (\text{t}_{2\text{n}} - T_{2(n+1)}) + \text{ ON}_{2\text{n}+1}(T_{2(n+1)}) + MP_{2n+1})} \tag{5.13}$$

Average rate of change of cluster head for 2 lane motorway at time t_{2n+1} is given by:

$$\Delta \text{CH} = \frac{v(A_{2(n+1)}) + v(A_{2(n+1)+1})}{2(OM - v(N_{2(n+1)}) * (\text{t}_{2\text{n}} + 1 - T_{2(n+1)} + 1) + \text{ ON}_{2(\text{n}+1)}(T_{2(n+1)+1}) + MP_{2(n+1)})} \tag{5.14}$$

The above expressions for cluster head changes for lane 1 and lane 2 can be used for different vehicular placement scenarios based on speed. For different speeds, there is change in the cluster head

a) On I_i crossing H_i

b) N_i coincides with P_i

c) The speed N_i and I_i governs the rate of change of cluster heads.

3) The third scenario is when the projection of A_2 does not fall between the segment A_1 and A_3 of the lane i.e. R $\notin [A_1A_3]$ as shown in the fig.5.7 , the cluster head will change from A_1 to A_3 as in case (a) for one lane scenario and then from A_3 to A_2 similar to the scenario mentioned in fig.5.6. The rate of change of cluster heads will be defined by the equations (5.2) for A1 to A3 and (5.13) for A_3 to A_2

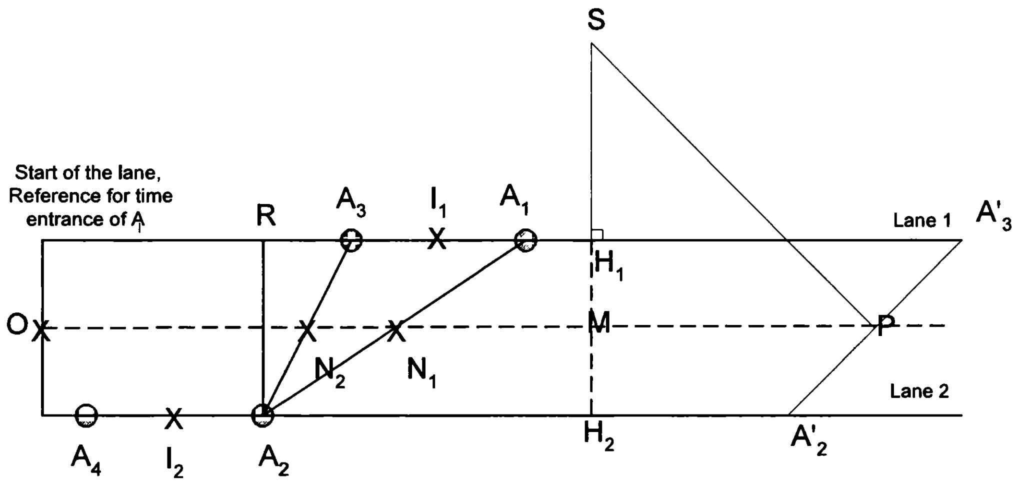

Fig 5.7 Change of cluster head for variable distance and constant speed in two lanes

4) In the fourth scenario, the vehicles placements are such that the distance between H_2 and A_2 is lesser than the distance between H_1 and A_1 as shown in fig.5.8. In that case, A_2 is the initial cluster head and it changes to A_1 when N_1 coincides with point P_1 and if A_1 projection is between A_2 and I_2. The mathematical expressions for ΔCH will follow the same as scenario two and can be derived by equations (5.13) and (5.14)

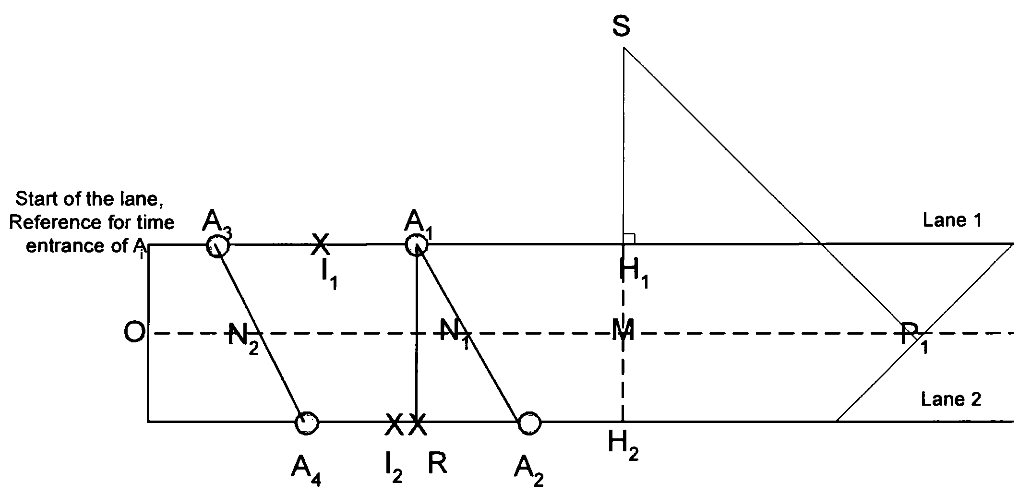

Fig 5.8 Change of cluster head for variable distance and constant speed in two lanes

5.3.3. Mathematical derivation for rate of change of cluster heads for three lanes

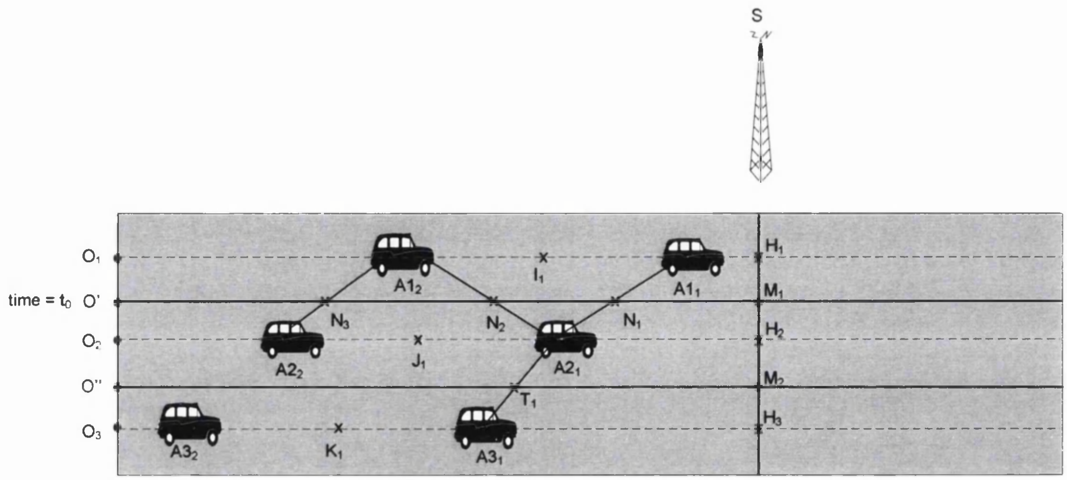

Fig 5.9 Change of cluster head for 3 lanes

Fig.5.9 shows the 3 lanes motorway setup. The vehicles are represented as $A1_i$, $A2_i$ and $A3_i$ for vehicles travelling in lane 1, lane 2 and lane 3. The base station or the roadside infrastructure is positioned by the side of the lane 1 and is given by SH_1. The point O_1, O_2 and O_3 denotes of the start of the lane 1, lane 3 and lane 3, which is used as a reference for the time of entrance for the vehicles. The vehicle closest to the base station becomes the cluster head. In the first instance, $A1_1$ is the cluster head. The cluster head will change from $A1_1$ to $A2_1$ when point N_1 crosses/coincides point P_1.

Notations:

The table 5.3 gives the notations used in the fig.5.9 and in the following derivations.

$A1_1$	Cluster head
$A1_2$,$A2_1$,$A3_1$	Immediate cluster members
I_i	Middle point of $A1_{2i+1}A1_{2(i+1)}$
SH_1	Distance of the base station to the lane 1
H_1H_2 and H_2H_3	Lane width (1.75m)
N_i	Mid point of $A1_{2i+1}$ and $A2_{2i+1}$ and is moving.
P_i	Imaginary static point between lane 1 and lane 2

M_1	Mid point of H_1H_2
J_i	Middle point of $A2_{2i+1}A2_{2(i+1)}$
M_2	Mid point of H_2H_3
T_i	Mid point of $A2_{2i+1}$ and $A3_{2i+1}$ and is moving.
Q_i	Imaginary static point between lane 2 and lane 3
K_i	Middle point of $A3_{2i+1}A3_{2(i+1)}$

Table 5.3 Notations for change of cluster head for 3 lane motorway

Mathematical Expressions

The cluster head changes in a 3 lanes motorway are based on the previous derived expressions for a two lanes and single lane motorway. As mentioned before, the rule for cluster head change is when $N_i/I_i/J_i/T_i/K_i$ crosses $P_i/H_1/H_2/Q_i/H_3$. In a cluster, there are n possible nodes that can succeed as a cluster head. A new cluster head is selected from a group of nodes which are the immediate neighbours of the current cluster head. This group of nodes varies according to the number of lanes. In a 3 lanes motorway, a cluster head can be selected from the immediate 3 nodes of the current cluster head. For a 2 lanes motorway, it will be a group of 2 nodes. The value of Δt_i is calculated for each of these nodes in the cluster and the node with the smallest value of Δt_i is selected as the next cluster head. These expressions can be used for different vehicular placement patterns and the objective for considering the special scenarios is to derive the generalized mathematical expressions for rate of change of cluster heads.

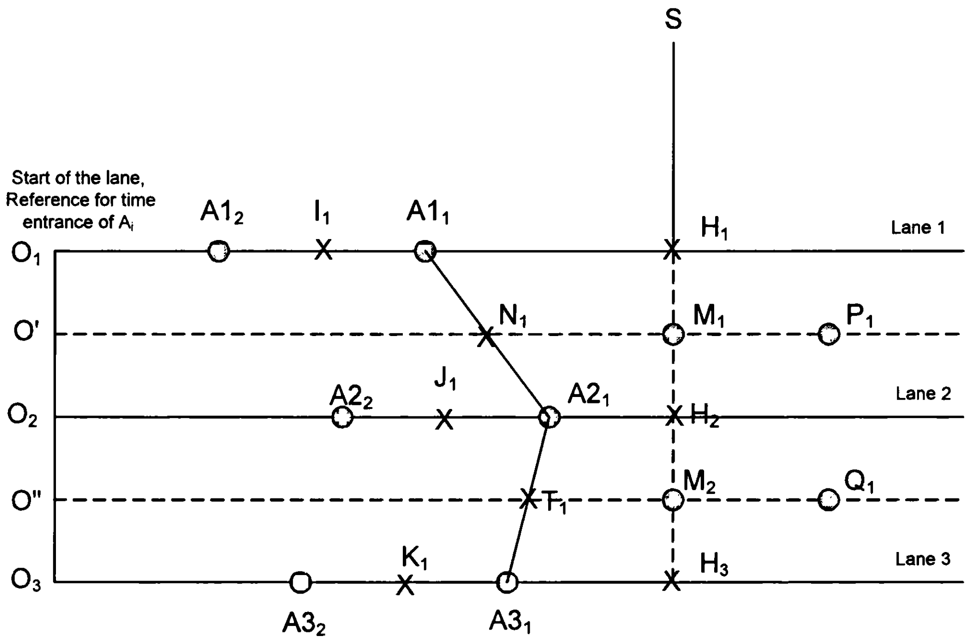

Fig 5.10 Change of cluster head for both constant and variable speeds in the 3 lanes

In fig.5.10, the first vehicle entering the motorway is $A2_1$ and it will be the cluster head initially. The mid point N_1 is formed between the segment $A2_1$ and $A1_1$ and mid point T_1 is formed between $A2_1$ and $A3_1$. For the same the lane, the mid point J_1 is formed between the successive vehicles $A2_1$ and $A2_2$. In the case of all vehicles travelling at the same speed, the cluster head will change in the following sequence: $A2_1$-> $A3_1$-> $A1_1$-> $A2_2$-> $A3_2$-> $A1_2$ where the symbol -> denotes vehicles following the predecessor will become the next cluster head. In the second case where the vehicles are travelling in different speeds, the cluster head change is based on the speed of the imaginary mid points (Ni and T_i) formed between the vehicles travelling in different lanes and also the mid points (I_i, J_i and K_i) formed between the vehicles travelling in the same lane.

For a change of cluster head at time t_0 , a series of possible cluster head changes can occur dependant on the position of the vehicles. The following derivations will consider those different cluster head changes that can occur and they are generalised to be used in any scenario.

1) Cluster head change between the vehicles in lane 1 - This is the case where the $A1_1$ is the cluster head travelling lane 1 and the first closest member in the cluster with a chance to be a cluster head is $A1_2$ travelling in same lane. Then the time (Δt_a) taken to change the cluster head from $A1_1$ to $A1_2$ is the time taken for the mid point I_1 to cross the point H_1.

$$\Delta t_a = \frac{I_1 H_1(t_0)}{v(I_1)}$$

2) Cluster head change between the vehicles in lane 1 and lane 2 – The cluster head change will from $A1_1$ to $A2_1$ when the mid point N_1 crosses the point P_1. This denoted by Δt_b

$$\Delta t_b = \frac{N_1 P_1(t_0)}{v(N_1)}$$

3) Cluster head change between vehicles in lane 2 – The time taken to change the cluster head from $A2_1$ to $A2_2$ is the time taken for the mid point J_1 to cross the point H_2 and is given by Δt_c

$$\Delta t_c = \frac{J_1 H_2(t_0)}{v(J_1)}$$

4) Cluster head change between vehicles in lane 2 and lane 3 – This case considers a scenario where the vehicle $A2_1$ is the initial cluster head and the first closest cluster member is $A3_1$. Hence at Δt_d, the cluster head will change from $A2_1$ to $A3_1$ when the mid point T_1 crosses Q_1.

$$\Delta t_d = \frac{T_1 Q_1(t_0)}{v(T_1)}$$

5) Cluster head change between vehicles in lane 3 - In this case, the initial cluster head is $A3_1$ and vehicle $A3_2$ can become the next cluster head when the mid point K_1 crosses H_3 first before any other vehicles in the adjacent lanes. The time taken to change the cluster head between the vehicles in the lane 3 is given by Δt_e

$$\Delta t_e = \frac{K_1 H_3(t_0)}{v(K_1)}$$

The time taken to change the cluster head Δt_i can be calculated. This can be obtained from the derivation explained for the 2 lanes and 1 lane motorway setup. Based on the smallest Δt_i, the cluster head is changed accordingly.

Average rate of change of cluster head is given by: $\langle \Delta CH \rangle = \frac{1}{\Delta t_i}$

Δt_i could be obtained from equations 5.13 and 5.14 according to the vehicular positions.

5.4. Proposed system setup

The proposed system scenario is based on a motorway with 3 unidirectional lanes. The lanes typically have different speeds with vehicle density varying from high to low in the lanes. It is assumed that the vehicle motion is directed and the arrival rates of the vehicles are obtained from the Traffic Wales data of Swansea-London M4 motorway. Base stations are installed every 5 km typically in the motorway. Each vehicle is equipped with two transceivers for communication between vehicles to the cluster head and the other for cluster head to base station.

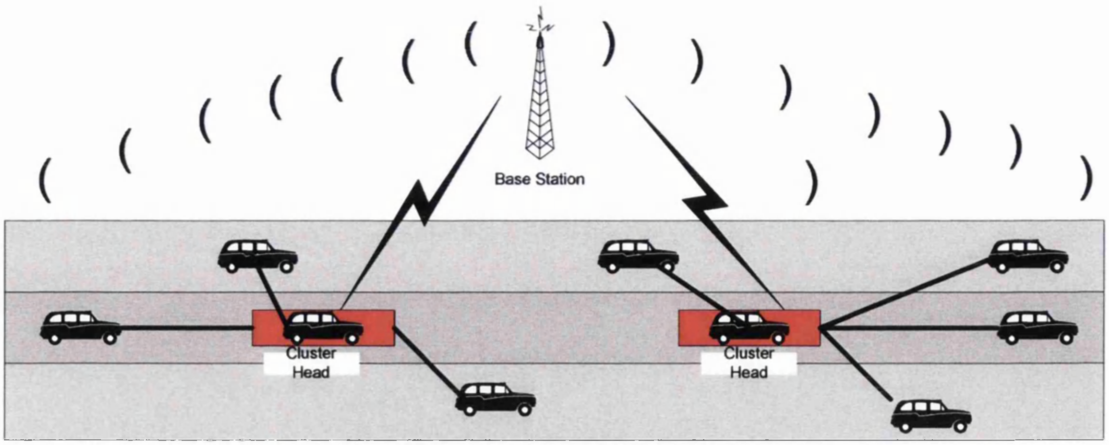

Fig.5.11 Proposed system setup

The communication architecture considered for this system setup is a hybrid setup and has two tiers of communication network. The lower tier is vehicle to vehicle (V2V) communication and the upper tier is vehicle to base station/roadside (V2R) communication. The vehicles within the transmission range of each other form a network group called cluster and select a cluster head based on the path loss parameter between the vehicle and the base station. The vehicles in the cluster communicate with each other using the WAVE technology and any communication to the base station is routed via the cluster head. The cluster head changes are dependent on the speed of the vehicles in the motorway.

The upper tier is used for the communication between cluster head and the base station. It is assumed that the base stations employ mobile LTE technology which can provide large service area coverage and provide higher data rates. Data is communicated to the cluster head/base station using a transceiver present in each vehicle.

The overview of the proposed system is shown in fig.5.12. The system comprises of four main components - a) the vehicular mobility model, b) the implementation of cluster dynamics, c) the analysis of the performance of the protocols behaviour on the V2V communication and finally d) the implementation and evaluation of scheduling algorithms for V2R communication.

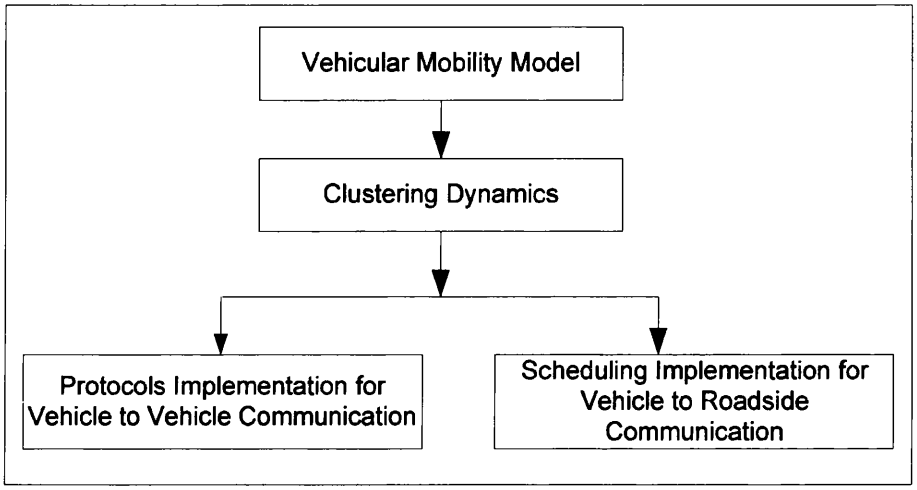

Fig.5.12 Overview of the system model

5.4.1. System simulator

This section is used to describe the system simulator. The purpose for a system simulator is three fold: - 1) to evaluate the performance of the proposed clustering algorithm with the motorway vehicular simulator, 2) to exhibit the accuracy of the experimental simulator by comparing the simulated and mathematical results for rate of change of cluster head metric and finally 3) to evaluate the performance of communication protocols and scheduling algorithms for the proposed hybrid communication network.

In the current market, there are several network simulators available. They include NS-2 (Network Simulator) [104], QualNet [105] and OMNet++ [106] to name a few. QualNet is one of the professional and popular simulation packages capable of modelling a large number of communication networks and systems. The main constraint on these packages is the cost. These packages can support a variety of networks, therefore the cost is quite high and to integrate the customised vehicular flow features and protocols can be complex or may not be accommodated. On the other hand NS-2 and OMNET++ are both freeware packages and both have powerful and efficient modelling features. However, both these packages face the same constraint of integration of customised features. A possible approach could be to extend the existing the network simulators to be integrated with discrete transportation simulators [103-106] thereby ensuring that already authenticated and verified models are used for the simulator to function in a seamless manner. But the biggest challenge for this approach will be in integrating the different modules and also to take advantage of the real time vehicular data. The task of guaranteeing inter-operability during the integration part can be quite taxing and can lack the adaptability and scalability to analyse the proposed clustering algorithm, protocol performance and scheduling algorithms. It was therefore concluded that a system simulator should be designed and developed from scratch. This offers full flexibility in terms of communication features and the vehicular mobility functions designed.

The discrete event system simulator is made up of five main components as shown in fig.5.13. The vehicular simulator simulates the movement of vehicles based on the vehicular and speed models. The traffic generation component is used to generate data packets. The clustering mechanism integrates the proposed clustering algorithm to work along with vehicular simulator. The MAC component is implemented on each cluster between the vehicles and the performance is evaluated. Finally, the Scheduler component is used to study the performance of scheduling algorithms for communication between the cluster head and road side infrastructure. Each of these components will be discussed in the relevant chapters.

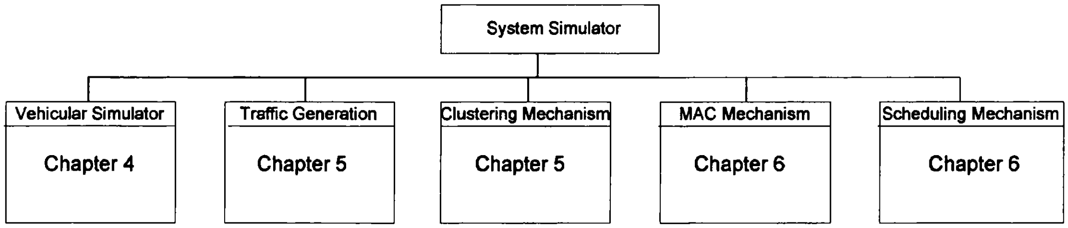

Fig. 5.13 System simulator

5.4.2. Network Traffic generation

The protocol performance of the simulator depends on one and only input parameter – the network traffic generated and applied to the vehicular nodes. Accurate results can be produced only if the traffic model is realistic i.e., the characteristics are close to the traffic measured in real networks.

The long held paradigm in the communication and performance communities has been that voice traffic and, by extension, data traffic are adequately described by certain Markov models such as Poisson. Poisson processes have attractive theoretical properties, which lead to well-developed analysis techniques capable of predicting accurate performance results. This kind of theory known as teletraffic theory was extremely suitable for modelling the behaviour of the public switched telephone network (PSTN). Willinger [107] considers this is as one of the most successful applications of mathematical techniques in industry. However, to describe the data traffic, the most suitable model will be the Self-Similar model. The Self-Similar model will maintain the variable and bursty nature of the data traffic for a longer period of time. But the success of the Poisson theory can be attributed to the fact that it is simple to model, physical interpretation and practical relevance. Hence the Poisson traffic model whose full dynamics can be described by one parameter has been widely adopted in network simulations and also in this thesis. Generating

Poisson traffic is quite straightforward. The packet inter-arrivals are exponentially distributed and it can be derived by using inverse transformation [108].

The main constraint in generating Poisson traffic is generating the real time traffic during the execution of simulation. This was mainly due to the limitation arising when producing random numbers. For the network sources to be different, a different seed is used to initialise the uniform distribution used to generate the exponential (poisson) variate for each vehicular node's traffic. As it is tedious to implement, this problem was overcome by generating the traffic for each vehicular node prior to the start of the simulation and stored in large files. On start of simulation, a function module is written to fetch the traffic into the vehicular node's transmission buffer.

The class diagram for traffic generation mechanism is shown in fig 5.14. This phase includes three classes – *TrafficGenerator*, and *PoissonOFF*.

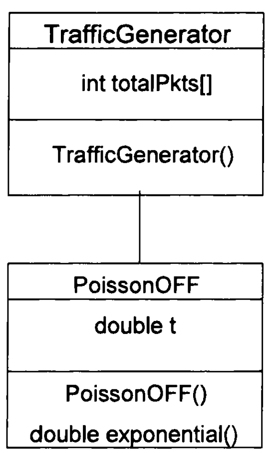

Fig. 5.14 Class Diagram for Traffic Generation

The class *PoissonOFF* has exponential function defined, which is called by class *TrafficGenerator*. The class *PoissonOFF* returns exponential variables X_{OFF} given by the below equation for inter arrival times of the packets

$$X_{OFF} = \frac{-\log(1\text{-}u)}{\lambda}$$

where u is a random number between 0.00 and 1.00

Variate X_{OFF} contains a stream of random numbers exponentially distributed. Each of the random number denote the inter arrival times of the packets. One million packets are generated for M traffic sources and stored in files leading to generation of M traffic files. The algorithm for the entire procedure is depicted by the flow chart in fig. 5.15.

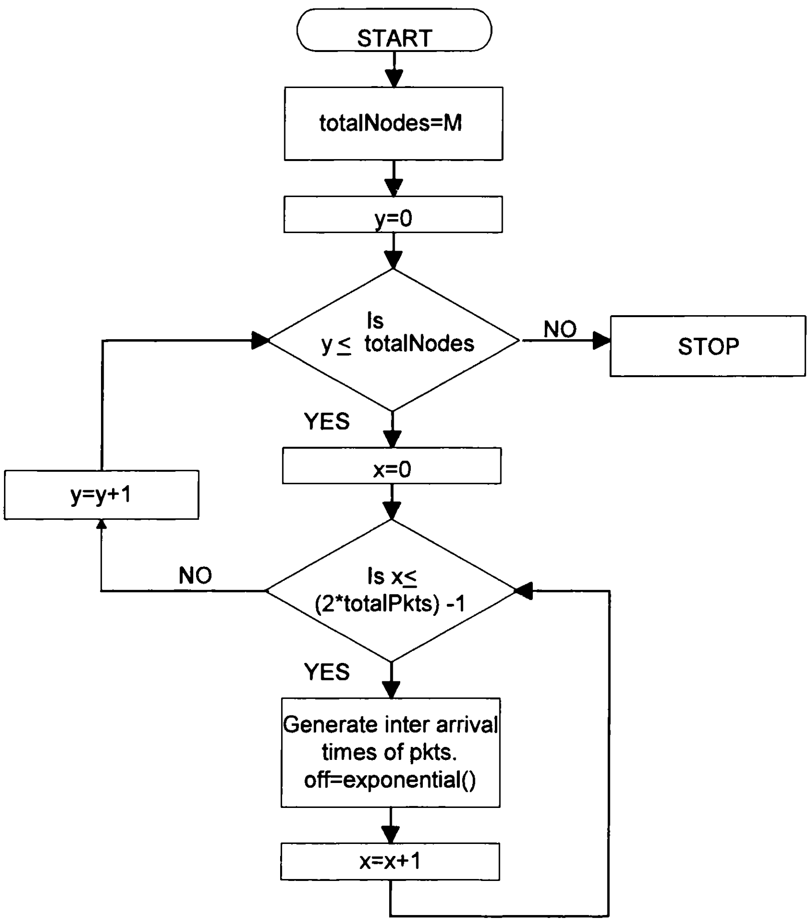

Fig. 5.15 Flow Chart for generating inter arrival times of packets

5.4.3. Clustering mechanism block

The flow chart in fig.5.16 shows the implementation of the clustering algorithm with the motorway vehicular simulator. The newly arrived vehicles are initialised as in the motorway vehicular simulator and positions updated based on the assigned speed of the vehicle. As soon as the vehicle enters the motorway, it scans for an existing cluster head (CH) within its *Coverage* range. If there is a CH in the vicinity, the next step is to see if the cluster size is less than 8. In the algorithm, the cluster size is limited to 8. The upper tier data rate between the CH and the road side base station is 50Mbps and the lower tier data rate between the vehicles and the CH is 6Mbps [46]. So with a maximum cluster size of 8, the CH can support 48Mbps data rate which is equivalent to the uplink data rate between the CH and the base station. The data rate parameters used in the simulation are given in Chapter 6. If the CH is able to accommodate the newly arrived vehicle in the cluster, the next step is to compare the path loss of the current CH with the newly arrived vehicle in the cluster. The cluster is updated if there is a change in CH or if a new vehicle has joined the cluster. Each iteration of the simulation is incremented by 1 second and is denoted by the variable *sysTimer*. Once the *sysTimer* reaches 24 hours, the simulation stops and the output is a text file with numbers using which the performance metrics can be extracted.

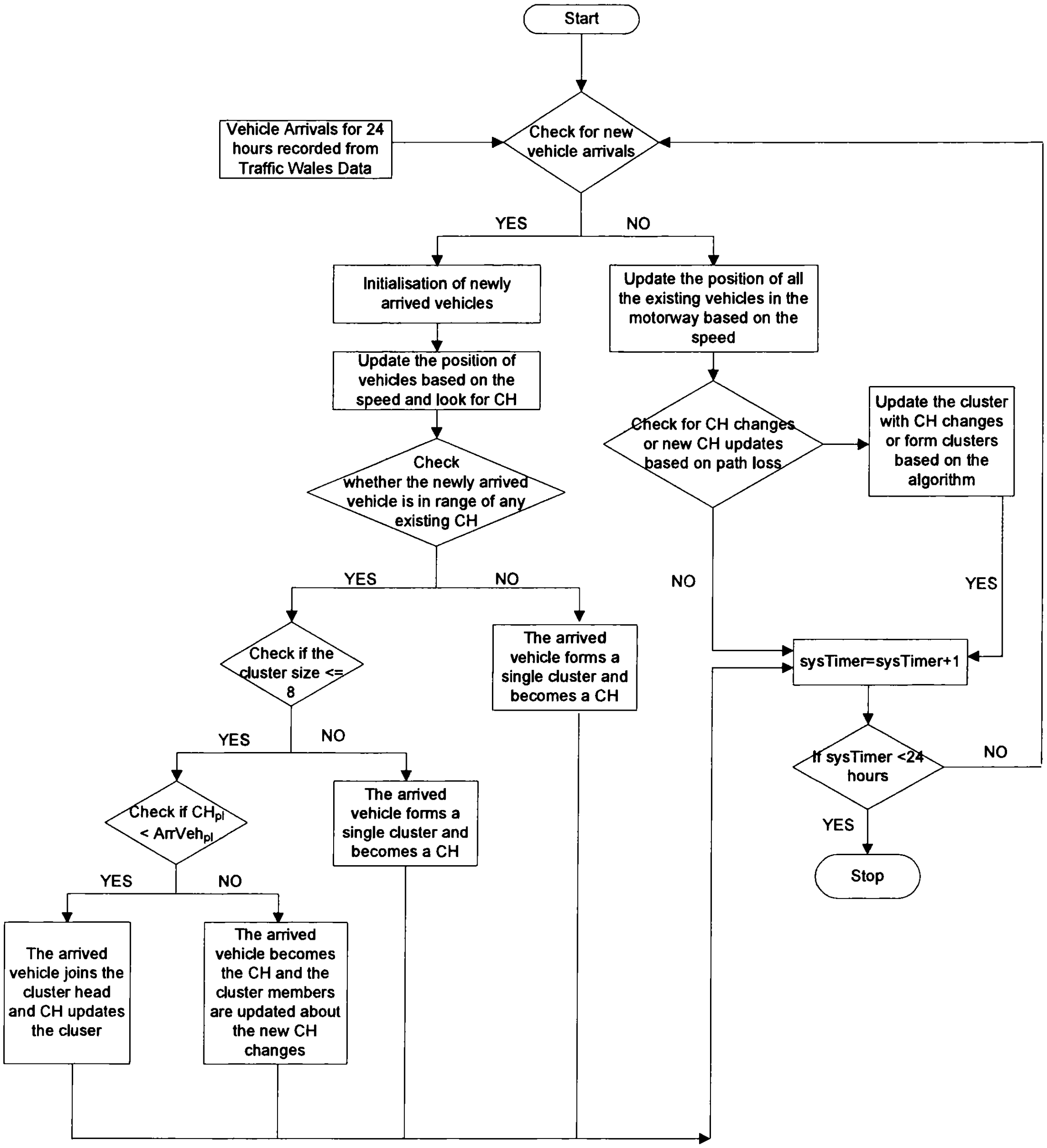

Fig.5.16 Flowchart for the clustering algorithm with motorway vehicular simulator

5.5. Performance metrics for the proposed MPLR clustering algorithm

The performance metrics for the MPLR clustering algorithm can be derived from the system simulator. The rate of change of cluster head metric is compared to the analytical results derived from the mathematical model. Simulated results for the other two performance metrics - average number of clusters and average cluster size are also given in the following sections.

5.5.1. Comparison of the analytical and simulated results for rate of change of cluster heads

The performance metric rate of change of cluster head ensures network stability and robustness with respect to V2V communication. The mathematical model was described in section 5.3 to define the rate of change of cluster head. The analytical results for 1 lane, 2 lane and 3 lane motorway are shown in fig. 5.17. As expected, 1 lane scenario has fewer number of cluster head changes than a 2 lane or 3 lane motorway.

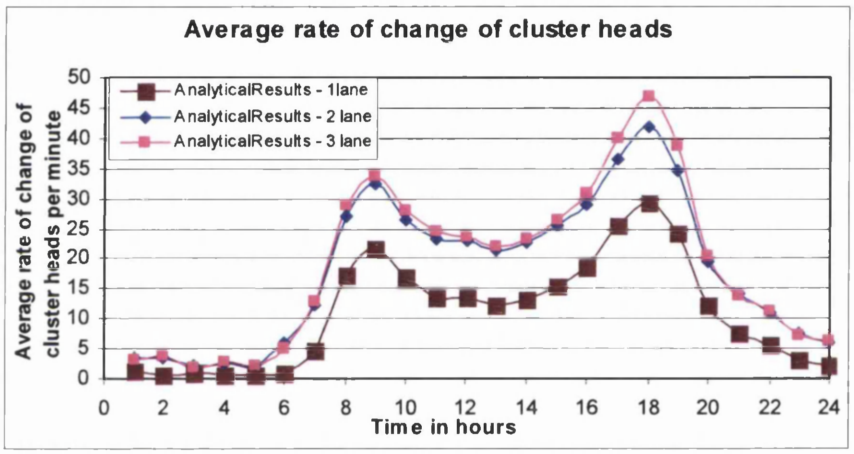

Fig.5.17. Analytical results for rate of change of cluster heads for different lanes

The rate of change of cluster heads is obtained from the system simulator as explained in section 5.4.1. This is compared with the analytical results derived from the mathematical model. The simulation is run for 24 consecutive hours and the metric is measured for each of 24 consecutive hours for all the 3 lanes. Fig. 5.18 shows that there is a good agreement existing between the analytical and simulated model, thereby validating the soundness of the analytical model. The cluster head changes are higher at the peak periods between 8 AM – 10 AM and 5 PM – 7 PM. This is due to the reason the number of vehicles in the motorway during morning and evening rush hours are significantly higher than the off peak hours. Fig.5.18. also shows the accuracy of the experimental motorway vehicular simulator as the analytical results are in close match to the simulated results.

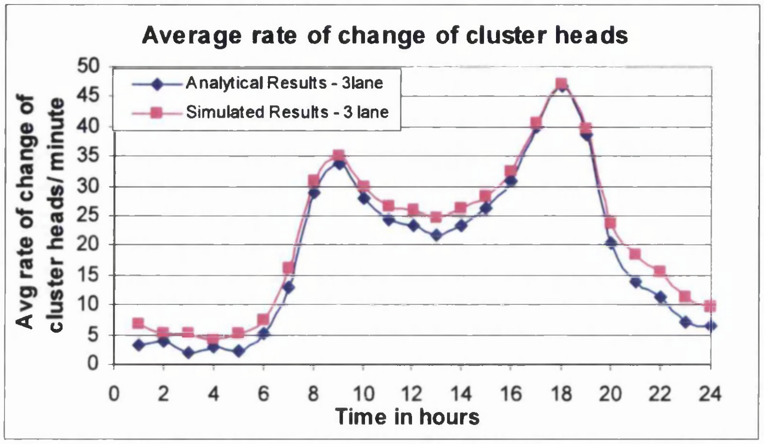

Fig.5.18. Comparison of simulated and analytical results for rate of change of cluster heads

5.5.2. Average number of clusters

Fig.5.19 gives the average number of clusters for different hours of the day. The hours are selected based on the peak hours and off peak hours. The results are computed for a 50km stretch of the motorway and average number of clusters existing per second is computed. The number of clusters is high during the morning and evening peak hours and reduces during the off peak hours. Maintaining the relay of communication without dropping the data is important for reliability of the network. Hence it is necessary to establish average number of clusters supported, to help determine allocation of bandwidth and also to anticipate the relay of communication.

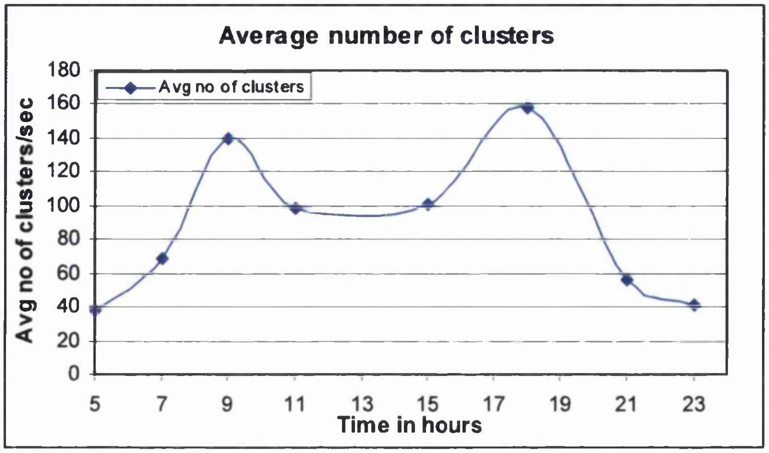

Fig.5.19 Average number of clusters vs time in hours

5.5.3. Average cluster size

The average cluster size denotes the average capacity of a cluster and helps in determining the average number of service requests that can emerge from the cluster. This information is useful for cluster head to base station communication, as channel allocated based on the number of service requests buffered at the cluster head. Fig. 5.20 represents average cluster size per second for different hours of the day. An average cluster size in the range between 5 and 6 is predominant for most of the hours in the day. The peak hours between 8 AM and 9AM and between 17 PM and 18PM, the cluster size reaches the maximum size of 8.

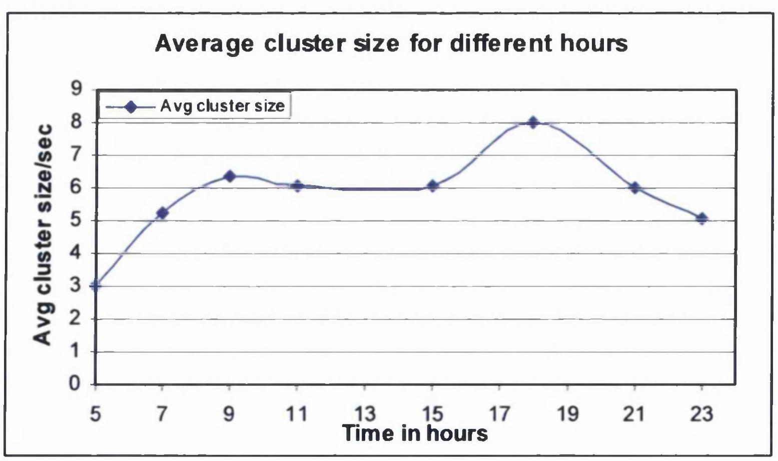

Fig.5.20 Average cluster size vs time in hours

5.6. Comparison of the MPLR clustering algorithm with other clustering techniques

The clustering algorithm based on path loss and interference is compared with the traditional cluster head selection algorithms:- Lowest-ID and Highest Degree algorithms as shown in fig.5.21. In Lowest-ID, the network is arranged into a group of nodes called cluster where each node belongs to at least one cluster. Each node in the cluster is assigned a distinct ID and the node with the lowest ID is selected as the cluster head (CH). Thus the IDs of the neighbour nodes will be higher than that of the cluster head. The highest connectivity (degree) algorithm is based on the number of neighbour nodes with which it can communicate and the node with the maximum number of neighbours (connectivity) becomes the CH. The algorithms and their drawbacks for vehicular scenarios were discussed in detail in chapter 3. As it was explained, the cluster head election procedure is not competent to suit the vehicular communication. This is proved by measuring the rate of change of cluster heads for different transmission ranges. The peak hour evening traffic between 5 PM – 7 PM is selected as an input to the vehicular arrivals model. The rush hour is selected as the motorway will be experiencing high vehicular density. As it can be seen from the fig.5.21, the Minimal Path Loss Ratio (MPLR) algorithm exhibits the minimal cluster head changes compared to the other two techniques. Thereby it offers greater robustness than the existing algorithms. Initially the cluster head changes are slightly higher for MPLR algorithm for shorter transmission ranges. The number of clusters for shorter transmission ranges will be higher as coverage range of the cluster head will not cover many vehicular nodes. This increased number of clusters leads to increased cluster head changes. The highest degree algorithm by far has the worst performance caused by variations in the cluster sizes. The lowest id algorithm has a lower cluster head changes compared to the highest degree. The vehicular node with the lowest id is selected as cluster head and the cluster head will hold to its status until a vehicular node with a lower id joins the cluster.

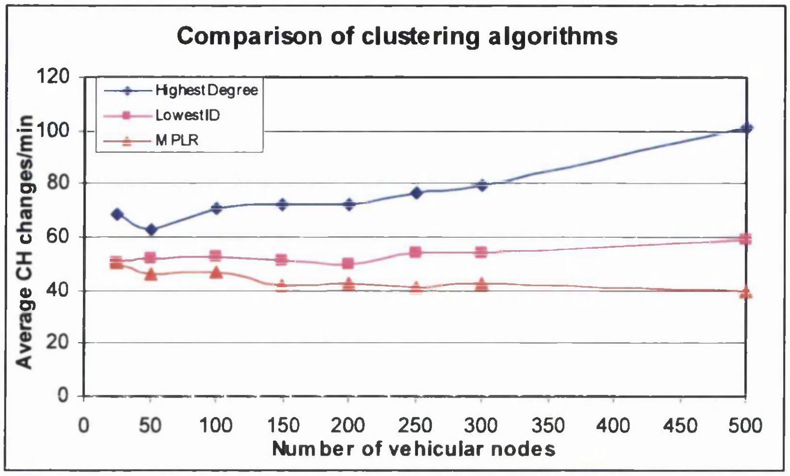

Fig. 5.21 Comparison of different clustering techniques based on rate of change of cluster head for different transmission ranges

5.7. Comparison of a pure V2R system with the proposed MPLR system

In VANET vehicles act as mobile nodes communicating with each other through short-range radios for direct vehicle to vehicle communication. For the pure V2R each vehicle can communicate to the base station with its long-range radio as in fig.5.22. In these kinds of networks, each vehicle can communicate to the base station directly. There is no hierarchy in the networks for coordinating on sending messages to the base stations. In comparison, by clustering, the cluster head can collect messages from the vehicles within its cluster and forward the messages to the base stations, and can receive notifications from the base stations and forward to the vehicles in its cluster. Clustering can be an efficient method to reduce bandwidth consumption and network congestion for large scale networks at no extra cost for infrastructure. It is important that the limited radio spectrum resources should be used as economically as possible. The base station sites usually dominate the deployment cost of the wireless networks and it is very essential that these resources are utilised effectively.

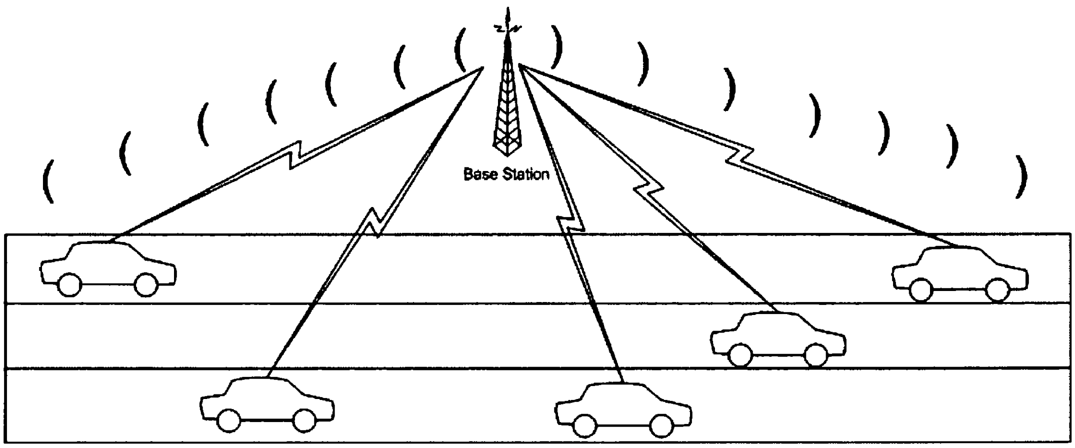

Fig.5.22 Proposed setup for a pure V2R system

The aim of the MPLR system is to maximise the spectral efficiency under the constraint that the Qos is not compromised [110,111]. The MPLR system uses clustering and the traffic is routed through the cluster head to the nodes. The base station can then split the spectrum resourcefully to the cluster heads and then route the traffic through the cluster heads. The number of channel links the base station has to maintain with the vehicles is lower than a V2R system thereby resulting in reduced infrastructure costs comparatively. For a V2R system, the base station is required to maintain individual links with the vehicles for any data transfer. The number of users sharing spectrum in a V2R system will be higher which increases the network congestion, increase in the number of communication links and reduction in spectral efficiency. Also, the over head incurred for each new connection in establishing and maintaining the links is higher for a V2R system than a MPLR system.

The proposed motorway system setup is used for this simulation. The vehicle arrivals and speed are obtained from the 2 peak Gaussian arrival and average speed models described in Chapter 4. The communication between the vehicles and base station uses the LTE technology [112]. The parameters used for this simulation is given in the table 5.4. The simulation considers a fixed size data file is transmitted from base station to all the vehicles in the motorway. This file could contain information ranging from safety messages to infotainment messages. The data is sent out to all the vehicles and resources are allocated based on the round robin scheduling in the downlink scheduler in the base station. The spectrum efficiency of MPLR network is compared to the pure V2R system in terms of the number of transmission links required for the downlink file transmission, the resource utilisation ratio, end to end delay and packet dropping probability. The packet arrival rate follows a Poisson distribution.

Parameters	Values
Channel bit rate	50 Mbps
Data bit rate	500 Kbps
Packet Size	4800 bits
TTI interval	1 ms
Frame duration	10 ms
Resource Blocks	50
Base station coverage	5 km

Table.5.4. Simulation parameters

5.7.1. Transmission links for service requests

The number of channel links required to transmit the data from the base station to vehicles is an indication of how much bandwidth is consumed at the base station for the data transmission to the vehicles. It is noted that lower the bandwidth required for the vehicle data transmission application, the better for the whole vehicle networks as the base station can use the unused bandwidth for other commercial applications. Results on the number of transmission links for both MPLR system and pure V2R system are given in the fig. 5.23. The number of transmissions the base station needs to maintain with vehicles for communication is much higher for a pure V2R system compared to a clustering system. This is because, in a MPLR system, the base station has to communicate only to the cluster head and therefore the number of ongoing transmission links is lower. The spectral efficiency is a measure of number of users or service requests that could be simultaneously supported by the radio spectrum. The maximum throughput or goodput summed over the entire users in the system divided by the channel bandwidth will define the spectral efficiency in bits/sec/Hz. As it can be seen in fig.5.23, for a pure V2R system, the numbers of users sharing the radio spectrum are higher thereby reducing available bandwidth per user. In case of the MPLR systems, the spectrum is shared between lesser number of users and each user will have a higher share of the spectrum than the V2R systems.

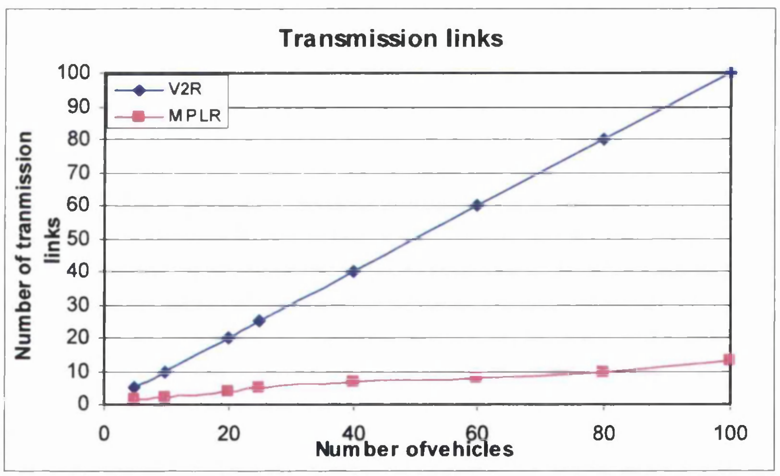

Fig.5.23.Transmission links vs number of nodes

5.7.2. Resource utilisation ratio

The resource utilisation ratio is defined as the resources used by the base station to transmit the data to all the vehicles in the motorway. As the V2R system use LTE technology for communication, a resource is defined as a slot in the frame structure of LTE. The data to be transmitted is fixed sized data file and resources for downlink transmission are allocated in a round robin basis. Fig. 5.24 shows the resource utilisation ratio against the number of vehicles. For a V2R system, the resources required to transmit the file to all the users is higher than the resources utilised for the MPLR system. In the MPLR system, the resources are used efficiently utilised increasing the number of users. For 100 vehicle users, the resource utilisation ratio for MPLR system is close to 20% compared to 50% for the V2R system. This is due to the number of serviced requests for a MPLR system is only 14 (fig.5.23) for the 100 vehicles density. This shows that a MPLR system can accommodate more number of users than a V2R system, thereby increasing spectral utilisation.

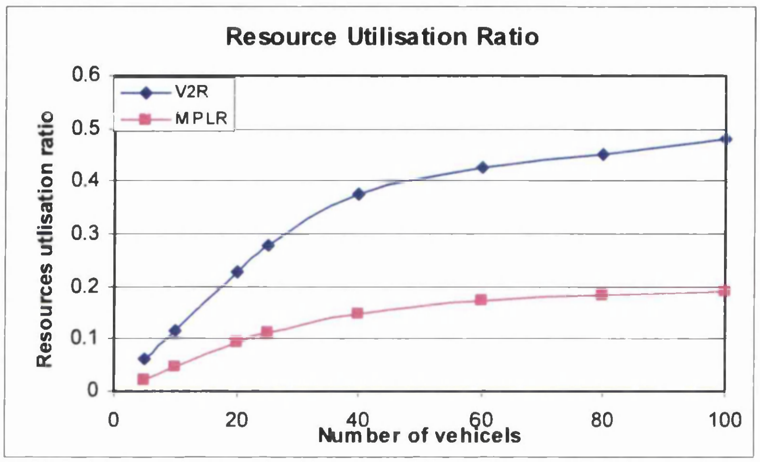

Fig.5.24 Resource utilisation ratio vs number of vehicles

5.7.3. Average access delay

Average Access Delay ($\overline{D}$) is the delay that is experienced by a packet while waiting in the queue at the base station. The average access delay is calculated as

$$Average\ Access\ Delay\,(\overline{D}) = \frac{totalDelay}{totalVehicles} \tag{5.1}$$

where *totalDelay* denotes the sum of the delays faced by all packets during the waiting period in the queue and *totalvehicles* gives the number of vehicles participating in the simulation. The average access delay is measure in seconds.

It can be seen from fig. 5.23 that the average access delay increases with increase in number of vehicles. On observing the results in Fig. 5.25 it can be seen that the average access delay is higher for V2R system than the MPLR system. There is little variation in the access delay for lower number of vehicles, around 2 ms for both V2R and the MPLR systems. As the number of vehicles increases the delay for a V2R system reaches around the margin for 55ms compared to 18ms delay for the MPLR system. Also for a MPLR system, when the number of vehicles is less than 20, the delay is in the insensitive region and the delay is quite minimal and any variation in the number of vehicles does not affect the delay significantly. However when it exceeds the value of 20, the average access delay $\overline{D}$ increases rapidly and the addition of vehicles at this point change the value of the delay quite significantly.

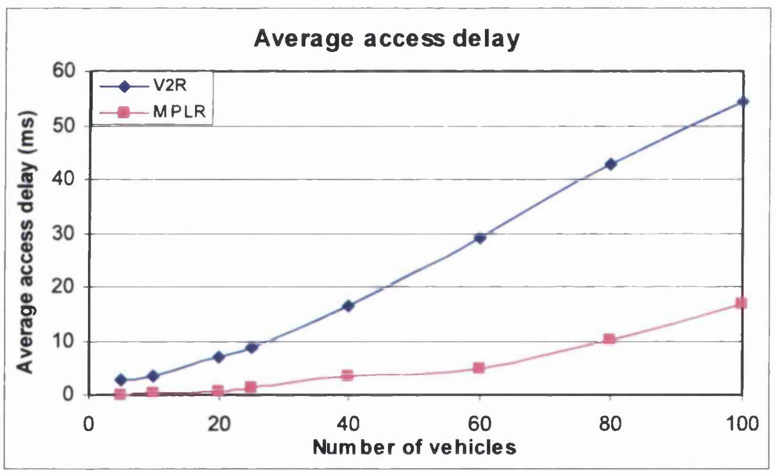

Fig.5.25 Average access delay vs number of vehicles

5.7.4. Packet dropping probability (PDP)

Considered to be one of the most important parameters in determining the performance of the system, PDP (%) is a percentage ratio of the number of packets dropped to the total number of packets. PDP (%) is given as

$$PDP\ (\%) = \frac{totPktsDropped}{totalPkts} \times 100 \tag{5.2}$$

To guarantee good quality of service (QoS), PDP should be less than 10-15%. The packets are sensitive to delay and once delay reaches a maximum limit D_{max} (=150ms), the packets are dropped to maintain the quality of the service.

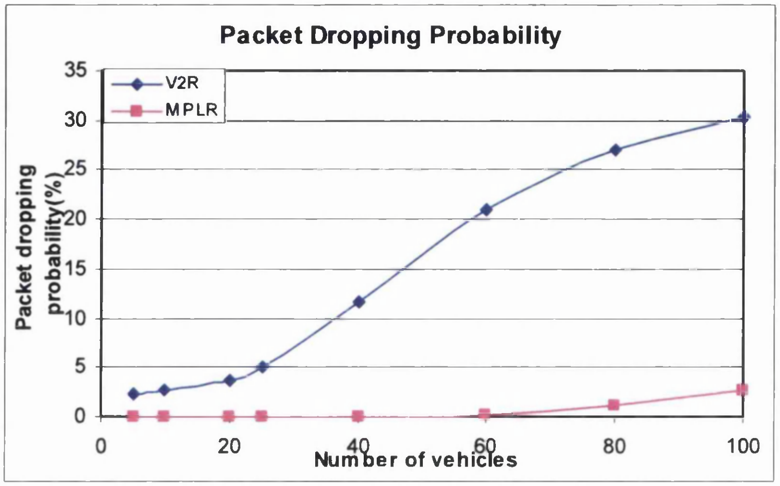

Fig.5.26 Packet dropping probability vs number of vehicles

Fig. 5.26 depicts the V2R and MPLR system results for packet dropping probability versus the number of vehicles in the system. It can be seen that the PDP is a lot higher for V2R system than the MPLR system. The number of participating vehicles in the clustering mechanism is reduced and this improves the packet dropping probability at least by 20%. For example, with participating vehicles count of 60 the PDP for a V2R system is around 20% compared to the 1% for the MPLR system.

5.8. Summary

This chapter presented the proposed clustering algorithm based on minimal path loss ratio (MPLR). The clustering technique, rules for cluster creation and the algorithm were described in detail. The performance of the clustering algorithm is measured in terms of rate of change of cluster head, average cluster size and average number of clusters. A mathematical analysis was derived to compute the rate of change of cluster heads. The clustering algorithm is integrated with the motorway simulator. The system simulator is divided into five main blocks – vehicular simulator, traffic generation, clustering mechanism, protocols simulator and scheduling mechanism. The performance metrics of the clustering algorithm are obtained from the system simulator. There is a good agreement between the mathematical analysis and simulated results for rate of change of cluster heads thereby showing the stability of the algorithm and accuracy of the simulator and the analytical model. The average cluster size and average number of clusters for the motorway stretch are measured and will be used in the Chapter 6. The MPLR algorithm is compared with two popular clustering techniques and the proposed algorithm shows a better performance implying the robustness of the algorithm. This chapter also compares the performance of the MPLR system (V2V+V2R) with a pure V2R system and it is found that the MPLR system performs better than a V2R in terms of number of ongoing transmissions the base station is required to support, resource utilisation ratio, average access delay and packet dropping probability.

6. Performance evaluation for Vehicle to Vehicle (V2V) and Vehicle to Roadside (V2R) Communication

6.1. Introduction

This chapter focuses on studying the effect of the MPLR clustering algorithm with the existing MAC protocols for V2V communication and scheduling algorithms for V2R communication. MAC protocols are required to efficiently share the medium and vehicular networks require MAC protocols that can quickly adapt to the changing environment. The objective is to provide reliable communication while guaranteeing the quality of service. The new WAVE standard has designed to address the problems in vehicular networks. The IEEE 802.11p MAC layer is based on the Distributed Co-ordination Function (DCF). The DCF employs Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) with binary exponential back off algorithm. In this chapter two protocols are studied for vehicle to vehicle communication - CSMA/CA and Dual Busy Tone Multiple Access (DBTMA). Due to the high mobile nature of the vehicular network, MAC protocols which don't require time synchronisation are selected. Both CSMA/CA and DBTMA senses the channel before sending the data and doesn't require synchronisation.

Traditionally, CSMA based MAC protocols have been used to share the communication channel between the users. However, CSMA/CA experience high collisions when more than one packet is received by the user at the same time. The presence of the hidden and exposed terminals can lead to decrease in the capacity of the network. MAC protocols such as MACA, MACAW were proposed to mitigate the hidden and exposed terminals. However the use of ready-to-send (RTS)/clear-to-send

(CTS) dialogues in those protocols is not sufficient to eliminate packet collision entirely. The Dual Busy Tone Multiple Access (DBTMA) protocol is proposed by [] to overcome the hidden and exposed terminal problems. The detailed description of CSMA/CA and DBTMA are given in previous chapter as part of the background. DBTMA can minimise the packet collisions by means of two busy tones for transmission and reception of packets. It is importance to compare the performance of CSMA/CA and DBTMA protocols. Hypothetically, DBTMA should perform better than CSMA/CA and in that case, DBTMA could be used as a standardized protocol for V2V communication. The aim of the study is to evaluate and compare the performance of these two protocols in terms of throughput, average access delay and packet dropping probability.

There are mainly two objectives for this chapter. The first is to evaluate and compare the performance of the MAC protocols for V2V communication. The second is to investigate scheduling algorithms for V2R communication in the proposed MPLR network. As mentioned in the earlier chapters, V2R communication requires high data rates with reliable links. This research work considers using Long Term Evolution (LTE) technology for V2R communication. LTE belongs to 3GPP family of standards and promises to deliver the requirements for the comfort applications. LTE aims to guarantee the quality of service (QoS) for services such as audio/video streaming, gaming and voice over IP (VOIP). To support QoS, scheduling algorithms are required to support quality of service (QoS) differentiation and provide guarantee for seamless wireless data networks. These algorithms are crucial for development of wireless networks. Scheduling algorithms provide mechanism for resource allocation and call admission control procedures and congestion control policies are highly dependent on the specific scheduling algorithms used.

This chapter is comprised of two parts. The first part is focused on measuring the performance of MAC protocols for V2V communication. Section 6.2 gives a detailed explanation about the implementation of the protocols in the simulator along with the flowcharts and finite state diagrams. Section 6.3 measures the performance for the protocols in terms throughput, average access delay and packet collision ratio and also compares the performance of both the protocols for various hours of the day. The second part of the chapter concentrates on comparing the scheduling algorithms for V2R communication. Section 6.4 looks into two scheduling algorithms, which are the round robin scheduling algorithm and a proposed scheduling algorithm based on the properties of clusters. Section 6.5 explains the system setup while Section 6.6 will deal with the performance evaluation of the scheduling algorithms for V2R communication.

6.2. MAC Simulator

This section explains the protocol simulator with flow charts and class diagrams. Fig.6.1 gives the flow chart for the algorithm of CSMA/CA protocol. The protocol is a basic access mechanism technique. The protocol employs binary exponential back-off algorithm to avoid collisions. The simulator is discrete event based simulation. As seen in fig.6.1, the simulation is triggered by the packet arrival event. On arrival of a packet, the vehicular node checks the status of the channel. If the channel is busy, the node sets its back-off timer for a random period of time. Once the timer expires, it checks for the status of the channel. If the channel is free, the node waits for DIFS period of time and check for the channel status. If it is still free, the node transmits the packet.

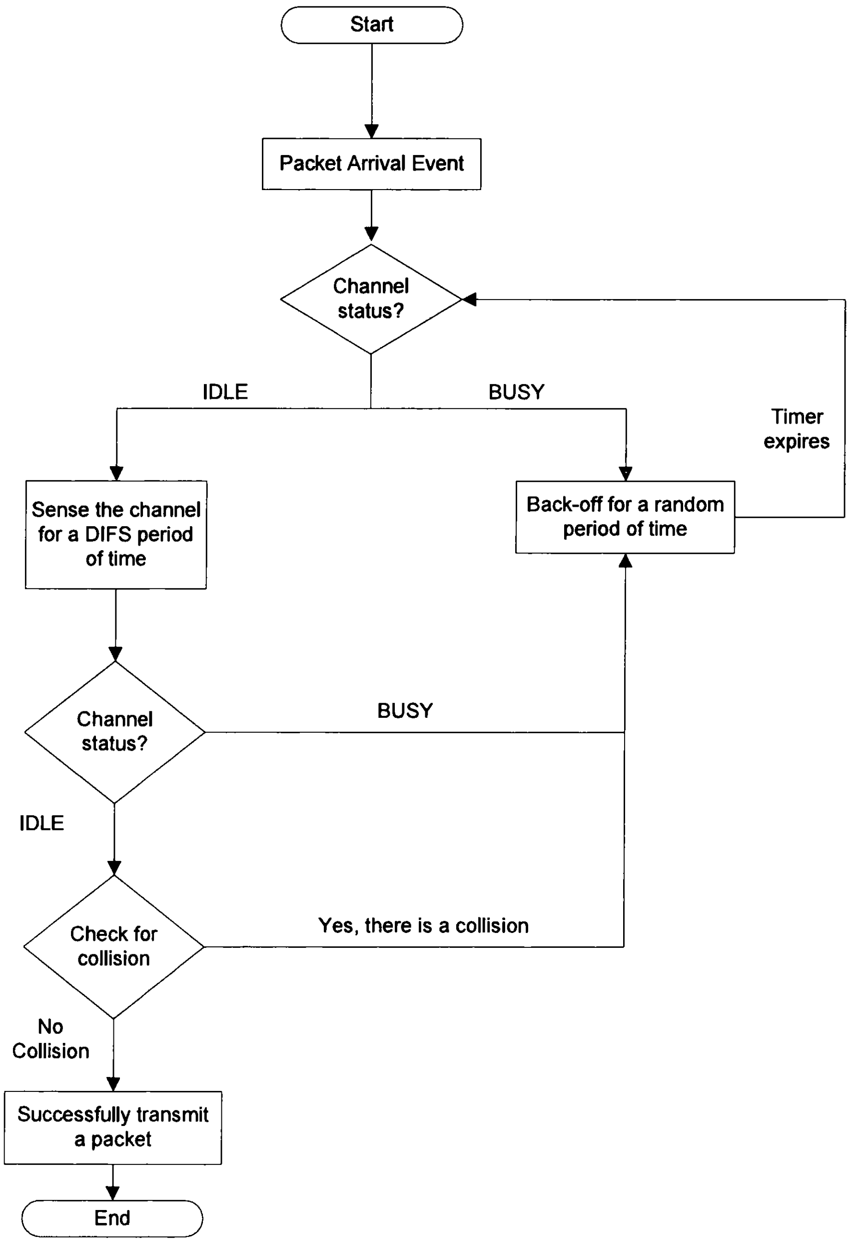

Fig.6.1 Flowchart for CSMA/CA algorithm

The second protocol used for V2V communication is Dual Busy Tone Multiple Access (DBTMA). The protocol has two busy tones- transmit busy tone and receive busy tone. These two tones protect the RTS and data packets. Fig.6.2 gives the flowchart of the algorithm. Similar to the CSMA/CA, the simulation starts on arrival of the packet at the node. The node with newly arrived packet senses both transmit and receive busy tones. If the tones are idle, the node sets the Transmit busy tone and sends the RTS packet. After sending the RTS packet, a timer is set for a random period of time while the node continually monitors the Receive busy tone. As an acknowledgement of the RTS packet, the receiver sets the Receive busy tone. On reading the busy state of the receive tone, the transmitting node waits for a mandatory period of time before it sends the data packet. This mandatory wait time is to allow all the ongoing RTS transmissions in the range of the receiver to be aborted. After the mandatory time period, the data is transmitted in the Receive busy tone. In case, if either of the tones is busy or if the timer expires at point waiting for the acknowledgement, the node is backed-off for a random period time. The back-off follows a binary exponential algorithm. Only after the back-off timer expires, the node is allowed to sense the tones.

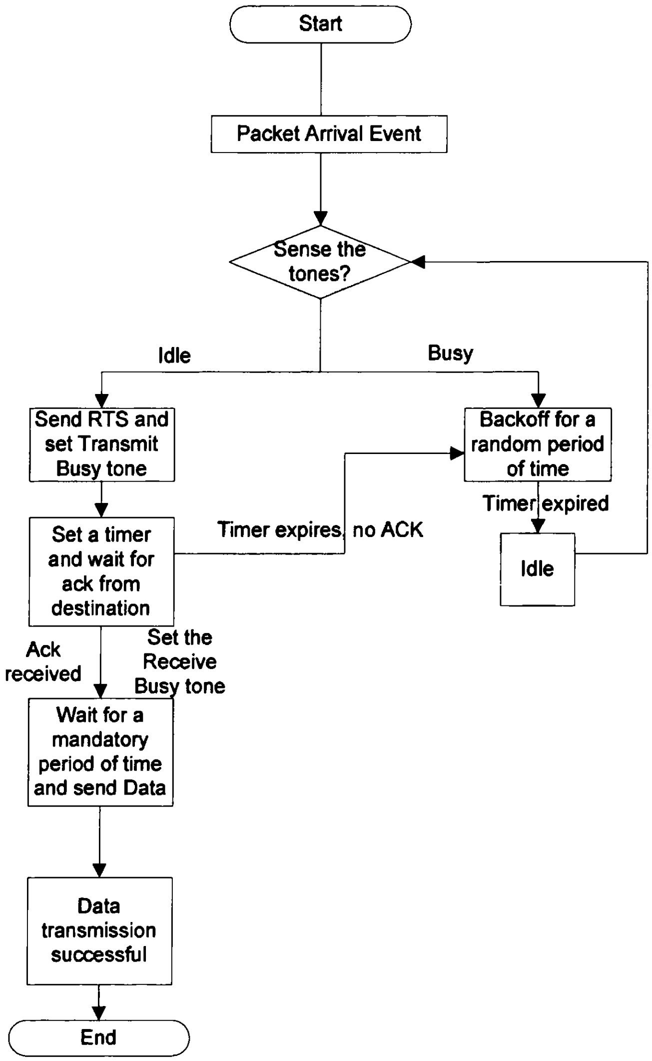

Fig.6.2 Flowchart for DBTMA protocol

The class diagrams and flow charts for the protocol simulator are described for CSMA/CA protocol and similar functionalities and algorithms are used for DBTMA protocol. The class diagrams for CSMA/CA and DBTMA will have little difference. There are 2 functions added for the DTBMA simulator for sending the RTS packet and processing the RTS packet based on whether it was successful or not. Fig.6.3 gives the class diagrams for CSMA/CA and DBTMA. The variable *sysTimer* is global timer which is incremented at every event. The variable *waitingEvents* holds all the event requests which needs to be processed. The variable *totalNodes* represents the participating vehicular nodes. The vehicular nodes are represented by the class *Node*.

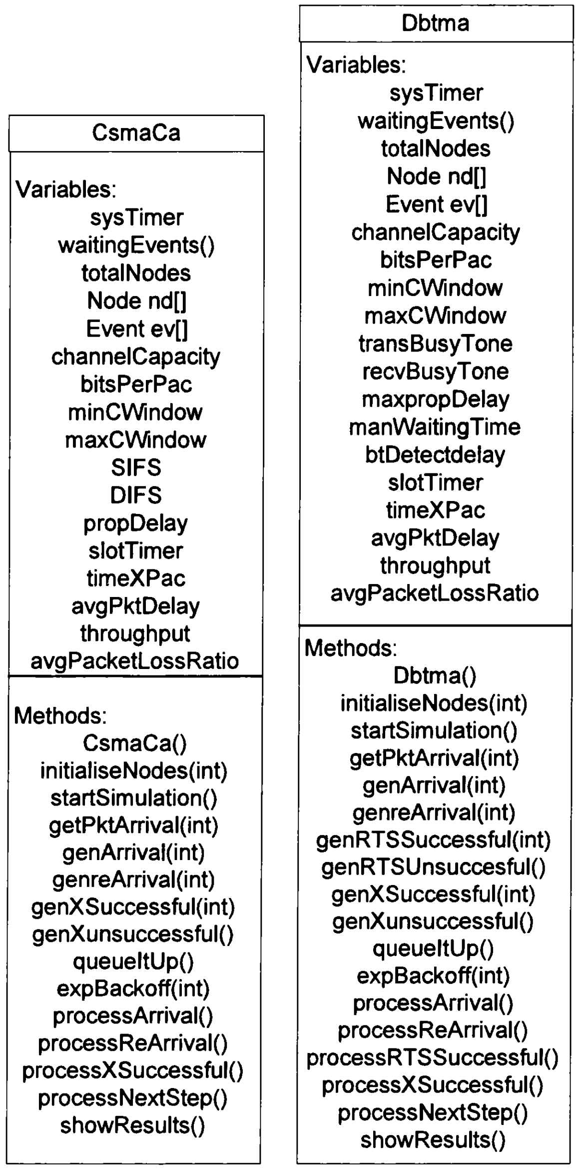

Fig.6.3 Class diagrams for CSMA/CA and DBTMA

There are series of flowcharts describing the MAC simulator. Fig.6.4 shows the starting point of the simulator along with the class diagram for Node. The Node class diagram represents the individual vehicular entities participating in the simulation with *nodeNo*, *waitingPackets* queue, *backoff* timer for variables.

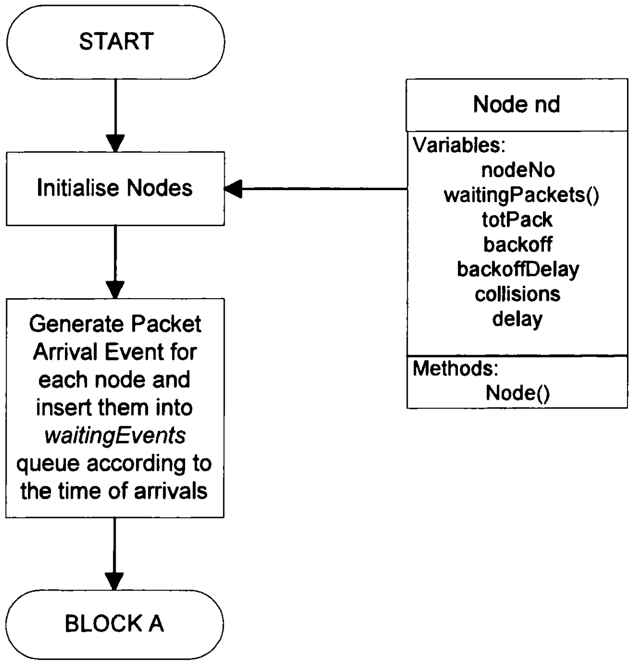

Fig.6.4 Nodes initialisation and the class diagram for Node

After the nodes are initialised and added to the *waitingEvents* queue, the next set of functions are executed. The *waitingEvents* queue is checked to see if there are events waiting to be processed and if there are events waiting, the event is retrieved and processed according to its ID. This is shown in fig.6.5.

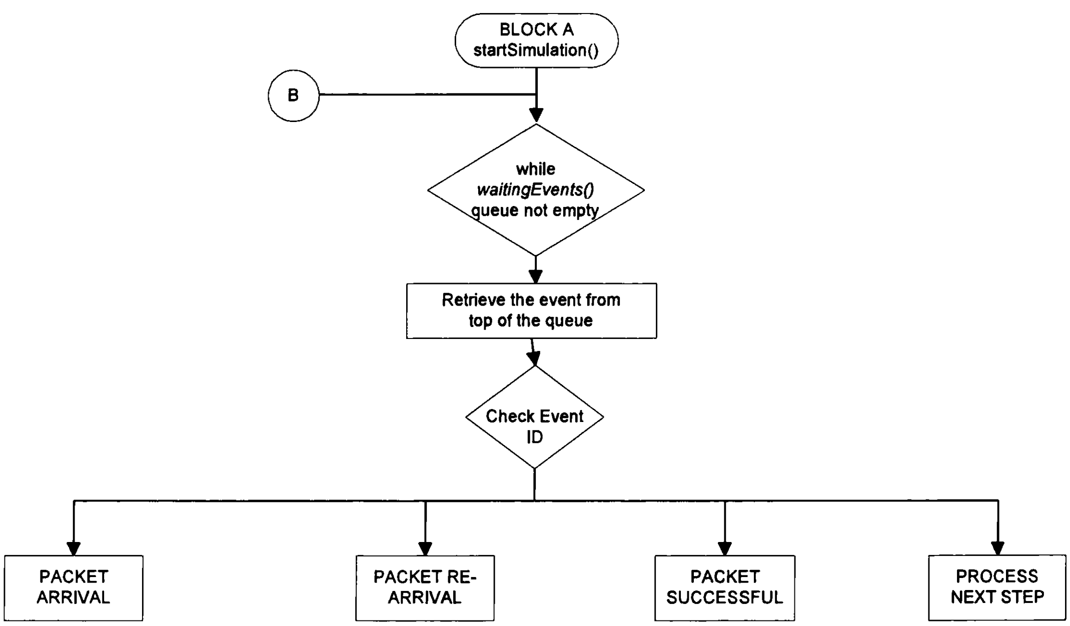

Fig.6.5 Process of retrieving the waiting events from the queue

There are total of four events in the MAC simulator. They are 1) *Packet Arrival,* 2) *Packet Re-Arrival,* 3) *Packet Successful* and 4) *Process Next step.* Each event is explained in the following flowcharts. Fig.6.6 gives the flowchart for the procedures following on a packet arrival and packet re-arrival.

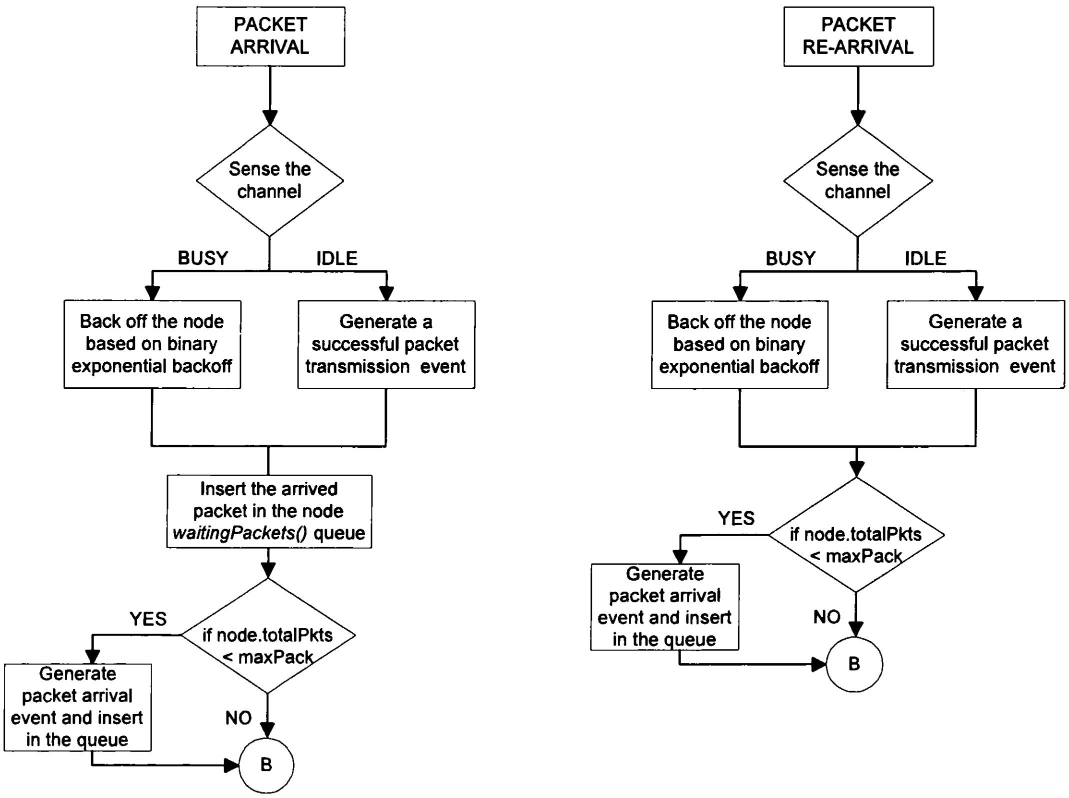

Fig.6.6 Flowchart for events PACKET ARRIVAL and PACKET RE-ARRIVAL

PACKET ARRIVAL – This event marks the arrival of any new packets. For each newly arrived packet, the channel is sensed for a busy or idle status. If the channel is free, *PACKET SUCCESSFUL* event is triggered and if it is busy, the node is backed off using a binary exponential algorithm. The arrived packet is stored in the node's *waitingPackets* queue and a new packet is generated.

PACKET REARRIVAL – This event is specific to the nodes in back-off. After the back-off timer expires, the node senses the channel to transmit the packet. If the channel is busy, the packet continues to wait in the queue.

The events *PACKET SUCCESSFUL()* and *PROCESS NEXT STEP()* are given in flowchart 6.7

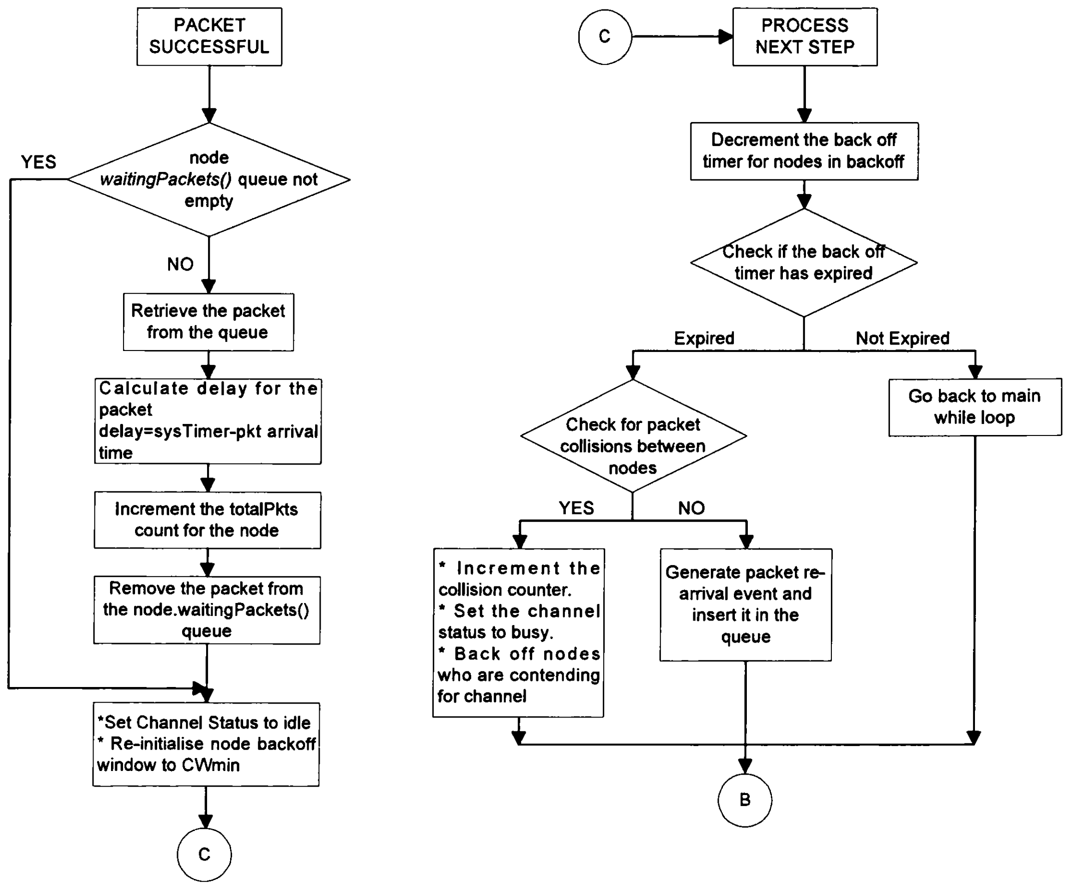

Fig.6.7 Flowchart for events PACKET SUCCESSFUL and PROCESS NEXTSTEP

PACKET SUCCESSFUL – The function of this event to process a successful packet transmission. It calculates the packet access delay which is the packet waiting time in the queue.

PROCESS NEXT STEP – This function decrements the back off timer of the nodes in back off and checks if the back off timer has expired or not. It also checks for packet collisions and back off nodes accordingly.

6.3. Performance evaluation of CSMA/CA and DBTMA protocols for V2V communication

We have evaluated the performance metrics by importing modelled data (based on real vehicular data) into the simulation to measure the QoS parameters required for data traffic for CSMA/CA and DBTMA protocols. The simulation evaluates the performance under 5 km base station coverage and the MAC protocols are run for the motorway system setup combined with the MPLR clustering algorithm. The performance metrics such as throughput, average access delay and packet loss ratio were evaluated through simulation. The protocols use the 802.11p for the communication between vehicles. The parameters used for the simulation are given in the table 6.1 and are based on the 802.11p MAC standards. The data traffic is generated using a Poisson traffic generator and traffic generation is explained in chapter 5.

Parameters	Values
Channel bit rate	6 Mbps
Coverage	400 m
Packet Size	4800 bits
CW_{min}	15
CW_{max}	1023
PHY header	128 bits
MAC header	272 bits
SIFS	28 bits
DIFS	128 bits
ACK	112 + PHY header
Slot time	50μs
Data bit rate	500 Kbps

Table 6.1 Communication Parameters used in the simulation

Fig. 6.8 shows throughput variation for different nodal densities. In both cases, the throughput decreases with increase of nodes and stabilises later on. The throughput is defined as the ratio of total number of packets sent successfully to the overall number of packets generated for all the nodes. The curve trend is similar to the performance of CSMA/CA proposed by the authors in [43]. However the DBTMA protocol exhibits better performance than the CSMA/CA protocol. The reason is that when CSMA/CA reserves the channel, they reserve both the forward and backward direction of the transmission, while DBTMA reserves the forward channel leaving the reverse channel for other transmissions. This results from in channel being under utilised in CSMA/CA due to interference from the neighbouring nodes in the overlapping clusters. The probability of channel being idle is higher for a CSMA/CA system than DBTMA. Also with the DBTMA protocol, the packet collisions are lower due to the presence of the busy tones which ensured the safety of the packets.

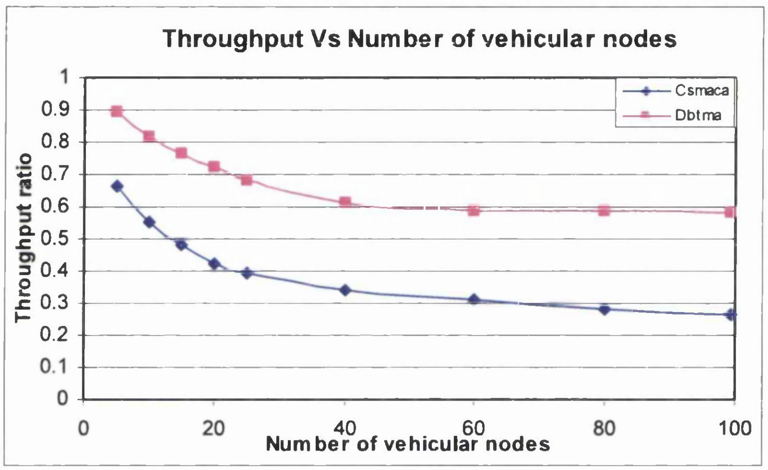

Fig.6.8 Throughput vs number of vehicular nodes

In fig.6.9 shows the packet collision ratio against the number of vehicular nodes. The packet collision ratio is defined as the ratio of collided packets to the total number of packets. The collision ratio increases with the increase in the number of vehicular nodes. As can be seen in the figure, the packet collision ratio for DBTMA protocol is lesser than the CSMA/CA. The busy tones in DBTMA shield the packets from collisions. The collisions are mostly experienced by the RTS packets which carries the control information. The lower the packet collisions, higher the throughput and this helps in the overall performance of the DBTMA protocol. In CSMA/CA, the collisions are higher due to the presence of the hidden and exposed terminals.

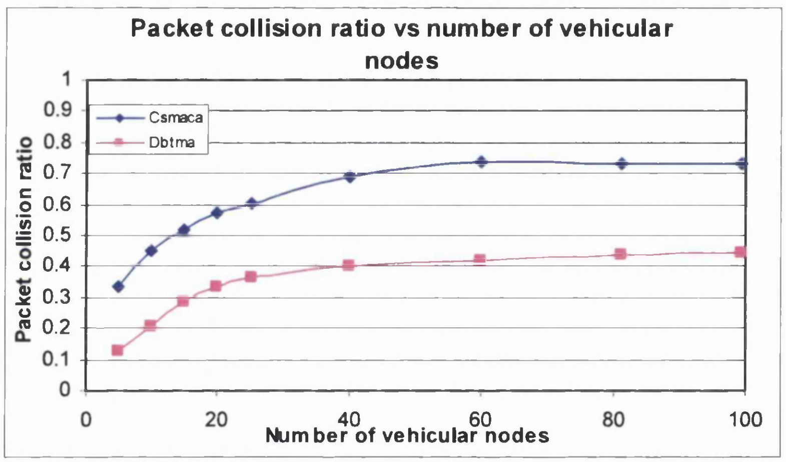

Fig.6.9 Packet collision ratio vs number of vehicular nodes

The average access delay is shown in fig. 6.10 and is measured in milliseconds against the number of vehicular nodes. The average access delay is measured from the waiting time of the packet from the time it arrived in the queue of the vehicular node till it accesses the channel. As seen in the figure, the delay increases with increase in number of nodes and the DBTMA protocol has a lower access delay compared to the CSMA/CA. The increased delay in CSMA/CA is attributed due to the presence of the hidden and exposed terminals. This causes the collisions and the nodes back-off which increases the access delay. With DBTMA, the busy tones remove the effect of the hidden and exposed terminals and the access delay experienced is due to the nodes contending for the channel.

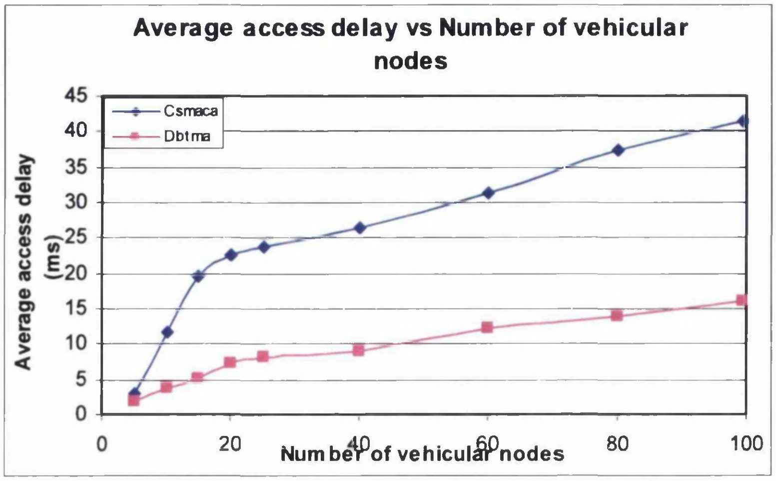

Fig.6.10 Average access delay vs number of vehicular nodes

The performance of these two protocols is also compared for different hours of the day. The hours consider three cases of vehicular densities – 1). High vehicular density (8:00 AM-9:00 AM and 17:00 PM – 18:00 PM); 2). Medium vehicular density (10:00 AM – 11:00 AM and 14:00 PM – 15:00 PM) and 3). Low vehicular density (6:00 AM – 7:00 AM, 20:00 PM – 21:00 PM and 22:00PM – 23:00 PM). The bandwidth requirements for the vehicular nodes differ during the different hours of the day. By comparing the DBTMA and CSMA/CA during those hours of the day, the protocol performance can be analysed for different bandwidth requirements. The channel will be heavily loaded during the peak hours and it will be interesting to study these comparative trends for the protocols in terms of throughput, packet collision ratio and average access delay.

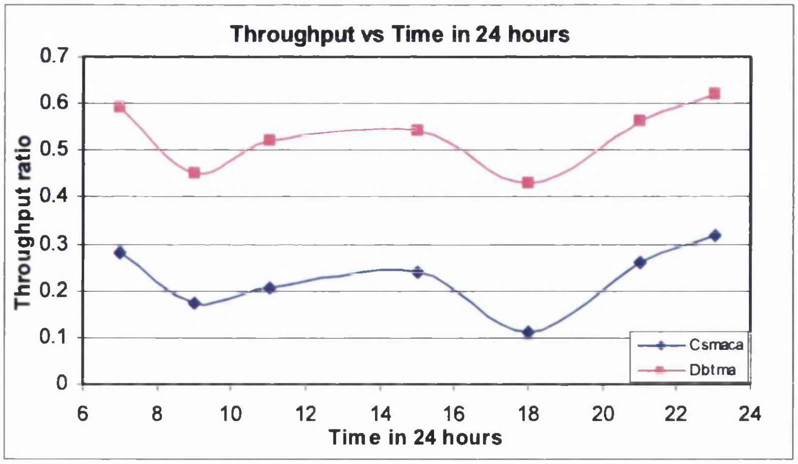

Fig.6.11 Throughput vs time in 24 hours

Fig.6.11 shows the throughput for the different hours of the day. The throughput decreases during the peak hours due to increased number of vehicular nodes entering the motorway and shows an increase during the medium and low vehicular densities. During the busy hours when the vehicular traffic density is high, the protocols suffer significantly due to higher collision rate. For the peak hour, the throughput ratio for the DBTMA protocol is at least 20% higher than the CSMA/CA.

Due to higher collisions caused by contention among vehicular nodes, similar trends can be seen for the packet collision ratio and average access delay for both the protocols in Figs. 6.12 and 6.13. The packet collisions are higher during the peak hours as the contending vehicular nodes are higher in those hours. Added on, the presence of the hidden and exposed terminals increases the collisions for the CSMA/CA. Fig.6.12. shows the collision ratio for DBTMA protocol is 40% lower (on an average) than the CSMA/CA.

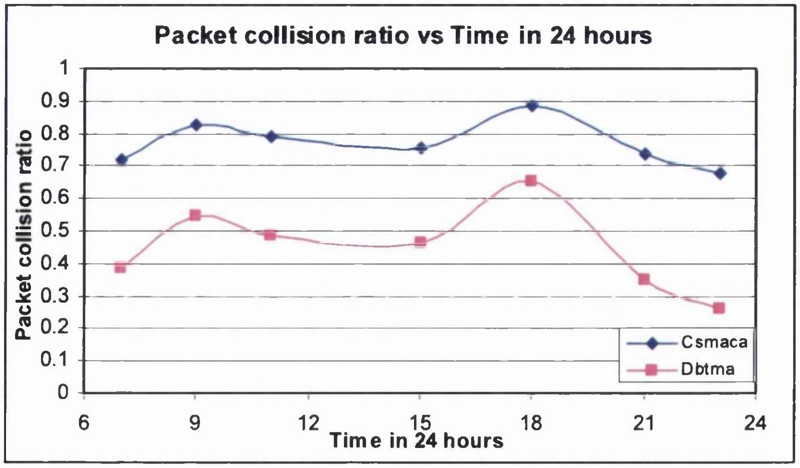

Fig.6.12 Packet collision ratio vs time in 24 hours

Further more the increase in the number of vehicular nodes causes the average access delay to increase significantly. In fig.6.13, the average access delay is about 22 ms at 17:00 – 18:00 PM for DBTMA protocol compared to the 110 ms delay for the CSMA/CA. Although this delay is permissible for the data traffic considered in this simulation but for delay sensitive traffic such as voice or video, the average access delay for CSMA/CA can leading packet dropping thereby reducing the Qos.

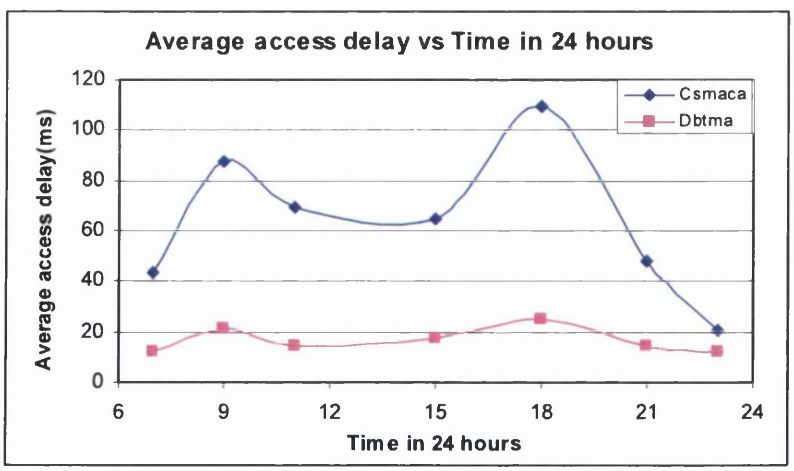

Fig.6.13 Average access delay vs time in 24 hours

The average access delay calculated in [95] for lower vehicular density using CSMA/CA is between 120 – 125 ms for average vehicular speed between 30 m/s to 35 m/s. As the average vehicular speed obtained in Chapter 4 is around 30 m/s, the corresponding delay of 120 ms for lower vehicular density in [95] is still higher compared to the 110 ms experienced by the MPLR system for CSMA/CA.

The above set of results measured for different hours of the day shows that the DBTMA protocol could be a better alternative than the CSMA/CA which has prominently been used as the standard protocol. However, the DBTMA protocol requires two busy tone transmitters and sensing circuits to be incorporated in the communication node. In [70], the authors suggest the busy tones can be implemented within the bandwidth of 10 KHz. The transceiver architecture proposed in [70] can help in cost reduction of the hardware for the busy tones. The authors show the performance gain for the DBTMA protocol is high enough to offset the bandwidth consumption of the two busy tones.

6.4. Scheduling algorithms for V2R communication

This section deals with the scheduling algorithms for the V2R communication using the LTE technology. The 3GPP LTE [113-115] has Orthogonal Frequency Division Multiple Access (OFDMA) for downlink and Single Carrier Frequency Division Multiple Access (SC-FDMA) as the core access technology. A packet scheduler is required to comprehend the potential efficiency of these technologies. The scheduler is expected to co-ordinate the access to the shared channel resources. In LTE systems co-ordination implies both the time dimension (allocation of time frames) and the frequency dimension (allocation of subcarriers). These two grades of freedom together with other system constraints make scheduling in LTE a challenging optimisation problem. In the frequency domain, the aggregate bandwidth available for resource allocation is divided into subcarriers of 15 kHz. Twelve subcarriers are grouped together to form the 180 kHz bandwidth sub-channel. In time domain, the sub-channels are organised as time slots of 0.5 ms each. Two slots of 0.5ms together are referred to as a 1ms sub-channel. This 1 ms sub-channel is called as TTI (Transmission Time Interval). The smallest scheduling unit is the intersection of the 180 kHz sub-channel with the 1ms TTI. Therefore at each TTI, the scheduler can assign N resource blocks to the active users. Scheduling decisions are made by the base station termed as eNodeB (evolved NodeB) in LTE. The scheduler determines how the downlink and uplink channels in the LTE air interface are used.

Downlink and Uplink transmissions are organised into radio frames with duration of 10ms. Each 10ms radio frame consists of 10 sub-frames. The transmitted signal in each slot is described by a resource grid (RB resource blocks x M subcarriers and N UL SC-FDMA symbols) as illustrated in Fig. 6.14. The value for RB resource blocks will vary depending on the uplink transmission bandwidth and shall satisfy the $RB_{min} \leq RB \leq RB_{max}$ where the minimum value=6 and maximum value=110 are the smallest and largest bandwidths supported respectively [116-120]

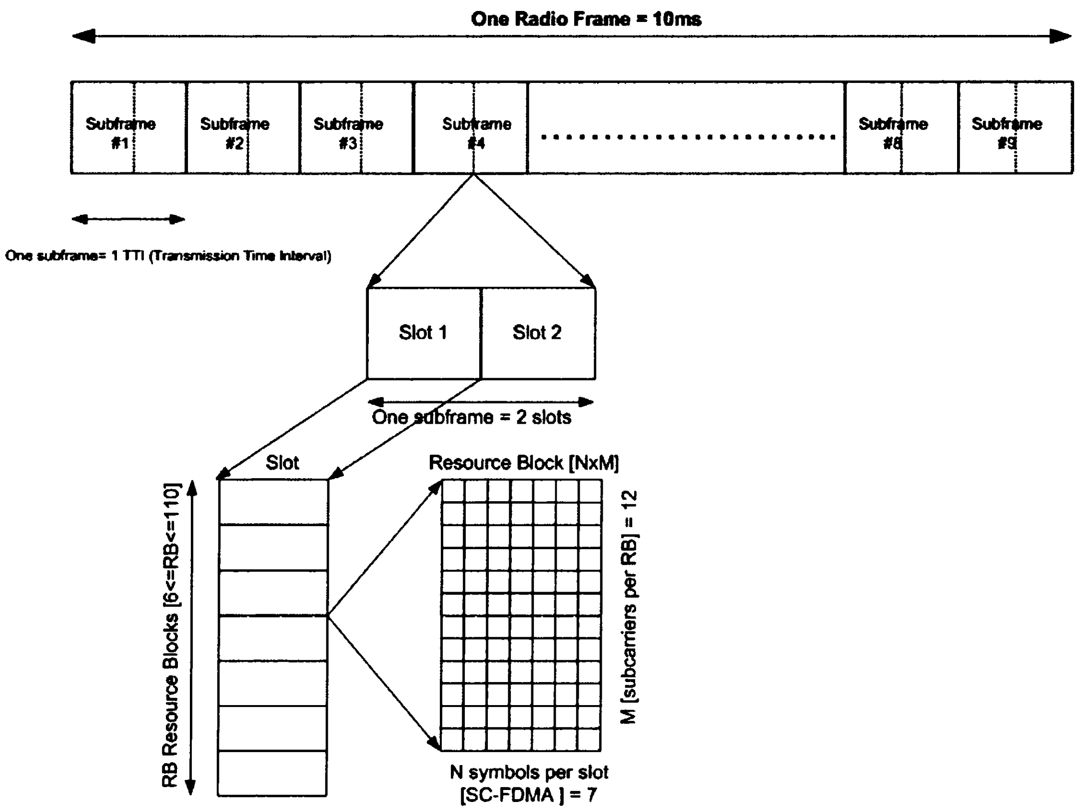

Fig.6.14 Uplink Resource Grid of LTE [112]

A physical resource block is defined as N consecutive SC-FDMA symbols in the time domain and M consecutive subcarriers in the frequency domain, where N and M are given by table 6.2. A physical resource block in the uplink thus consists of NxM resource elements, corresponding to one slot in the time domain and 180 kHz in the frequency domain.

Configuration	M	N
Normal cyclic prefix	12	7
Extended cyclic prefix	12	6

Table 6.2 Resource block parameters

The physical resource block structure of LTE permits for packing efficiency and exploitation of time/frequency channel selectivity through opportunistic scheduling which results in high user throughputs. However due to the volatile nature of the wireless links, higher capacity does not always turn into better user-perceived QoS for delay sensitive flows. The scheduling mechanism should trade-off between maximizing the channel bit rate to balancing the QoS metrics (e.g. delay and packet drops) for various users. Resources are allocated to user allowing them to receive data via the downlink and transmit data through the uplink. The scheduler has to assign the resources to satisfy quality of service (QoS) requirements and optimise system performance.

A lot of research on LTE scheduling has been carried out for downlink scheduling [121, 122] and in comparison; lesser work has been done for treating the uplink [123,124]. In this section, there are two scheduling polices put forward for uplink scheduling. One is based on the round robin scheduling scheme where a prior number of slots are assigned to each user at each TTI independent of the channel conditions. The second one is proposed based on the cluster properties of the MPLR algorithm.

6.4.1. Round Robin Scheduling

Round robin scheduling is one of the most popular and simplest scheduling techniques used. The round robin scheduling assigns an equal number of slots to each user and in a circular order without any priority. The main advantage of this scheduling is the users are starvation free, which implies every active user irrespective of the traffic type is given a chance to transmit in the slot. The disadvantages for this scheduling are lower throughput and system spectral efficiency. The reasons are the scheduling policy doesn't consider the channel conditions before assigning slots to the active users which results in lower spectral efficiency. Also, a busy user with long queues is given the same priority as near to idle user which results in resource wastage leading to low throughput. Hence in a wireless packet radio system where QoS is an important factor, round robin scheduling can prove to be inept policy.

6.4.2. Cluster Based Scheduling (CBS)

The round robin algorithm cannot be efficient in a vehicular environment due to above reasons. An alternative scheduling algorithm is proposed, which takes into consideration three main factors; cluster size, QoS requirement and path loss experienced by the cluster head. There are algorithms which use channel conditions or the buffer size for scheduling but it can easily lead to starvation for active users with bad channel conditions. Fig. 6.15 showsThe proposed algorithm uses the cluster size as one of the main criteria for scheduling. The concept is a larger cluster size can have higher traffic flow coming into the cluster head. To avoid overflows at the queues, the proposed algorithm has two main rules for scheduling:

1. The first priority is given to cluster heads with larger cluster sizes. As mentioned earlier, larger cluster size implies more users and hence more traffic flow. To avoid starvation for cluster heads with smaller cluster size, the QoS constraint is taken into deliberation. In case of a cluster head with smaller cluster size has a fast accumulating traffic queues, priority is given to this type of scenario over cluster heads with larger cluster size but with lower delay. By doing this, the packets dropping probability is lower and also the algorithm minimises starvation for the active users.
2. The second scenario where the cluster heads have the same cluster size with similar QoS requirement, the path loss for the cluster head is considered. The cluster head with minimal path loss is used as a factor to prioritise for resource allocation.

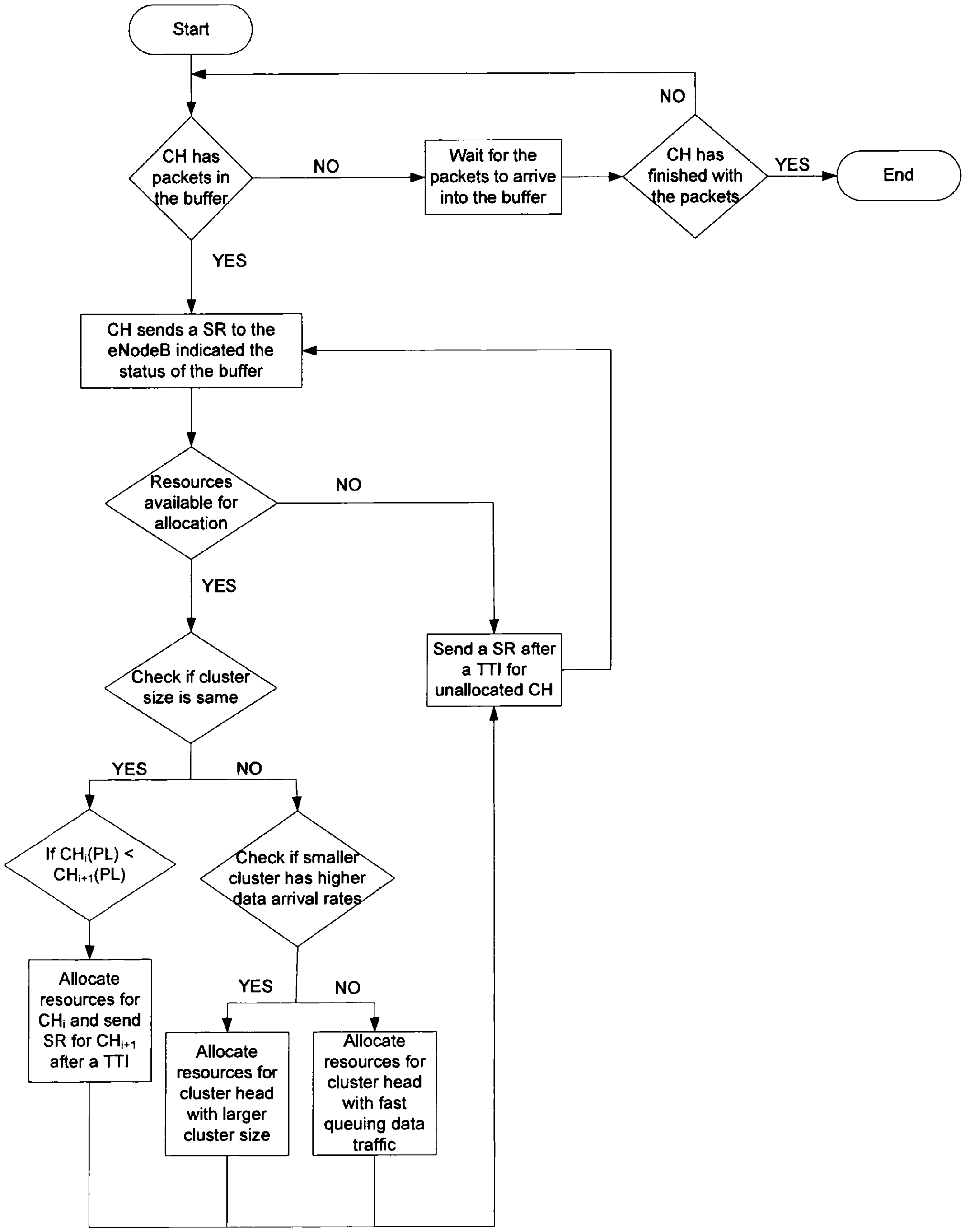

Fig.6.15 Generic flow for the CBS scheduling algorithm

By using the above rules for resource allocation, the proposed CBS algorithm could eliminate the problem of starvation, lower throughput while maintaining the QoS constraints. The comparison for the scheduling algorithms will be given in Section 6.6.

6.5. System model for V2R communication

This section looks into the implementation of scheduling algorithms with the proposed system model [125,126] as described in chapter 5. The proposed system model is a hybrid model where the vehicles communicate to the cluster head and the cluster head communicates to the base station (eNodeB). The fast movement in the vehicular nodes can result in missing their assigned resource blocks thereby causing increased contention between the vehicles to share the channel. Consequently, this may incur considerable traffic loss, as the data traffic is tolerant to delay and may drop delayed packets. By using cluster head to communicate to the base station, the channel utilisation can be optimised.

As shown in Fig. 6.16 the base station (eNodeB) covers a large area of 5km. The scheduler resides at the base station and the active vehicular nodes request for an uplink resource by sending a Scheduling Request Indicator (SRI). The contention based synchronized Random Access Channel (RACH) in the 3GPP Release 8 of LTE standardization process, was compared to the contention free SRI mechanisms. It was shown that the contention free SRI approach suited the LTE uplink utilisation because it provided better coverage, smaller overhead in the system and better delay performance in contrast to the contention based procedures [117]. This thesis uses the contention free SRI mechanisms principle in proposing the CBS scheduling algorithm.

The vehicular nodes within the cluster use DBTMA protocol to communicate to the cluster head and employs DSRC/WAVE technology. Each vehicular node in the cluster has a queue for the data traffic stream. With this technique, access delay and packet dropping probability can be reduced although the worst case scenario of collisions can still exist. By employing DBTMA the packet collisions are minimised by the use of two busy tones as explained in the previous section.

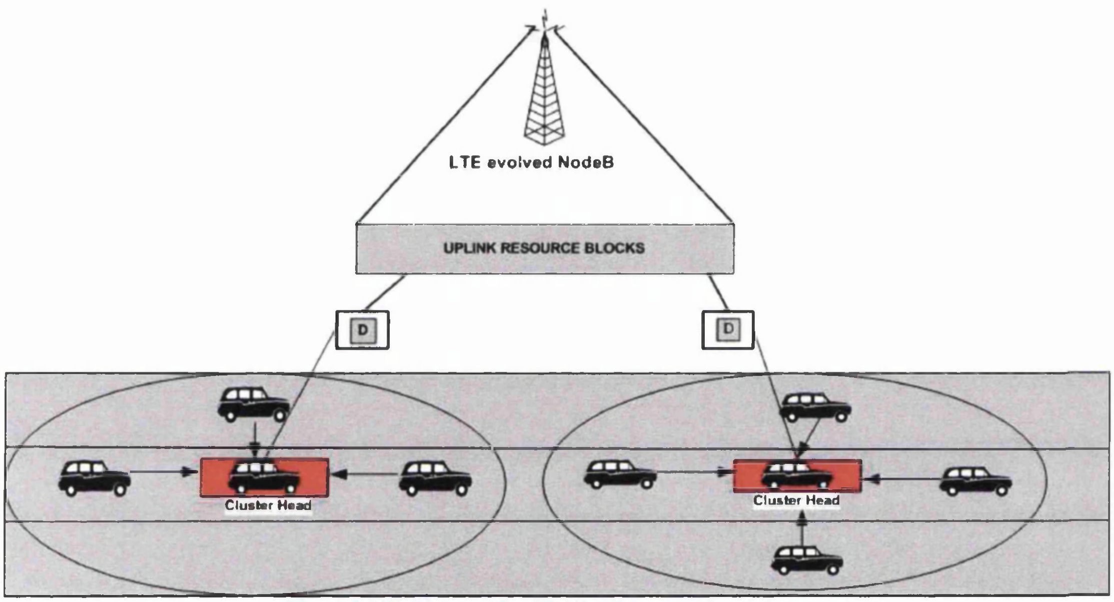

Fig.6.16 Vehicle to Roadside Communication

The cluster head as seen in Fig.6.16 is responsible for the data traffic streams. Apart from the data buffer queues in each vehicle, the cluster head will have buffer queue for the data traffic class.

As the cluster heads keep changing based on the MPLR clustering algorithm, all the vehicular nodes are equipped with two transceivers, one for the V2V tier and the other for the V2R tier. The vehicles communicate to the cluster head through the transceiver for V2V tier and once the data is received at the cluster head, they are maintained in separate queues as shown in Fig.6.16. The transceiver for V2R tier is used for communication between the cluster head and the base station. The scheduler at the eNodeB base station allocates the resource blocks to the users according to their scheduling request. The scheduling request is based on the packet received at the cluster head. The round robin scheduling algorithm allocates a fixed number of slots for each user and these slots are fixed for each TTI. However over a period of time, with increased number of vehicular nodes, the allocation of resource blocks will become dynamic and will depend on the cluster size and the path loss factor as explained in Section 6.4.2.

The impact of the two scheduling algorithms on the system is studied and the flowchart in fig.6.17 gives the implementation of the scheduling algorithm in the system. The main aim of this study is to see the scheduling technique most suited for the MPLR network model and effect of the algorithms on the channel utilisation, queuing delays and the packet drops.

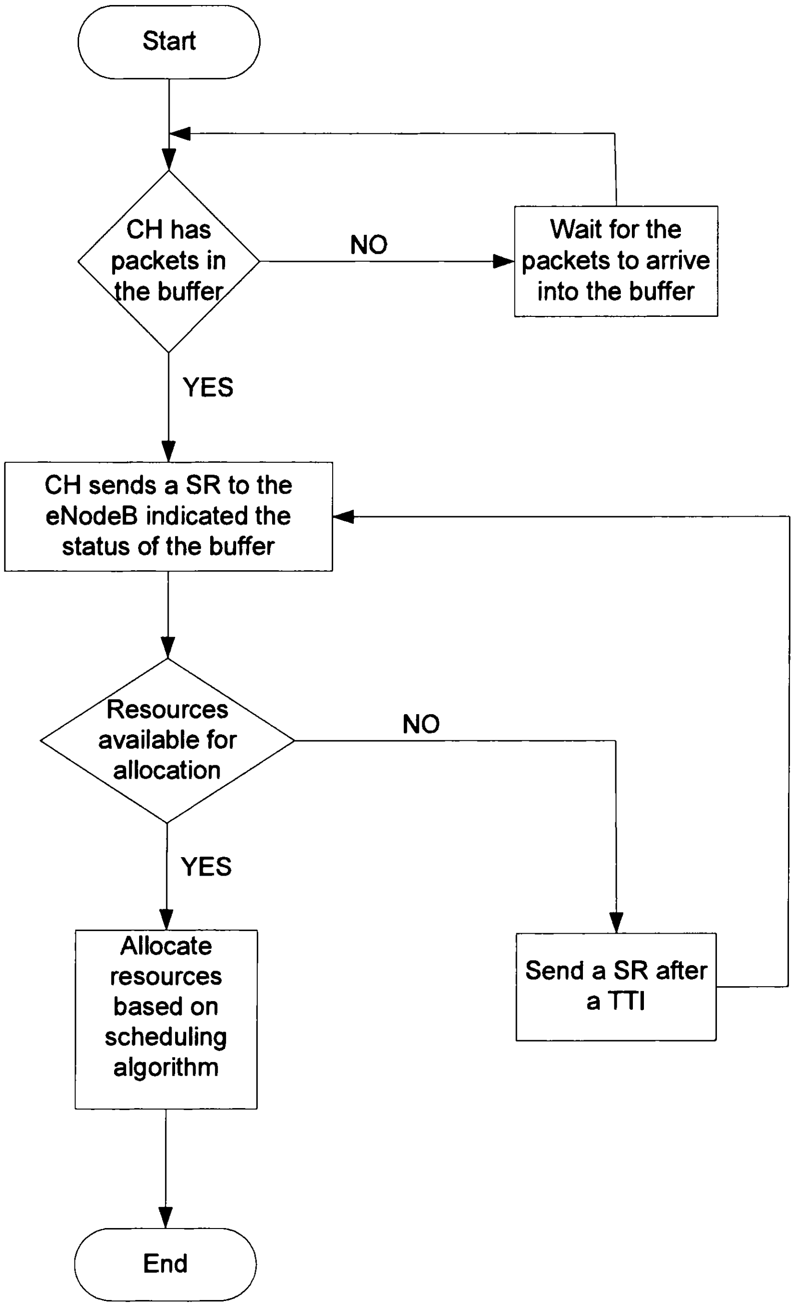

Fig.6.17 Generic flow for the scheduler simulation

The parameters used for the scheduler simulation based on the LTE and WAVE standards are given in table 6.3. The parameters used for V2V simulation is given in table 6.1.

Parameters	Values
Bandwidth	10 MHz
Uplink Channel Bit Rate	50 Mbps
Resource Blocks	50
Base Station Coverage area	5 km
TTI (one slot)	1ms
Number of symbols per slot	14
Packet Size	600 bytes
Data Source Bit Rate	500 Kbps
Data Call Arrival Duration	30 min
Data Call Inter-arrival duration	5 min

Table 6.3 Simulation Parameters

6.6. Performance Evaluation of scheduling algorithms

The algorithms performance is evaluated in terms of throughput, average access delay and packet dropping probability.

Fig. 6.18 shows the throughput (η) for CBS has a marked improvement over the round robin scheduling method. There are two factors which causes the increase in throughput. One main factor is attributed to the resource blocks allocation based on the cluster size. A large cluster size as mentioned earlier implies higher number of data traffic sources with increasing flow rate coming into the CH. The other factor is the CH with fast accumulating data traffic queues are given priority over delay tolerant data traffic queues.

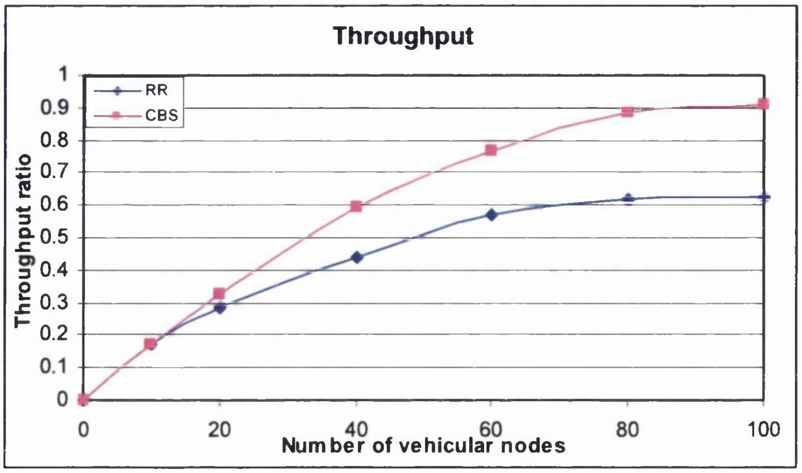

Fig.6.18 Throughput vs number of vehicular nodes

Fig. 6.19. shows, for both scenarios the packet dropping probability (P_{drop}) increases as the number of users increase. However, for round robin scheduling the P_{drop} is higher than the CBS. This is because the service rate for packets in round robin scheduling is equally distributed irrespective of the data traffic queue length. Hence fast accumulating queue can incur longer delays due to poor allocation technique and eventually leading to packet drops. In CBS algorithm, the first priority is given to users with rapidly increasing buffer size. By doing this, the packet drops are minimised and lead to better system performance.

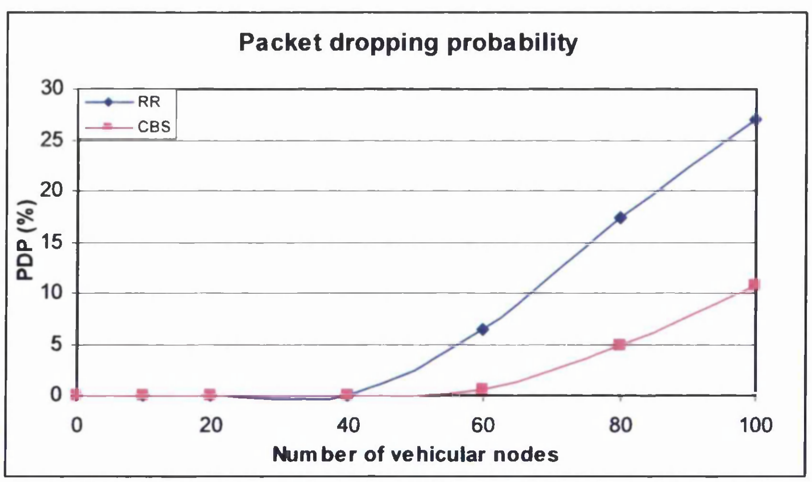

Fig.6.19 Packet dropping proability vs number of vehicular nodes

Fig. 6.20. shows the average access delay for both the algorithms. The delay curve follows the same trend for both the scheduling algorithms till vehicular nodes reach 40.The average access delay also includes the delay incurred by the packets at the V2V tier level. The CBS scheduling algorithm outperforms marginally as the packets are made to wait in the queue based on the cluster size and path loss which incurs the delays in CBS method. As for round robin scheduling, the starvation is lower till the channel is saturated and hence the packets are served at an equal rate of the arrivals.

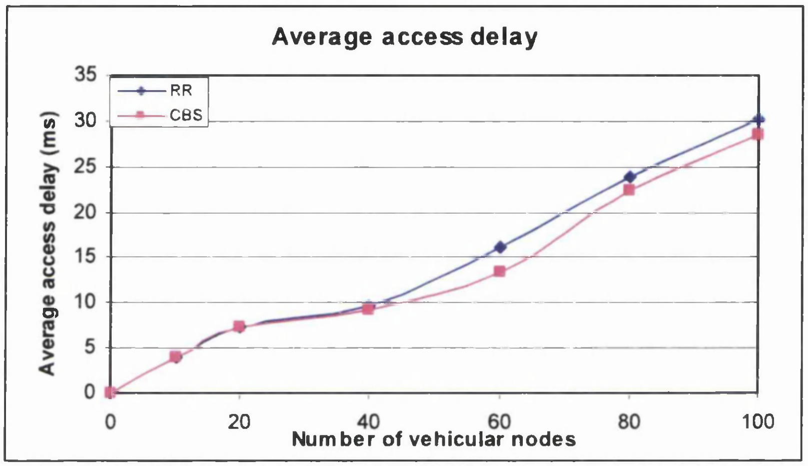

Fig.6.20 Average access delay vs number of vehicular nodes

6.7. Summary

This chapter focussed on studying the performance evaluation of the MAC protocols for V2V communication and scheduling techniques for V2R communication using LTE. CSMA/CA and DBTMA protocols are employed for the comparative study. The simulator component implementing the MAC protocols are explained in detail. The performance of the protocols are analysed for different vehicular densities and different hours of the day capturing low, medium and highly dense motorway scenarios. The performance metrics are measured in terms of the throughput, average access delay and packet collision ratio. With all the three metrics, the DBTMA protocol performs better than the CSMA/CA protocol, with the conclusion, DBTMA could be deployed instead of the standardised CSMA/CA for the V2V communication. For V2R communication, the LTE resource block structure was studied in detail. A cluster based scheduling (CBS) technique was proposed and compared with a traditional round robin scheduling. The performance of these two scheduling algorithms was measured in terms of throughput, packet dropping probability and average access delay. The CBS showed marked improvement over round robin scheduling for throughput and packet dropping probability. But for average access delay, the CBS scheduling performs slightly better than the RR algorithm due to characteristic nature of serving all users equally.

Chapter 7

Conclusions and Future Work

7.1. Conclusions

The demand for ubiquitous personal communications with high data rate and support for multimedia services has led to a huge development in the fields of vehicular networks. Recent research activities in vehicular networks have aimed at improving the safety of the roads. But the increasing demand for wireless communications and high bit rate services has led to the emergence of comfort applications. This thesis has based its research on the comfort applications and has considered the evaluation of a hybrid vehicular communication system while maintaining the quality of service.

As the key requirement for comfort applications is to provide reliable data links with high data rate, a solution is proposed where the two vehicular networks are combined to provide a hybrid network (V2V+V2R). The hybrid network combines both the systems advantages and thereby eliminates the disadvantages of the individual networks to a certain degree. However, the high mobile nature of the network still makes the communication between vehicles challenging.

Little research work has been carried on the UK motorway traffic profiles. As part of this work, empirical vehicular data measured at the inductive loops on the M4 motorway are analysed in detail. Key traffic characteristics such as vehicular arrivals, vehicular speed and vehicular inter-arrival times were used in designing and developing a bespoke motorway simulator. Gaussian arrival is used to model the vehicular arrivals and is fed as input to the motorway simulator. The simulator designed is fast, simple, flexible and reliable. Discrete event driven simulation was employed by the simulator and was coded in Java. The simulator is validated by comparing the real time vehicular data to the modelled data and also comparing a single hop CSMA/CA protocol with the theoretical results obtained by the authors in [67,68]. The results are in close agreement with each other thereby demonstrating the accuracy of the developed motorway simulator.

Current VANET communication protocols use different methods for data dissemination. This thesis uses hierarchical clustering architecture as an efficient method to reduce data congestion, optimise communication and improve network stability. A minimal path loss ratio (MPLR) clustering algorithm is proposed. The algorithm elects the cluster head whose path loss experienced between the vehicle and the base station is minimal from a group of vehicles in transmission range of each other. The performance of the clustering algorithm is measured in terms of rate of change of cluster head, average cluster size and average number of clusters. The main performance indicator is the rate of change of cluster heads and a mathematical model was derived to calculate the rate of change of cluster head. The results obtained from the simulator were in good agreement with the mathematical model results for the rate of change of cluster heads. The other two performance metrics- average number of clusters and average cluster size are measured for different hours of the day. The average number of clusters increases at the peak morning and evening hours. The curve follows the vehicular arrivals pattern showing the number of clusters is dependent on the number of vehicles in the motorway. The average cluster size varies between 3 and 8 indicating sparsely and densely populated motorway. The cluster reaches its maximum size of 8 during the evening rush hours and averages at a size of 5 for the most of the morning.

To exhibit the effectiveness of the MPLR clustering algorithm, this thesis compares the performance of the hybrid system (V2V+V2R) to a pure V2R system. The hybrid system employs MPLR clustering algorithm for data dissemination while the pure V2R system has direct links with the vehicles. LTE technology is used for communication between the base station/roadside infrastructure and vehicular nodes. The network traffic used for this study is modelled based on Poisson data traffic. The experiment considered transmission of a fixed size file from the road side infrastructure to the vehicle and analysed the efficiency of the hybrid system in terms of number of transmission links required, resource utilisation ratio, packet dropping probability and average access delay. The hybrid system with the MPLR algorithm shows a marked improvement compared to a pure V2R system. The resources required for transmission of the file is only 20% for a hybrid system compared to the 50% for a pure V2R system. The MPLR algorithm is also compared with the other popular clustering algorithms such as Lowest ID algorithm and highest degree algorithm by measuring the rate of cluster head change. The MPLR algorithm shows a fewer cluster head changes compared to the other two algorithms thereby proving the robustness of the proposed algorithm.

Furthermore, the performance of the MPLR algorithm with the MAC protocols for V2V communication is studied. Two protocols CSMA/CA and DBTMA are deployed along with the MPLR algorithm. The performance is analysed with respect to the throughput, average access delay and packet collision ratio for various vehicular densities and for different hours of the day. The DBTMA protocol demonstrates significant improvement over the CSMA/CA protocol and the comparative study concludes with DBTMA outperforming the CSMA/CA protocol for the V2V communication.

To extend the work, the scheduling algorithms for V2R communication using the LTE technology are studied. A traditional round robin scheduling was studied and analysed. Although round robin scheduling can be fair and has lower starvation, the algorithm induces higher packet dropping probability and reduces the network throughput. A scheduling algorithm based on the MPLR algorithm is proposed. The cluster based scheduling (CBS) algorithm allocates the resource slots in the LTE frame based on the cluster size and path loss. It is found that CBS has better throughput and packet dropping probability compared to the round robin scheduling with a marginal difference in performance for average access delay.

7.2. Future Work

The designed motorway simulator is an experimental simulator with input of the real world vehicular data from the inductive loops. The functionalities of the simulator can be enhanced by introducing the macro-mobility and additional micro-mobility patterns. Each vehicle could be represented as individual entities in the motorway and incorporate concurrency by deployment of threads. The macro-mobility patterns takes into account the traffic signs such as stop signs, speed warning and traffic lights, road restrictions, junctions and micro-mobility patterns include the individual vehicle speed, acceleration and deceleration. By introducing these additional functions, the performance of the simulator can be improved.

The proposed MPLR clustering algorithm uses the path loss ratio for selecting the cluster head. As part of the future study, other constraints such as the environment noise, fading and road side infrastructure characteristics can be used as part of cluster head election. This will ensure a better channel condition for the cluster head communication. Also the path loss is measured as the distance of the vehicle to the base station. The longer distance, the path loss experience is higher. In addition, a Hata path loss model can be implemented to measure the path loss accurately and use it for the MPLR algorithm.

The existing system simulator implemented the MAC protocols and scheduling algorithms. A physical layer module considering multi path fading, noise and with user defined specification for the antenna and base station design, can be added as part of this simulator. This will help in modelling the characteristics of the wireless channel more accurately. All the analytic and simulation results in this thesis are based on Poisson traffic. Recent progress in traffic theory shows that data traffic has self similar behaviour and therefore it is of interest to evaluate analytically and through simulation all the protocols proposed in this thesis, but under self similar traffic. Multimedia traffic (voice, video and data) modelling can also be separate module which can be added as part of the simulator. It will be interesting to see the performance of the MPLR algorithm with MAC protocols for the delay sensitive triple play data while maintaining the Qos.

This entire thesis had used a motorway setup as the background for the research work. The performance of MPLR algorithm could be analysed in a city based scenario. Initially a typical Manhattan grid can be used followed by incorporating real road maps with real time vehicular data and evaluating the performance. To enhance the performance of the V2V communication, storage buffers can be introduced which can act as a static router for the packets. These storage buffers can be deployed in the dense traffic areas of the city with minimal infrastructure. This can help in reduction of the end to end delay and packet dropping probability.

7.3. Summary

This chapter has presented a concise summary of the research work and also has put forward some of the potential areas of future work. It will be of great interest and a challenge to modify the existing system to enhance the system performance.

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