University of Southern Queensland

Faculty of Health, Engineering and Sciences

Reducing Road Fatalities – Vehicular Ad Hoc Network

A dissertation submitted by

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in fulfilment of the requirements of

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towards the degree of

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Abstract

Intelligent transport systems (ITS) are communication networks used for the delivery of important safety, environmental and efficiency data between vehicles, to enable public safety applications and improve traffic flow. These communication systems allow private and public transport by rail and road to be able to be connected to the system. Vehicular ad-hoc networks (VANET) between vehicles, between a vehicle and a roadside unit (RSU) and between RSUs allow vehicles equipped with wireless devices to communicate with each other and form a self-organised network without the requirement of permanent infrastructures.

ITS and VANET have the potential to help with the growing problems the country is facing due to the increasing number of vehicles using the road networks**.** An increase in road traffic leads to accidents and road crashes. Road traffic congestions cost the nation billions of dollars a year.

A model of the ITS and VANET needs to be developed. Network models as well as vehicular traffic models needs to be analysed and used to create the model that will be used for simulation.

The tasks can be broken down into the following activities:

- Review of relevant literatures
- Development of models
- Development of simulation program
- Simulation of the models and analysis of results; and
- Formulation of recommendation and conclusion.

Interference, signal power and vehicular density can greatly reduce the throughput of the packets in the network, as well as increase the number of dropped packet.

ITS and VANET offers a lot of benefits for road users and the public in general. The current implementation gives a solid foundation of what a good vehicular communications can be, but it still has a lot of room for improvement to be a reliable safety application for reducing road fatalities.

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Nomenclature

AP	Access Point
BSS	Basic Service Set
CCH	Control Channel
DSRC	Dedicated Short Range Communication
FCC	Federal Communications Commission
ITS	Intelligent Transport System
OBU	On-board Unit
RSU	Roadside Unit
SCH	Service Channel
STA	Station
VANET	Vehicular Ad-hoc Network

Chapter 1

Intelligent Transport System

1.1 Introduction

Intelligent transport systems (ITS) are communication networks used for the delivery of important safety, environmental and efficiency data between vehicles, to enable public safety applications and improve traffic flow. These communication systems allow private and public transport by rail and road, as well as biking and walking to be able to be connected to the system.

Dedicated Short Range Communications (DSRC) are short to medium range wireless communication channels specifically designed for use in vehicles. In 1999, the United States, through the Federal Communications Commission (FCC), allocated the 75Mhz spectrum of Dedicated Short Range Communications (DSRC) at 5.9GHz band to be used solely for ITS. In Europe, the European Telecommunications Standards Institute (ETSI) has allocated 30MHz spectrum of the 5.9GHz band for its ITS.

In Australia, Austroads, which is the association of Australian and New Zealand road transport and traffic authorities, asked the Australian Transport Council (ATC) to develop a national guideline for ITS in 1998. e-Transport was developed as a result of this, and was financed by Austroads and supported by the commonwealth government, as well as the states' and territories' transport ministers. This is considered as one of the foundations for the development of ITS in Australia. Austroads has recently started a new project to develop a National ITS Architecture with the involvement of state, territory and Commonwealth members (SCOTI 2012).

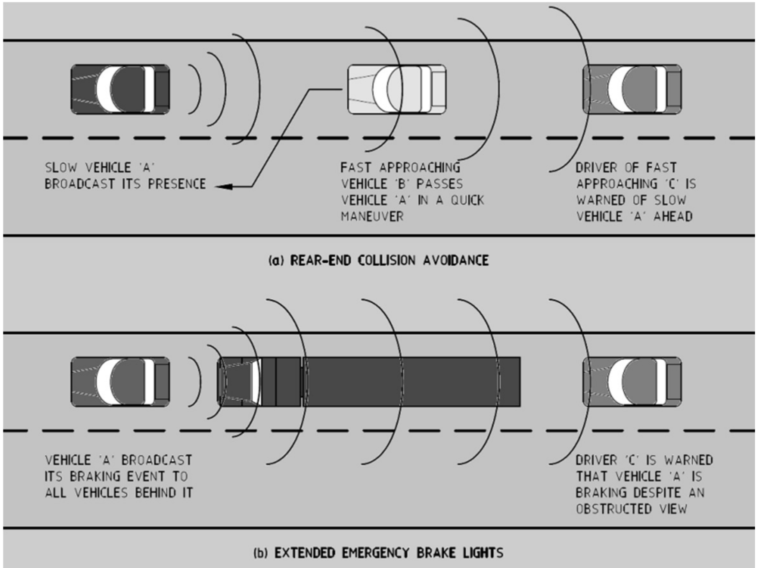

Fig 1.1 Vehicle safety communication examples (Jiang & Delgrossi 2008).

ITS has the potential to develop and address current and future traffic challenges that Australia will be facing. Transport networks are expected to grow over the next few years, and according to the Standing Council on Transport and Infrastructure (2012), this would include the following:

- the expected growth in the freight task, with road freight alone projected to increase by 80 per cent by 2030;
- road crashes cost the nation in the order of $27b a year;
- road traffic congestion will cost the nation in the order of $20b a year by 2020. Delays result in lower productivity, cause flow-on delays in supply chains and increase the transaction cost of business;
- managing CO_2 emissions, with road transport accounting for 14 per cent of Australia's total greenhouse emissions;
- driving in stop-start congested traffic increases fuel consumption and greenhouse gas emissions by around 30 per cent compared with normal driving conditions during the day;
- delivering national approaches and regulatory reforms that facilitate competition, open access and compatible systems;
- pressures created by the growth of our major cities limiting transport efficiency and flow on productivity benefits to the economy including the mobility requirements and social inclusiveness of our cities;
- increasing complexity in the operational environment in delivering ITS services; and

- increasing barriers to the construction of major new infrastructure to address urban transport issues – for financial, space, planning and environmental reasons.

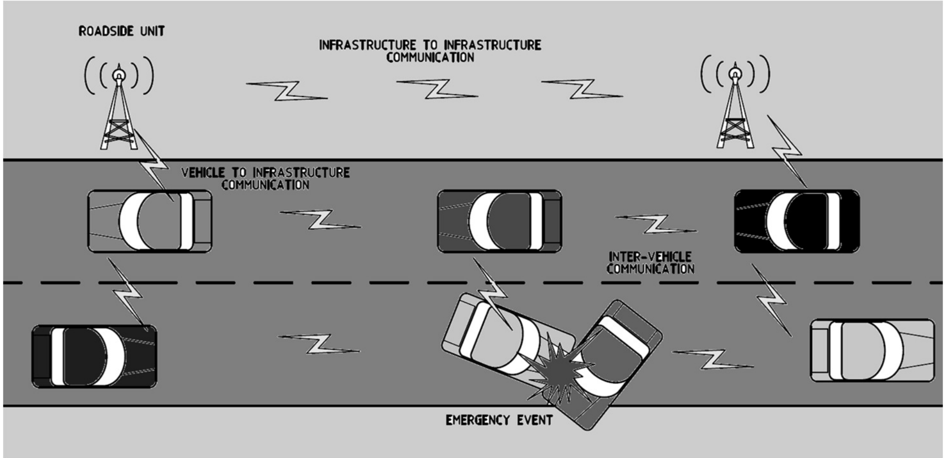

Fig 1.2 Basic architecture of VANET (Sumro et al. 2010).

Vehicular ad hoc networks (VANET) between vehicles equipped with on-board units (OBU), between a vehicle with OBU and a roadside unit (RSU) and between RSUs, which are connected to each other through a high capacity mesh networks allows vehicles equipped with wireless devices to communicate with each other and form a self-organised network without the requirement of permanent infrastructures (Neelakantan & Babu 2012). Most of the applications of a VANET are focused on improving the safety of the vehicle on the road and providing commercial and entertainment services to the vehicles. The specific characteristics of a VANET according to Murali et al. (2011) are:

- highly dynamic topology
- frequently disconnected network
- mobility modelling and prediction
- communication environment
- hard delay constraints, and
- interaction with on-board sensors.

Vehicle related crashes cause thousands of unnecessary injuries and fatalities across the world despite the advances of safety systems installed inside the vehicles, such as seatbelt, airbag and anti-lock braking system, which most of them focus on after-the-crash scenario or right before crashing the vehicle.

1.2 Project Aim

Intelligent Transport Systems are being developed and used around the world to enhance the safety and the efficiency of vehicles on the road, and improve the management of traffic congestions on existing road infrastructures.

The primary aim of this research is to be able to analyse the performance of an Intelligent Transport System, specifically, of a Vehicular Ad Hoc Network and be able to develop a software program for simulation.

1.3 Project Objectives

The aims of the project are divided into the following objectives:

- Research the fundamentals of a VANET, including associated equipment, standards and protocols.
- Evaluate current implementation of a VANET, its application and usage.
- Identify current limitations and other negative factors affecting the wide adoptions of a VANET.
- Research future implementations and other possible usage of a VANET.
- Implementing and performance evaluation of the latest standard for Intelligent Transport System.
- Develop a computer program to simulate VANET.
- Analyse the simulation's performance, its limitations and results.

1.4 Overview of the Dissertation

The dissertation is organised as follows:

Chapter 2 discusses the background of Intelligent Transport System and Vehicular Ad hoc Networks, the current standards and protocols. It also touches on the issues affecting the implementation of the framework as well as their current uses.

Chapter 3 defines the methodology that was used for this dissertation and also includes the risk analysis, ethical responsibilities and the resources needed for the performance evaluation of the network.

Chapter 4 discusses different types of models and simulation programs used for simulation of the network. It also discusses how the simulation is setup and what the results are for each of scenarios.

Chapter 5 summarised the work that has been done and discusses some recommendation and other future work that will be done to further evaluate the performance of the network.

Chapter 2

Literature Review

2.1 Standards

2.1.1 Dedicated Short Range Communications (DSRC)

In 1999, The US Federal Communications Commission (FCC) allocated the 75 MHz of Dedicated Short Range Communications (DSRC) spectrum at 5.9 GHz to be used exclusively for vehicle-to-vehicle and infrastructure-to-vehicle communications (Jiang & Delgrossi 2008). The main reason for the allocation of the spectrum is for safety usage as well as for enhancing traffic flow. The FCC does not charge a fee to use the spectrum, but they regulate the usage within certain channels and needs the devices to be compliant to the standard.

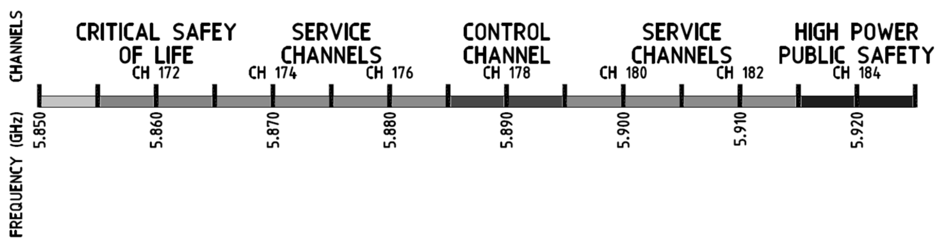

Fig 2.1 DSRC spectrum band and channels in the US (Jiang & Delgrossi 2008).

The DSRC channel has seven 10 MHz channels, with channel 178 as the control channel, which is for safety communications, and channel 172 and 184 as reserved for special uses. The rest of the channels are used for safety or non-safety applications.

In addition to different frequency being used, different maximum transmit powers are allotted for each channels, with the control channel having the highest maximum transmit power for critical safety related use and non-critical channels have a smaller transmit powers.

2.1.2 IEEE 802.11p Standard

The 802.11 standard is a standard for the PHY and MAC layer of the standard OSI model. Transmission of data between nodes can be done by several different methods in the physical layer. According to Maqsood and Khan (2012), Direct Sequence Spread Spectrum (DSSS), Orthogonal Frequency Distribution Modulation (OFDM), or Frequency Hopping Spread Spectrum (FHSS) can be used by nodes and Distributed Coordination Function (DCF) and Point Coordination Function (PCF) can be used for access mechanism.

Parameter	IEEE802.11a/e	IEEE 802.11p
Channel Width	20 MHz	10 MHz
Date Rates	6, 9, 12, 18, 24, 36, 48, 54 Mbit/s	3, 4.5, 6, 9, 12, 18, 24, 27 Mbit/s
Symbol Duration	4 µs	8 µs
Guard Time	0.8 µs	1.6 µs
PLCP Preamble Duration	16 µs	32 µs
Signal Field Duration	4 µs	8 µs
Subcarrier Spacing	0.3125 MHz	0.15625 MHz
Frequency Range	USA: 5.15 - 5.35 GHz & 5.725 - 5.825 GHz	USA: 5.850 - 5.925 GHz
	EU: 5.15 - 5.35 GHz & 5.47 - 5.725 GHz	EU: 5.875 - 5.905 GHz & optionally other
		channels of USA band
Maximum EIRP	USA: 800 mW	30 W (emergency vehicles in USA)
	EU: 500 mW	2 W (normal vehicle USA & EU)
SIFS Duration	16 µs	32 µs
Slot Time	4 µs	13 µs
CW Min (V0, VI, BE, BK)	3, 7, 15, 15	3, 3, 7, 15 (CCH Channel)
CW Max (V0, VI, BE, BK)	7, 15, 1023, 1023	7, 7, 15, 1023 (CCH channel)
AIFSN (V0, VI, BE, BK)	2, 2, 3, 7	2, ., 3, 9 (CCH channel)
Multi-Channel Operation	Not Supported	USA: Channel switching single radio
		EU: One radio CCH + One radio SCH

Table 2.1 Differences between IEEE 80.211a/e and IEEE 802.11p (Vandenberghe et al. 2011)

The IEEE 802.11p physical layer is similar to the IEEE 802.11a physical layer design, and one of the main differences of IEEE 802.11p and IEEE 802.11a is the difference in the bandwidth used by the protocols, which is 10MHz for IEEE 802.11p and 20MHz for IEEE 802.11a. The other main difference between the two standards is the transmit power and the operating frequencies (Grafling et al. 2010). The other changes to the PHY layer are based on the difference in bandwidth used by the two standards. Because the channel width is reduced from 20 MHz to 10 Mhz in IEEE 802.11p, the symbol duration, guard time, PLCP preamble duration and signal field are doubled, and, the subcarrier spacing is halved. And because of this, the data rates are halved and the reduced bandwidth reduces the effect of Doppler spread and the larger guard interval reduces inter-symbol interference caused by multi-path propagation (Vandenberghe et al. 2011).

The operating frequency band for IEEE 802.11p is 5.9GHz in the US ITS band. The 75MHz is divided between seven channels of 10MHz channel bandwidth and a safety margin of 5MHz channel bandwidth at the lower end of the band. The 10MHz bandwidth reduces the effects of Doppler spread. The main and central channel in which all important safety messages are broadcasted is the control channel (CCH) and the other channels which are used for other safety and non-safety applications are the service channels (SCH). There are four levels of maximum allowable Effective Isotropic Radiated Power (EIRP) defined in the IEEE 802.11p standard, which are used to support communications between the RSUs and the OBUs. The highest EIRP defined in the IEEE 802.11p standard is used for the CCH at 44.8dBm. 40dBm is used for the SCH 184 for traffic efficiency, and 33dBm is used for SCH 172, 174 and 176 for non-safety applications for the first two and traffic efficiency services for the last one. SCH 180 and 182 uses 23dBm for its critical and traffic efficiency applications, respectively. The double guard bands reduce the interference and make the signal more effective against fading (Murali et al. 2011).

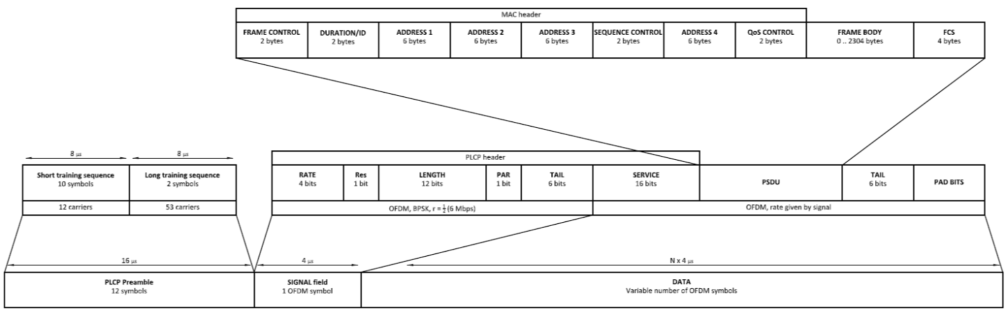

Fig 2.2 IEEE 802.11 packet format (Vandenberghe et al. 2011).

It uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as the main access method to the wireless medium.

802.11p radio can be a single physical radio (single-PHY) or multiple physical radio (multi-PHY). Single-PHY radio can only tune in to one channel, and it must switch between CCH and SCH at all times to be able to monitor and receive data between the two channels. Multi-PHY radio is able to tune in continuously at CCH and at the same time communicate with one or more SCH channels.

CHANNEL NUMBER	172	174	176	178	180	182	184
CHANNEL TYPE	SERVICE CHANNEL	SERVICE CHANNEL	SERVICE CHANNEL	CONTROL CHANNEL	SERVICE CHANNEL	SERVICE CHANNEL	SERVICE CHANNEL
APPLICATION	NON- SAFETY	NON- SAFETY	TRAFFIC EFFICIENCY	CRITICAL SAFETY	CRITICAL SAFETY	TRAFFIC EFFICIENCY	TRAFFIC EFFICIENCY
RADIO RANGE	C2C	MEDIUM	MEDIUM	ALL	SHORT	SHORT	INTERSECTIONS
TX POWER LEVEL	33dBm	33dBm	33dBm	44.8dBm	23dBm	23dBm	40dBm

Fig 2.3 The set of channels defined in the WAVE standard for multi-channel operation (Grafling et al. 2010).

A Basic Service Set (BSS) is a group of stations (STA) that are connected together through an Access Point (AP). The stations are configured to be able to communicate with each other over wireless communications. The BSS manages the connections of the stations, as well as filtering out the other radio transmission nearby.

An Independent BSS (IBSS) is an ad hoc operating mode of the 802.11 standard. In this mode, the requirement for an access point in not needed, however, it still carries a lot of overhead and still much complex for vehicular communication applications.

2.1.3 IEEE 1609 Wireless Access in Vehicular Environments (WAVE)

IEEE 1609 Wireless Access in Vehicular Environments is an enhancement to the 802.11. Most of the changes in the standard are related to the MAC layer, which is advantageous as changes to the MAC layer can be done by just using software and can easily be updated, while the PHY layer are mostly hardware based.

IEEE 1609 WAVE consists of five standards: IEEE 1609.0 – Architecture, IEEE 1609.1 – Resource Manager, IEEE 1609.2 – Security Services for Applications and Management Messages, IEEE 1609.3 – Networking Services, and IEEE 1609.4 – Multichannel Operations.

IEEE 1609.0 describes the WAVE architecture using DSRC to communicate between vehicles. IEEE 1609.1 describes the data and management of services in the architecture, as well as defining the command and reply message formats, data storage formats, and status and request message formats. IEEE 1609.2 defines secure message formats and how it is to be processed and exchanged between the nodes. IEEE 1609.3 defines network and transport layer services, addressing and routing. It defines the use of

WAVE Short Messages (WSM), an alternative to Internet Protocol Version 6 (IPv6). IEEE 1609.4 improves on IEEE 802.11 MAC and supports WAVE operation, and defines the number and the type of channels to be used, routing and node synchronisation.

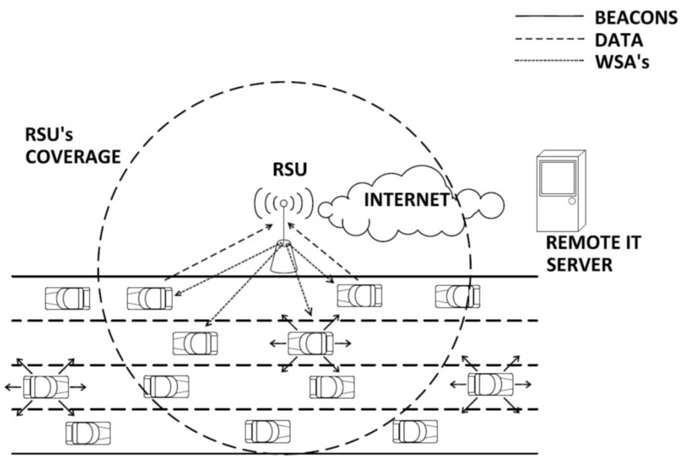

Fig 2. 4 Reference scenario (Campolo & Molinaro 2011).

The PHY layer came from the IEEE 802.11a protocol and the MAC layer uses the Enhanced Distributed Channel Access (EDCA) mechanism that came from IEEE 802.11e protocol (Felice et al. 2012). EDCA is a distributed contention-based channel access mechanism which selects the packets to send based on its priority. For each channels, four Access Categories are defined (AC0 – AC3), with AC3 having the highest priority. Frames are categorised by the access category and are placed in different queues and are sent based on an internal contention procedure (Grafling et al. 2010).

Barradi et al. (cited in Barradi et al. 2012) gave examples for the use of each access category: AC0 handles information for establishing new non-safety related communications through the CCH; AC1 handles information sent by other vehicles asking for help who does not pose any threat to other adjacent vehicles; AC2 handles speed and location information sent by vehicles; and AC3 handles emergency information from RSU and vehicles.

High priority traffic has a higher chance of being sent and the station sending these packets waits less before it can send its packets than lower priority packets and stations. The IEEE 1609.4 is on top of the 802.11p protocol and enables the use of the DSRC band. The layers above the Data link layer follow the standard OSI model.

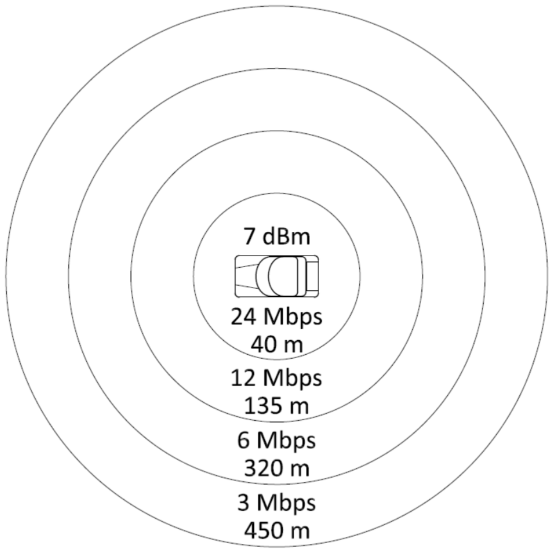

Fig 2.5 Transmission range for different data rates (Campolo & Molinaro 2011).

In the IEEE 802.11p specification, multiple transmission rates are allowed at the PHY layer by using different modulation and coding Transmitting the data packet at higher transmission rate will result in a shorter transmission time and higher channel efficiency, but are more prone to bit errors due to noise and interference. Transmitting the data packet at lower transmission rate can be more reliable but will result in underutilisation of the bandwidth and will have a lower throughput.

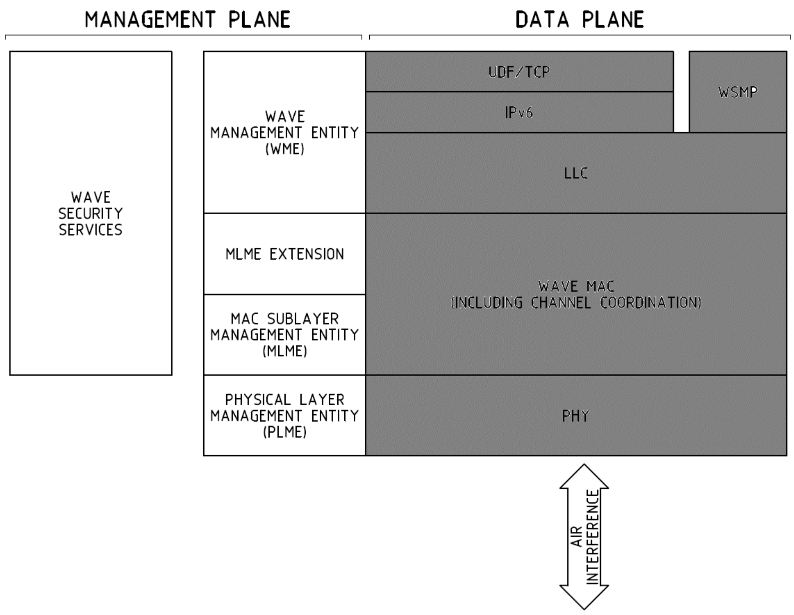

Fig 2.6 WAVE stack of protocols as defined in IEEE 1609.4-2010 (Cespedes et al. 2013).

IEEE 1609 WAVE defines two types of devices used, Road Side Unit (RSU) and On Board Unit (OBU). RSUs are stationary units that is installed by the road that host an application or several applications providing safety or non-safety services. OBUs are units installed on the vehicles that can either provide or use safety or non-safety services.

In order to use the multi-channel DSRC band using a single radio transceiver, all the vehicles must switch between the control channel (CCH) and service channel (SCH) synchronously. To be able to achieve this, the vehicles must maintain a synchronisation with the Coordinated Universal Time (UTC). During the CCH interval, the vehicles are tuned at the CCH and during the SCH interval, the vehicles are tuned at any of the SCH channels. A Guard Interval (GI) is observed between the intervals to increase timing accuracies and to cancel transmission delay effects. The SYNC interval is the sum of the SCH and CCH intervals and is equal to 100ms, the default length of the SCH and CCH intervals is 50ms, and the guard interval ranges from 4 to 6ms. (Felice et al. 2012).

In order to control switching between the different channels at the right time, channel coordination is needed. The channel coordination function provides access to the channel when high priority data is detected during the CCH interval, as well as high layer traffic during the SCH interval. When the WAVE device uses single radio, channel coordination is mandatory. The WAVE standard defines four types of channel access: continuous, alternate, extended and immediate (Ameixieira et al. 2011).

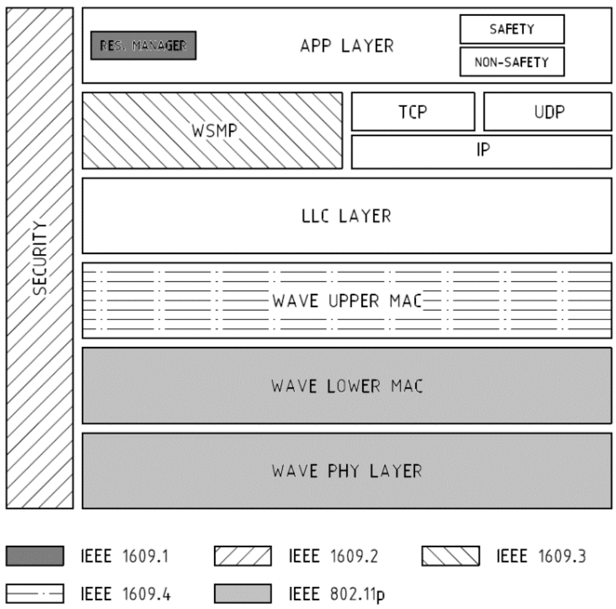

Fig 2.7 WAVE stack architecture (Felice et al. 2012).

Devices that are compliant to 802.11p standard are configured to have the same channel and the same Basic Service Set ID (BSSID) for safety communication. Safety communication uses case demand instantaneous data exchange capabilities and 802.11 MAC operations are not practical as they require more time to execute multiple handshakes to establish communications. When a vehicle approaches an RSU, the total time that the vehicle would be in range with that RSU is limited, and the vehicle would not be able to afford a long setting up time required for by a BSS. In WAVE BSS (WBSS) however, the process is more instantaneous as joining the process requires just a little overhead. The focus is to simplify the BSS operations into a truly ad hoc manner for vehicular usage (Jiang & Delgrossi 2008). WBSS is an enhancement of the BSS introduced by the 802.11p standard. The station (STA) forms a WBSS by first transmitting an on-demand beacon, and the WAVE station uses that demand beacon to advertise a WBSS. The advertisement contains all essential information offered by the WBSS, and the STA just decides whether it needs the services offered by the WBSS and joins it. This means that two vehicles can communicate with each other easily with just a little overhead as long as they are on the same channel and using the wildcard BSSID.

BSS are uniquely identified by BSSID. For a BSS in infrastructure mode, the BSSID is the MAC address of the access point (AP). For an IBSS, the BSSID is a MAC address randomly generated, and have the individual/group bit of the address set to 0, and the universal/local bit of the address is set to 1. Wildcard BSSID is a BSSID with a value of all 1's.

WAVE providers send WAVE service advertisement (WSA) through the CCH to announce setting up a WBSS over a given SCH. When the WSA message is received by the vehicles, data exchanges between the RSU and the OBUs over SCH occur. The reception of the advertisement can be affected by channel impairments and collisions with interfering traffic going through the CCH, such as other packets delivered over CCH, and event-based safety messages and beacons. When a vehicle does not receive the WSA message during the CCH interval, they are not allowed to join the advertised WBSS during the next SCH interval. As the radio switches between the CCH and SCH as described before, and the vehicle is receiving data from a service across multiple SCH intervals, when for some reason the vehicle was not able to receive the WSA in between the SCH interval, the connection would lead to a poor and intermittent transmission between the OBU and the service provider. WAVE short message protocol (WSMP) can be used to send out the beacons to the vehicle's adjacent neighbours. Beacons are short status or safety messages that contain the vehicle's information, such as speed, position and heading. They are transmitted during the CCH interval and are typically generated at a rate of 5-10 Hz. The standard does not specify a format for the packet, and they can be encapsulated as a low-overhead WSMP packet. Beaconing, where the dissemination of safety messages can help spread the awareness of the vehicles of the presence of the RSU even when the vehicles miss he WSA during the CCH interval. It can do this by piggybacking the WBSS information onto the beacons. The standard also suggests multiple copies of the WSA can be sent for reliability issues, but might not be sufficient for high data traffic (Campolo and Molinaro 2011).

To enable the DSRC system to function as what it was intended to do, it is important that both information from the CCH and SCH be received by all vehicles within a practicable time.

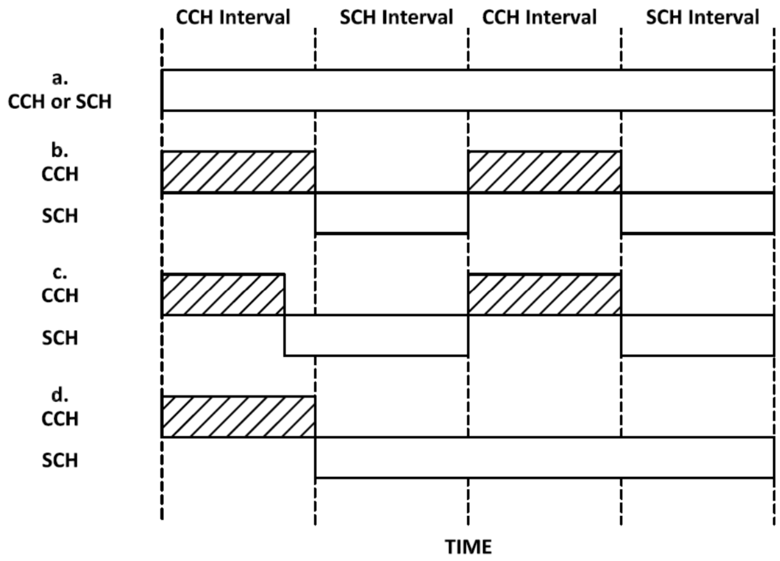

Fig 2.8 Channel access: (a) continuous, (b) alternate, (c) immediate and (d) extended (IEEE standard cited in Ameixieira et al. 2011).

There are two types of safety messages sent in VANET: routine safety messages and emergency safety messages (Sharafkandi & Du 2010). Routine messages are sent periodically by the vehicles. They send status information, location and speed, and are sent to adjacent vehicles only as they are the only ones who are of a potential danger from collision from the sending vehicle. Emergency safety messages are sent whenever there are dangerous conditions detected, and are broadcasted to all vehicles that could be affected.

Internet Protocol (IPv6) as well as the transport protocols Transmission Control Protocol (TCP) and User Datagram Protocol (UDP), are also included in the WAVE protocols for IP-based communication. By supporting IP-based communication, vehicles equipped with WAVE devices are able to be connected to other IP-based network for information and entertainment applications, and be able to help with market penetration and the cost of the devices can be more justifiable.

Several details of the latest draft of the standard is still not defined, and are left for user implementation, there are still a lot of improvement and potential that can be developed for the implementation of VANETs. The main role of the IEEE 802.11p/WAVE standard defines the minimum specifications to ensure connectivity between VANET wireless devices from different manufacturers.

2.2 Protocols

The design of an efficient routing protocol is very important for VANET since the nodes are not stationary as with a typical ad hoc network. The bandwidth is very limited and the topology of the network changes frequently (Aswathy & Tripti 2012). A lot of works are focused on the techniques to implement the existence of the safety non-safety application operating on the same network scenario. There are a lot of protocols being developed and used today for VANET's implementation, and some of the basic and common protocols are discussed below.

2.2.1 Adaptive Ad Hoc (A-ADHOC) Protocol

When the number of vehicles is low, there is the potential to have a connection with a higher speed, where the requirement of response time would be in demand. When the number of vehicles is high, the requirement of response time is less, but must have all nodes get connected. An adaptive frame length has the ability to adjust the length of the frame depending on the number of nodes available.

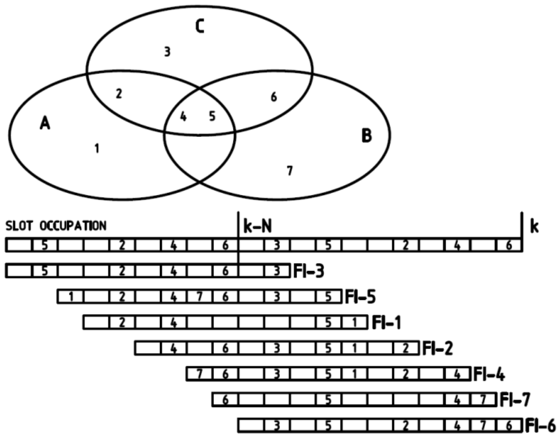

Fig 2.9 Wireless network example with ADHOC MAC protocol (Borgonovo et al. 2004).

ADHOC is based on the Reliable Reservation ALOHA (RR-ALOHA) protocol, a new distributed reservation protocol capable of dynamically establishing a reliable single-hop broadcast channel (Liu et al. 2010). The allocation of Time Division Multiple Access (TDMA) slot to provide a prompt access and reliable channels for information delivery is the most important feature of the RR-ALOHA protocol.

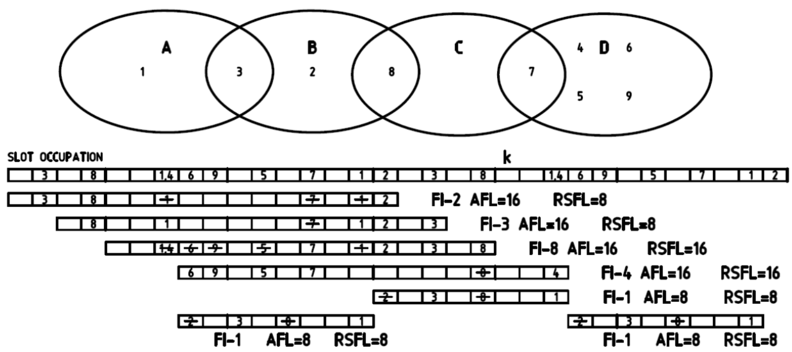

Fig 2.10 An example of A-ADHOC MAC protocol (Liu et al. 2010).

Liu et al. (2010) proposed Adaptive ADHOC (A-ADHOC) protocol. A-ADHOC works by doubling the frame length when the number of nodes in the network becomes more than the upper threshold. When this happens, every node sends out a message to double up the frame length. When the number of nodes in the network becomes less than the lower threshold, every node sends out a message to cut the frame length in half.

According to Liu et al. (2010), there are several rules to follow to be able to have the A-ADHOC protocol to work properly.

- A slot can be 'BUSY by node X' when node X has occupied the slot. The adjacent node S generate this message when it receives node X's broadcasted packet containing Frame Information (FI). Frame Information is a vector with N entries specifying the status of each of preceding N slots. Node S copy node X's FI to its own FI.

  A slot can be 'RESEREVED by node X' when node X has occupied the slot adjacent to node S. This information is passed on to node S by an adjacent node in the middle.
- A slot can be 'AVAILABLE' when none of the two situations applies. Any new node can use this slot.
- The frame length of any two adjacent networks can only be equal or double only.

- When two nodes that are communicating with each other have different frame lengths, the one that has the shorter frame length will keep the FI message of the longer frame length for two frames.
- Every node can decide to double the frame length by using

$$b_{n-2} + \sum_{i=n-1}^{n+2} (a_i + b_i) > S_{\text{upper}} \cdot N \tag{3.1}$$

where,

$N =$ total number of slots

$S_{\text{upper}} =$ upper bound of ratio of unavailable slot number to total number of slots

$a_i, b_i =$ number of nodes in none-intersectional area of network

$b_{n-2} =$ overlapped nodes

- Every node can decide to start halving the frame length if the above equation becomes untrue.

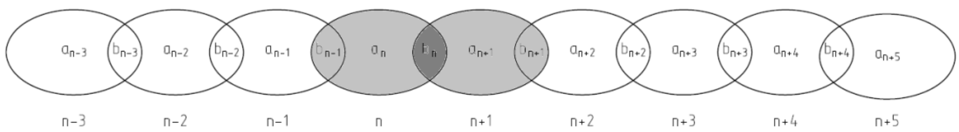

Fig 2.11 Example of doubling influence delivery between networks (Liu et al. 2010).

The most important feature of A-ADHOC protocol is that the process is very efficient, has a reliable implementing mechanism and has an affordable overhead.

2.2.2 Ad Hoc On-Demand Distance Vector (AODV) Protocol

On demand routing protocols are crucial for the effective operation of a VANET, and as the nodes moves, so as the topology of the network. The node changes and shortens the time of routing and reduces the utilisation rate of routing information. Ad hoc On-demand Distance Vector (AODV) is the most commonly used topology based routing protocol for VANET (Aswathy & Tripti 2012).

On demand routing protocols mainly involve two processes – Route Discovery and Route Maintenance (Aswathy & Tripti 2012). Route discovery involves the establishment of the routing table needed to communicate to a destination node. It does this by flooding routing request packets across the network until it receives a route response packet from the destination node. The routing information in AODV is only created when the nodes need it and the routes are kept for as long as it is needed. When the source node does not have the routing information for a destination node, a route request message (RREQ) is sent by the source node. It broadcast the message across the network and carries with it a time to live (TTL) value, which indicates the life of the message. As the message is passed along the network, each node changes the value of the TTL and indicates how many times it has been forwarded. This allows the node to determine which path is the most direct path to its destination. A route reply message (RREP) is sent by a node when it has a valid route to the destination node or if it is the destination itself. The message is unicasted back to the source, and constructs a reverse path from the destination to the source. Unicast routing is a fundamental operation for a node to create a source-to-destination routing in a VANET.

Since the nodes in the network are moving, it may drop out of the network without any warning, and an established routing path may break, route maintenance needs to be performed. AODV broadcast Hello messages to detect and monitor adjacent nodes. When the messages are not received, it interprets it as having a link failure, and updates its routing table. A route error message (RERR) is sent when a node detects a link breakage. This allows the node to notify all other nodes of the loss of the link and have their routing table updated. Every node in the network maintains its own routing table that stores routing information.

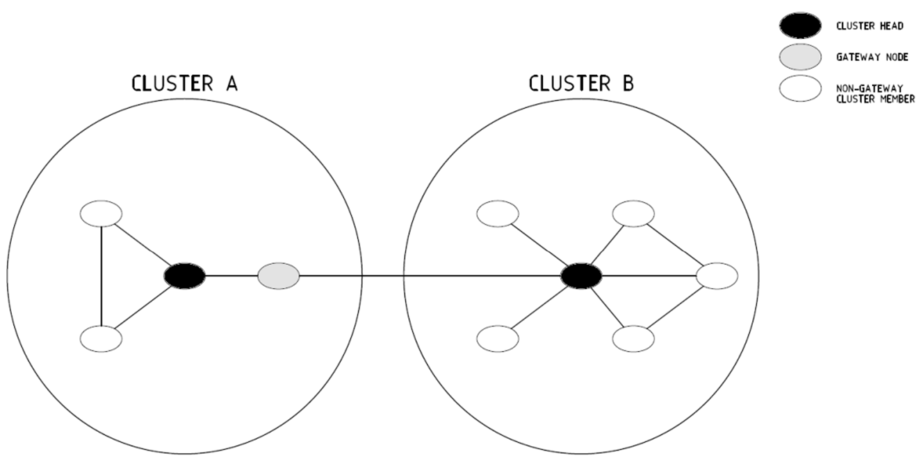

Fig 2.12 VANET Clusters with 10 nodes (Aswathy & Tripti 2012).

Aswathy and Tripti (2012) proposed a cluster based enhancement to AODV for VANET. During the route discovery process, the network is flooded by RREQ messages from the source node to destination nodes resulting into multiple unused routes discovered between the two of them. This consumes a lot of bandwidth and causes a lot of routing overhead. By dividing the network into multiple clusters, the required bandwidth is reduced. Instead of looking for the destination node directly, the RREQ packet is forwarded to the cluster head of which the destination node is a member of. A cluster has a Cluster Head and a set of Cluster Members, having a single-hop link from the Cluster Head (Aswathy & Tripti 2012). The Cluster Head maintains a table of the Cluster Member's IDs and every node has a GATEWAY-TABLE in which it contains the ID of the Cluster Head it can reach in a single hop.

In clustered routing, when a node needs to send data to another node, it first checks its routing table if it has a valid route to its destination. If it does have one, it just sends the data directly to the destination node. If the destination is not on the sender's routing table, it sends an RREQ to its Cluster Head. The Cluster Head checks if its members have a valid route to the destination or if it's the destination itself, if it has a valid route destination or if it is the destination, it replies with an RREP message. If not, the Cluster Head will forward the message to its members and the members will forward it to the Cluster Heads written on their GATEWAY-TABLE. This process repeats itself until the message reaches a node where it has a valid route to the destination or if is the destination itself. A reverse path for RREP packet is then constructed back to the source.

2.2.3 Unicast Routing Protocols

Unicast transmission is the sending of data from a single source to a single network destination. There are two types of unicast transmission, multi-hop transmission, wherein the node relays the data from the source to the destination as soon as it receives it; and carry-and-forward transmission, wherein the node keeps the data as long as possible and reduce data packets.

In Minimum-Delay Routing Protocols, the data is transmitted from the source node to the destination node as soon as possible, and the transmission delay time is of high importance, and usually the most direct route is chosen. Lochert et al. (cited in Lin et al. 2010) proposed Greedy Perimeter Coordinator Routing (GPCR). Data is sent through using a greedy forwarding procedure and adjusted using a repair strategy based on the topology of the location. Zhao et al. (cited in Lin et al. 2010) proposed Vehicle-Assisted Data Delivery Routing Protocol (VADD). VADD uses a carry-and-forward transmission, delivering data from a moving node to a static node. VADD requires that the nodes have pre-loaded digital maps to estimate the data delivery delay in different roads and decides which route to take the data through. Naumov et al. (cited in Lin et al. 2010) proposed Connectivity-Aware Routing (CAR) protocol. CAR protocol searches for the destination node like how AODV protocol does it. CAR, however, set up anchor points, which are junctions passed through by the reply packets, to which it sends the data through using greedy method. Diagonal-Intersection-Based routing (DIR) protocol is an improvement of the CAR protocol proposed by Chen et al. (cited in Lin et al. 2010). Instead of routing the data towards every junction until it reaches the destination, DIR construct a series of diagonal intersections between the source and destination nodes. The advantage of this is that it reduces the data packet delay between the source node and the destination node as the data travels more directly to the destination node through fewer anchor nodes. According to Taleb et al. (cited in Lin et al. 2010), unstable routing occurs due to loss of connections between nodes, if it moves out of transmission range from neighbouring nodes. He proposed Receive on Most Stable Group-Path (ROMSGP) protocol. ROMSGP protocol divides all the nodes into four different groups based on a velocity vector. To be able for the transmission of data to be stable, the nodes must be on the same velocity group.

2.2.4 Multicast and Geocast Routing Protocols

Multicast routing is defined as a transmission of multicast packets from a single node to multiple destination nodes using multi-hop communications. Geocast routing is transmission of geocast packets from a single node to a specific geocast region. Nodes located in this region should receive and forward the geocast packet, otherwise, the packet is dropped (Lin et al. 2010).

Bachir et al. (cited in Lin et al. 2010) proposed Inter-Vehicle Geocast (IVG) protocol. IVG protocol is used to give vehicles on the road information of any danger present, such as vehicular accidents. A risk area is determined by the position of the vehicle in regards to the information. The geocast group is determined by the location, speed and direction of the vehicles; and the group is defined dynamically, and changes as the vehicle change its position, speed and direction. To overcome network defragmentation, IVG uses periodic broadcast to send data to other group members.

2.2.5 Contention Protocol

Sharafkandi and Du (2010) proposed a novel MAC layer protocol for vehicular communications that guarantees the delivery of safety messages within a certain upper bound. The protocol is based on the distributed time division multiple access (TDMA). Each vehicle is placed on a cluster where each cluster has its own cluster head (CH), and the vehicles in each clusters, cluster members (CM), communicate through their own CH using a TDMA-based scheduling algorithm.

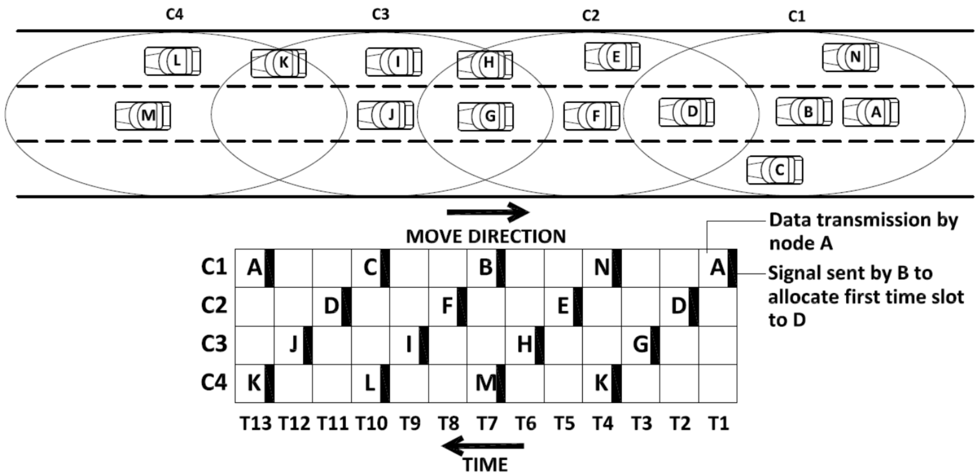

Fig 2.13 Scheduling protocol example (Sharafkandi & Du 2010).

The proposed protocol consists of three protocols: Cluster Formation Protocol (CFP), Scheduling Protocol (SP), and Cluster Adjustment Protocol (CAP). CFP is initialised when no clusters exists in the system at a certain section of the network. It identifies a node and assign them as the CH and any node that is in transmission range from the CH as CM. A node that is within the transmission range of two or more CH are said to be a gateway. The gateway is used for controlling data transmission between clusters to avoid interference. The scheduling protocol tries to maximise the number of vehicles that can broadcast their data packets at the same time by enforcing a waiting/transmission schedule within each cluster to avoid interference with the other adjacent cluster. The cluster adjustment protocol adjust the scheduling of the cluster's transmission time when a node drops out or in the network due to its very dynamic property (Sharafkandi & Du 2010).

Bana and Varaiya (2001) proposed space division multiple access (SDMA) network architecture that relies on user location information and provides access to the network based on its location. It is compatible with any multiple access scheme such as TDMA, FDMA and CDMA. SDMA provides a delay-bounded medium access to all vehicles based on their location in space, and every vehicle needs to know the real-time location information. The geographical area is divided into smaller space division, where at most is one vehicle per division, to avoid data collision. The bandwidth is also divided according to multiple access scheme.

2.3 Issues

2.3.1 Security

Inter-vehicular communications are very power tools in vehicular safety, but a set of dangerous attacks are possible. Nodes can send malicious information to the ad hoc network, and securing the network is crucial for their efficient deployment. Threats such as injections of false data, modification of legitimate information, denial of service and threat to privacy of user's credentials can cause serious effects to the network.

A certification authority is central to a public key infrastructure, which controls the issuance of certificates to the nodes at time of registration. These certificates are used for authentication before the nodes can communicate with each other. The certificates are sent along with the message to the node and validity is check by the receiver. When the certificate is found to be invalid, the message is rejected. If a certificate is valid, but the information is discovered to be malicious, the node is said to be faulty. Faulty nodes should be identified, and the certificate revoked.

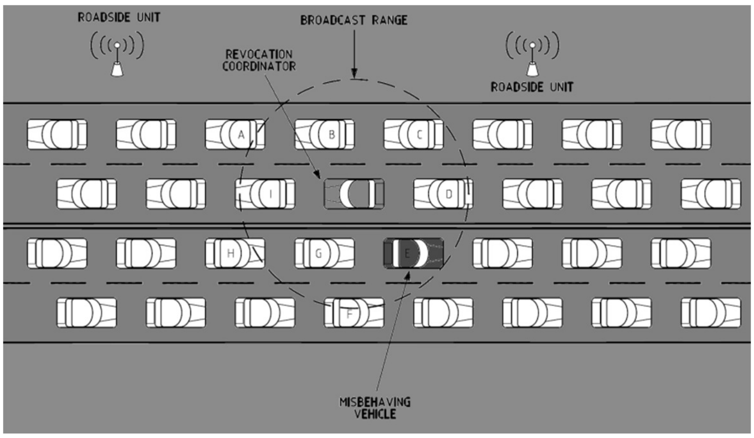

Fig 2.14 Revoking faulty nodes in vehicular ad-hoc networks (Harit et al. 2012).

Harit et al. (2012) proposed a node eviction scheme based on RSA threshold signature from Tang (Cited in Harit et al. 2012). The private key of an RSA is divided between the nodes in the network. When a faulty node is detected, any node can start the eviction process by broadcasting the message on the network and combine all the partial signatures into one complete signature. When the completed signature is created, it is broadcasted to all the nodes and they will ignore all the data coming off the evicted node. When the broadcasted message reach an RSU, the message is forwarded to the certification authority and have the certificate of the faulty node revoked.

Raya et al. (cited in Harit et al. 2012) proposed Local Eviction of Attackers by Detection System (LEAVE) protocol. When a node detects a faulty node, it broadcast a warning message on the network. The faulty node is added on a list and if the number of times that the node is added exceeds the threshold, a revocation process is started.

Wasef and Shen (Cited in Harit et al. 2012) proposed Efficient Decentralised Revocation (EDR) protocol. When a faulty node is found, the nodes in the network vote to revoke the faulty nodes certificate. The votes are collected by revocation coordinator and broadcast the revocation message once the sufficient number of votes is collected.

Task	Commu-nication Types	Exchanged Messages	Mode of Trans-mission	Example of Use Cases	Security Requirements
Road Safety	V2V	Cam	Broadcast	• Emergency vehicle approaching indication • Stationary vehicle indication • Emergency electronics brake lights warning	Authenticity Integrity Privacy Plausibility Availability
		DENM	GeoBroadcast		
	I2V	CAM	Broadcast	• Traffic condition indication • Roadwork Warning	Authenticatio n Integrity Plausibility Availability
		DENM	GeoBroadcast		
		SPAT	Broadcast		
Traffic Efficiency	I2V	SAM + other messages	Broadcast	• Traffic information and recommended itinerary • Regulatory / contextual speed limits notification	Authenticatio n Authorisation Integrity Availability
Other Applicatio ns	I2V	SAM + EVCSN	Broadcast	• Point of interest notification: charging point of electric vehicles	Authenticatio n Authorisation Integrity Availability
	V2I & I2V			• Insurance and financial services	Authenticatio n Authorisation Integrity Privacy Confidentiality Non repudiation

Table 2.2 ITS applications and security requirements (Moalla et al. 2012).

Data exchanges between nodes may not be encrypted, however data that contains personal information must be encrypted. If a node uses the same ID whenever they send data packets, an attacker could listen to their packets and build a profile of their locations, which can jeopardise their privacy (Mershad & Artail 2013). Pseudonym was proposed to deceive the attacks. A mix zone is the area in which several nodes change their pseudonym together so that an attacker wouldn't recognise each pseudonym from each other. Dummy users can also be created before the pseudonym change and removed after it ends, which increases the number of users and increase the anonymity of the pseudonym and the nodes.

There are several ITS requirements in implementing ITS architecture. Moalla et al. (2012) and Svitek et al. (2012) listed some of the very important requirements and system parameter of ITS architecture:

- Availability of the system to perform the required function at the initialisation of the operation.
- Authentication and authorisation methods to ensure that the vehicles have the proper rights and that the information is authentic.
- Information exchanged between vehicles needs to be reliable and secure from being altered in between communications.
- Information sent by the sender might require that it can only be access by the intentional receivers.
- It is crucial for some instance to get the identity of the sender for accountability.
- ITS applications must comply with the necessary privacy and data protection laws relevant to the country.
- Plausibility of the data needs to be validated and checked for correctness and it must reflect the actual physical state.
- The system should be reliable to meet the required function under given conditions at an acceptable time interval.
- The system should be able to perform the required function without spontaneous interruption during the operation.

2.3.2 Internet Protocol

According to Baccelli et al. (cited in Cespedes et al. 2012), the recommendation of the operation of IPv6 over WAVE is rather minimal in the specification of the IEEE 1609.3 standard, compared to WAVE Short Message Protocol (WSMP). The protocols in which the IPv6 uses for addressing routines are not recommended in the standard, and multi-hop support of infrastructure-based IP services is not currently being supported by the standard.

2.3.3 Doppler Shift

According to Xiang et al. (2012), in a vehicular environment, Doppler shift leads to the loss of orthogonality between subcarriers of an OFDM signal resulting in inter-subcarrier interference (ICI).

2.3.4 Hidden Node

In wireless networking, one problem that MAC can have difficulty in is the hidden node problem. Hidden node problem occurs when the node think that the channel is free even though the channel is being used by another node that is out of radio range from the first node. This leads to overlapping or partially overlapping transmission (Sjoberg et al. 2011). In 802.11, request-to-send (RTS) and clear-to-send (CTS) handshakes are used to prevent hidden node problem. The sender sends an RTS message to the receiver to check if the receiver is available for communication. If the receiver is available, the receiver sends a CTS message to every node in its range that it is currently waiting for data from the sender node. In VANET, however, due to the large number of nodes and the high mobility of the nodes make the use of RTS/CTS impractical (Barradi et al. 2012). Applications using unicast transmission is more affected as several transmitters can potentially be contending for a single receiver, while in broadcast transmission, majority of the receiver will still receive the data packet.

2.3.5 Sustainability

Intelligent transport system uses such as traffic management and safety application are public infrastructures and thus need public funding for support and maintenance. Investments to multimedia and internet applications by private entities are needed for the expansion of these services. Commercial applications provided by private entities may conflict with government network policies and therefore both must work together to be able to have a successful implementation.

Software and hardware products need to be able to be used in different consumer market so that developmental costs of these products are feasible and developers doesn’t need a different set of specifications to be able to have these devices work on different markets.

Intelligent transport system applications generate, collect and process private data to function correctly. Data, like IP address, location and other personal information such as car registration, name and credit card information, can create potential issues for privacy and security. Privacy and security issues need to be addressed early on the development of the system.

Software and hardware needs to be updated regularly to be able to address future vulnerabilities as well as expansions and upgrades and be able to function effectively. The responsibility of making sure that the devices are up-to-date lies with the vehicle owner, and the private and public entities that owns the infrastructures.

Devices need to be regulated by the necessary authorities to be able to make sure that the standards are correctly implemented and that substandard devices are not offered to the public.

2.3.6 Reliability

Reliability of ITS and VANET equipment are very important to maintain as they are responsible for providing a wide range of critical safety information to the public. A wide range of established operations and maintenance are based on the combinations of preventative and corrective maintenance techniques, but are at a relatively high cost. They have been demonstrated and verified to reduce the probability of equipment failures, length of system downtime and risk of service interruption (Vorakitolan et al. 2011). The cost of maintenance varies based on the size of the implementation area of ITS and VANET, the range of equipment used and the number of equipment. Implementation of maintenance operations and testing of ITS and VANET equipment can be costly, but there are a number of popular low cost strategies that are being used to perform this. An example is by following the manufacturer's mean time before failure (MTBF) estimates and perform the maintenance and replacement of parts or equipment around this time. A study done by Vorakitolan et al. (2011) in UPS battery replacement has concluded that the manufacturer's specific maintenance and device monitoring solutions suffer from an extremely conservative MTBF estimates. They have determined that the lifetimes of UPS were about six times longer than the MTBF estimates, and by replacing the batteries according to the discovered lifetime, they have reduced the possibility of UPS failures at a lower cost. The study recommends that overall, the manufacturer's suggested MTBF is not the best solution to follow for maintenance planning in terms of cost. Taking in to account the safety aspect, if you don't have any other reliable system for monitoring and identifying failing equipment, following the manufacturer's suggested MTBF is crucial to maintain the network's reliability.

2.4 Uses

The current trends of the uses of an intelligent transport system focuses on safety applications, traffic management and multimedia services.

Management of traffic, especially in urban area is very important. Traffic congestion causes financial loss, environmental and social problems. Roads can be retrofitted with equipment such as signalling devices, detectors, speed limit and variable message signs. Such devices can be controlled to manage traffic remotely or be programmed to run automated. Managed motorways technology aims to provide a safer and reliable road networks across the country and are expected to reduce road accidents and vehicular emissions.

Traffic can be managed by giving the driver information about the road conditions ahead. Live traffic updates are sent to GPS navigation systems which also provide traffic directions. These traffic directions can be programmed to give the driver the best route to the destination he wishes to go. Traffic disruptions, such as accidents, roads closed due to repair or hazards on the road can be sent to the human machine interface (HMI), such as the GPS navigation system and provides the best path for the driver to use to go to its intended destination.

Telematics is the use of informatics and communication for use in vehicular application. Telematics can be used to monitor a vehicle's movement, including speed, location and weight. Telematics is mostly used for freight management, road regulation for charging and compliance, and safety and security of the vehicle being monitored.

The potential benefits of the system are ultimately for making the road safe for all the road users, reducing the number of crashes and road fatalities. Vehicles are equipped with sensors and are able communicate what is happening around them. Sensors can be used to warn of any danger that the driver is not able to see, such as proximity sensors. Messages can be sent to the vehicle to inform it of the road's current condition, the weather or any accidents occurring in the area.

Vehicular applications are classified into two categories, ITS applications and non-ITS applications. ITS applications are said to be applications that aim to minimise vehicular accidents and improve traffic flow; and non-ITS applications are applications used primarily for multimedia and entertainment. The European Telecommunications Standards Institute (ETSI) have classified ITS cooperative applications into three categories: Road Safety, Traffic Efficiency and Other Applications.

Road Safety applications are applications designed to reduce the number of vehicular accidents. Moalla et al. (2012) classify Road Safety applications into two categories: Driver Assistance applications, which assist drivers to avoid accidents, and Actions on Vehicle applications, which gives information to the vehicle to avoid accidents.

Traffic Safety applications are applications that are focused on improving traffic. Some examples include traffic flow management, traffic assistance and cooperative navigation.

Most applications being developed and researched on are focused on Driver Assistance application, according to Moalla et al. (2012). There are three applications that are being standardised by ETSI: Cooperative Awareness Applications CAA, which provide information of presence, position, as well as basic status of communicating ITS stations to neighbouring ITS stations that are located within single hop distance; Longitudinal Collision Risk Warning (LCRW), which warns the driver of a risk of longitudinal collision behind or in front of its vehicle and provides assistance to prevent a collision by urging a driver action to break or change lane; and Intersection Collision Risk Warning, which uses the Cooperative Awareness Message (CAM) and Decentralised Environmental Notification Message (DENM) to warn the vehicle of the location of the other vehicles around it.

The US Department of Transportation (TMC Operator Requirements and Position Description 2004) characterise eight different classification for it ITS national architecture: Advanced Traffic Management Systems (ATMS), Advanced Public Transport Systems (APTS), Advanced Traveller Information Systems (ATIS), Advanced Vehicle Safety Systems (AVSS), Commercial Vehicle Operations (CVO), Emergency Management (EM), Archived Data (AD), and Maintenance and Construction Management (MCO).

ATMS is used for traffic management. Some of the packages include:

- ATMS01 Network Surveillance
- ATMS02 Probe Surveillance
- ATMS03 Surface Street Control
- ATMS04 Freeway ControlATMS05 High Occupancy Vehicle (HOV) Lane Management
- ATMS06 Traffic Information Dissemination
- ATMS07 Regional Traffic Control
- ATMS08 Incident Management System

- ATMS09 Traffic Forecast and Demand Management
- ATMS10 Electronic Toll Collection
- ATMS11 Emissions Monitoring and Management
- ATMS12 Virtual TMC and Smart Probe Data
- ATMS13 Standard Railroad Grade Crossing
- ATMS14 Advanced Railroad Grade Crossing
- ATMS15 Railroad Operations Coordination
- ATMS16 Parking Facility Management
- ATMS17 Regional Parking Management
- ATMS18 Reversible Lane Management
- ATMS19 Speed Monitoring
- ATMS20 Drawbridge Management

APTS is used for public transportation, such as buses and trains. Some of the packages include:

- APTS1 Transit Vehicle Tracking
- APTS2 Transit Fixed-Route Operations
- APTS3 Demand Response Transit Operations
- APTS4 Transit Passenger and Fare Management
- APTS5 Transit Security
- APTS6 Transit Maintenance
- APTS7 Multi-modal Coordination
- APTS8 Transit Traveller Information

ATIS is used for getting information prior or while travelling. Some of the packages include:

- ATIS1 Broadcast Traveller Information
- ATIS2 Interactive Traveller Information
- ATIS3 Autonomous Route Guidance
- ATIS4 Dynamic Route Guidance
- ATIS5 Information Service Provider (ISP) Based Route Guidance
- ATIS6 Integrated Transportation Management/Route Guidance

- ATIS7 Yellow Pages and Reservation
- ATIS8 Dynamic Ridesharing
- ATIS9 In Vehicle Signing

AVSS is used for vehicular safety installed inside the vehicle. Some of the packages include:

- AVSS01 Vehicle Safety Monitoring
- AVSS02 Driver Safety Monitoring
- AVSS03 Longitudinal Safety Warning
- AVSS04 Lateral Safety Warning
- AVSS05 Intersection Safety Warning
- AVSS06 Pre-Crash Restraint Deployment
- AVSS07 Driver Visibility Improvement
- AVSS08 Advanced Vehicle Longitudinal Control
- AVSS09 Advanced Vehicle Lateral Control
- AVSS10 Intersection Collision Avoidance
- AVSS11 Automated Highway System

CVO is used for commercial vehicles, such as busses, trucks and taxis. Some of the packages include:

- CVO01 Fleet Administration
- CVO02 Freight Administration
- CVO03 Electronic Clearance
- CVO04 CV Administrative Processes
- CVO05 International Border Electronic Clearance
- CVO06 Weigh-In-Motion
- CVO07 Roadside CVO Safety
- CVO08 On-board CVO Safety
- CVO09 CVO Fleet Maintenance
- CVO10 HAZMAT Management

EM is used for emergency services. Some of the packages include:

- EM1 Emergency Response
- EM2 Emergency Routing
- EM3 Mayday Support
- EM4 Roadway Service Patrols

AD is used for data management for the network. Some of the packages include:

- AD1 ITS Data Mart
- AD2 ITS Data Warehouse
- AD3 ITS Virtual Data Warehouse

MCO is used for maintenance and construction management of road networks. Some of the packages include:

- MCO1 Maintenance and Construction Vehicle Tracking
- MCO2 Maintenance and Construction Vehicle Maintenance
- MCO3 Road Weather Data Collection
- MCO4 Weather Information Processing and Distribution
- MCO5 Roadway Automated Treatment
- MCO6 Winter Maintenance
- MCO7 Roadway Maintenance and Construction
- MCO8 Work Zone Management
- MCO9 Work Zone Safety Monitoring
- MC10 Maintenance and Construction Activity Coordination

Intelligent transport system is not limited to the road infrastructure. It can also be used in waterways as well as railways and rail crossings. Vehicles would be able to be informed by oncoming trains as well as RSU installation if any trains are coming and a necessary warning signals can be sent to the vehicle. Boats can, in the same way, be able to utilise ITS for safety application and shipping management.

Chapter 3

Methodology

3.1 Research Methodology

To be able to achieve the objectives of the project, the objectives need to be understood and develop the methodology needed to accomplish each objectives and a breakdown of the tasks needs to be determined.

The tasks can be broken down into the following activities:

- Review of relevant literatures
- Development of models
- Development of simulation program
- Simulation of the models and analysation of results; and
- Formulation of recommendation and conclusion.

A review on relevant literatures needs to be done to be able to gather an overview of Intelligent Transport System and Vehicular Ad Hoc Network. The literatures need to be analysed and be able to arrive at a complete understanding of the system, be able to create a model of the network for simulation and be able to formulate topics that need further research.

A model of the Intelligent Transport System and Vehicular Ad Hoc Network needs to be developed. Network models as well as vehicular traffic models needs to be analysed from the relevant literature, a mathematical analysis is performed and the resulting expressions acquired are used to create the model that will be used for simulation.

A review of simulation software needs to be done to identify which software can be used to successfully simulate the model that was developed. The models are to be simulated using NCTUns 6.0 and NS2 software. The simulation is written using the selected software and run.

The simulation is run several times and the performance evaluation of the model is noted. The necessary tables and graphs are to be produced for easy comparison and evaluation of the data. The data is to be compared to the other models in the literature review and analyse its performance against them.

3.2 Resources

The project objectives require the use of computer software to simulate models that has been researched and developed during the span of the project. In order to analyse and simulate an intelligent transport system and a vehicular ad-hoc network, the following software packages need to be used in line with the software packages used in the literature review:

- VMware
- Fedora 12
- NCTUns
- ns2
- Java
- Matlab

Java is an object-oriented programming language developed by Sun Microsystems in the early 1990s. The language borrows syntax from C and C++ but has a simpler object model and fewer low-level facilities (History of Java Programming Language 2009). The Java Runtime Environment (JRE) is the required software to run Java-based applications.

VMware Player allows the user to run virtual machines on top of a Windows or Linux PC installation. VMware Player is a free to use software for non-commercial usage. Using virtual machines to run another operating system on top of Windows installation has the advantage of being able to test the operating system without compromising the current operating system installation. The virtual machine running is a fully functioning operating system and the hardware can be set depending on the user's or the operating system's requirements.

Fedora is an operating system based on the Linux kernel, developed by the community-supported Fedora Project, which is owned by Red Hat. The main objective of Fedora is to develop a free and open-source operating system that is current and at the forefront of technological advancement.

A new version of Fedora is released approximately every 6 months and is provided updates for approximately 13 months, which allows the users to skip a release, but still have a system that is still updated (Fedora Project 2013).

Fedora release 12, codenamed 'Constantine', was released on 17 November 2009. The new release brought in a more optimised performance and network enhancements to name a few.

A computer capable of running the software is required, and the available Intel dual core i5 computer with 4GB of RAM is used.

Most of the research material that was used in this research came from IEEE Xplore digital library and was accessed using the USQ Library database links, as well as using Google Scholar website searches.

3.3 Ethical Responsibilities

The development of models of an intelligent transport systems and a vehicular ad-hoc network are based on research and experiment done by different academic and researcher, and thus needs to be cited and credited. Simulations need to be done with high precision and data collected must be analysed and interpreted carefully and honestly.

3.4 Risk Assessment

As the project is mostly based on research and simulations, there are only minimal risk involved in the execution and development of the project. Most of the hazard is just based on manual handling, posture, good housekeeping and behavioural skills.

Based on the control pyramid, the least effective way of controlling the risk is behavioural management and elimination of the hazard is the most effective.

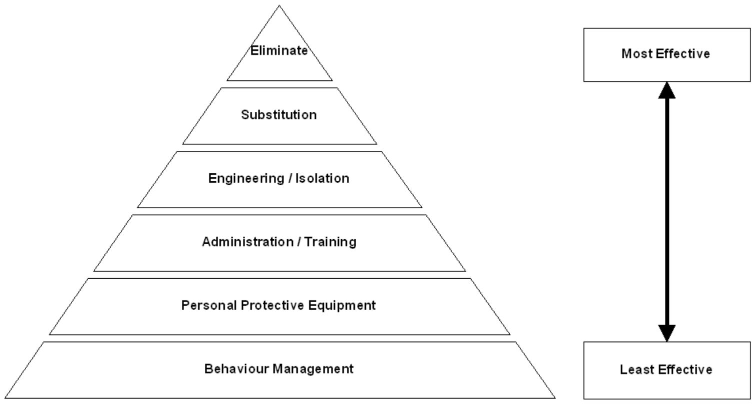

Fig 3.1 Control Pyramid.

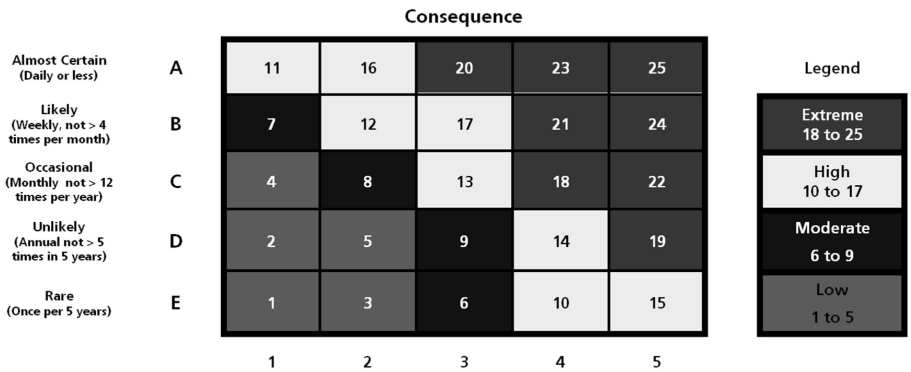

Fig 3.2 Risk Matrix.

Task	Existing / Potential Hazard	Conse-quence	Likeli-hood	Risk Score	Controls
Using the computer	Vision impairment due to number of hours spent staring at the computer monitor	2	A	2A - High	• Adjust brightness of the screen. • Make sure that screen is of correct height. • Make sure that the room has ample lighting. • Have rest breaks every hour.
Using the computer	Strain on fingers from repetitive typing and clicking of mouse.	1	A	1A - High	• Make sure that arms are correctly laid out on the table. • Use hand pads for mouse and keyboard for hand support. • Take breaks every hour.
Using the computer	Strain on the back from sitting down	1	A	1A - High	• Make sure to be using the correct posture while sitting down. • Use a good ergonomic chair and set it up correctly. • Take breaks every hour and do some stretching

Table 3.1 Risk Assessment.

3.5 Research Timeline

The project deliverables has been divided into several tasks to help with delivering the project on time and identifying milestones in the project.

		Task Name	Duration	Start	Finish	Predecessors
1	✓	Project Specification	3 wks	Mon 25/02/13	Fri 15/03/13	
2		Research	32 wks	Mon 25/02/13	Fri 4/10/13	
3		Project Preliminary Report	6 wks	Mon 15/04/13	Fri 24/05/13	
4		Latex Tutorial	1 wk	Mon 24/06/13	Sun 30/06/13	
5		Model Development	4 wks	Mon 1/07/13	Fri 26/07/13	4
6		Model Simulations	4 wks	Mon 29/07/13	Fri 23/08/13	5
7		Preliminary Draft of Dissertation	8 wks	Mon 1/07/13	Fri 23/08/13	4
8		Residential School Presentation	1 wk	Mon 26/08/13	Fri 30/08/13	7
9		Final Dissertation	8 wks	Mon 26/08/13	Fri 18/10/13	7

Table 3.2 Project Activities.

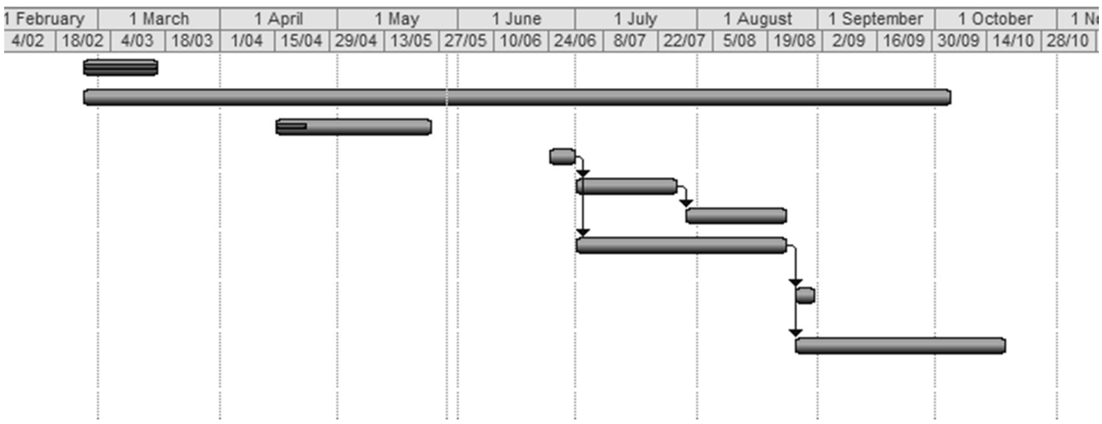

Fig 3.3 Gantt Chart.

Chapter 4

Performance Evaluation

4.1 Models

4.1.1 Analytical Model

Neelakantan and Babu (2012) developed an analytical model to simulate the network connectivity of a VANET on a one-way street and two-way street scenario. On this scenario, the road consists of two lanes, lower lane and upper lane, with both lanes having vehicles moving in opposite directions. If the connectivity probability on a specific lane is less than 1, the number of clusters that is formed on that lane is more than 1. When vehicles are members of a different cluster, direct communications between them is not possible. To improve the probability of connectivity on a specific lane, vehicles on the other lane should be considered. The effect of fading is considered in the analytical model and the transmission range of each vehicle is modelled as a random variable. The VANET formed is a one-dimensional linear network. The vehicle density is low and the vehicle speed and traffic flow is independent. The vehicle speed follows truncated Gaussian probability distribution function, and the vehicle density ρ is

$$\rho = \frac{2\lambda / \sqrt{2\pi\sigma}}{erf\left(\frac{v_{\max} - \mu}{\sigma\sqrt{2}}\right) - erf\left(\frac{v_{\min} - \mu}{\sigma\sqrt{2}}\right)} \times \int_{v_{\min}}^{v_{\max}} \frac{1}{v} \exp\left(\frac{-(v-\mu)^2}{2\sigma^2}\right) dv \tag{3.2}$$

where,

$\lambda =$ rate of vehicles per hour passing the observer

$\mu =$ average speed

$\sigma =$ standard deviation of the vehicle speed

$v_{\max} =$ maximum speed

$v_{\min} =$ minimum speed

$erf(\ ) =$ error function.

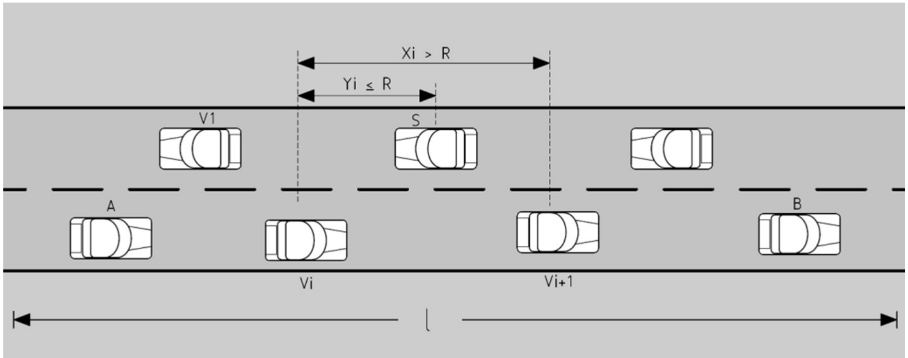

Fig 4.1 Vehicles in a typical two-lane highway (Neelakantan & Babu 2012).

Network connectivity probability on a one way street developed by Neelakantan and Babu (2012) is computed using

$$P_{NC} = \left[\rho_1 (2\pi)^{\frac{1-\alpha}{2}} \sum_{k=0}^{m-1} \frac{1}{k!} \left(\frac{m\psi P_{noise}}{\beta P_T} \right)^k \times \alpha^{\alpha k + \frac{1}{2}} \rho_1^{-(\alpha k+1)} \right.$$

$$\left. \times G_{1,\alpha}^{\alpha,1} \left(\frac{\beta P_T \rho_1^{\alpha}}{m\psi P_{noise} \alpha^{\alpha}} \middle| \begin{matrix} 1 \\ \frac{\alpha k+1}{\alpha}, \ \ldots \ , \frac{\alpha k+1}{\alpha} \end{matrix} \right) \right]^{N_1 - 1} \quad (3.3)$$

where,

$\alpha =$ path loss exponent

$\beta =$ constant associated with path loss model

$P_T =$ transmit power

$P_{noise} =$ total additive noise power

$m =$ Nakagami fading parameter $(0.5 \le m \le \infty)$

$N_1 - 1 =$ average number of vehicles

$G_{p,q}^{m,n} =$ Meijer's G function.

The network connectivity probability on a two way street is computed using

$$P_{NC} = \sum_{j=0}^{N_1-1} P_{(C/J=j)} P_J(j) \tag{3.4}$$

where,
$P_J(j) =$ probability that J links will be broken
$P_{(C/J=j)} =$ number of fixable broken links.

Sou (2013) developed a VANET model to simulate the performance of collision avoidance applications. In his example, a vehicle V_0 got into an accident. Vehicle V_1, which is travelling behind V_0, sees the accident at time t_0. It takes vehicle V_1 1.5s to initiate an emergency deceleration. Vehicle V_2 is travelling behind vehicle V_1, and is travelling at the same speed. It also takes 1.5s to initiate an emergency deceleration, and started breaking at $t_0 + 3$. When both vehicles V_1 and V_2 have wireless collision avoidance system, and vehicle V_1 broadcast an emergency message at time t_0, vehicle V_2 would have initiated emergency deceleration at $t_0 + 1.6$ instead of $t_0 + 3$, as the wireless latency t_l is usually less than 0.1s in DSRC standard.

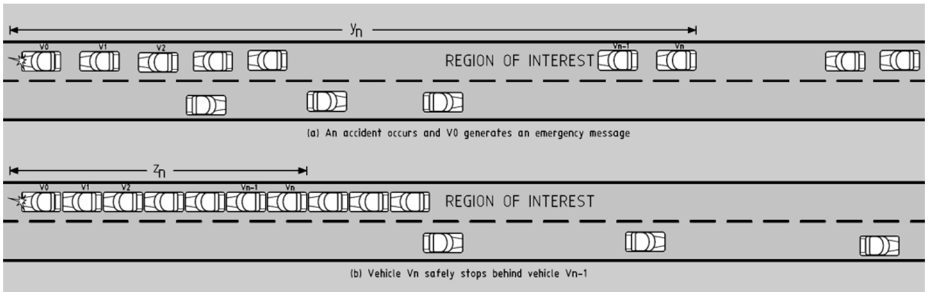

Fig 4.2 Deriving the number of crashed vehicles (Sou 2013).

When a driver receives an ample amount of time to react to a hazard, he can safely manoeuvre the vehicle to avoid the hazard. The vehicle’s speed and the deceleration rate are two properties that affect the performance of a collision avoidance system.

According to Duranni et al. (2010), the average number of vehicles *N* on the highway segment under steady state is given by

$$N = \frac{L\lambda}{\mu_{\text{eff}}} \quad (3.5)$$

And μ_{eff} is the equivalent speed which is

$$\mu_{\text{eff}} = \frac{1}{\frac{\frac{2}{\sqrt{2\pi\sigma}}}{erf\left(\frac{V_{max}-\mu}{\sigma\sqrt{2}}\right) - erf\left(\frac{V_{min}-\mu}{\sigma\sqrt{2}}\right)} \int_{V_{min}}^{V_{max}} \frac{1}{v} exp\left(-\frac{(v-\mu)^2}{2\sigma^2}\right) dv} \quad (3.6)$$

4.1.2 Mobility Models

4.1.2.1 Freeway Mobility Model

In a freeway mobility model, the vehicles are restricted to their lanes on the road. There is no random movement of the vehicles, and the vehicles are following a specific direction. Maps are used in the model and all the vehicles follow a path in a certain direction. There is a safe distance between the vehicles that are being maintained and the velocity of the vehicles follows the velocity in front of it, so no overtaking is taking place. Changing of lanes is also not allowed, and the vehicle stays in its original lane until it reaches the simulation area limit. The vehicle will then be randomly place to a different position in the simulation, and the process is repeated.

4.1.2.2 Manhattan Mobility Model

In a Manhattan mobility model, the vehicles are allowed to change its lane when it passes an intersection. Maps are also used in the model, and each street has two lanes for each direction. When the vehicle encounters an intersection, the vehicle randomly chooses which direction it should go – turn left, turn right or go straight ahead. Speed is also restricted, much like the freeway model.

4.1.2.3 Stop Sign Mobility Model

In a Stop Sign model, there are stop sign on every intersections. The purpose of the stop sign is to limit the speed of the vehicles coming towards the intersection. The vehicle stops for a while, and wait for a fixed amount of time before starting to accelerate again. If several vehicles arrive at an intersection, a queue is established, and each one wait for its turn to move.

4.1.2.4 Traffic Sign Mobility Model

In a Traffic Sign model, instead of a stop sign, traffic signals are on every intersection. The idea is similar to the Stop Sign model, and all vehicles must stop when the lights are red, and drive through when the traffic lights are green. When the first vehicle arrives at the intersection, the light has the probability *p* to turn red, with a random delay. All vehicles behind it are forced to stop, and when the light turns green, all vehicles in the queue moves one at a time. When the next vehicle arrives at the intersection, the process repeats again.

4.2 Simulation Program

In order to simulate a VANET, there are two components that needs to be simulated. The first one is the simulation of the vehicle, which is the mobility component, and the network component. Some simulator needs a separate mobility simulator in order to operate. A trace file is produced by the mobility simulator that gives information about the behaviour of the vehicles for a certain topology setup and their coordinates. This trace file is then fed into the network simulator. There are also some simulators that have both mobility and network component integrated in the simulation program, making it easier modify both components.

There are several advantages and disadvantages of using software to simulate a VANET according to Vandenberghe et al. (2011). The main advantage of using software to simulate a VANET is that they can use it on a large scale and is a very cheap to implement. One of the disadvantage of using software to simulate a VANET is that they are not entirely accurate compared to the real-life performance of the network. There are several reasons for this inaccuracy, and some factors include: simplified traffic behaviours, models used, hardware and software programming, weather, and other naturally occurring properties that is not considered during the simulations.

Kotz et al. (2004) identifies that there are six axioms used in modelling of wireless communications: the world is flat, a radio transmission is circular, all radios have equal range, if I can hear you, you can hear me (symmetry), If I can hear you at all, I can hear you perfectly, and, signal strength is a simple function of distance.

According to Kotz et al. (2004), most common models assume that the earth is flat, which is not, and the changes of the height of terrain can pose a significant effect on the propagation of wireless signals. The signal coverage of a radio is complex and is often non-contiguous and the packets received by the receiver antenna depend on the angle between the sender and the receiver antennas. Since node A and node B may be moving, there is a higher probability that the data packets would not be received by the other node due to collisions caused by the differences in transmission power. From the data that they have gathered, it shows that when the distance between the sender and the receiver increases, the reception probability distribution over distance decreases, as opposed to the common simulation models, which assume that as long as it can receive the signal and there are no collisions, the frame transmission is perfect. From the power-law model, it is assumed that the average signal strength is inversely proportional to distance, but in reality, variations in the environment can cause obstructions, reflections, refractions and scatterings of the signal.

4.2.1 Mobility Simulators

4.2.1.1 Traffic Software Integrated System – Corridor Simulation (TSIS-CORSIM)

TSIS, according to its website, is an integrated development environment that enables users to conduct traffic operations analysis. It allows the user to define and manage traffic analysis projects, define traffic networks and creates inputs for simulations. The simulator was developed at the University of Florida in the United States, and was funded by the Federal Highway Administration (FHWA). The current version is TSIS 6.3 and was released back in August 2012.

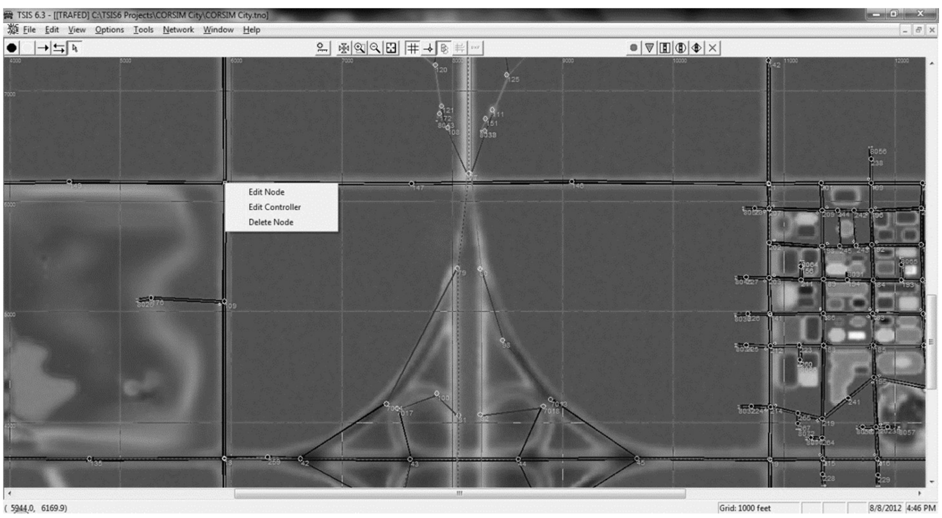

Fig 4.3 TSIS CORSIM TRAFED Graphical input editor (Trafed n.d.).

The simulator is made up of two components: NETSIM, which is used for simulating surface streets, and FRESIM for simulating highways.

4.2.1.2 PTV VisSim

PTV VisSim is a microscopic simulation tool for modelling multimodal traffic flows according to its website, which means that it simulates each object individually. It provides ideal conditions for testing different traffic scenarios in a realistic and highly detailed manner. It can be used for arterial, freeway, public transit and pedestrian simulation.

Fig 4.4 PTV VisSim GUI (PTV VisSim n.d.).

4.2.1.3 VanetMobiSim

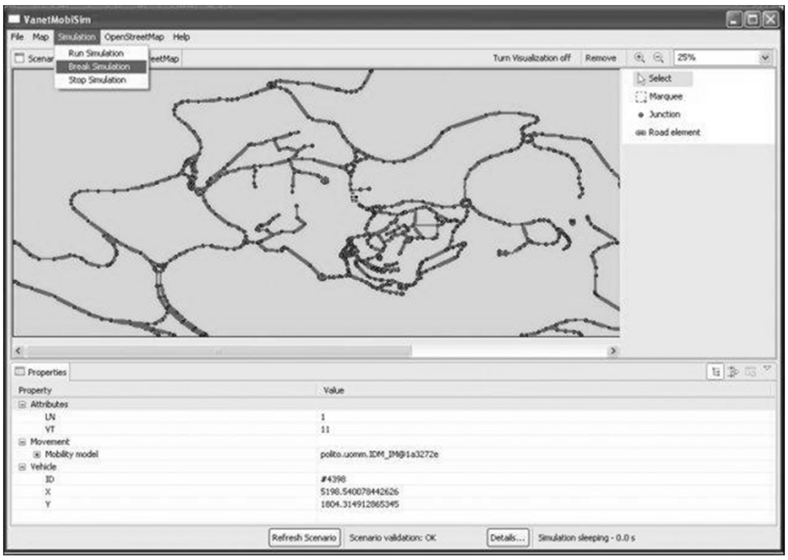

Fig 4.5 VanetMobiSim topology view during simulation (VanetMobiSim n.d.).

VanetMobiSim is an extension for the CanuMobiSim, which focus on vehicular mobility and features new realistic automotive motion models at both macroscopic and microscopic level. VanetMobiSim can import the US Census Bureau Tiger/line database, and it implements new mobility models, providing realistic interaction between cars and infrastructure.

4.2.1.4 Simulation of Urban Mobility (SUMO)

SUMO is an open source, microscopic, multi-modal traffic simulator. It is written in C++, and started with the goal to support the traffic research community back in 2000. Each vehicle is modelled explicitly, has an own route and moves individually through the network.

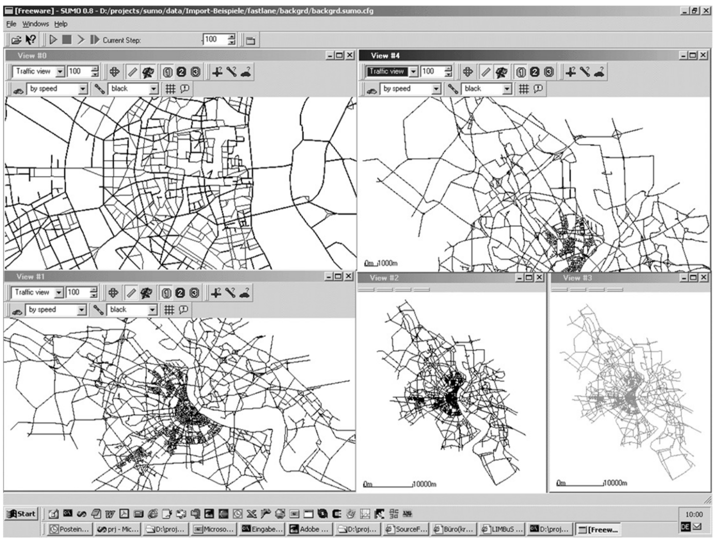

Fig 4.6 SUMO simulation GUI (SUMO n.d.).

4.2.1.5 Mobility Model Generator for Vehicular Networks (MOVE)

Move is built on top of SUMO to facilitate a rapidly generated realistic mobility model for VANET simulation. The output trace file can be used by network simulator, such as ns2 or QualNET. It can interface with real world map databases such as Tiger/line as well as Google Earth. It allows the user to quickly generate realistic simulation scenarios without writing simulation scripts and learning the internal details of the simulator by providing a graphical user interface (GUI).

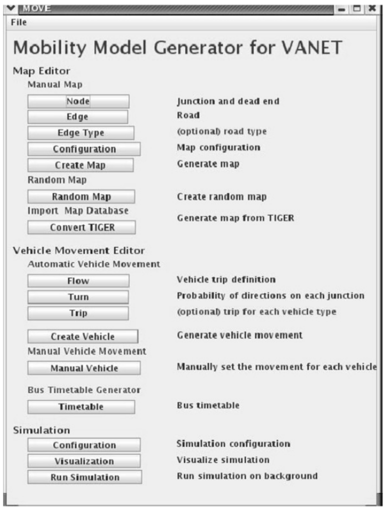

Fig 4.7 MOVE main window.

4.2.2 Network Simulators

4.2.2.1 Ns2

Ns is a discrete event simulator used for network research. Ns supports simulations for network protocols, routings and networks. Ns2 is a free software publicly available under the GNU licence for research and development. Ns2 is written in C++, and the simulation scripts are written in Object-oriented Tool Command Language (OTcl) scripting language. C++ defines the structure of the simulation, and the OTcl sets up the simulation by configuring objects and scheduling discrete events (Issariyakul & Hossain 2012). The simulation outputs a trace file, which can be viewed using an animation software, such as NAM, and a plotting software, such as Xgraph.

Ns started in 1989 as a variant of REAL network simulator, which was originally intended for studying of dynamic behaviour flow and congestion control scheme in packet-switched data networks. REAL network simulator was developed by University of California and Cornell University. In 1995, the United States' Defence Advanced Research Project Agency (DARPA) funded the development of Ns through many projects, specifically the Virtual Inter-Network Testbed (VINT), which was aimed to develop a network simulation software to study different protocols for communication networks. Throughout the years, several groups of research and developer communities further develop the program to what it is today (Keshav 1997).

4.2.2.2 NCTUns

National Chiao Tung University Network Simulator (NCTUns) is purely written in C++. NCTUns was developed by Shie Yuan Wang in the Network and System

Laboratory at National Chiao Tung University, Taiwan in 2000. NCTUns has now been commercialised and the name of the commercial version is EstiNet and its latest version is EstiNet 8.0. The last version of NCTUns before it was commercialised is NCTUns 6.0 which runs in Fedora 12.

NCTUns is a software for network planning, testing, protocol development and simulation. It uses the real-life application programs and protocols in its simulation to get a more realistic simulation results. Real-life programs can be run on the simulated network and generate a realistic network traffic that generates more reasonable results. NCTUns can also be used as an emulator, and be connected to a real-life network and have a real-life node and a simulated node communicate with each other.

NCTUns combines the kernel re-entering simulation methodology with discrete event simulation methodology, and executes simulations quickly (Wang et al. 2010). NCTUns can output a high repeatability results by modifying the process scheduler of the Linux kernel to control the execution order of the simulation process.

NCTUns can simulate the most common networking devices such as Ethernet hubs, switches, routers, hosts, IEEE 802.11a wireless access points and interfaces, and many devices. It can also simulate different optical devices for optical network simulations and other IEEE 802.11 standard networks and devices for VANET and ITS simulations.

4.2.2.3 OPNET

Opnet is a high level event-based network level simulation tool that operates at a packet level and is mainly used for research and network design. The source code is constructed from C and C++ and has as huge library of network functions. The program is divided to three main domains: Network domain, which simulates networks, subnet, network topologies, geographical coordinates and mobility; Node domain, which simulates single network nodes such as routers and workstations; and Process domain, which simulates single modules and source code inside network nodes. The network domain defines the scope of the system to be simulated, as well as their location, connections and configurations. The node model defines the structure of the node. The process domain defines the behaviour of the processor and modules (Prokkola 2006).

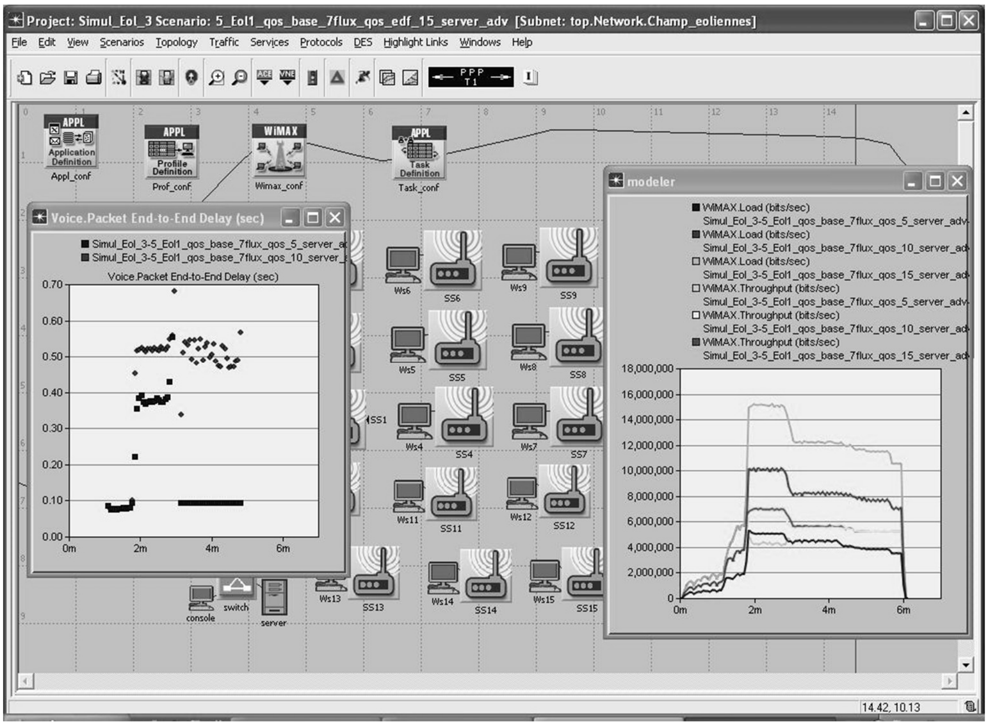

Fig 4.8 Opnet simulation GUI (Opnet n.d.).

4.2.2.4 QualNET

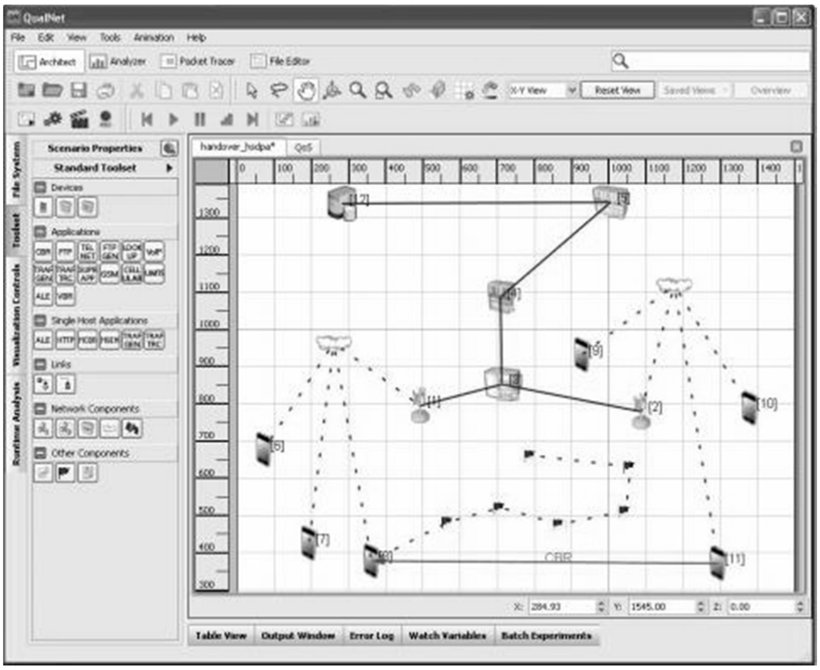

Fig 4.9 QualNET simulation GUI (Qualnet 2013).

QualNET is a simulation program for planning, testing and training tool that simulate the behaviour of a real network. QualNET is composed of several components: QualNET Architect, which is a graphical scenario design and visualisation tool to setup terrain, network connections, subnets, and other network parameters; QualNET Analyser, which is a statistical graphing tool that display the metrics during the simulation; QualNET Packet Tracer, which is a graphical tool that provides the graphical representation for the packet trace generated during the simulation; QualNET File Editor, which is a text editing tool; and QualNET Command Line Interface, which is a command line access to the simulator (QualNET 2013).

4.2.2.5 OMNeT++

OMNeT++ is as discrete event simulation environment for simulation of communication networks for complex IT systems, queuing networks and hardware architecture. It is programmed in C++ that is assembled into a larger components and models using a high level language. Some network design simulations that OMNeT++ is used are internet, mobility and ad hoc simulations (OMNeT 2013).

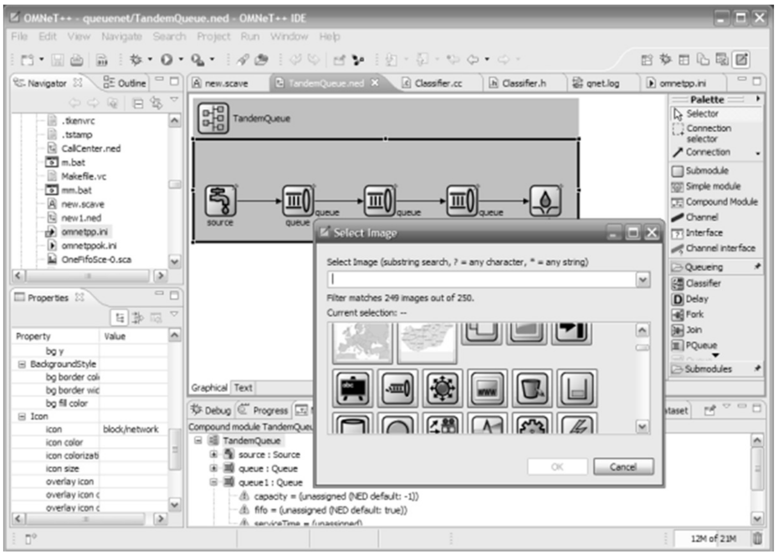

Fig 4.10 OMNeT++ NED source editor (OMNeT 2013).

4.3 Simulations

4.3.1 Speed Simulation

In the first scenario, six vehicles are equipped with 802.11p OBU using NCTUns agent program to control the vehicular traffic and to run it based on its assigned car profile. The data rate of transmission is set at 6 Mbps, the transmit power is 28.8 dBm and the receiver sensitivity is -82 dBm, which are the default settings for the WAVE 802.11p PHY layer in the simulator. The simulation also uses the default parameter settings: Fading Variance is 10, Average Building Height is 10 m, Average Building Distance 80 m, Street Width is 30 m, Path Loss Exponent is 2, Shadowing Standard Deviation is 4, Close-in Reference Distance is 1 m, System Loss is 1, Antenna Height is 1.5 m, Ricean Factor K is 10 dB, and using two ray ground Path Loss Model. The size of the

UDP data packet being send is 1200 byte. All six vehicles are broadcasting the data packets, all three vehicles are receiving the data packets from the other vehicles and the transmission used is single hop transmission. The cars maximum speed is 30 km/h, maximum acceleration is 1 m/s^2 and maximum deceleration is 4 m/s^2. The simulation last for 120 seconds.

In the second scenario, all the settings are unchanged except for the speed settings: maximum speed is 60 km/h, maximum acceleration is 3 m/s^2 and maximum deceleration is 5 m/s^2.

In the third scenario, all the settings are unchanged except for the speed settings: maximum speed is 80 km/h, maximum acceleration is 10 m/s^2 and maximum deceleration is 3 m/s^2.

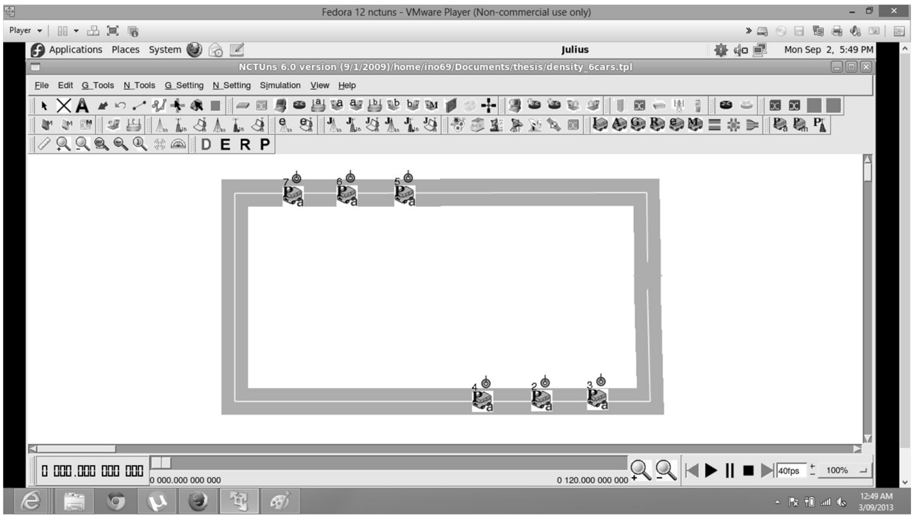

Fig 4.11 NCTUns speed simulation.

4.3.2 Density Simulation

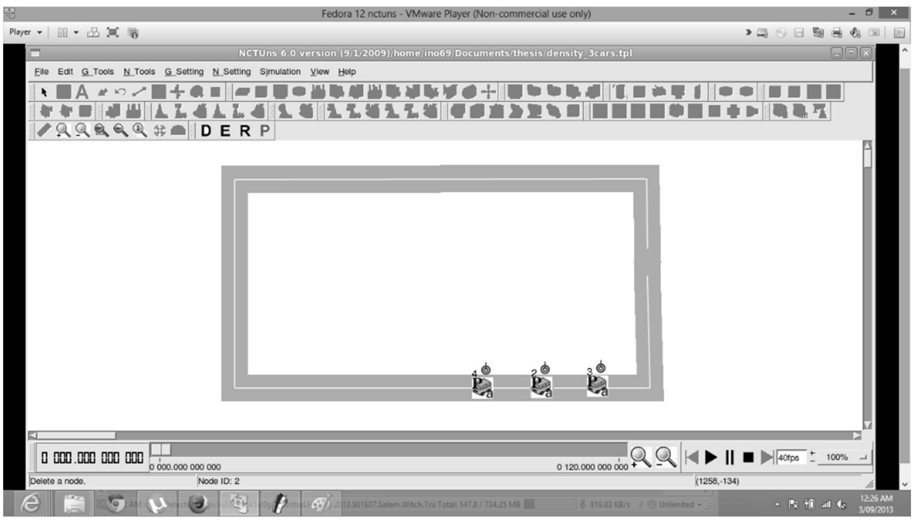

Fig 4.12 NCTUns 3 cars density simulation.

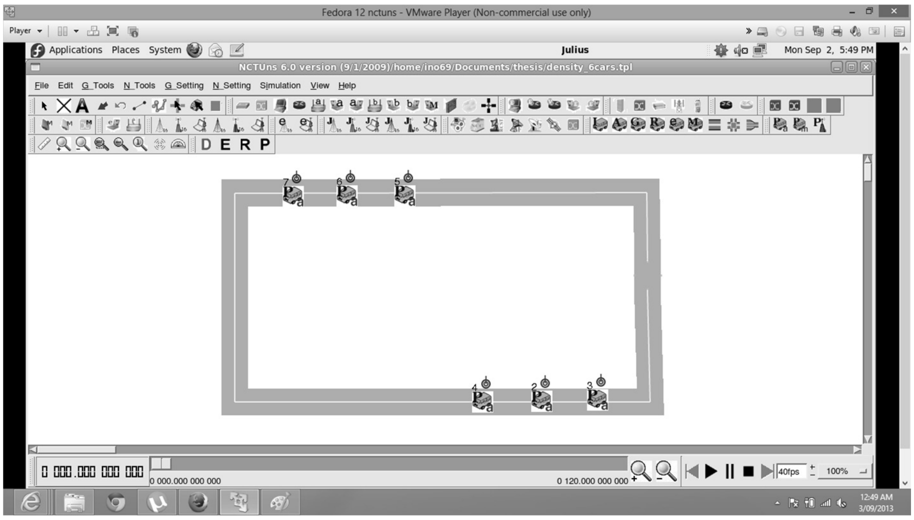

Fig 4.13 NCTUns 6 cars density simulation.

In the first scenario, there are three vehicles on the road; for the second scenario, six vehicles are on the road; and for the third scenario, there are nine vehicles on the road. All the other settings for the three scenarios are the same with that of the first scenario in speed simulation.

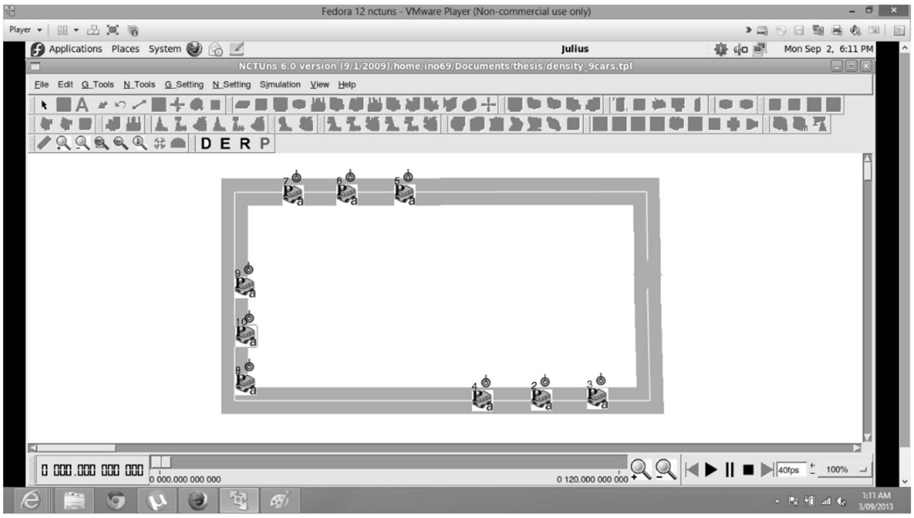

Fig 4.14 NCTUns 9 cars density simulation.

4.3.3 Power Simulation

In the first scenario, the transmit power of the six vehicles is 28.8 dBm; for the second scenario, the transmit power of the six vehicles is 60 dBm; and for the third scenario, the transmit power of the six vehicles is 100 dBm. All the other settings for the three scenarios are the same with that of the first scenario in speed simulation.

4.3.4 Obstacle Simulation

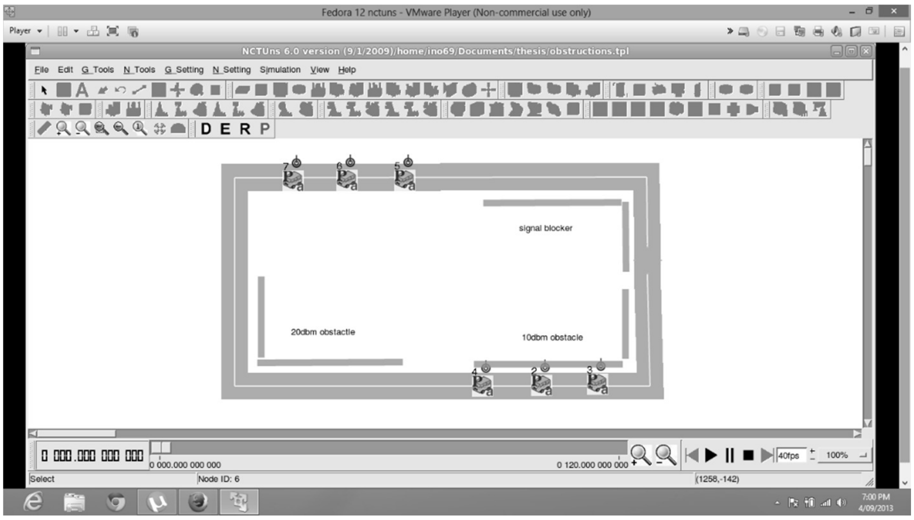

Fig 4.15 NCTUns obstacle simulation.

In this scenario, there is a 20 dBm obstacle on the first corner, a signal blocker on the third corner, and a 10 dBm obstacle on the fourth corner. There is no obstacle placed on the second corner. All settings for this scenario is the same with that of the first scenario in speed simulation.

4.3.5 Analytical Simulation

The analytical expression was evaluated using Matlab. In the simulation, the highway length (L) used is 10 km, arrival rate (λ) is 0.1, average speed (μ) is 90 km/hr, and standard deviation (σ) of between 1 to 40 km/hr. A random vehicular speed (v) is generated using the rand command and the truncated Gaussian Probability Function (PDF) was computed using the normpdf command.

4.4 Results

The results are based on the data of vehicle 2 for all the simulation that was done so that all of the results are comparable to the other simulation scenarios. All three vehicles on vehicle's 2 group (lower right group) as well as the other three vehicles (top left group) start the simulation at the same exact position.

The first peak of dropped packet for the first speed simulation happened in the 5 second mark, vehicle 2 is turning around the first corner. For every instance that the car is turning around the corner, the number of dropped packet is at a peak. Peaks of dropped packets also happens when the other three vehicles are on the opposite road from vehicle 2. The lowest dropped pocket peaks happens when all six vehicles are on the same side of the road.

For the second speed simulation, the number of dropped packet peaked when vehicle 2 is turning around the corner, as well as when the other three vehicles are on the opposite road from vehicle 2. The lowest dropped packet peaks also happens when all six vehicles are on the same side of the road. For the third speed simulation, the results are the same with the other two speed simulation, higher dropped packet peaks when vehicle 2 is turning around a corner and when the other three vehicles are on the opposite road from vehicle 2 and lowest dropped packet peaks when all of the vehicles are on the same side of the road.

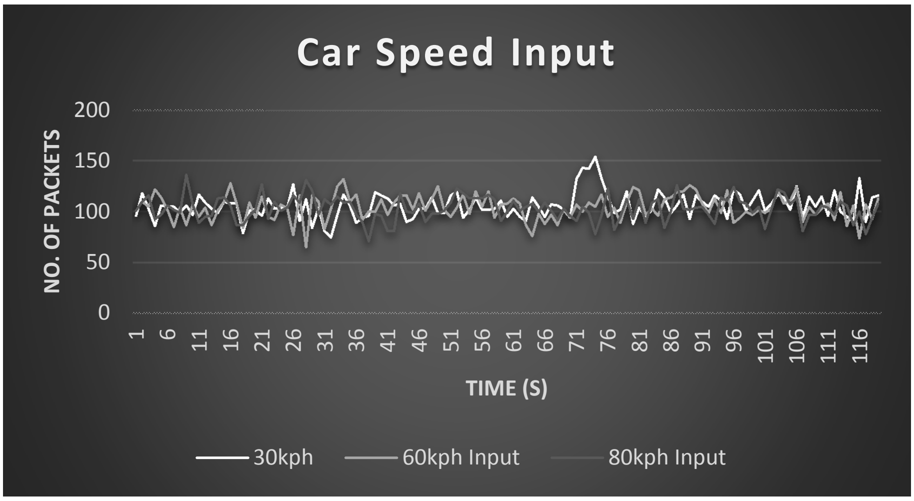

Fig 4.16 Car speed simulation input graph.

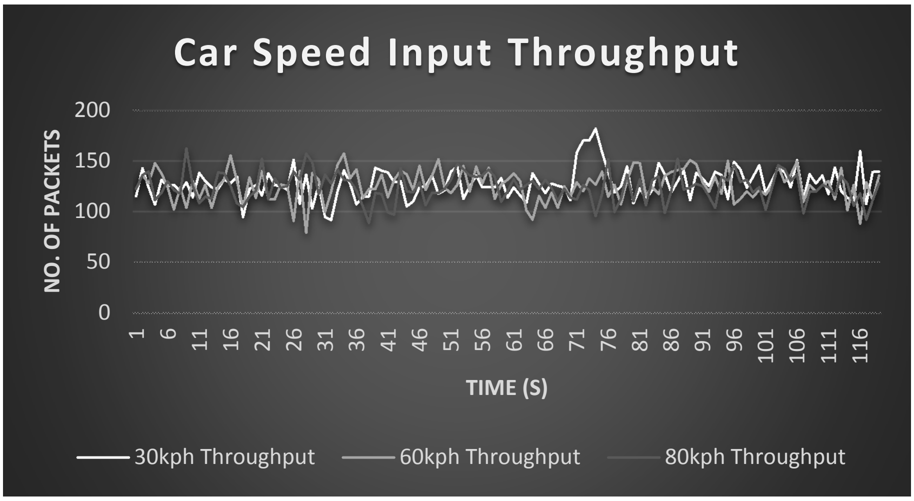

Fig 4.17 Car speed input simulation throughput graph.

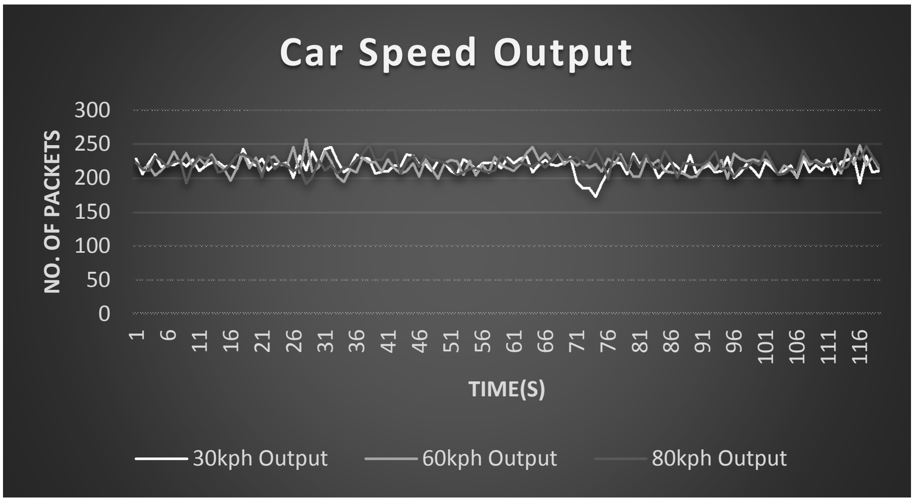

Fig 4.18 Car speed simulation output graph.

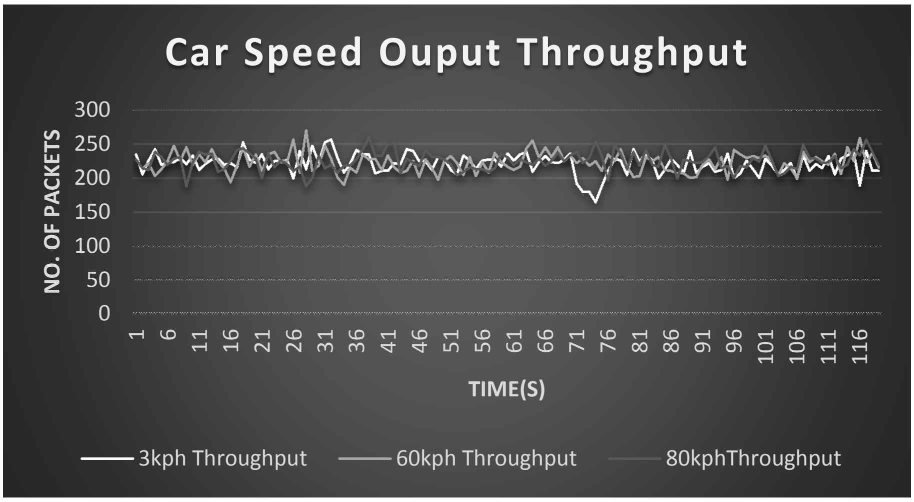

Fig 4. 19 Car speed simulation output throughput graph.

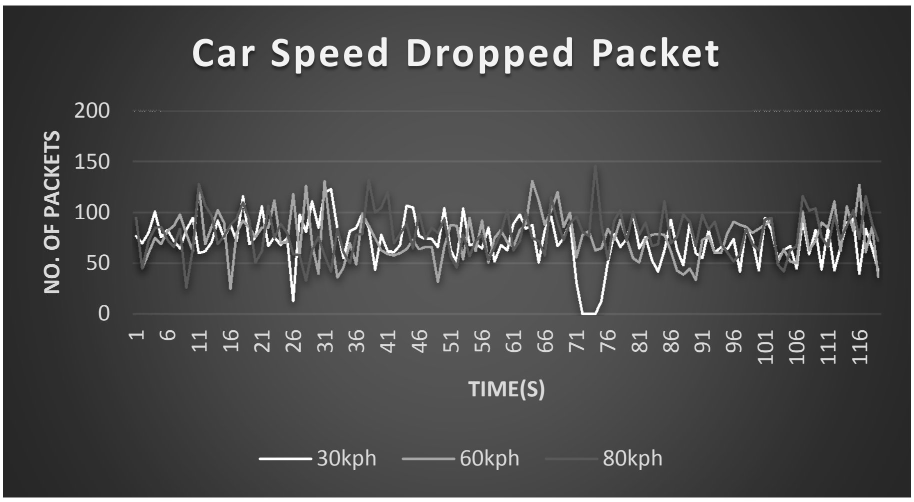

Fig 4.20 Car speed simulation dropped packet graph.

Looking at the graph generated, it is not correct to compare the graphs side by side for each of the scenarios, this is because the car's position in the road is different from the other scenarios at a given time as they have different speeds. Looking at the average dropped packet between the three scenarios, the number of dropped packets increases as the speed is increased.

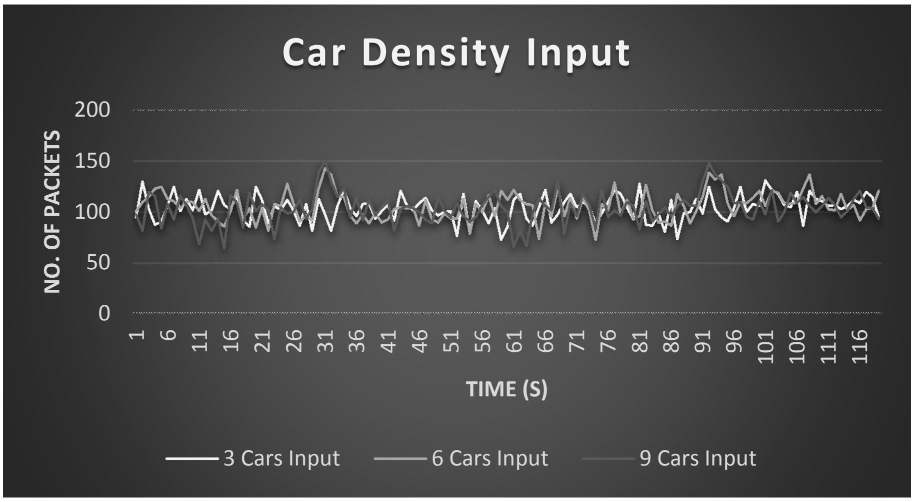

Fig 4.21 Car density simulation input graph.

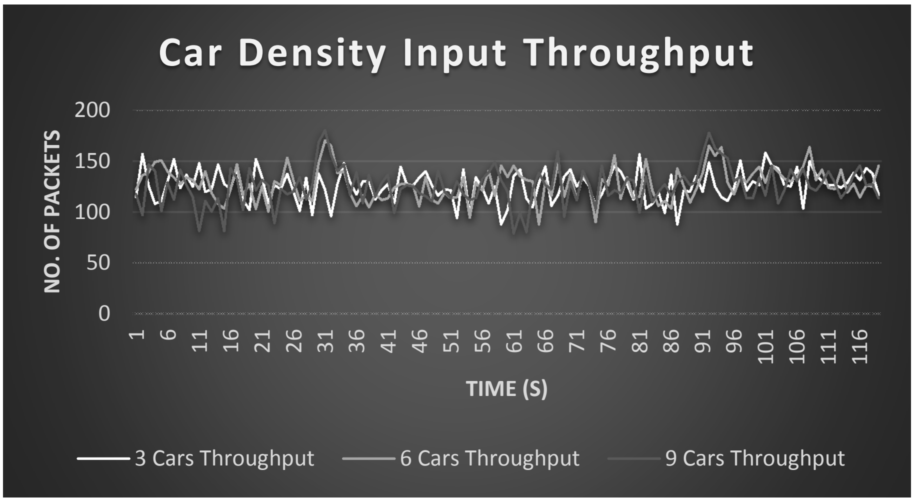

Fig 4.22 Car density simulation input throughput graph.

The first scenario for the car density simulation, the number of dropped packet peaked when vehicle 2 is turning around the corner and a bit low when all three vehicles are running on the straight road. The second scenario is the same with the first scenario for the speed simulation. For the third scenario, the first dropped packet peak happens when all three groups of vehicles are on different roads. The next peaks happened when the other 2 groups are going through the upper left corner. When the three groups are again on different roads, the number of dropped packet peaked at 56 seconds. The lowest dropped packet happened at around 85 seconds to 90 seconds when all nine vehicles are on the same road and close to each other.

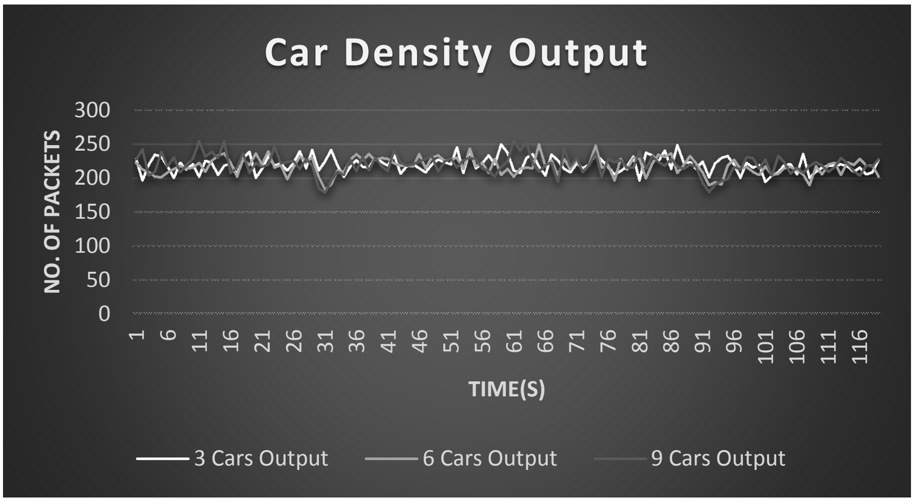

Fig 4. 23 Car density simulation output graph.

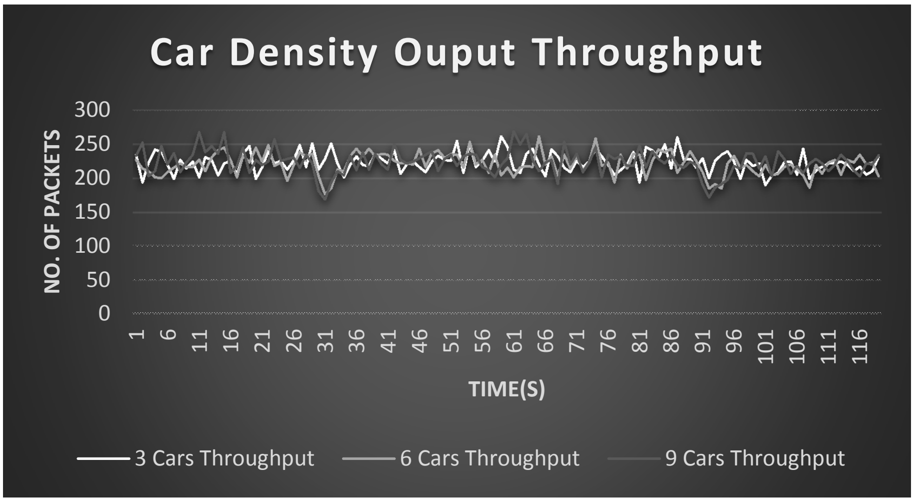

Fig 4. 24 Car density simulation output throughput graph.

Looking at the graph generated, the average dropped packet decreased when the number of vehicles are increased, this is because there are more time where all the vehicles are together, but if are not to consider the low peaks of the graph, the number of dropped packets increases when the number of vehicles are increased on the road.

The first scenario for the transmit power simulation, is the same as that with the first scenario for the speed simulation. The dropped packet peaked when vehicle 2 is turning around the corner and when the other group is on the opposite road, and the dropped packet is low when all the vehicles are on the same road. For the second and third scenario, the dropped packet peaked when vehicle 2 is turning around a corner and when the other group of vehicles are on the opposite road, and the dropped packet is low when all vehicles are on the same road. The dropped packets went down to zero when all of the vehicles were side-by-side after stopping at the traffic lights.

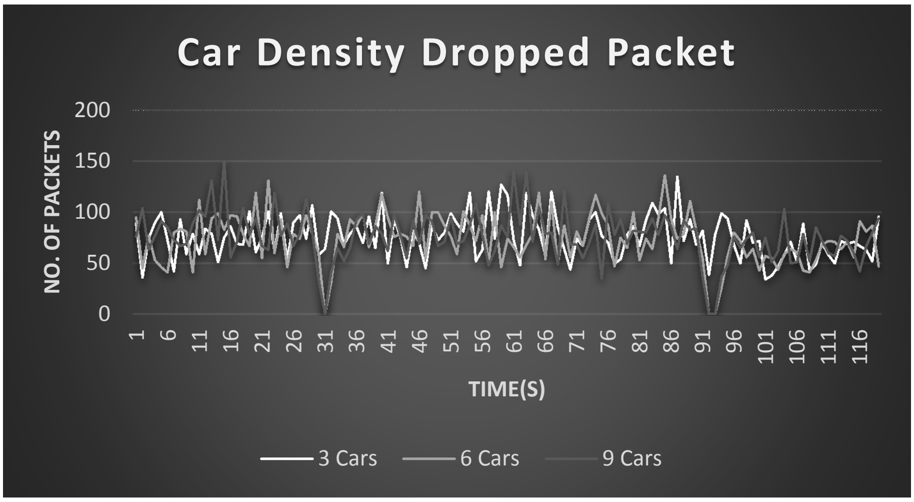

Fig 4.25 Car density simulation dropped packet graph.

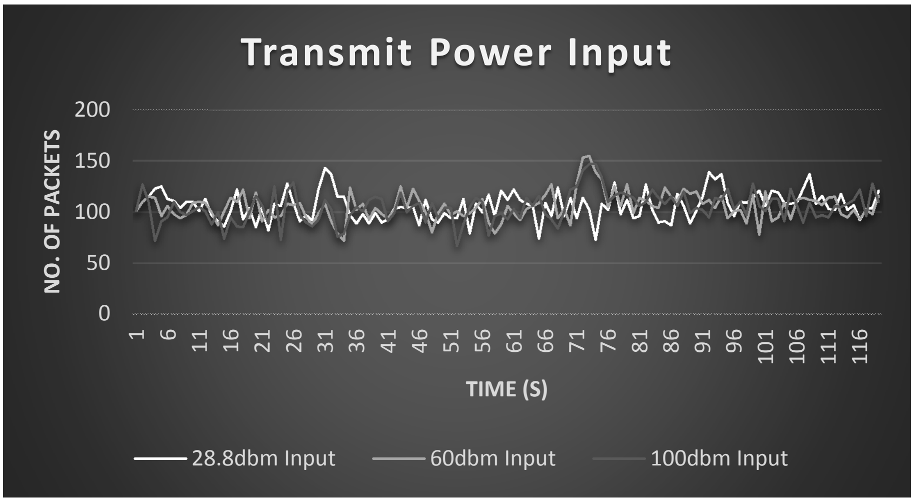

Fig 4.26 Transmit power simulation input graph.

Looking at the graph generated, the average dropped packet increased as the transmit power is increased. There were also more dropped packet peaks observed during the third scenario compared to the first.

For the obstruction simulation, dropped packet can be observed when the vehicles are in between the obstructions and signal blocker. There are minimal dropped packets when the vehicles are around the 10 dBm obstructions and it increases when they are around the 20 dBm obstructions. The dropped packet peaked when the vehicles are around the signal blocker and at a minimum when they are in between the signal blocker and obstructions.

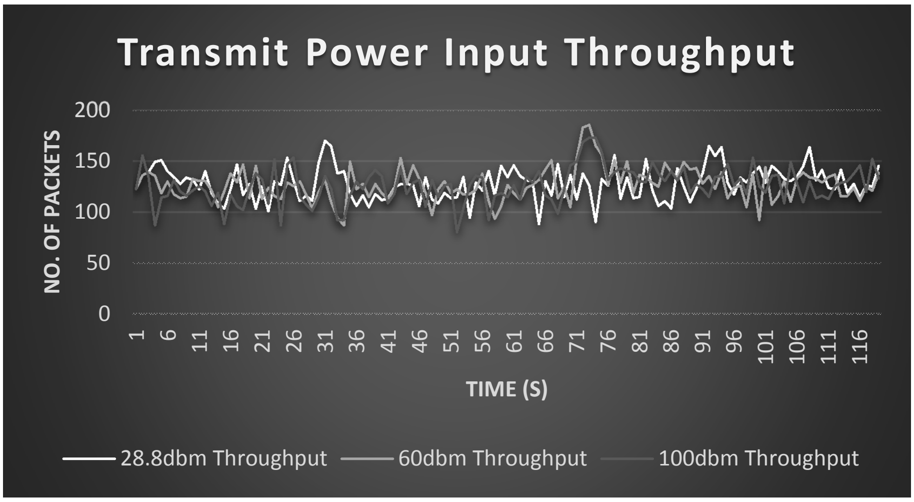

Fig 4.27 Transmit power simulation input throughput graph.

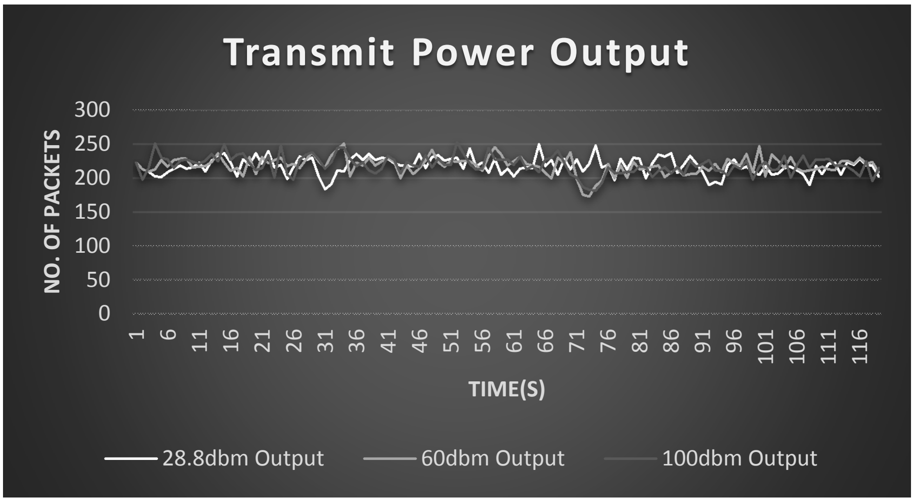

Fig 4. 28 Transmit power simulation output graph.

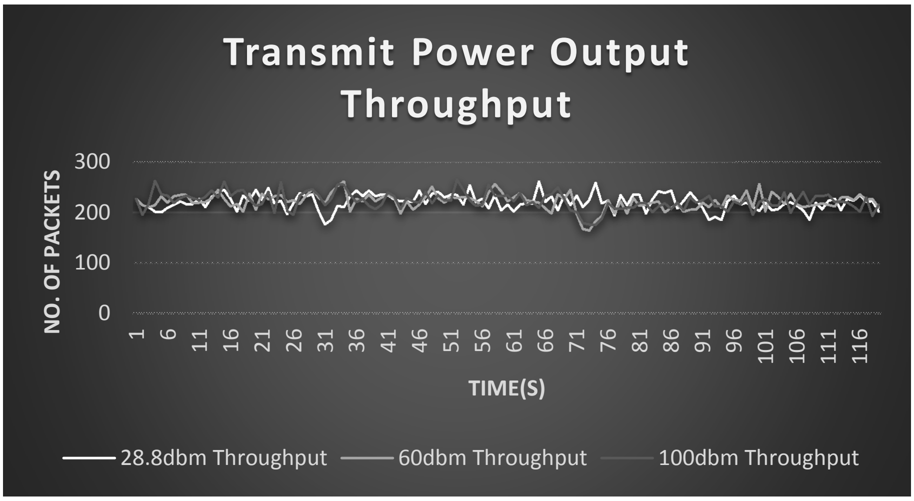

Fig 4.29 Transmit power simulation output throughput graph.

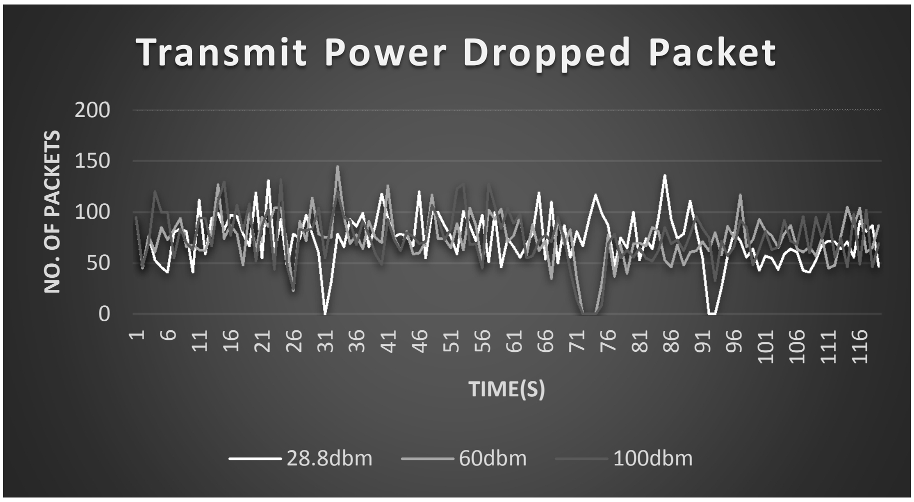

Fig 4. 30 Transmit power simulation dropped packet graph.

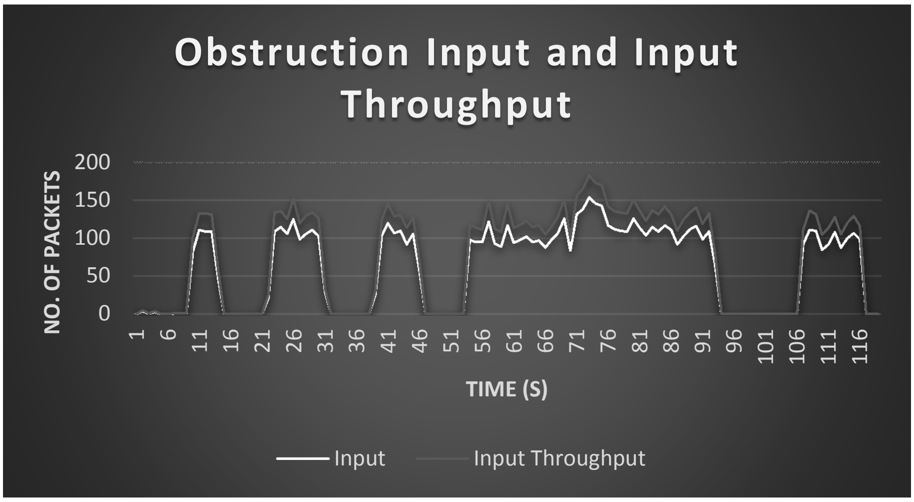

Fig 4.31 Obstruction simulation input and input throughput graph.

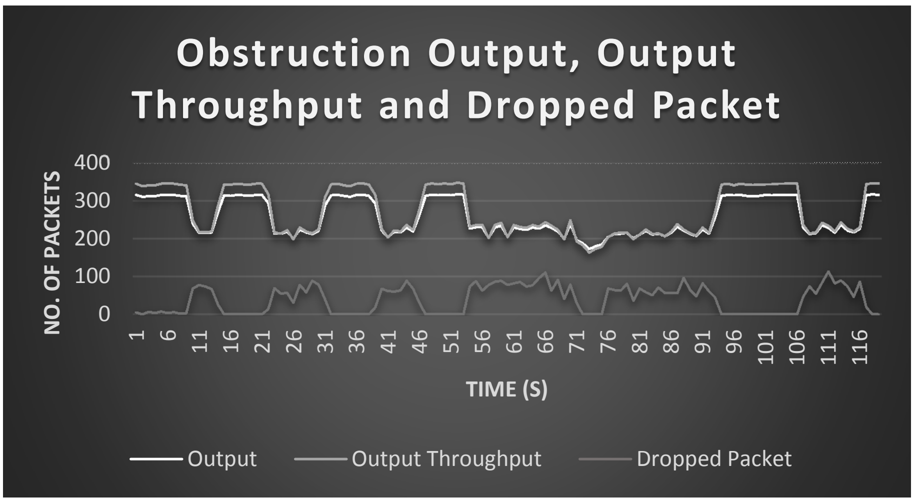

Fig 4.32 Obstruction simulation output, output throughput and dropped packet graph.

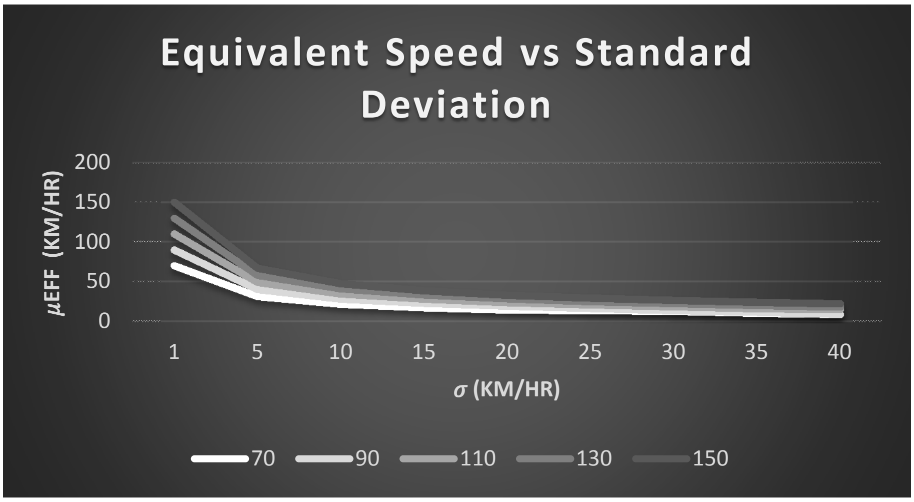

Fig 4.33 Equivalent speed vs. standard deviation graph.

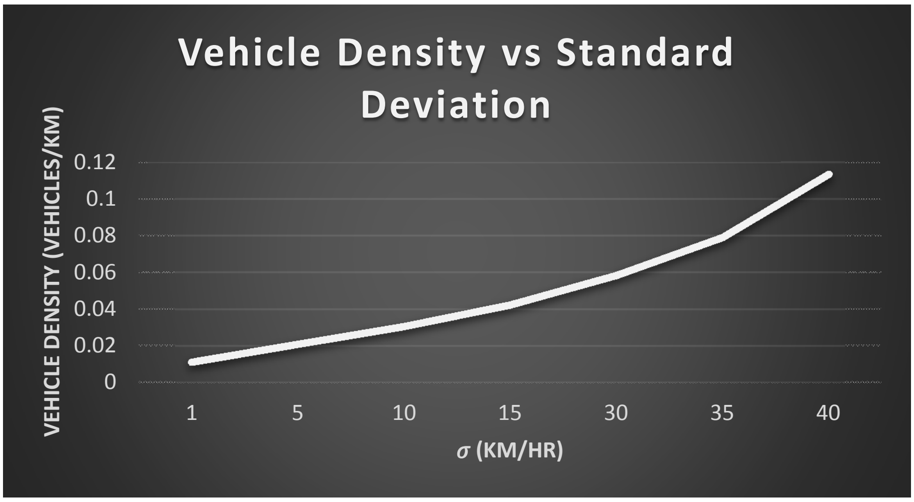

Fig 4.34 Vehicle density vs. standard deviation graph.

From the result of the analytical simulation, the equivalent speed is different from the average speed and as the standard deviation increases, the equivalent speed decreases; and as the standard deviation increases, the vehicular density increases. When the vehicular density is high, the probability of connectivity between vehicles increases as well.

Chapter 5

Conclusion

5.1 Recommendation

Performance evaluation of a VANET relies on using mobility and network simulator to obtain a realistic assessment of the network connectivity properties; and it enables the study of the network at a minimal cost. Simulators need to depict real-world representation of events and features to be able to obtain a realistic simulation of the network connectivity. The models used in the simulator must not be simplistic and care should be observed when doing assumptions about environmental conditions.

The potential of VANET to improve safety and traffic is very promising as different implementations, services and programs that uses the IEEE 802.11p and WAVE standards are being developed. The current research, as well as the current standards and protocols are sufficient enough to deliver most of the applications being developed.

Reliability of the network is crucial to deliver high priority safety messages, and latency and security are the most important properties that most of the research are concerned about. Most of the security features that can be applied in IEEE 802.11 standards cannot be applied to IEEE 802.11p and WAVE standards as this would increase the latency and would not make the system a true ad-hoc network. Latency is very important because the extra time the vehicle takes to perform handshakes and handle the extra overheads can mean safely braking or crashing into another vehicle.

Developing the architecture and framework for ITS and VANET technology in Australia has a lot of positive advantages, and having them installed on the road makes perfectly good sense. Looking forward to what the predictions are for the traffic conditions in a few decades makes investing to this technology feasible, even though at the moment, there are only several equipment that follow the draft protocol and the prices are higher compared to other alternative system.

5.2 Conclusion

Vehicular Ad-hoc networks are communication networks that are mainly used for delivery of safety information between vehicles equipped with on-board units (OBU), between vehicles and roadside unit (RSU) and between RSUs. They are also referred to as vehicle to vehicle communications (V2V), vehicles to infrastructure communications (V2I) and infrastructure to infrastructure communications (I2I). The network is based on the IEEE 802.11p and IEEE 1609 standards using the dedicated short range communication (DSRC) spectrum at 5.9 GHz.

VANET is currently being tested and to some degree being implemented across the United State, European Union and some Asian countries like Japan and Korea. Some of the major players in VANET research and development are the biggest car manufacturers in the world, which include BMW, General Motors, Nissan, Ford, Chrysler, Toyota and Audi. There are many protocols that have been developed to manage the communication in VANET, and the research is still on-going for further improvement. Some of the applications include collision warning, rollover warning, electronic toll collection, work zone warning and inter-vehicle communications.

There are a lot manufacturers that are working on equipment that are used for VANET, and these manufacturers will use different types of implementation and use different types of protocols and specifications bound by the difference in standards for each other countries. VANET communications has to deal with the highly dynamic environment as well as the changing speed and mobility of the vehicles. Latency is very important to deliver safety messages between vehicles, and therefore the setting up of the network and processing of the information, while keeping the network secure, has to be optimised to meet the necessary time requirements. Information being sent through the network requires that it is true, accurate and reliable, as it could affect a person's life. Security and privacy are two of the most important aspect of data communications and the vehicle's personal data and identity should not be shared to any unauthorised access.

Pawlikowski et al. (cited in Kotz et al. 2004) said that "An opinion is spreading that one cannot rely on the majority of the published results on performance evaluation studies of telecommunication networks based on a stochastic simulation, since they lack credibility". There are a lot of journals and articles that are based on simplistic assumptions and should be based on real-world representation of network properties and environmental conditions and behaviours to be able to properly simulate with high accuracy the performance of the network.

There are still a lot of room for improvements and research still needs to be done to be able to truly convince everybody that installing and using ITS and VANET devices in our vehicles and in our roads will make their life safer. Unless majority of the population use these devices, it would totally be a useless technology and would not really have real effect that would be able to reduce road accidents and reduce road fatalities.

5.3 Future Works

There have already been a lot of research that was done for the performance evaluation of a VANET as well as for the development of new or an improvement of an existing routing protocols. Due to time constraints, and availability of the tools required for further simulation, the simulation of this research is focused on the traditional routing protocols and further work is needed:

- Simulation using different metrics, using multi-hop transmission of data packets and using other routing methods;
- Simulation using other ITS technologies; and
- Simulation using other simulation software packages to verify the preliminary results.

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Appendix A

Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 RESEARCH PROJECT

PROJECT SPECIFICATION

FOR: JULIUS RINO PESTANO

TOPIC: REDUCING ROAD FATALITIES – VEHICULAR AD HOC NETWORK

SUPERVISOR: Dr. WEI XIANG

PROJECT AIM: To be able to analyse the performance of a VANET and develop a software program to simulate a VANET.

PROGRAMME: (Issue B, 20 March 2013)

1. Research the fundamentals of a VANET, including associated equipment, standards and protocols.
2. Evaluate current implementation of a VANET, its application and usage.
3. Identify current limitations and other negative factors affecting the wide adoptions of a VANET.
4. Research future implementations and other possible usage of a VANET.
5. Implementing and performance evaluation of the latest standard for Intelligent Transport System.
6. Develop a computer program to simulate VANET.
7. Analyse the simulation's performance, its limitations and results.

As time permits:

8. Develop a prototype to simulate VANET that can be used on its own.

Appendix B

Typical Values of Velocity Distributions

μ [km/h]	V85 [km/h]	σ [km/h]
30	40	9
50	65	15
70	90	21
90	120	27
110	145	33
130	170	39
150	195	45

Table B. 1 Typical values of velocity distribution (Rudack et al. 2002).

Appendix C

NCTUns Applications

C.1 RTCP

Usage: rtcp [-options]

[-options] -p port port number to listen at

-l readsize read size (byte)

-w LogFilename record per-second throughput results into a specified file

C.2 RTG

Usage: rtg -type [-options]

[-type] -t TCP connection

-u UDP connection

[-options] -v display the per-packet results to standard output

(e.g., pkt loss, pkt delay.)

-sb bufSize set the size of the used socket buffer (kbyte)

-p port number to listen at (default 3000)

-o LogFilename record the per-packet results into a specified file

(only support UDP)

-w LogFilename record per-second throughput results into a specified file

C.3 RTPRECVONLY

Description:

A simple rtp_receive_only application for NCTUns, developers can rewrite it to suit their needs.

Usage: rtprecvonly [local_ip] [local_port] [CNAME] [local_sdp]

[local_ip] : The IP address of the local host.

[local_port] : The port number used by the application.

[CNAME] : The CNAME used by the application, the definition of CNAME is specified in RFC3550.

[local_sdp] : The SDP file read by the application, the SDP format is specified in RFC2327.

C.4 RTPSENDRECV

Description:

A simple rtp_send_receive application for NCTUns, developers can rewrite it to suit their needs.

Usage: rtpsendrecv [local_ip] [local_port] [CNAME] [local_sdp] [-options]

[local_ip] : The IP address of the local host.

[local_port] : The port number used by the application.

[CNAME] : The CNAME used by the application, the definition of CNAME is specified in RFC3550.

[local_sdp] : The SDP file read by the application, the SDP format is specified in RFC2327.

[-options]

[-t trace_file]: Trace Mode.

Trace File Format:

Each line in a trace file represents a packet that should be transmitted.

In each line, the first column indicates the length of the packet in byte.

The second column indicates the idle time between transmitting the current and the next packet.

Format:

PacketSize(in byte) IntervalTime(in second)

C.5 STP

Usage: stcp [-options] hostIPaddr

[-options] -p port port number to listen at

-l writesize write size (byte)

-lip localIPaddr   local IP address (may be used in multi-interface node)

C.6 STG

Usage: stg -modes hostIPaddr [-options]

[-modes] TCP greedy mode:

-t Duration(sec)

UDP greedy mode: (support broadcast, e.g., 1.0.3.255)

-u PacketDataPayLoadSize(byte) Duration(sec)

-m Bandwidth(Mbit/sec) MaxQueueLength(packets)

(-m Only for UDP greedy mode, default 100Mbit/sec, 50 packets)

Trace mode: (UDP packets)

-trace InputTraceFilename

Self-similar mode: (UDP packets)

-s AvgBw(KB/s) AvgPktSize(byte) Duration(sec) OutputFilename

(Note: In the self-similar mode, the desired self-similar

traffic flow will first be calculated and saved to

the file whose name is given by OutputFilename.

Then, stg will automatically use the trace mode to

open and read this file. Based on this file, stg will

then automatically generate and send out packets.

)

ConfigFile mode:

-i ConfigFilename

[-options] -p port port number to send to (default 3000)

-v display the per-packet results to standard output

-seed random seed (default current time)

Trace File Format:

Each line in a trace file represents a packet that should be transmitted.

In each line, the first column indicates the length of the packet in bytes.

The second column indicates the idle time between transmitting the current and the next packet. Each packet is transmitted as a UDP packet.

Format:

PacketSize(in bytes) IntervalTime(in seconds)

An example:

100 0.02

234 0.1

431 1.5

200 0.001

Config File Format :

The content of a configuration file describes a traffic generation scenario, which can be very flexible and versatile. For example, it can specify a UDP flow with a particular packet size distribution (e.g., constant, uniform, or exponential) and with a particular packet inter-transmitting time distribution (e.g., constant, uniform, or exponential).

File Format:

type: udp

start_time: 10

on-off: 4

on: time: 30 const 0.01 length: const 1000

on: packet: 1000 uniform 0.05 0.1 length: exponential 800 50 1000

off: time: 40

.....

..... (more than one "on:" or "off:" statements can be put here)

.....

End

"type: ###"   ==> The protocol type ### can be udp or tcp

"start_time: ###"   ==> The time ### to start transmitting the first packet

"on-off: ###"   ==> the lines between the current line and the line
with "end" (the last line) will be repeatedly performed
times

"on: [time:XXX or packet:YYY] inter-transmitting_time_distribution
packet_length_distribution"

==> means that UDP packets should be generated and sent out based on
the specified time interval and packet length distributions

[time:XXX] means that the traffic generator should generate and send
out packets for XXX seconds

[packet:YYY] means that the traffic generator should only generate
and send out YYY packets

(Note: Only one option can be specified!)

inter-transmitting_time_distribution can be:

[const XXX] means that the time between sending consecutive packets
is a fixed value of XXX seconds

[uniform XXX, YYY] means that the times between sending consecutive
packets is a uniform distribution with MIN = XXX and
MAX = YYY seconds

[exponential XXX, YYY, ZZZ] means that the times between sending
consecutive packets is an exponential distribution

with MEAN = XXX, MIN = YYY, and MAX = ZZZ seconds

packet_length_distribution can be:

[const XXX] means that the length of generated packets is a fixed

value of XXX bytes

[uniform XXX, YYY] means that the lengths of generated packets

is a uniform distribution with MIN = XXX and

MAX = YYY bytes

[exponential XXX, YYY, ZZZ] means that the lengths of generated

packets is an exponential distribution

with MEAN = XXX, MIN = YYY, and MAX = ZZZ bytes

"off: time: ###" ==> stop transmitting packets for ### seconds

Notes for UDP connections:

Stg support four types of time interval distributions for a UDP flow:

(1) const #1 ==> constant #1 (CBR packet stream)

(2) uniform #1 #2 ==> min #1, max #2

(3) exponential #1 #2 #3 ==> ave #1, min #2, max #3 (Poisson packet stream)

(4) greedy ==> 0

Stg support three types of packet size (in bytes) for a UDP flow:

(1) const #1 ==> constant #1

(2) uniform #1 #2 ==> min #1, max #2

(3) exponential #1 #2 #3 ==> ave #1, min #2, max #3

[note] The maximum packet size specified cannot be large than the

Ethernet MTU 1500 bytes!

Notes for TCP connections:

Stg ONLY supports the "greedy" mode for a TCP connection.

A UDP Traffic Config Example:

type: udp

start_time: 1

on-off: 5

on: packet: 1000 greedy length: uniform 100 1000

on: time: 30 const 0.001 length: const 400

off: time: 20

on: packet: 15 uniform 1.5 4 length: uniform 500

on: time: 25 exponential 1 3 5 length: const 300

off: time: 20

on: packet: 100 uniform 0.1 0.5 length: exponential 500 100 1000

end

A TCP Traffic Config Example:

type: tcp

start_time: 1

on-off: 1

on: time: 30 greedy

off: time: 10

end

C.7 TTCP

Usage: ttcp -t [-options] host [< in]

ttcp -r [-options > out]

Common options:

-l ## length of buf read from or written to network (default 1000)

-u use UDP instead of TCP

-p port port number to send to or listen at (default 5001)

-s -t: source a pattern to network

-r: sink (discard) all data from network

-A align the start of buffers to this modulus (default 16384)

-O start buffers at this offset from the modulus (default 0)

-v verbose: print more statistics

-d set SO_DEBUG socket option

-b ## set socket buffer size (if supported)

-f X format for rate: k,K = kilo{bit,byte}; m,M = mega; g,G = giga

Options specific to -t:

-n ## number of source bufs written to network (default 2^20)

-D don't buffer TCP writes (sets TCP_NODELAY socket option)

Options specific to -r:

-B for -s, only output full blocks as specified by -l (for TAR)

-T "touch": access each byte as it's read

-w name log per-second throughput to file

Appendix D

Matlab VANET Simulator

D.1 Computing Exact Closed-Form Distance Distributions in Regular Polygons

%% CONTRIBUTION:
% This script displays and plots the closed form expressions of the distance distributions.
%
% It illustrates the usage of the function "distance_dist_Lgon(L,R,x,y)" which implements the algorithm in [1] to compute:
%(i) the exact closed-form probability density function and (ii) the exact closed-form cumulative
% density function of the distance between a randomly located node and any arbitrary reference point
% inside a regular L-sided polygon.

%% CITING THIS WORK:
% If you use this code to generate the distance distribution results, please cite our paper:

% [1] Z. Khalid and S. Durrani, "Distance Distributions in Regular Polygons,"
% to appear in IEEE Transactions on Vehicular Technology, 2013.
% http://ieeexplore.ieee.org/xpl/articleDetails.jsp?reload=true&tp=&arnumber=6415342
% http://arxiv.org/abs/1207.5857

%% USAGE INSTRUCTIONS:
% Please note the following:
% (i) Generally, enter reference point x and y coordinates in decimals (e.g., 0.5) , rather than as fractions (e.g. 1/2).
% (ii) This code has been tested using Matlab R2011a and Symbolic Math Toolbox Version 5.6 (based on MuPAD and not Maple).
% (iii) The ability of the code to produce the most simplified expressions is dependant on the "simple" command
% (used in line 102 in the function "distance_dist_Lgon(L,R,x,y)". Verify answers by comparing with the Mathematica implementation.
%
% For comments, suggestions and bug reports, please email: salman.durrani@anu.edu.au.

%% COPYRIGHT: © Zubair Khalid and Salman Durrani.
% Applied Signal Processing (ASP) research group,
% Research School of Engineering,
% The Australian National University, Canberra, Australia, May 2013.

clc
% clear all
close all

```
%% Define Variables
% no. of sides of polygon L>3
L=4;
% x-coordinate of reference point
x=0.5;
% y-coordinate of reference point
y=0.5;
% Circum-radius of the regular convex polygon, which is centered at (0,0)
R=1;

%% Compute the distance distributions
[F_cdf F_pdf dist_r] = distance_dist_Lgon(L,R,x,y);

%% Display the distance distributions
fprintf('----Closed Form Expressions of PDF---------\n\n');
display_dist(F_pdf,dist_r);
fprintf('----Closed Form Expressions of CDF---------\n\n');
display_dist(F_cdf,dist_r);


%% Plot the distance distributions
plot_dist(F_pdf,dist_r);
ylabel('f(r)','FontSize',14,'FontName','Arial');
plot_dist(F_cdf,dist_r);
ylabel('F(r)','FontSize',14,'FontName','Arial');
```

D.2 Computing Exact Closed-Form Distance Distributions in Regular Polygons

```
%% CONTRIBUTION:
% This function implements the algorithm in [1] to compute:
%(i) the exact closed-form probability density function and (ii) the exact closed-form cumulative
% density function of the distance between a randomly located node and any arbitrary reference point
% inside a regular L-sided polygon.

%% CITING THIS WORK:
% If you use this code to generate the distance distribution results, please cite our paper:

% [1] Z. Khalid and S. Durrani, "Distance Distributions in Regular Polygons,"
% to appear in IEEE Transactions on Vehicular Technology, 2013.
% http://ieeexplore.ieee.org/xpl/articleDetails.jsp?reload=true&tp=&arnumber=6415342
% http://arxiv.org/abs/1207.5857

%% USAGE INSTRUCTIONS:
% See demo.m provided with this code.
%
% Inputs
% L = no of sides of the regular convex polygon (L-gon), which is centered at (0,0)
% R = circumradius
% x,y = coordinates of reference point inside the L-gon.
%
% Outputs
% F_cdf = the exact closed-form cumulative density function
% F_pdf = the exact closed-form probability density function
% dist_r = piece-wise unique ranges
%
% For comments, suggestions and bug reports, please email: salman.durrani@anu.edu.au.

%% COPYRIGHT:  ©  Zubair Khalid and Salman Durrani.
% Applied Signal Processing (ASP) research group,
% Research School of Engineering,
% The Australian National University, Canberra, Australia, May 2013.


%% Implement the proposed algorithm in Section V in [1] to automatically pick the correct border and corner effects for all distance ranges
```

```
function [ F_cdf F_pdf dist_r] = distance_dist_Lgon( L,R,x,y)

%% check if the point (x,y) is inside the L-gon
if  point_inside_polygon(L,R,x,y)
   %% Allocate variables to be computed
   % We use this as a tolerance level comparable to numerical precision.
   % We treat any quantity as zero, if the quantity is less than TOL.
   global TOL
   TOL = 10^(-10);

   F_cdf = [];
   F_pdf = [];
   dist_r = 0;

   %% Compute distance vectors
   dv_all = distance_vector_full(L,R,x,y);
   % Effects of finite precision can show up in the distances:
   % if present these are corrected by the check_precision function
   dv_all = check_precision(dv_all);
   dist_vector = dv_all(L+1:end);
   dv_sides = dv_all(1:L);
   dv_sides_polygon = dv_all(L+1:2*L);

   %% Sort distance vector
   [dist_vector_sorted,IX] = sort(dist_vector);

   %% Select unique ranges
   R1 = 0;
   R2 = dist_vector_sorted(1);

   syms r real;

   %% compute cdf and pdf for the first range when there are no boundary effects
   if abs(R2-R1)>TOL
      F_cdf = [F_cdf pi*r.^2];
      F_pdf = [F_pdf 2*pi*r];
      dist_r = [dist_r R2];
   end

   %% Compute cdf and pdf for the different ranges, taking into account boundary effects
   for j= 2:1:2*L

      R1 = dist_vector_sorted(j-1);
      R2 = dist_vector_sorted(j);
```

```
        if abs(R2-R1)>TOL
            F_cdf = [F_cdf pi*r.^2 - compute_cdf_out(IX,j-
1,L,R,x,y,r,dv_sides,dv_sides_polygon,dv_all)];
            F_pdf = [F_pdf 2*pi*r - compute_pdf_out(IX,j-1,L,r,dv_sides)];
            dist_r = [dist_r R2];
        end

    end

    %% Normalize cdf and pdf by area of polygon
    F_cdf =   F_cdf/A_gon(L,R);
    F_pdf =   F_pdf/A_gon(L,R);

    %% Add final ranges over which F_cdf =1 and F_pdf =0
    if abs(dist_r(length(dist_r)-2*R))> TOL
        F_cdf = [F_cdf 1];
        F_pdf = [F_pdf 0];
        dist_r = [dist_r 2*R];
    end
    F_cdf = simple(F_cdf);
    F_pdf = simple(F_pdf);
else
    error('The point (x,y) is not inside the polygon.');
end

end

%% Subfunctions used in the main function

%% Function 1: Find the polygon area: Equation (1) in [1]
function  A =  A_gon(L,R)
A = (L*R^2*sin(2*pi/L))/2;
end

%% Function 2: Find the polygon interior angle: Equation (2) in [1]
function vartheta  = theta_interior(L)
vartheta = (pi*(L-2)/(L));
end

%% Function 3: Find the rotation matrix: Equations (3) and (4) in [1]
function T_matrix = rotation_matrix(L,l)
theta_out = 2*pi/L;
T_matrix = [cos(l*theta_out) -sin(l*theta_out) ; sin(l*theta_out)  cos(l*theta_out) ];
end
```

```
%% Function 4: Find distance to the vertices: Equations (5) and (6) in [1]
function distance_V = distance_vertex(L,R,x,y,l)
rot_point = rotation_matrix(L,-(l-1))*transpose([x y]);
x1 = rot_point(1);
y1 = rot_point(2);
distance_V = sqrt( y1.^2 + (x1-R).^2 );
end

%% Function 5: Find the perpendicular distance to the sides: Equations (7) and (9) in [1]
function distance_S = distance_side(L,R,x,y,l)
rot_point = rotation_matrix(L,-(l-1))*transpose([x y]);
x1 = rot_point(1);
y1 = rot_point(2);
distance_S = abs(y1 + x1*tan(theta_interior(L)/2 ) - R*tan(theta_interior(L)/2 ))/ (sqrt(1 +
(tan(theta_interior(L)/2 )).^2));
end

%% Function 6: Find the shortest distance to the sides: Equations (8) and (9) in [1]
function distance_S = distance_side_polygon(L,R,x,y,l)
global TOL

rot_point = rotation_matrix(L,-(l-1))*transpose([x y]);
Q1 = [R 0];
Q2 = transpose(rotation_matrix(L,1)*transpose(Q1));
x1 = R;
y1 = 0;

x2  =Q2(1);
y2 = Q2(2);

x3 = rot_point(1);
y3 = rot_point(2);

u=((x3-x1)*(x2-x1) + (y3-y1)*(y2-y1))/ ((x1-x2).^2 + (y1-y2).^2);

xx = x1+u*(x2-x1);
yy = y1+u*(y2-y1);

distance_S = norm([xx-x3,yy-y3]);

dd1 = norm([x1-xx,y1-yy]);
dd2 = norm([x2-xx,y2-yy]);
dd12 = norm([x1-x2,y1-y2]);

if dd1 > dd12 || dd2>dd12
```

```
    distance_S = min(norm([x3-x1, y3-y1]), norm([x3-x2,y3-y2]));
end

if distance_S < TOL
    distance_S=0;
end
end

%% Function 7: Find the distance vector: Equation (10) in [1], appended with the distances from the sides which are needed in the main algorithm
function distance_vector = distance_vector_full(L,R,x,y)
distance_vector = zeros(1,3*L);
for l=1:1:L
    distance_vector(l) = distance_side(L,R,x,y,l);
end
for l=1:1:L
    distance_vector(L+l) = distance_side_polygon(L,R,x,y,l);
end
for l=1:1:L
    distance_vector(2*L+l) = distance_vertex(L,R,x,y,l);
end
end


%% Function 8: Find the circular segment areas formed outsides the side: Equations (13) and (14) in [1]
function [ BB ] = sym_border_function(L,R,x,y,l,r, dv_sides,dv_sides_polygon)
global TOL

if distance_side_polygon(L,R,x,y,l) < TOL
    BB = pi*r.^2/2;
else
    BB1 = r.^2.*acos(dv_sides(l)./r) - dv_sides(l).*sqrt(r.^2 - (dv_sides(l)).^2);
    BB2 = (dv_sides_polygon(l)).^2.*acos(dv_sides(l)./dv_sides_polygon(l)) - dv_sides(l).*sqrt((dv_sides_polygon(l)).^2 - (dv_sides(l)).^2);
    BB = BB1-BB2;
end
end

%% Function 9: Find the corner overlap areas formed outside the vetrices: Equations (15) and (16) in [1]

function [ CC ] = sym_corner_function(L,R,x,y,l,r, dv_sides,dv_all)
global TOL
dv_sides_L = (circshift(dv_sides',1))';
```

```
A = dv_all(2*L+l);
if A< TOL
   CC = 0.5.*r.^2*theta_interior(L);
else
   F1 =   0.5*r.^2.*(acos(dv_sides(l)./r  ) + acos(dv_sides_L(l)./r  )) ;
   F2 =   0.5.*(A).^2.*( acos(dv_sides(l)./A  ) + acos(dv_sides_L(l)./A  ) );
   F3 =   0.5.*dv_sides(l).*(sqrt((A).^2 - (dv_sides(l)).^2  ) - sqrt(r.^2 - (dv_sides(l)).^2  )   );
   F4 =   0.5.*dv_sides_L(l).*(sqrt((A).^2 - (dv_sides_L(l)).^2  ) - sqrt(r.^2 -
(dv_sides_L(l)).^2  ));
   F5 =   (-pi/L).*(r.^2 - (A).^2 )   ;
   CC =  F1-F2+F3+F4+F5;
end
end

%% Function 10: Find the derivatives: Equation (21) in [1]
function [ BB ] = sym_border_function_derivative(l,r,dv_sides )
BB = 2*r.*acos(dv_sides(l)./r );
end

%% Function 11: Find the derivatives: Equation (22) in [1]
function [ CC ] = sym_corner_function_derivative(L,l,r,dv_sides )
dv_sides_L = (circshift(dv_sides',1))';
CC = r.*(acos(dv_sides(l)./r  ) + acos(dv_sides_L(l)./r  )) -  2*pi*r/L;
end

%% Function 12: Find the CDF: Algorithm 1
function area_outside = compute_cdf_out(IX,j,L,R,x,y,range, dv_sides,
dv_sides_polygon,dv_all)
area_outside = 0;
for k=1:1:j
   if(IX(k)<=L )
      el = IX(k);
      area_outside = area_outside +
sym_border_function(L,R,x,y,el,range,dv_sides,dv_sides_polygon );
   else
      el = IX(k)-L;
      area_outside = area_outside -  sym_corner_function(L,R,x,y,el,range,dv_sides,dv_all );
   end
end
end

%% Function 13: Find the PDF: Algorithm 1
function area_outside = compute_pdf_out(IX,j,L,range,dv_sides)
area_outside = 0;
for k=1:1:j
```

```
  if(IX(k)<=L )
    el = IX(k);
    area_outside = area_outside +  sym_border_function_derivative(el,range,dv_sides );
  else
    el = IX(k)-L;
    area_outside = area_outside -  sym_corner_function_derivative(L,el,range,dv_sides );
  end
end
end

%% Function 14: Find if the point (x,y) is inside or on the boundary the L-gon
function check = point_inside_polygon(L,R,x,y)
VV = linspace(0,2.*pi,L+1); xv = R*cos(VV)';yv = R*sin(VV)';
xv = [xv ; xv(1)]; yv = [yv ; yv(1)];
[IN ON] = inpolygon(x,y,xv,yv);
check = IN||ON;
end

%% Function 15: Check the distance vector for erros due to numerical precision. If present,
remove the effects of finite precision in the distance calculations.
function dist_vec_out = check_precision(dist_vec_in)
global TOL
dist_vec_out = dist_vec_in;
%(1st check) if the absolute value of any distance in the “dist_vec_out” vector is less than a
tolerance value, it is set to 0
for i=1:1:length(dist_vec_out)
  if abs(dist_vec_out(i))< TOL
    dist_vec_out(i) =0;
  end
end
% (2nd check) if any two distances in the “dist_vec_out” vector are the same, within the
tolerance limit, then they are set as the same (first) distance value
for i=1:1:length(dist_vec_out)
  for j=i:1:length(dist_vec_out)
    if abs(dist_vec_out(i) -dist_vec_out(j) )< TOL
      dist_vec_out(j) =dist_vec_out(i);
    end
  end
end
end
```

D.3 Display Distance

```
% This function is used for displaying the piecewise distance distributions in the command window.

%% COPYRIGHT:  ©  Zubair Khalid and Salman Durrani.
% Applied Signal Processing (ASP) research group,
% Research School of Engineering,
% The Australian National University, Canberra, Australia, May 2013.

function display_dist(F_dist,dist_r)
  for el=1:1:length(dist_r)-1
    if(dist_r(el+1)-dist_r(el)>0)
      fprintf('For distance,\t %1.4f <= r  <= %1.4f\n \n',dist_r(el),dist_r(el+1));
      fprintf('Distribution: \t %s\n\n\n', char(vpa(F_dist(el),5) ));
    end
  end

end
```

D.4 Display Distance

```
% This function is used for plotting the piecewise distance distributions.

%% COPYRIGHT:  ©  Zubair Khalid and Salman Durrani.
% Applied Signal Processing (ASP) research group,
% Research School of Engineering,
% The Australian National University, Canberra, Australia, May 2013.

function plot_dist(F_dist,dist_r)

  figure1 = figure('PaperSize',[20.5 29],'Color',[1 1 1]);
  axesh = axes('Parent',figure1,'FontSize',14,'FontName','Arial');

  % vpa transforms fractions in the distribution to floating point - precision (5) used here
  F_dist = vpa(F_dist,5);

  for el=1:1:length(dist_r)-1
      if(dist_r(el+1)-dist_r(el)>0)
        r_inc = (dist_r(el+1)-dist_r(el))/20;
        plot(dist_r(el):r_inc:dist_r(el+1),
real(subs(F_dist(el),dist_r(el):r_inc:dist_r(el+1))),'LineWidth',2.5);
        hold on;
      end
```

```
    end

    xlabel('distance, r','FontSize',14,'FontName','Arial');
    grid on;
    axis tight;

end
```

Appendix E

NCTUns Simulation Log

E.1. Speed Log

Speed Input						
Time	30kph	30kph Throughput	60kph Input	60kph Throughput	80kph Input	80kph Throughput
1	96	115.128	101	122.61	101	122.61
2	118	143.068	110	136.304	110	136.304
3	103	124.018	105	127.69	116	139.396
4	86	106.956	122	148.148	93	111.318
5	106	131.224	114	137.988	97	118.662
6	105	125.426	102	125.012	106	130.092
7	105	126.558	85	102.29	102	121.616
8	99	120.07	104	124.156	99	117.806
9	106	128.96	87	103.698	136	162.532
10	97	114.134	107	130.23	107	125.702
11	117	138.402	95	112.726	89	108.502
12	109	130.506	104	126.42	95	114.99
13	103	124.018	87	103.698	96	112.864
14	99	122.334	101	124.874	113	138.982
15	110	131.776	110	131.776	114	137.988
16	108	128.104	128	155.768	106	125.564
17	108	134.896	108	130.368	87	108.226
18	79	94.67	84	104.416	87	104.83
19	101	122.61	109	133.902	96	115.128
20	102	126.144	94	113.72	102	120.484
21	96	116.26	115	140.39	127	152.234
22	113	137.85	95	112.726	93	112.45
23	103	126.282	92	112.312	110	132.908
24	104	125.288	107	126.834	101	123.742
25	103	121.754	104	125.288	104	125.288
26	127	151.102	77	90.998	116	139.396
27	91	107.646	116	140.528	109	131.638
28	112	136.58	65	79.154	131	157.314
29	84	103.284	116	138.264	121	149.142
30	104	126.42	110	131.776	97	117.53
31	81	94.946	83	99.75	112	136.58
32	75	91.854	103	119.49	107	127.966
33	97	119.794	125	146.298	115	141.522
34	117	140.666	132	157.452	109	131.638
35	106	127.828	110	132.908	110	130.644
36	89	107.37	117	141.798	97	120.926
37	94	114.852	92	113.444	90	105.244
38	96	115.128	100	122.472	71	89.038
39	119	143.206	100	122.472	98	118.8
40	116	140.528	112	136.58	96	117.392
41	113	138.982	97	114.134	81	99.474
42	106	128.96	109	131.638	81	97.21
43	108	130.368	116	140.528	118	143.068
44	90	105.244	116	137.132	100	120.208
45	93	110.186	102	121.616	99	118.938
46	103	124.018	118	145.332	108	129.236
47	103	125.15	101	121.478	90	106.376
48	114	135.724	112	135.448	98	118.8
49	99	117.806	125	151.958	98	118.8
50	99	121.202	101	123.742	101	122.61
51	116	139.396	95	118.386	109	131.638
52	120	144.476	104	126.42	123	147.154
53	94	112.588	117	145.194	118	141.936
54	102	125.012	98	119.932	113	135.586
55	114	135.724	120	144.476	113	134.454
56	102	123.88	105	127.69	113	135.586
57	102	123.88	120	143.344	117	141.798
58	103	124.018	94	112.588	112	134.316
59	111	133.046	107	126.834	91	109.91
60	95	113.858	108	131.5	100	120.208

61	103	124.018	113	137.85	111	131.914
62	95	116.122	108	130.368	101	121.478
63	91	108.778	87	101.434	105	126.558
64	114	137.988	76	91.992	108	130.368
65	105	127.69	98	115.404	100	122.472
66	95	118.386	88	103.836	109	131.638
67	107	127.966	97	118.662	101	123.742
68	106	125.564	87	103.698	92	111.18
69	102	123.88	103	125.15	103	122.886
70	94	111.456	94	114.852	96	113.996
71	132	158.584	107	129.098	91	112.174
72	143	170.29	100	120.208	105	126.558
73	142	170.152	109	132.77	99	121.202
74	154	181.996	105	126.558	78	95.664
75	133	158.722	117	139.534	96	117.392
76	115	139.258	95	114.99	123	151.682
77	99	118.938	104	126.42	82	99.612
78	102	125.012	89	107.37	95	112.726
79	120	144.476	109	130.506	112	136.58
80	88	108.364	124	148.424	93	110.186
81	104	123.024	121	148.01	112	132.052
82	95	112.726	97	116.398	89	106.238
83	102	121.616	103	124.018	109	131.638
84	122	148.148	96	117.392	112	134.316
85	114	136.856	112	135.448	84	98.756
86	99	118.938	114	139.12	100	120.208
87	106	130.092	119	140.942	126	152.096
88	117	140.666	120	142.212	103	121.754
89	93	111.318	126	150.964	102	123.88
90	116	138.264	122	147.016	104	127.552
91	110	132.908	108	129.236	105	125.426
92	105	125.426	99	120.07	97	115.266
93	116	139.396	113	134.454	88	103.836
94	111	136.442	99	117.806	114	134.592
95	93	112.45	121	150.274	111	130.782
96	122	149.28	89	107.37	124	146.16
97	117	141.798	94	112.588	110	129.512
98	101	123.742	100	120.208	108	131.5
99	111	134.178	97	114.134	99	118.938
100	121	145.746	102	121.616	105	124.294
101	101	118.082	99	116.674	83	102.014
102	108	130.368	103	125.15	102	122.748
103	117	142.93	121	145.746	122	145.884
104	114	139.12	108	129.236	119	142.074
105	102	123.88	111	136.442	107	130.23
106	125	150.826	124	149.556	114	136.856
107	94	112.588	90	109.772	81	98.342
108	115	136.994	105	126.558	97	119.794
109	105	127.69	97	119.794	97	119.794
110	115	135.862	103	126.282	106	126.696
111	96	117.392	108	130.368	104	124.156
112	121	143.482	92	112.312	97	116.398
113	100	120.208	119	143.206	110	135.172
114	95	113.858	86	101.296	106	127.828
115	90	110.904	106	126.696	87	105.962
116	133	159.854	74	88.32	100	117.944
117	90	107.508	107	129.098	78	92.268
118	114	139.12	93	111.318	94	111.456
119	116	139.396	113	135.586	108	128.104
Speed Output						
Time	30kph Output	3kph Throughput	60kph Output	60kph Throughput	80kph Output	80kphThroughput
1	229	234.95	223	227.33	223	227.33
2	206	205.74	213	214.63	213	214.63
3	222	226.06	219	222.25	211	212.09
4	235	242.57	204	203.2	232	238.76

5	217	219.71	212	213.36	226	231.14
6	220	223.52	221	224.79	217	219.71
7	220	223.52	239	247.65	224	228.6
8	225	229.87	222	226.06	226	231.14
9	218	220.98	237	245.11	193	188.098
10	228	233.68	217	219.71	220	223.52
11	211	212.09	229	234.95	232	238.76
12	218	220.98	220	223.52	229	234.95
13	223	227.33	235	242.57	231	236.358
14	224	228.6	221	224.79	209	209.55
15	217	219.71	214	214.768	212	213.36
16	219	222.25	197	194.31	221	224.79
17	214	215.9	216	218.44	234	241.3
18	243	252.73	237	245.11	236	243.84
19	223	227.33	215	217.17	230	236.22
20	219	222.25	230	235.088	224	228.6
21	229	234.95	210	210.82	202	199.528
22	212	213.36	229	234.95	233	236.634
23	221	224.79	232	238.76	214	215.9
24	221	224.79	220	223.52	222	226.06
25	223	226.198	221	224.79	218	220.98
26	201	199.39	246	256.54	211	210.958
27	233	240.03	208	208.28	215	217.17
28	212	213.36	257	270.51	192	187.96
29	239	247.65	210	210.82	202	200.66
30	220	223.52	216	218.44	227	232.41
31	243	252.73	240	247.788	212	214.492
32	246	256.54	225	228.738	219	219.986
33	225	229.87	203	200.798	207	208.142
34	209	208.418	195	190.638	216	218.44
35	217	220.842	213	215.762	217	218.578
36	235	241.438	209	208.418	227	227.882
37	229	234.95	230	235.088	236	242.708
38	229	234.95	223	227.33	249	260.35
39	207	207.01	224	228.6	227	232.41
40	210	210.82	210	211.952	227	232.41
41	210	210.82	228	233.68	241	250.19
42	219	222.25	215	216.038	242	251.46
43	218	220.98	207	208.142	207	207.01
44	235	242.57	211	210.958	225	228.738
45	233	240.03	222	226.06	233	223.05
46	221	224.79	203	201.93	217	217.446
47	221	224.79	228	228.02	234	241.3
48	211	212.09	213	214.63	227	231.278
49	226	231.14	200	198.12	226	231.14
50	223	227.33	222	226.06	223	227.33
51	211	212.09	227	232.41	217	219.71
52	206	205.74	225	221.946	205	204.47
53	228	233.68	205	204.47	209	209.55
54	222	226.06	226	231.14	214	215.9
55	213	213.498	204	203.2	215	213.774
56	222	226.06	220	223.52	212	213.36
57	223	227.33	208	208.28	209	209.55
58	223	227.33	231	237.49	212	214.492
59	215	217.17	220	223.52	235	235.778
60	230	236.22	215	217.17	226	231.14
61	222	226.06	211	212.09	217	219.71
62	229	234.95	221	216.866	223	227.33
63	232	238.76	237	243.978	220	223.52
64	209	209.55	246	255.408	217	219.71
65	220	223.52	227	230.146	224	228.6
66	227	232.41	237	245.11	216	218.44
67	220	223.52	226	231.14	227	225.618
68	219	222.25	238	245.248	240	237.6
69	223	227.33	221	224.79	227	224.486
70	231	236.358	228	233.68	229	233.818

71	195	191.77	219	222.25	231	238.622
72	186	180.34	225	229.87	220	222.388
73	186	180.34	216	218.44	225	229.87
74	173	164.962	221	224.79	244	254
75	193	188.098	210	210.82	228	233.68
76	210	210.82	229	234.95	199	196.85
77	224	228.6	221	224.79	240	248.92
78	222	226.06	235	242.57	231	236.358
79	206	204.608	216	217.308	212	213.36
80	236	242.708	203	201.93	232	238.76
81	221	224.79	203	203.062	216	218.44
82	230	236.22	227	231.278	235	241.438
83	221	225.922	221	224.79	217	219.71
84	201	199.39	227	231.278	215	217.17
85	212	212.228	211	212.09	240	248.92
86	224	228.6	209	210.682	224	228.6
87	217	219.71	208	207.148	201	199.39
88	207	208.142	207	207.01	223	227.33
89	234	240.168	202	200.66	221	224.79
90	208	208.28	203	201.93	220	222.388
91	215	217.17	216	219.572	220	223.52
92	219	222.25	224	227.468	227	232.41
93	209	209.55	212	213.36	239	245.386
94	211	212.09	227	231.278	213	214.63
95	231	236.358	200	198.12	216	218.44
96	201	200.522	236	241.576	203	200.798
97	208	207.148	229	234.95	215	218.302
98	221	225.922	225	229.87	215	216.038
99	213	213.498	228	232.548	225	229.87
100	202	200.66	225	229.87	220	224.652
101	224	228.6	228	233.68	239	247.65
102	216	218.44	221	224.79	223	226.198
103	206	205.74	205	204.47	205	203.338
104	211	212.09	219	222.25	207	207.01
105	219	222.25	213	214.63	214	217.032
106	201	199.39	202	200.66	212	213.36
107	228	233.68	232	238.76	241	249.058
108	209	210.682	220	223.52	225	229.87
109	219	221.118	227	231.278	224	228.6
110	212	214.492	221	224.79	219	222.25
111	228	232.548	217	219.71	220	223.52
112	206	205.74	229	236.082	227	232.41
113	224	228.6	207	205.878	213	214.63
114	227	233.542	243	245.938	217	219.71
115	232	237.628	221	224.79	236	242.708
116	193	189.23	248	259.08	228	233.68
117	233	240.03	219	222.25	247	256.678
118	209	210.682	231	237.49	232	238.76
119	211	210.958	214	215.9	219	219.986
Speed Dropped Packet						
Time	30kph	60kph	80kph			
1	77	95	95			
2	70	45	45			
3	80	60	72			
4	101	75	85			
5	76	69	86			
6	83	82	73			
7	72	87	66			
8	65	98	84			
9	83	79	26			
10	95	62	64			
11	60	126	128			
12	62	69	107			
13	71	86	97			
14	92	102	69			
15	75	90	77			

16	88	25	88			
17	72	80	94			
18	116	92	110			
19	69	85	92			
20	76	76	51			
21	106	85	62			
22	67	85	107			
23	76	112	75			
24	68	70	89			
25	75	71	80			
26	13	118	59			
27	98	59	58			
28	81	126	33			
29	111	69	63			
30	85	40	76			
31	120	131	58			
32	123	77	42			
33	84	36	84			
34	55	46	61			
35	82	70	50			
36	85	49	78			
37	99	99	79			
38	85	87	132			
39	44	75	100			
40	78	63	105			
41	62	59	120			
42	61	58	70			
43	68	60	79			
44	107	64	89			
45	105	73	65			
46	77	64	100			
47	74	66	74			
48	74	66	85			
49	66	32	80			
50	104	66	94			
51	63	88	57			
52	52	87	46			
53	104	54	78			
54	68	95	57			
55	69	62	72			
56	65	92	78			
57	85	51	53			
58	52	75	66			
59	68	83	80			
60	63	71	103			
61	89	66	63			
62	98	83	72			
63	84	89	100			
64	88	131	75			
65	51	112	72			
66	83	88	58			
67	96	102	115			
68	67	120	90			
69	75	86	73			
70	90	100	90			
71	31	56	96			
72	0	78	81			
73	0	82	77			
74	0	63	146			
75	13	65	89			
76	51	84	54			
77	79	73	92			
78	66	93	102			
79	74	74	72			
80	99	55	101			
81	65	51	78			

82	76	74	90			
83	53	78	67			
84	42	79	69			
85	63	78	111			
86	93	62	70			
87	64	43	76			
88	48	39	98			
89	90	45	91			
90	60	34	67			
91	55	73	98			
92	83	77	83			
93	60	60	91			
94	66	60	69			
95	64	79	61			
96	74	91	52			
97	42	88	59			
98	86	86	84			
99	73	80	69			
100	43	84	63			
101	95	88	93			
102	83	93	95			
103	55	51	49			
104	63	64	42			
105	67	52	63			
106	45	50	67			
107	93	101	116			
108	59	63	102			
109	83	72	104			
110	44	90	76			
111	85	85	66			
112	43	111	97			
113	66	62	74			
114	90	106	87			
115	94	82	102			
116	40	127	74			
117	84	61	116			
118	65	86	89			
119	43	37	72			

E.2 Density

Density Input						
Time	3 Cars Input	3 Cars Throughput	6 Cars Input	6 Cars Throughput	9 Cars Input	9 Cars Throughput
1	95	114.99	101	122.61	98	117.668
2	130	157.176	110	136.304	82	97.348
3	104	126.42	115	139.258	120	146.74
4	88	108.364	123	149.418	116	140.528
5	91	111.042	125	150.826	84	101.02
6	106	130.092	113	140.114	108	129.236
7	125	151.958	111	134.178	93	112.45
8	101	123.742	104	127.552	116	141.66
9	113	136.718	110	134.04	107	126.834
10	102	125.012	110	131.776	94	114.852
11	122	148.148	101	122.61	69	81.97
12	98	119.932	113	140.114	93	111.318
13	102	122.748	97	118.662	82	100.744
14	121	146.878	91	108.778	94	113.72
15	107	127.966	86	103.56	65	81.418
16	103	122.886	101	122.61	117	142.93

17	117	144.062	122	147.016	109	132.77
18	93	112.45	93	116.978	85	102.29
19	86	102.428	104	127.552	119	143.206
20	125	151.958	85	103.422	101	121.478
21	112	134.316	104	125.288	108	131.5
22	89	108.502	82	100.744	102	126.144
23	106	126.696	108	130.368	74	89.452
24	102	122.748	106	126.696	105	123.162
25	112	137.712	128	153.504	99	117.806
26	102	120.484	109	131.638	100	120.208
27	87	101.434	91	111.042	112	134.316
28	108	133.764	97	116.398	94	112.588
29	82	97.348	92	111.18	103	126.282
30	113	137.85	123	148.286	139	168.606
31	98	122.196	143	170.29	151	180.45
32	82	96.216	137	164.934	130	156.044
33	106	127.828	115	138.126	115	140.39
34	122	148.148	115	140.39	123	147.154
35	105	129.954	97	118.662	95	117.254
36	96	117.392	89	106.238	114	139.12
37	108	130.368	98	116.536	92	108.916
38	109	130.506	89	105.106	112	136.58
39	94	112.588	99	117.806	97	115.266
40	101	121.478	90	112.036	105	128.822
41	107	127.966	93	113.582	112	136.58
42	92	108.916	103	124.018	82	99.612
43	121	144.614	105	127.69	103	122.886
44	107	127.966	104	127.552	106	126.696
45	102	126.144	105	126.558	104	125.288
46	109	133.902	87	105.962	100	119.076
47	114	140.252	112	134.316	93	115.846
48	102	126.144	93	112.45	89	110.766
49	97	116.398	90	108.64	115	140.39
50	100	122.472	99	118.938	101	120.346
51	101	121.478	94	113.72	95	113.858
52	77	94.394	94	114.852	109	130.506
53	118	141.936	113	134.454	96	117.392
54	80	97.072	79	94.67	91	112.174
55	111	134.178	108	129.236	95	113.858
56	102	123.88	100	121.34	107	132.494
57	89	108.502	117	140.666	115	139.258
58	104	125.288	96	116.26	122	149.28
59	73	88.182	121	145.746	106	131.224
60	86	102.428	112	134.316	100	120.208
61	112	135.448	122	145.884	66	79.292
62	118	141.936	112	135.448	82	99.612
63	94	113.72	108	131.5	67	80.562
64	87	104.83	107	130.23	99	122.334
65	105	128.822	74	88.32	113	138.982
66	122	144.752	109	130.506	106	126.696
67	90	106.376	96	116.26	102	122.748
68	98	116.536	124	147.292	131	159.578
69	110	135.172	96	115.128	79	95.802
70	118	141.936	114	136.856	109	129.374
71	105	125.426	94	112.588	96	111.732
72	110	134.04	114	137.988	118	140.804
73	106	125.564	102	126.144	107	126.834
74	89	106.238	73	90.446	84	103.284
75	99	117.806	108	132.632	122	145.884
76	110	130.644	102	126.144	95	116.122
77	122	145.884	129	155.906	102	121.616
78	118	139.672	98	113.14	97	118.662
79	105	127.69	112	134.316	110	132.908
80	93	112.45	94	113.72	106	131.224
81	128	156.9	96	115.128	83	99.75
82	88	103.836	127	152.234	111	135.31

83	87	108.226	102	121.616	91	109.91
84	99	120.07	90	106.376	98	119.932
85	81	99.474	91	111.042	105	127.69
86	112	136.58	87	103.698	96	116.26
87	74	88.32	118	143.068	106	128.96
88	99	121.202	106	125.564	112	135.448
89	100	120.208	89	109.634	106	126.696
90	113	135.586	101	122.61	106	130.092
91	99	120.07	115	138.126	130	157.176
92	125	148.562	139	165.21	148	177.772
93	103	125.15	132	155.188	137	162.67
94	95	114.99	137	163.802	131	157.314
95	91	111.042	109	129.374	125	153.09
96	104	124.156	96	117.392	109	130.506
97	125	150.826	110	134.04	110	135.172
98	100	121.34	109	129.374	96	113.996
99	108	130.368	114	137.988	93	113.582
100	106	126.696	121	144.614	111	134.178
101	131	158.446	106	128.96	98	116.536
102	122	145.884	121	145.746	122	145.884
103	118	143.068	119	139.81	91	108.778
104	107	126.834	109	132.77	100	121.34
105	105	125.426	108	130.368	119	142.074
106	120	144.476	110	135.172	109	130.506
107	87	103.698	123	144.89	115	142.654
108	121	150.274	137	163.802	106	124.432
109	113	136.718	108	131.5	100	121.34
110	111	130.782	116	141.66	106	128.96
111	106	126.696	103	124.018	114	140.252
112	107	126.834	102	122.748	107	129.098
113	103	124.018	118	141.936	95	113.858
114	106	128.96	102	119.352	101	122.61
115	112	138.844	107	127.966	113	136.718
116	109	131.638	92	114.576	121	145.746
117	120	143.344	103	126.282	105	126.558
118	115	138.126	104	125.288	104	127.552
119	95	117.254	121	145.746	94	113.72

Density Output						
Time	3 Cars Output	3 Cars Throughput	6 Cars Output	6 Cars Throughput	9 Cars Output	9 Cars Throughput
1	229	234.95	223	227.33	228	233.68
2	197	194.31	213	214.63	243	252.73
3	220	223.52	210	210.82	204	203.2
4	235	242.57	203	201.93	210	210.82
5	232	238.76	202	200.66	239	247.65
6	218	220.98	209	209.55	218	220.98
7	201	199.39	214	215.9	231	237.49
8	223	227.33	219	222.25	209	209.55
9	213	214.63	214	217.032	220	223.52
10	221	224.79	216	217.308	229	234.95
11	203	201.93	223	227.33	255	267.97
12	226	231.14	210	210.82	232	238.76
13	223	227.33	226	231.14	239	247.65
14	205	204.47	234	241.3	230	236.22
15	219	222.25	237	245.11	255	267.97
16	222	226.06	223	227.33	208	208.28
17	206	205.74	203	201.93	216	218.44
18	230	236.22	228	233.68	237	245.11
19	239	247.65	220	223.52	208	208.28
20	201	199.39	237	245.11	223	227.33
21	214	215.9	221	224.79	217	219.71
22	233	240.03	240	248.92	221	224.79
23	219	222.25	216	218.44	247	257.81
24	222	226.06	220	223.52	222	226.06
25	212	213.36	199	196.85	224	228.6
26	222	226.06	216	218.44	226	231.14

27	240	248.92	232	238.76	214	215.9
28	215	217.17	227	232.41	229	234.95
29	242	251.46	230	236.22	219	222.25
30	212	213.36	203	203.062	186	181.472
31	225	228.738	184	176.668	179	169.186
32	242	251.46	191	185.558	197	194.31
33	219	222.25	212	213.36	210	210.82
34	203	201.93	210	210.82	205	204.47
35	217	219.71	227	232.41	228	233.68
36	227	232.41	236	243.84	211	212.09
37	217	219.71	227	232.41	232	238.76
38	216	218.44	236	243.84	212	213.36
39	230	236.22	227	232.41	230	236.22
40	224	228.6	230	236.22	218	220.98
41	219	222.25	229	234.95	211	213.222
42	234	241.3	222	226.06	242	250.328
43	207	207.01	219	222.25	223	227.33
44	218	220.98	219	222.25	219	222.25
45	221	224.79	218	220.98	221	224.79
46	215	217.17	236	243.84	225	229.87
47	209	209.55	215	217.17	229	234.95
48	221	224.79	231	237.49	233	240.03
49	228	233.68	234	241.3	210	210.82
50	224	227.468	226	230.008	225	228.738
51	221	225.922	229	236.082	229	234.95
52	246	255.408	230	235.088	216	218.44
53	208	208.28	214	215.9	227	232.41
54	242	251.46	244	254	230	236.22
55	215	217.17	218	220.98	229	234.95
56	222	226.06	223	227.33	215	217.17
57	234	241.3	208	208.28	211	212.09
58	221	224.79	229	234.95	203	201.93
59	250	261.62	205	204.47	217	219.71
60	238	246.38	214	215.9	225	229.87
61	212	213.36	203	201.93	256	269.24
62	208	208.28	214	215.9	241	250.19
63	230	236.22	216	218.44	253	265.43
64	236	243.84	215	217.17	223	227.33
65	218	220.98	250	261.62	210	210.82
66	204	203.2	218	220.98	220	223.52
67	235	242.57	227	232.41	223	227.33
68	227	232.41	205	204.47	195	191.77
69	214	215.9	229	234.95	244	254
70	209	209.55	213	214.63	218	220.98
71	222	226.06	228	233.68	230	236.22
72	215	217.17	210	210.82	209	209.55
73	221	224.79	221	224.79	220	223.52
74	236	243.84	248	259.08	238	246.38
75	227	232.41	216	218.44	203	201.93
76	217	219.71	220	223.52	229	234.95
77	206	205.74	197	194.31	224	228.6
78	211	212.09	229	234.95	227	232.41
79	218	220.98	213	214.63	216	218.44
80	232	238.76	230	236.22	216	218.44
81	197	194.31	229	234.95	240	248.92
82	238	246.38	200	198.12	214	215.9
83	234	241.3	222	226.06	233	240.03
84	225	229.87	235	242.57	224	228.6
85	241	250.19	232	238.76	219	222.25
86	214	214.768	237	243.978	229	233.818
87	249	260.35	208	208.28	218	220.98
88	223	227.33	220	223.52	214	215.9
89	224	228.6	233	240.03	221	224.79
90	214	215.9	222	226.06	217	219.71
91	225	229.87	209	209.55	194	190.5
92	202	200.66	190	185.42	180	172.72

93	222	226.06	195	191.77	191	186.69
94	230	235.088	191	185.558	196	191.908
95	233	240.03	219	222.25	199	197.982
96	221	224.79	228	233.68	217	218.578
97	201	199.39	214	215.9	213	214.63
98	223	227.33	217	219.71	231	237.49
99	216	218.44	210	210.82	230	236.22
100	220	222.388	205	203.338	214	214.768
101	195	190.638	218	219.848	228	232.548
102	204	204.332	205	204.47	204	203.2
103	209	208.418	207	207.01	233	240.03
104	220	223.52	215	217.17	224	228.6
105	221	224.79	217	220.842	207	207.01
106	206	205.74	212	213.36	216	218.44
107	236	243.84	206	204.608	208	208.28
108	201	199.39	190	186.552	219	222.25
109	210	211.952	218	219.848	224	228.6
110	216	217.308	206	206.872	219	222.25
111	219	222.25	221	223.658	210	210.82
112	219	222.25	223	227.33	217	220.842
113	221	224.79	205	205.602	230	235.088
114	218	220.98	224	227.468	222	226.06
115	210	210.82	220	223.52	211	212.09
116	216	217.308	229	234.95	204	203.2
117	206	205.74	219	221.118	219	222.25
118	209	210.682	219	223.382	218	220.98
119	228	232.548	203	203.062	229	233.818
Density Dropped Packet						
Time	3 Cars	6 Cars	9 Cars			
1	89	95	76			
2	36	45	104			
3	74	77	63			
4	90	53	77			
5	100	46	91			
6	73	41	85			
7	42	80	73			
8	93	84	67			
9	59	81	69			
10	79	41	89			
11	59	112	102			
12	84	59	96			
13	79	94	131			
14	51	99	73			
15	75	83	150			
16	86	97	56			
17	69	96	71			
18	68	79	104			
19	101	67	78			
20	61	119	94			
21	75	55	67			
22	101	131	63			
23	62	60	119			
24	99	93	77			
25	53	46	89			
26	90	79	67			
27	97	74	79			
28	74	97	113			
29	107	79	80			
30	58	60	34			
31	64	0	0			
32	101	31	41			
33	94	79	65			
34	68	66	52			
35	79	93	65			
36	86	86	93			
37	70	99	99			

38	96	66	69			
39	65	87	86			
40	119	118	79			
41	50	95	62			
42	93	76	98			
43	75	79	77			
44	46	76	55			
45	82	67	92			
46	70	120	69			
47	45	55	97			
48	87	100	91			
49	73	100	67			
50	80	87	71			
51	99	76	96			
52	89	59	69			
53	81	101	72			
54	119	87	87			
55	52	72	109			
56	63	97	78			
57	120	51	48			
58	74	100	62			
59	127	46	87			
60	117	74	76			
61	73	66	140			
62	48	56	88			
63	119	68	139			
64	97	79	71			
65	83	119	105			
66	58	54	79			
67	120	110	80			
68	85	50	49			
69	64	87	121			
70	44	56	68			
71	74	81	68			
72	67	67	55			
73	93	94	70			
74	100	117	88			
75	77	99	35			
76	70	87	108			
77	50	47	78			
78	54	75	93			
79	78	65	69			
80	86	100	82			
81	67	53	81			
82	92	74	80			
83	109	64	94			
84	98	94	78			
85	104	136	97			
86	50	93	86			
87	135	74	64			
88	72	79	92			
89	93	111	83			
90	68	83	84			
91	82	55	37			
92	39	0	0			
93	78	0	0			
94	99	26	37			
95	94	57	48			
96	68	80	76			
97	50	72	65			
98	92	56	74			
99	70	64	80			
100	72	43	56			
101	34	57	75			
102	38	55	51			
103	47	44	62			

104	58	59	103			
105	71	64	50			
106	51	61	51			
107	89	43	79			
108	43	41	52			
109	49	53	85			
110	70	68	72			
111	58	72	60			
112	50	71	57			
113	72	64	77			
114	69	71	72			
115	71	56	60			
116	67	91	42			
117	63	81	67			
118	52	87	80			
119	96	47	94			

E.3 Power

Power Input						
Time	28.8dbm Input	28.8dbm Throughput	60dbm Input	60dbm Throughput	100dbm Input	100dbm Throughput
1	101	122.61	101	122.61	101	122.61
2	110	136.304	110	136.304	127	155.63
3	115	139.258	115	139.258	110	134.04
4	123	149.418	114	135.724	72	86.912
5	125	150.826	96	118.524	91	114.438
6	113	140.114	106	130.092	95	116.122
7	111	134.178	98	117.668	110	131.776
8	104	127.552	94	113.72	100	120.208
9	110	134.04	97	115.266	97	116.398
10	110	131.776	109	132.77	101	121.478
11	101	122.61	110	130.644	105	125.426
12	113	140.114	109	130.506	101	120.346
13	97	118.662	100	121.34	88	106.1
14	91	108.778	87	104.83	100	119.076
15	86	103.56	101	120.346	74	88.32
16	101	122.61	114	137.988	95	117.254
17	122	147.016	110	129.512	86	105.824
18	93	116.978	122	147.016	85	102.29
19	104	127.552	94	113.72	100	123.604
20	85	103.422	119	145.47	116	138.264
21	104	125.288	91	113.306	107	132.494
22	82	100.744	102	123.88	89	108.502
23	108	130.368	95	116.122	125	151.958
24	106	126.696	96	112.864	73	87.05
25	128	153.504	108	129.236	121	146.878
26	109	131.638	107	125.702	129	153.642
27	91	111.042	109	130.506	97	115.266
28	97	116.398	95	117.254	90	107.508
29	92	111.18	88	103.836	86	101.296
30	123	148.286	99	120.07	93	114.714
31	143	170.29	108	131.5	112	135.448
32	137	164.934	91	109.91	103	122.886
33	115	138.126	79	94.67	76	91.992
34	115	140.39	72	86.912	79	92.406
35	97	118.662	124	149.556	97	116.398
36	89	106.238	102	122.748	105	129.954
37	98	116.536	108	128.104	101	122.61
38	89	105.106	93	114.714	112	134.316

39	99	117.806	104	127.552	115	141.522
40	90	112.036	98	118.8	113	135.586
41	93	113.582	94	112.588	91	108.778
42	103	124.018	102	122.748	99	117.806
43	105	127.69	125	153.09	119	143.206
44	104	127.552	104	127.552	100	117.944
45	105	126.558	123	146.022	106	128.96
46	87	105.962	111	133.046	109	131.638
47	112	134.316	100	119.076	90	105.244
48	93	112.45	80	97.072	109	131.638
49	90	108.64	99	122.334	94	114.852
50	99	118.938	108	130.368	104	126.42
51	94	113.72	97	118.662	104	127.552
52	94	114.852	101	122.61	67	80.562
53	113	134.454	96	117.392	88	103.836
54	79	94.67	99	117.806	105	126.558
55	108	129.236	104	121.892	114	135.724
56	100	121.34	113	137.85	110	134.04
57	117	140.666	90	110.904	77	92.13
58	96	116.26	79	93.538	96	116.26
59	121	145.746	88	106.1	99	118.938
60	112	134.316	106	126.696	93	114.714
61	122	145.884	99	118.938	103	126.282
62	112	135.448	92	112.312	94	112.588
63	108	131.5	103	124.018	114	134.592
64	107	130.23	106	126.696	106	128.96
65	74	88.32	109	131.638	116	140.528
66	109	130.506	117	141.798	98	116.536
67	96	116.26	127	151.102	93	112.45
68	124	147.292	94	113.72	84	98.756
69	96	115.128	103	125.15	101	122.61
70	114	136.856	87	104.83	122	145.884
71	94	112.588	128	153.504	125	149.694
72	114	137.988	153	182.99	141	168.882
73	102	126.144	155	185.53	147	173.106
74	73	90.446	139	165.21	147	173.106
75	108	132.632	132	156.32	134	158.86
76	102	126.144	105	126.558	110	131.776
77	129	155.906	125	150.826	116	139.396
78	98	113.14	106	128.96	119	143.206
79	112	134.316	127	149.97	117	140.666
80	94	113.72	99	118.938	114	139.12
81	96	115.128	114	136.856	106	130.092
82	127	152.234	111	134.178	110	129.512
83	102	121.616	106	128.96	122	149.28
84	90	106.376	104	125.288	114	137.988
85	91	111.042	124	148.424	108	130.368
86	87	103.698	115	139.258	115	140.39
87	118	143.068	111	134.178	106	131.224
88	106	125.564	123	149.418	120	144.476
89	89	109.634	118	141.936	99	118.938
90	101	122.61	120	143.344	104	127.552
91	115	138.126	108	128.104	102	122.748
92	139	165.21	112	135.448	95	114.99
93	132	155.188	104	123.024	114	134.592
94	137	163.802	116	139.396	112	135.448
95	109	129.374	94	113.72	123	147.154
96	96	117.392	101	123.742	103	126.282
97	110	134.04	102	126.144	110	132.908
98	109	129.374	89	105.106	97	117.53
99	114	137.988	117	137.27	128	153.504
100	121	144.614	78	92.268	106	125.564
101	106	128.96	120	144.476	101	119.214
102	121	145.746	91	107.646	113	135.586
103	119	139.81	95	116.122	113	136.718
104	109	132.77	109	130.506	91	108.778

105	108	130.368	93	110.186	123	149.418
106	110	135.172	112	133.184	106	127.828
107	123	144.89	114	139.12	90	109.772
108	137	163.802	112	134.316	109	130.506
109	108	131.5	111	133.046	95	113.858
110	116	141.66	107	129.098	97	116.398
111	103	124.018	114	134.592	95	112.726
112	102	122.748	115	136.994	106	125.564
113	118	141.936	98	115.404	105	128.822
114	102	119.352	95	116.122	108	130.368
115	107	127.966	102	123.88	112	137.712
116	92	114.576	93	111.318	122	145.884
117	103	126.282	102	125.012	96	119.656
118	104	125.288	98	121.064	128	152.372
119	121	145.746	116	138.264	110	132.908
Power Output						
Time	28.8dbm Output	28.8dbm Throughput	60dbm Output	60dbm Throughput	100dbm Output	100dbm Throughput
1	223	227.33	223	227.33	223	227.33
2	213	214.63	213	214.63	198	195.58
3	210	210.82	210	210.82	215	217.17
4	203	201.93	213	214.63	251	262.89
5	202	200.66	227	232.41	230	236.22
6	209	209.55	217	219.71	228	233.68
7	214	215.9	227	232.41	215	219.434
8	219	222.25	229	234.95	226	228.876
9	214	217.032	229	234.95	228	233.68
10	216	217.308	216	218.44	224	228.6
11	223	227.33	217	219.71	221	224.79
12	210	210.82	218	220.98	226	231.14
13	226	231.14	224	228.6	236	243.84
14	234	241.3	237	245.11	225	229.87
15	237	245.11	223	227.33	250	261.62
16	223	227.33	211	212.09	227	232.41
17	203	201.93	215	217.17	235	242.57
18	228	233.68	203	201.93	237	245.11
19	220	223.52	231	237.49	222	226.06
20	237	245.11	206	205.74	212	213.36
21	221	224.79	231	237.49	215	217.17
22	240	248.92	222	226.06	234	241.3
23	216	218.44	227	232.41	201	199.39
24	220	223.52	230	235.088	249	260.35
25	199	196.85	218	220.98	205	203.338
26	216	218.44	221	224.79	198	195.58
27	232	238.76	215	217.17	228	233.68
28	227	232.41	228	233.68	235	242.57
29	230	236.22	238	246.38	238	246.38
30	203	203.062	225	229.87	228	234.812
31	184	176.668	216	218.44	214	214.768
32	191	185.558	233	240.03	223	227.33
33	212	213.36	243	252.73	245	255.27
34	210	210.82	251	261.758	246	255.408
35	227	232.41	203	201.93	229	234.95
36	236	243.84	223	227.33	218	220.98
37	227	232.41	219	222.25	223	227.33
38	236	243.84	230	236.22	212	213.36
39	227	232.41	219	222.25	207	207.01
40	230	236.22	225	229.87	214	215.9
41	229	234.95	230	236.22	233	240.03
42	222	226.06	224	228.6	227	232.41
43	219	222.25	200	198.12	207	207.01
44	219	222.25	219	222.25	224	228.6
45	218	220.98	206	205.74	219	222.25
46	236	243.84	214	215.9	217	219.71
47	215	217.17	226	231.14	234	241.3
48	231	237.49	242	251.46	216	218.44

49	234	241.3	224	228.6	229	234.95
50	226	230.008	217	219.71	220	223.52
51	229	236.082	226	231.14	220	223.52
52	230	235.088	224	228.6	253	265.43
53	214	215.9	226	231.14	237	245.11
54	244	254	225	228.738	221	224.79
55	218	220.98	220	223.52	213	213.498
56	223	227.33	211	212.09	214	215.9
57	208	208.28	233	240.03	245	255.27
58	229	234.95	246	256.54	228	233.68
59	205	204.47	235	242.57	227	232.41
60	214	215.9	219	222.25	228	234.812
61	203	201.93	225	229.87	220	222.388
62	214	215.9	232	238.76	232	238.76
63	216	218.44	221	224.79	213	214.63
64	215	217.17	219	222.25	218	220.98
65	250	261.62	217	219.71	209	209.55
66	218	220.98	208	208.28	228	233.68
67	227	232.41	200	198.12	230	236.22
68	205	204.47	230	236.22	241	250.19
69	229	234.95	222	226.06	223	227.33
70	213	214.63	238	245.248	206	204.608
71	228	233.68	199	196.85	201	201.654
72	210	210.82	176	167.64	187	179.346
73	221	224.79	173	164.962	183	176.53
74	248	259.08	189	183.018	182	176.392
75	216	218.44	196	193.04	193	188.098
76	220	223.52	221	224.79	216	218.44
77	197	194.31	200	198.12	208	208.28
78	229	234.95	219	222.25	207	207.01
79	213	214.63	201	198.258	210	209.688
80	230	236.22	224	228.6	209	209.55
81	229	234.95	213	213.498	218	219.848
82	200	198.12	214	215.9	216	218.44
83	222	226.06	217	219.71	202	200.66
84	235	242.57	219	222.25	211	212.09
85	232	238.76	202	200.66	216	218.44
86	237	243.978	209	209.55	207	207.01
87	208	208.28	214	217.032	217	219.71
88	220	223.52	204	202.068	205	204.47
89	233	240.03	206	205.74	226	231.14
90	222	226.06	206	206.872	217	219.71
91	209	209.55	217	219.71	221	224.79
92	190	185.42	211	210.958	227	233.542
93	195	191.77	221	224.79	212	212.228
94	191	185.558	209	209.55	211	212.09
95	219	222.25	229	233.818	204	202.068
96	228	233.68	221	224.79	219	222.25
97	214	215.9	220	223.52	214	217.032
98	217	219.71	236	243.84	226	230.008
99	210	210.82	209	210.682	198	195.58
100	205	203.338	247	256.678	218	222.112
101	218	219.848	203	203.062	224	227.468
102	205	204.47	235	241.438	212	214.492
103	207	207.01	226	231.14	213	213.498
104	215	217.17	215	217.17	233	240.03
105	217	220.842	231	237.49	201	199.39
106	212	213.36	214	215.9	220	223.52
107	206	204.608	210	210.82	233	241.162
108	190	186.552	212	213.36	215	216.038
109	218	219.848	213	215.762	228	233.68
110	206	206.872	217	218.578	227	232.41
111	221	223.658	213	215.762	229	236.082
112	223	227.33	212	212.228	219	221.118
113	205	205.602	225	229.87	219	222.25
114	224	227.468	226	231.14	217	219.71

115	220	223.52	221	224.79	211	212.09
116	229	234.95	230	236.22	203	201.93
117	219	221.118	221	225.922	225	229.87
118	219	223.382	224	227.468	196	194.172
119	203	203.062	209	210.682	215	216.038
Power Dropped Packet						
Time	28.8dbm	60dbm	100dbm			
1	95	95	95			
2	45	45	47			
3	77	77	69			
4	53	61	120			
5	46	85	100			
6	41	73	100			
7	80	83	55			
8	84	94	84			
9	81	66	70			
10	41	68	63			
11	112	63	94			
12	59	62	94			
13	94	80	67			
14	99	127	111			
15	83	74	130			
16	97	87	77			
17	96	79	107			
18	79	48	82			
19	67	102	108			
20	119	61	52			
21	55	95	86			
22	131	86	103			
23	60	104	44			
24	93	104	132			
25	46	67	46			
26	79	23	25			
27	74	91	83			
28	97	72	82			
29	79	114	84			
30	60	79	104			
31	0	75	55			
32	31	75	90			
33	79	145	120			
34	66	96	95			
35	93	69	92			
36	86	78	68			
37	99	64	91			
38	66	91	78			
39	87	75	59			
40	118	70	49			
41	95	126	93			
42	76	75	73			
43	79	62	62			
44	76	81	80			
45	67	59	76			
46	120	60	69			
47	55	71	71			
48	100	117	107			
49	100	74	94			
50	87	74	73			
51	76	65	84			
52	59	89	123			
53	101	63	128			
54	87	104	68			
55	72	87	69			
56	97	48	45			
57	51	102	128			
58	100	93	106			
59	46	103	84			

60	74	71	104			
61	66	77	89			
62	56	96	98			
63	68	57	55			
64	79	88	57			
65	119	62	72			
66	54	72	78			
67	110	35	71			
68	50	95	95			
69	87	68	74			
70	56	83	42			
71	81	35	15			
72	67	0	0			
73	94	0	0			
74	117	0	0			
75	99	30	9			
76	87	78	69			
77	47	37	79			
78	75	68	55			
79	65	40	63			
80	100	69	56			
81	53	70	65			
82	74	67	55			
83	64	85	52			
84	94	81	62			
85	136	53	85			
86	93	46	69			
87	74	68	73			
88	79	48	62			
89	111	61	78			
90	83	62	96			
91	55	71	84			
92	0	62	75			
93	0	80	33			
94	26	58	72			
95	57	86	57			
96	80	75	66			
97	72	117	92			
98	56	66	85			
99	64	73	48			
100	43	93	64			
101	57	82	81			
102	55	77	63			
103	44	65	66			
104	59	79	92			
105	64	87	72			
106	61	64	68			
107	43	61	96			
108	41	66	60			
109	53	57	95			
110	68	75	74			
111	72	45	98			
112	71	48	56			
113	64	77	74			
114	71	105	46			
115	56	86	98			
116	91	104	49			
117	81	61	102			
118	87	65	46			
119	47	87	69			

E.4 Obstruction

Obstruction					
Time	Input	Input Throughput	Output	Output Throughput	Dropped Packet
1	0	0	316	345.44	5
2	4	5.08	311	339.09	0
3	1	1.27	313	341.63	7
4	3	3.81	313	341.63	4
5	0	0	316	345.44	8
6	0	0	316	345.44	4
7	1	1.27	316	345.44	6
8	1	1.27	314	342.9	2
9	1	1.27	313	341.63	4
10	82	100.744	240	248.92	69
11	111	133.046	215	217.17	78
12	109	132.77	215	217.17	74
13	109	131.638	217	219.71	67
14	48	58.696	271	288.29	26
15	0	0	315	344.17	0
16	0	0	314	342.9	0
17	0	0	316	345.44	0
18	0	0	315	344.17	0
19	0	0	314	342.9	0
20	0	0	316	345.44	0
21	0	0	316	345.44	0
22	21	25.538	294	317.5	15
23	109	133.902	214	215.9	70
24	115	135.862	214	214.768	55
25	106	125.564	219	223.382	57
26	125	151.958	201	198.258	31
27	99	120.07	225	229.87	78
28	106	130.092	217	219.71	59
29	111	134.178	213	214.63	89
30	103	126.282	221	224.79	79
31	29	33.434	288	309.88	40
32	0	0	315	344.17	0
33	0	0	316	345.44	0
34	0	0	314	341.768	0
35	0	0	311	339.09	0
36	0	0	316	345.44	0
37	0	0	317	346.71	0
38	0	0	314	342.9	0
39	25	30.618	293	316.23	19
40	103	124.018	222	226.06	68
41	120	145.608	204	203.2	62
42	107	129.098	219	222.25	60
43	110	130.644	217	219.71	64
44	92	113.444	230	236.22	89
45	106	127.828	220	223.52	68
46	59	71.534	261	275.59	32
47	0	0	314	342.9	0
48	0	0	317	346.71	0
49	0	0	315	344.17	0
50	0	0	317	346.71	0
51	0	0	315	344.17	0
52	0	0	318	347.98	0
53	0	0	317	346.71	0
54	98	117.668	227	232.41	74
55	95	113.858	231	236.358	88
56	95	111.594	231	237.49	63
57	122	149.28	203	201.93	78
58	93	112.45	230	236.22	87
59	89	108.502	235	242.57	89
60	117	145.194	205	204.47	78

61	94	113.72	230	236.22	82
62	98	117.668	226	231.14	86
63	102	122.748	224	228.6	74
64	95	114.99	230	236.22	77
65	97	117.53	227	232.41	96
66	88	104.968	236	243.84	111
67	98	115.404	229	234.95	63
68	107	127.966	220	223.52	92
69	126	152.096	200	198.12	41
70	84	99.888	240	248.92	79
71	132	156.32	197	193.178	30
72	138	165.072	188	182.88	0
73	154	183.128	173	163.83	0
74	146	172.968	181	173.99	0
75	143	170.29	185	179.07	0
76	117	141.798	205	204.47	69
77	112	135.448	213	214.63	65
78	110	134.04	214	215.9	63
79	109	132.77	216	217.308	81
80	126	150.964	201	199.39	37
81	114	136.856	211	210.958	69
82	104	123.024	221	224.79	59
83	115	136.994	211	213.222	51
84	109	131.638	214	214.768	71
85	117	141.798	207	207.01	57
86	111	131.914	216	218.44	58
87	92	110.048	232	238.76	56
88	103	125.15	221	224.79	97
89	112	134.316	213	214.63	65
90	116	140.528	208	208.28	48
91	99	118.938	225	229.87	82
92	109	132.77	214	215.9	61
93	65	79.154	256	269.24	45
94	0	0	314	342.9	0
95	0	0	316	345.44	0
96	0	0	315	341.906	0
97	0	0	316	345.44	0
98	0	0	314	342.9	0
99	0	0	313	342.762	0
100	0	0	314	342.9	0
101	0	0	316	344.308	0
102	0	0	315	344.17	0
103	0	0	316	345.44	0
104	0	0	316	345.44	0
105	0	0	316	345.44	0
106	0	0	317	346.71	0
107	92	111.18	230	237.352	47
108	111	136.442	213	214.63	74
109	110	131.776	215	217.17	55
110	85	104.554	236	242.708	84
111	92	113.444	229	234.95	114
112	108	128.104	216	219.572	82
113	88	104.968	237	243.978	90
114	100	120.208	222	227.192	75
115	107	129.098	217	219.71	47
116	99	116.674	226	230.008	87
117	0	0	315	345.302	20
118	0	0	318	346.848	0
119	0	0	316	346.572	0