

**PERFORMANCE EVALUATION OF AD HOC ROUTING  
PROTOCOLS FOR VEHICULAR AD HOC NETWORKS**

**A Thesis Presented to**

**Mohammad Ali Jinnah University**

In Partial Fulfillment

of the requirement for the Degree

Master of Science

(Computer Science)

by

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Reg #: MS063012

Fall, 2009

**THIS THESIS ENTITLED**

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NETWORKS”**

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# Abstract

Vehicular Ad hoc Network (VANET) is a new communication paradigm that enables the communication between vehicles moving at high speeds on the roads. This has opened door to develop several new applications like, traffic engineering, traffic management, dissemination of emergency information to avoid hazardous situations and other user applications. VANETs are direct offshoot of Mobile Ad hoc Networks (MANETs) but with distinguishing characteristics like, movement at high speeds, constrained mobility, sufficient storage and processing power, unpredictable node density and difficult communication environment with short link lifetime etc.

In this thesis, the performance analysis of proactive and reactive routing protocols in both urban and highway scenarios is presented. The protocols evaluated are Ad hoc On demand Distance Vector (AODV), Dynamic MANET On demand (DYMO) and two variants of Optimized Link State Routing (OLSR) namely, OLSR-DEF and OLSR-MOD. In OLSR-DEF the default values of *TC* and *Hello* messages, 5 and 2 seconds respectively, are used. While in OLSR-MOD, these values are changed to 3 and 1 second respectively. The simulations performed in the thesis are of two types; bi-directionally coupled simulations and offline simulations. This thesis is the only work so far that makes use of bi-directionally coupled simulations. In both of these types, urban and highway scenarios are simulated. In bi-directionally coupled simulations, network and traffic simulators are integrated at runtime to exchange different commands. This integration of network and traffic simulators at runtime helps in modeling emergency scenarios on the roads like accidents, etc. In offline

simulations, real world maps are used to model urban and highway topologies and then vehicles with different attributes like length, maximum speed and acceleration, etc. move on these topologies.

The performance evaluation matrices used in this thesis are packet delivery ratio, normalized routing overhead, end-to-end delay and end-to-end delay of 1<sup>st</sup> data packet. In all four scenarios proactive routing protocol OLSR-MOD performed better in terms of packet delivery ratio, end-to-end delay against OLSR-DEF, AODV and DYMO. However its routing overhead was consistently above OLSR-DEF and others, as the frequency of its control messages was higher than its competitors. OLSR-DEF, because of less frequent exchange of *TC* and *Hello* messages, performed comparatively equal to AODV and DYMO. In fact AODV and DYMO performed better than OLSR-DEF in some scenarios.

# Acknowledgment

All Praises be to “ALLAH” Almighty who enabled us to complete this task successfully and our utmost respect to His last Prophet Mohammad (S.A.W.).

First of all, my gratitude to my supervisor Prof. Dr. Amir Qayyum whose constant encouragement and guidelines at each step made this thesis possible. I am very grateful for his motivation and support throughout this endeavor.

I am also thankful to members of Center of Research in Networks and Telecom (CoReNeT) for providing valuable feedback in weekly meetings. A word of thanks to Jensen Chou, Francisco J. Ros, Daniel Krajzewicz and members of SUMO and NS mailing list for suggesting solutions to countless implementation and integration problems faced during the installation of NS2, patches, SUMO and TraCI.

Supporting every worker is an understanding family, or nothing would ever get written or done! I am obliged to express gratitude to my Mother, my Brother and my Sister for their support and understanding when I worked on this thesis.

During my stay in the university I have made some great friends, especially, Mohammad Aazam and Haroon Sarfraz. I will be not out of place to thank them for their support, encouragement and affection during all these years.

Imran Khan

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## List of Acronyms

VANET	Vehicular Ad hoc Network
AODV	Ad hoc On demand Distance Vector
DYMO	Dynamic MANET On demand
OLSR	Optimized Link State Routing
SUMO	Simulation of Urban Mobility
BDC	Bi-Directionally Coupled Simulations
TraCI	Traffic Control Interface
NoW	Networks on Wheels
SeVeCom	Secure Vehicular Communications
TraNS	Traffic and Network Simulator
MOVE	MObility model generator for VEhicular networks
DSR	Dynamic Source Routing
TBRPF	Topology Dissemination Based on Reverse-Path Forwarding
FSR	Fisheye State Routing
OLSR-MOD	OLSR – Modified
OLSR-DEF	OLSR- Default

# Chapter 1

## Introduction

---

Vehicular Ad Hoc Network (VANET) is a new challenging network environment that pursues the concept of ubiquitous computing for future. Vehicles equipped with wireless communication technologies and acting like computer nodes will be on the road soon and this will revolutionize the concept of travelling. VANETs bring lots of possibilities for new range of applications which will not only make the travel safer but fun as well. Reaching to a destination or getting help would be much easier. The concept of VANETs is quite simple: by incorporating the wireless communication and data sharing capabilities, the vehicles can be turned into a network providing similar services like the ones with which we are used to in our offices or homes.

For the wide spread and ubiquitous use of VANETs, a number of technical challenges exist. Many demonstrative and research projects were initiated all over the world, starting from FleetNet project (Hartenstein et al., 2001) in Europe with objectives to develop a platform for inter-vehicular communication, implement demonstrator applications and to standardize the solutions. Some more recent and ongoing projects include Network on Wheels (NoW) (Torrent-Moreno, Schnauffer, Eigner, Catrinescu, & Kunisch, 2008), CarTALK2000 (Reichardt, Miglietta, Moretti, Morsink, & Schulz, 2003), SAFESPOT (Schubert, Schlingelhof, Cramer, & Wanielik, 2007), SeVeCom (Papadimitratos & Haas, 2003), Aktiv (Aktiv on 28<sup>th</sup> September, 2009), CityMobil (CityMobil on 27<sup>th</sup> September, 2009), EVITA (Kelling et al., 2009) in Europe, PATH (Path on 28<sup>th</sup> September, 2009) in USA, and SmatWay

(SmartWay on 1<sup>st</sup> October, 2009) in Japan. At present European Union is funding the majority of the R&D projects in the field of vehicular communications.

VANETs are considered as an off-shoot of Mobile Ad hoc Networks (MANETs), however they have some distinguishing characteristics too. The solutions proposed for MANETs need to be evaluated carefully and then adapted in order to be used in VANET context. Besides, VANETs are also similar to MANETs in many ways. For example, both networks are multi-hop mobile networks having dynamic topology. There is no central entity, and nodes route data themselves across the network. Both MANETs and VANETs are rapidly deployable, without the need of an infrastructure. Although, MANET and VANET, both are mobile networks, however, the mobility pattern of VANET nodes is such that they move on specific paths (roads) and hence not in random direction. This gives VANETs some advantage over MANETs as the mobility pattern of VANET nodes is predictable. MANETs are often characterized by limited storage capacity and low battery and processing power. VANETs, on the other hand, do not have such limitations. Sufficient storage capacity and high processing power can be easily made available in vehicles. Moreover, vehicles also have enough battery power to support long range communication.

Another difference is highly dynamic topology of VANETs as vehicles may move at high velocities. This makes the lifetime of communication links between the nodes quite short. Node density in VANETs is also unpredictable; during rush hours the roads are crowded with vehicles, whereas at other times, lesser vehicles are there. Similarly, some roads have more traffic than other roads.

## **1.1 Problem Statement**

Early VANET prototypes and studies have used MANET routing protocols as such. The research community feels that there is a lack of a systematic comparison and performance evaluation study that evaluates the performance of these protocols in VANET environment (Y. Toor, A. Laouiti, & P. Muhlethaler, 2008).

There are few studies that compare various traditional ad hoc routing protocols in VANET environment. The simulations performed in these few studies are very basic and do not incorporate the real VANET environment. Simple network topologies are used, where vehicles travel at constant speed, without taking care of road conditions or driver behavior. We believe that in order to compare and evaluate protocols and applications for VANETs we not only need network traffic simulator but also a road traffic simulator, and then there is a need to integrate both to correctly model driver behavior. This way, it is easy to model real life scenarios, like accidents etc.

The main focus of this research thesis is to evaluate the performance of both proactive and reactive ad hoc routing protocols, by using both network and traffic simulators under realistic network conditions.

## **1.2 Thesis Goals**

The overall goals of the thesis are as follows

- Developing a realistic road traffic scenario by coupling the traffic and network simulators at runtime.
  - Comparison of proactive and reactive routing protocols
- Developing a topology, based on real world maps, and then artificially generating mobility patterns using traffic simulator.
  - Comparison of proactive and reactive routing protocols

### **1.3 Research Methodology**

A literature survey of the existing work regarding the comparison of ad hoc routing protocols in VANET context has been carried out. The reactive routing protocols AODV, DYMO are compared against proactive routing protocol OLSR using bi-directionally coupled (BDC) simulation and also without BDC using artificially generated traces for offline simulations. Different scenarios are generated by using SUMO and then NS2 is used to generate network traffic. TraCI is used to help these two simulators interact with each other to correctly model real world scenarios. Impact of different factors like node density and number of active users are evaluated. A detailed analysis backed by simulations to check the performance of each protocol under varied network conditions is presented.

### **1.4 Contribution**

A major contribution of the thesis is comparison of both proactive and reactive routing protocols in VANET environments. Previously, the available research work was focused on the evaluation of reactive routing protocols, and did not include proactive routing protocols. This study has been carried out with the intention to fill this gap. Moreover, another significant contribution of this thesis is the use of both traffic and network simulators and their integration at the runtime, to facilitate a realistic simulation scenario. With the help of this integration we were able to create an emergency scenario and study its effects on the performance of the routing protocols. This technique is still maturing and is at very early stage of its development by the research community.

At the time of writing, this thesis is the only research work that makes use of integrated approach and evaluated proactive and reactive routing protocols.

# Chapter 2

## Literature Review

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In this chapter a survey of routing protocols, network simulator, traffic simulator and Traffic Control Interface (TraCI) module used to couple both network and traffic simulator is presented. VANETs consist of mobile nodes having dynamic topology hence the mechanism of finding, maintaining and using routes for communication is not trivial for fast moving vehicles. Short lifetime of communication link, less path redundancy, unpredictable node density and strict application requirements make routing in VANETs quite challenging. In the related and similar domain of MANETs, there has been extensive research about the routing protocols during the past decade. Because MANETs and VANETs have many similar characteristics, early prototypes and studies about VANETs made use of the routing protocols developed for MANETs, however there is a lack of a systematic comparison and performance evaluation study that presents conclusive results about the performance of both reactive and proactive routing protocols in VANET environment.

### **2.1 Ad hoc Routing Protocols**

Ad hoc routing protocols are classified into two main categories: proactive and reactive. Proactive routing protocols continuously update the routing table, thus generating sustained routing overhead, whereas reactive routing protocols do not periodically update the routing table. Instead, when there is some data to send, they initiate route discovery process through flooding which is their main routing overhead. Reactive routing protocols also suffer from the initial latency incurred in



the route discovery process, which potentially makes them unsuitable for safety applications. AODV (C. Perkins, E. Belding-Royer, & S. Das, 2003), DYMO (I. Chakeres, & C. Perkins, 2006) and DSR (D. Johnson, D. Maltz, and Y. Hu, 2004) are the examples of reactive routing protocols whereas OLSR (T. Clausen (Ed.), and P. Jacquet (Ed.) Oct. 2003), TBRPF (R. Ogier, F. Templin, & M. Lewis, 2004) and FSR (M. Gerla, X. Hong, and G. Pei, 2002) are the examples of proactive routing protocols. In this thesis the chosen protocols are AODV, DYMO and OLSR. While both AODV and OLSR achieved RFC status, DYMO is expected to achieve this status in the near future.

### **2.1.1 Ad hoc On demand Distance Vector (AODV) Routing Protocol**

AODV is a well known distance vector routing protocol and works as follows. Whenever a node wants to start communication with another node, it looks for an available path to the destination node, in its local routing table. If there is no path available, then it broadcasts a route request (RREQ) message to its neighborhood. Any node that receives this message looks for a path leading to the destination node. If there is no path then, it re-broadcasts the RREQ message and sets up a path leading to RREQ originating node. This helps in establishing the end to end path when the same node receives route reply (RREP) message. Every node follows this process until this RREQ message reaches to a node which has a valid path to the destination node or RREQ message reaches to the destination node itself. Either way the RREQ receiving node will send a RREP to the sender of RREQ message. In this way, the RREP message arrives at the source node, which originally issued RREQ message.

At the end of this request-reply process a path between source and destination node is created and is available for further communication. In scenarios where there is no

path available to the destination node or a node loses connectivity to its neighbor, a route error (RERR) message is issued for nodes that potentially received its RREP message. This message helps to update or recalculate the path when an intermediate node leaves a network or loses its next hop neighbor. Every node using AODV maintains a routing table, which contains the following information: a next hop node, a sequence number and a hop count. All packets destined to the destination node are sent to the next hop node. The sequence number acts as a form of time-stamping, and is a measure of the freshness of a route. This helps in using the latest available path for the communication. The hop count represents the current distance between the source and the destination node.

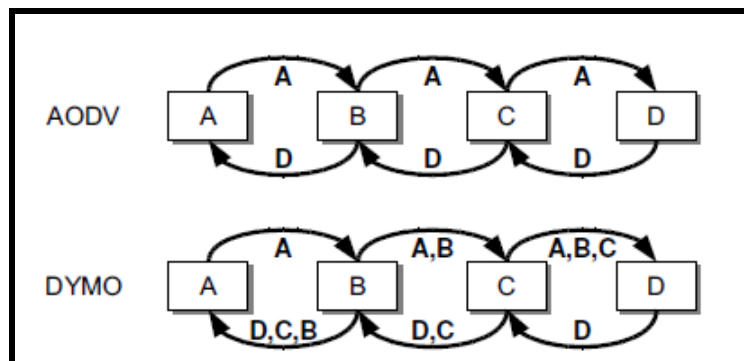
It is important to understand that AODV does not introduce routing overhead, until a RREQ is made. This is helpful as bandwidth is not wasted unnecessarily by the routing protocol. But on the other hand this introduces an initial latency, where a node has to wait for some time to find the path to the destination and then start communication. This can be problematic for time critical and safety related emergency applications.

### **2.1.2 Dynamic MANET On demand (DYMO) Routing Protocol**

DYMO is another reactive routing protocol that works in multi hop wireless networks. It is currently being developed in the scope of IETF's MANET working group and is expected to reach RFC status in the near future. DYMO is considered as a successor to the AODV routing protocols. DYMO has a simple design and is easy to implement. The basic operations of DYMO protocol are route discovery and route maintenance (I. Chakeres, & C. Perkins, 2006). When a node wants to discover a path to a destination node, it initiates the route discovery operation. A RREQ

message is broadcast to the network. Every intermediate node participates in hop-by-hop dissemination of this message and records a route to the originator. When a destination node receives this RREQ message, it responds with a RREP message unicast toward the originating node. Every node receiving this message creates a route to the destination node and eventually this RREP message arrives at the originator of the RREQ message.

It appears that DYMO work much like the AODV routing protocol, but there is a subtle and important difference between the two routing protocols. In addition to the route about the requested node, the originator of the RREQ message using DYMO protocol will also get information about all intermediate nodes in the newly discovered path. In AODV, only information about destination node and the next hop is maintained, while in DYMO, path to every other intermediate node is also known.



**Figure 2. 1: DYMO vs. AODV** (Reproduced from C. Sommer & F. Dressier, 2007)

Consider figure 2.1 above for the illustration of this phenomenon; In AODV, when node A initiated a route discovery process for node D, it only learned about routes to node B, its next hop neighbor, and the destination node D after route discovery process is finished. While when DYMO is used in the same scenario, node A

additionally learned about the route to node C and B. This important feature in DYMO is referred to as path accumulation.

Route maintenance consists of two steps. First, in order to preserve the existing routes in use, the lifetime of the route is extended upon successful forwarding of a packet. Whenever a packet is successfully forwarded, the lifetime of the route is extended automatically to use it for further communication. Second, when a route to a destination is lost or a route to a destination is not known, then a RERR message is sent towards the packet source node, to notify it about a particular route being invalid or missing. Upon receiving RERR message the source node deletes the route. If the source node has another packet to forward for the same invalid or missing destination node, it will again initiate a route discovery process.

DYMO is envisioned to handle variety of mobility and traffic patterns. As DYMO is a reactive protocol in nature, it uses very little resources, and is ideal for memory constrained devices.

### **2.1.3 Optimized Link State Routing (OLSR) Protocol**

OLSR is the proactive routing protocol that is evaluated in this thesis. OLSR achieved RFC status in 2003 (T. Clausen (Ed.), and P. Jacquet (Ed.) Oct. 2003). Basically OLSR is an optimization of the classical link state algorithm adapted for the use in wireless ad hoc networks. In OLSR, three levels of optimization are achieved. First, few nodes are selected as MultiPoint Relays (MPRs) to broadcast the messages during the flooding process. This is in contrast to what is done in classical flooding mechanism, where every node broadcasts the messages and generates too much overhead traffic.

Second level of optimization is achieved by using only MPRs to generate link state information. This results in minimizing the “number” of control messages flooded in the network. As a final level of optimization, an MPR can chose to report only links between itself and those nodes which have selected it as their MPR. This results in the distribution of partial link state information in the network.

OLSR periodically exchanges topology information with other nodes at regular intervals. MPRs play a major role in the functionality of the protocol. Every node selects a subset of its one hop neighbor nodes as MPR. MPRs periodically announce in the network that it has reachability to the nodes which have selected it as an MPR. Nodes which are not selected as MPR by any node, will not broadcast information received from it.

The functionality of OLSR lies in the exchange of HELLO and TC messages. The periodic dissemination of HELLO packets also enables a node to know whether a node or a set of nodes have selected it as MPR. This information is known as ‘Multipoint Relay Selector Set’, and is critical to determine whether to broadcast forward the information received from a node(s) or not. In a dynamic and rapidly changing environment, this set of nodes can change over the time. HELLO messages are also used for link sensing and neighborhood detection.

TC messages are used to provide every node enough link-state information for the calculation of routes. Basically, a TC message is sent by a node to advertise a set of links, which includes the links to all nodes of its MPR selector set. TC message is only broadcast forwarded by MPRs and offers controlled flooding of the topology information into the whole network.

OLSR is designed to support large and dense wireless networks. The levels of optimization discussed above, make it better suited for such networks. OLSR is tailored for networks where the traffic is random and sporadic between large number of nodes. It is also suitable for scenarios, where the communicating pairs change over time. Once the communicating pair changes, a route to new pair is readily available, and no control traffic or route discovery process is needed as in the case of reactive protocols. This can be beneficial for situations where time critical or safety related data needs to be delivered with minimum possible delay.

Due to its proactive nature, OLSR periodically generates overhead traffic. Although it is helpful in avoiding initial latency involved with route discovery, it uses precious network bandwidth for its control traffic. But it is a sustained overhead, and does not start suddenly as is the case with reactive protocols, when they start flooding the network with their control information with some application data packets waiting.

Over the years, both reactive and proactive routing protocols have been used to enable communication in wireless ad hoc networks. Each approach has its own pros and cons and is suitable for its respective scenarios.

## **2.2 Road Traffic Simulator**

Road Traffic simulators provide a way to accurately model the roads, vehicles, pedestrians and other factors we find on the roads. We know that VANETs differ from other network types in their mobility patterns. Vehicles, no matter small or large move on predefined paths i.e. roads. This leads to the constrained mobility of vehicles as compared to the random mobility of MANET nodes. There also many factors associated with the vehicle and with the roads as well. For example, there is a maximum speed of vehicle, its length, and its acceleration and deceleration

capabilities. For roads, we have factors like its length, speed limit on that road, the number of lanes, junctions, and traffic signals on that road.

To correctly model these factors, research community has developed road traffic simulators. These simulators allow the users to create different type of road topologies and use them in their work. They allow the flexibility to change the impact of factors discussed above. Many commercial road traffic simulators are also used to model the behavior of road traffic for engineering and management purposes.

### **2.2.1 Simulation of Urban MObility (SUMO)**

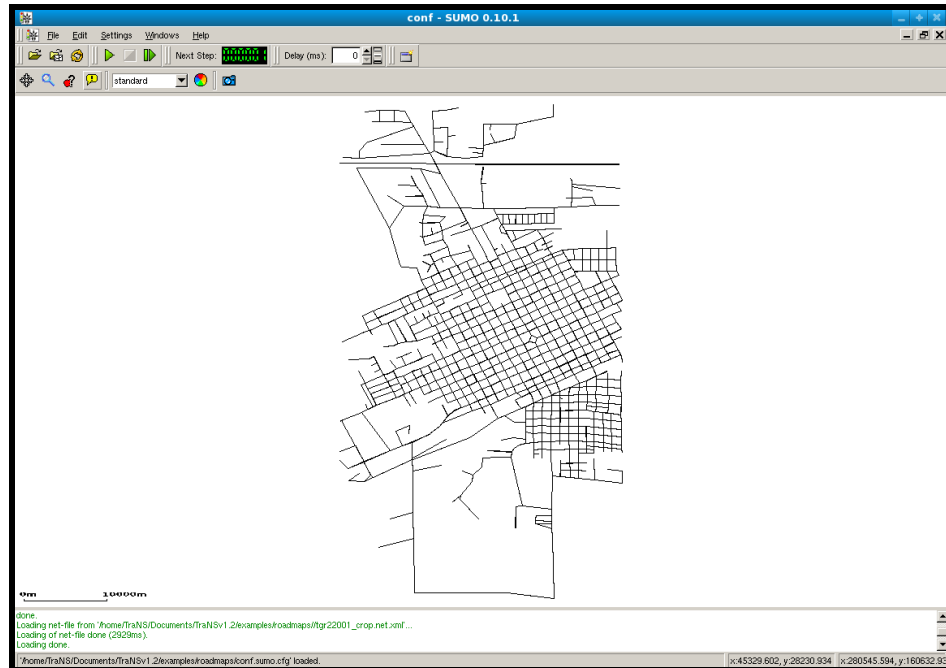
There are many tools available for microscopic simulation of road traffic like FARSI and VISSIM, but a popular road traffic simulation tool among the research community is Simulation of Urban MObility (SUMO) (Krajzewicz, Hertkorn, Rossel, & Wagner, 2002).

SUMO is an open source, portable microscopic road traffic simulator. It allows the user to build a customized road topology, in addition to the import of different readymade map formats of many cities and towns of the world. The later feature helps in generating real world road topology. SUMO also supports feature of microscopic simulation model, like imposing speed limits, defining number of lanes, junctions and traffic lights etc.

It is also possible to define vehicles with specific properties like vehicle length, its maximum speed and its acceleration and deceleration properties. SUMO also provides the option to assign user defined as well as random routes to the vehicles. There is also an option available to model public transport system, where every vehicle arrives and leaves according to a timetable.

All the user inputs are in XML format, and the output file is a SUMO trace file, which contains information about the road topology created. It is also possible to visualize the created road topology using the GUI mode of SUMO.

Figure 2.3 shows the SUMO interface with a topology map loaded.



**Figure 2. 2: SUMO Interface**

### 2.2.2 NS2 Trace File Generator for SUMO

The final output by SUMO is only usable by itself. NS2 is a discrete event simulator hence it needs to know the location information of the nodes at every timestamp. This information is present in SUMO trace file, but not in a format recognizable to NS2. However, in order to use the generated road topology for simulations purposes using NS2, we need a tool which generates a movement pattern file from the SUMO generated trace file.



MObility model generator for VEhicular networks (MOVE) (Karnadi, Mo, & Lan, 2007) is the required java based tool with GUI, built on top of SUMO, which does the interpretation between NS2 and SUMO. It has two modes of operation.

- ***Mobility Model Generator***
  - Provides a user friendly interface for generating mobility model for simulations using SUMO. User can either create customized topology or by importing maps.
- ***Network Traffic Model generator***
  - Takes the SUMO trace file as the input and generates the network traffic model as required by either NS2 or Qualnet. It provides all the configurable option of NS2 TCL files, like specifying MAC, routing protocol to use, etc.

### **2.3 Bi-directional Coupling of Network Simulator and Road Traffic Simulator**

Bi-directional coupling of network and road traffic simulators is a relatively new approach in creating real life simulations. In VANETs, the influence of external events, like an accident, is a major factor in determining the continuation of journey towards the destination. In other types of networks, like MANET, there is no such event like accident, road block or traffic congestion, etc. All these factors are external and almost unforeseeable, but they do impact the behavior of drivers, resulting in stopping the vehicle or changing the route.

Consider an example of an accident, where two vehicles had a head on collision on the road. The vehicles immediately behind these two vehicles will either have to stop

or slow down to avoid the danger of bumping into these vehicles. The vehicles that are 4 or 5 hops away might slow down their speed, change their lane and then may continue with their journey.

When this example is applied to the standalone simulation, using only network simulator, it is not possible to model these events. Even if the road traffic simulator is used to generate the mobility patterns of the vehicles, still an event like this cannot be accommodated, because the mobility pattern contains information of movement of vehicles from start to end of the simulation. Even if it is managed to stop two vehicles during the simulation to create accident like event, influencing the mobility of the neighboring vehicles is not trivial.

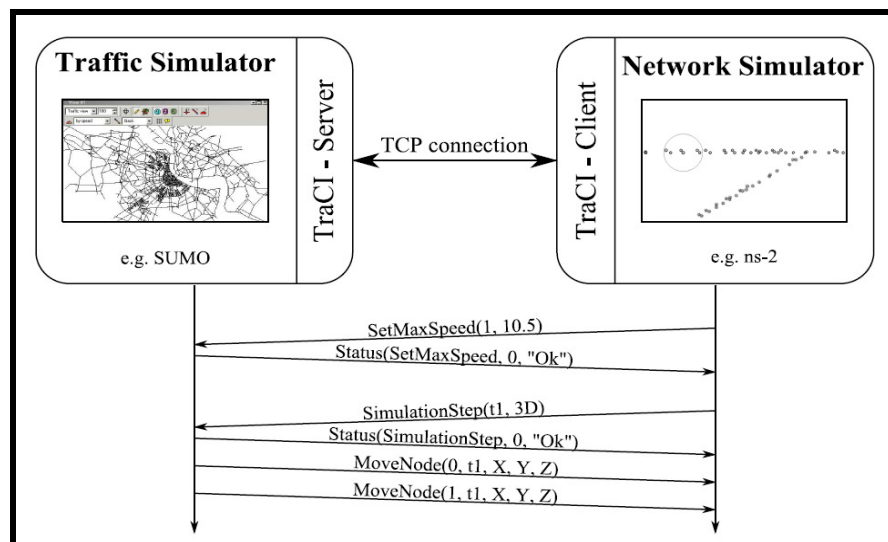
The change in speed of the vehicle, change of route or even change of lane is only managed by the road traffic simulator. This requirement calls for some means to integrate both network simulator and road traffic simulator at the runtime and make them exchange information regarding the simulation, so that decisions like change in speed of the vehicle, change of route or change of lane can be made.

### **2.3.1 Traffic Control Interface (TraCI)**

TraCI (Wegener et al., 2008) is the software module that enables bi-directional coupling of network and road traffic simulator. It uses client server architecture to give access to SUMO. The TraCI server is a part SUMO while TraCI client is available for integration with network simulators like NS2 and OMNET++ (Varga, 2001). Once the TraCI server is started by running SUMO, it waits for an application using TraCI client to take control of the simulation. The client application implemented in network simulator sends messages regarding the current events in the simulation, to which the SUMO will respond by sending necessary updates.

Consider the following example; SUMO is run by giving the road topology map file and the vehicle routes file, along with a remote port number as an input. This will also start the TraCI server that will listen to that remote port for requests from TraCI client. In NS2 TCL file, a VANET application is run, e.g. emergency broadcast at time interval 't'. By using TraCI client, this information is sent to the remote port, where the TraCI server is listening. Upon receiving information about the emergency event, the SUMO will respond by sending commands about the measures to be taken e.g. *StopNode*, *ChangeRoute* and *SetMaxSpeed* etc.

The figure below reproduced from (Wegener et al., 2008) illustrates a scenario where two nodes exchange messages and one node decides to change its maximum speed.

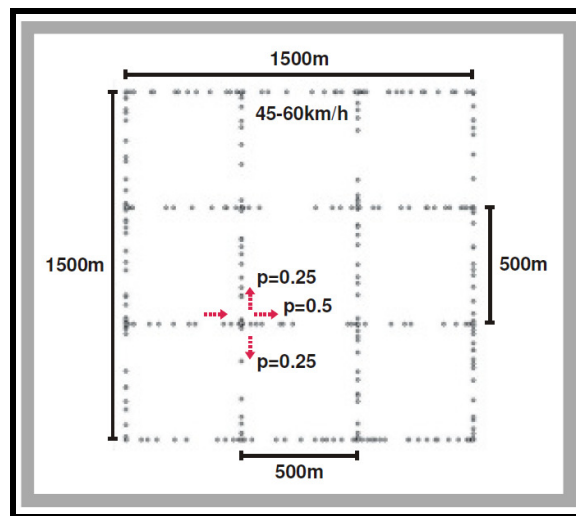


**Figure 2. 3: Command Exchange between TraCI client and server** (Reproduced from Wegener et al., 2008)

It must be noted that although TraCI server provides as many as twelve commands that can be use to manipulate the movement of nodes, the TraCI client for NS-2 provides support for only three commands.

## 2.4 Existing Performance Evaluation Studies

Very few comparative studies (S. Jaap, M. Bechler, & L. Wolf, 2005), (J. Haerri, F. Filali, and C. Bonnet, 2006), (W. Chan, M. Sim, and S. Lee, 2007), (H. Ho, A. H. Ho, and K. A. Hua, 2008) have been conducted to evaluate performance of both proactive and reactive routing protocols in VANETs. In (S. Jaap et al., 2005) the performance of AODV, DSR, TORA and FSR is evaluated. The simulation carried out depicts an urban scenario; it shows that AODV performed better than others. TORA suffered due to high routing overhead, resulting in low throughput. DSR and FSR both had similar performance expect that DSR had higher average delay than FSR. This study has not considered an important proactive routing protocol OLSR. Similarly, the study only takes urban scenario into account.



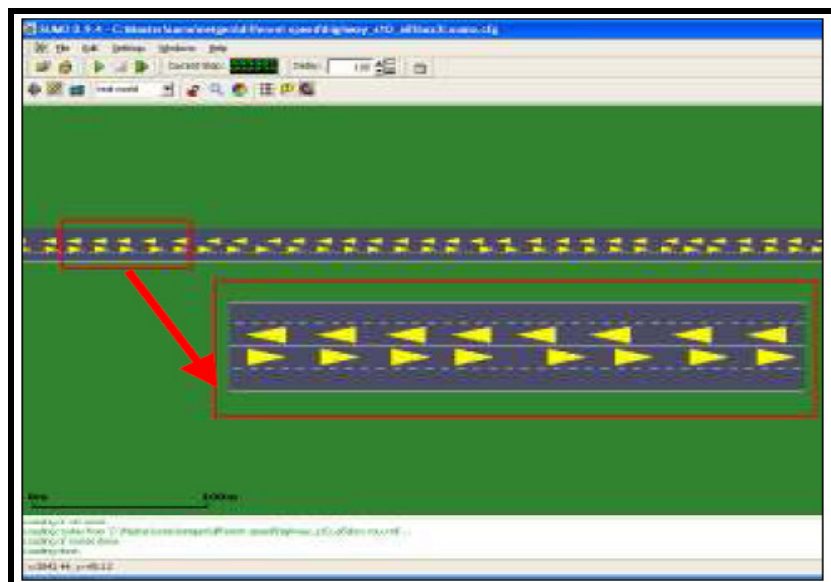
**Figure 2. 4: Urban scenario, vehicles travel between 45-60km/h and with left right turn probability of 0.25 (reproduced from S. Jaap et al., 2005)**

Another study (J. Haerri et al., 2006) carried out performance comparison of AODV and OLSR in urban environments and found that OLSR outperforms AODV in VANETs. The study uses many performance metrics (such as Packet Delivery Ratio (PDR) against average velocity, Constant Bit Rate (CBR) data generation, node

density, Routing Overhead Ratio (ROR) against CBR data generation and node density, delay and average number of hops, etc.) and evaluated protocols using them. OLSR was able to cope with node density, end-to-end delays and has less ROR and high PDR than AODV. Again this study focuses only on the urban scenario and they fail to analyze the effects of emergency events during communication. Moreover, they have used a tailor made mobility model.

In (W. Chan et al., 2007) AODV, DSR and OLSR are simulated to measure their performance in urban environment with traffic signals and stop signs. SUMO is used to create both urban and rural topologies. The results again show that OLSR outperforms both AODV and DSR in the urban environment. Better throughput, little or no delay and jitter make OLSR a better choice over other ad hoc routing protocols.

The authors in (H. Ho et al., 2008) have discussed ad hoc, geographic based and clustered-based routing protocols. The simulation scenario is an urban setting which has high obstacles such as buildings. Through simulations, it was found that geographic routing protocols perform better than ad hoc routing protocols.



**Figure 2. 5: Highway Scenario used in (W. Chan et al., 2007) (Reproduced from W. Chan et al., 2007)**

An important thing is that the implementation of most of the geographic routing protocols in NS2 is proprietary. So, they are not available for public use. So, in order to evaluate geographic and clustered-based routing protocols, they are first implemented and then used for research purposes. This paper also ignored proactive routing protocol like OLSR.

**Table 2. 1: Performance tradeoffs of each routing protocol** (Reproduced from H. Ho et al., 2008)

Different approaches	Performance metrics			
	Fraction of packet deliver	End-to-end delay	Normalized routing load	Packet duplication
AODV	Good	Average	Fair	Low
DSR	Fair	Good	Good	Low
LAR	Good	Fair	Fair	Low
GRID	Fair	Fair	Good	Low
TMNR	Average	Fair	Fair	Low
GPSR	Average	Fair	Fair	Low
CBF	Good	Good	Good	High
CLA	Good	Good	Good	Low

**Table 2. 2: Environment characteristics, suitable for every routing protocol** (Reproduced from H. Ho et al., 2008)

Different approaches	Environment characteristics				
	Mobility	Pause time	Comm. load	Density	Terrain size
AODV	Low	Long	Low	Low	Small
DSR	Low	Long	Low	Low	Small
LAR	Low	Long	Low	Low	Small
GRID	Medium	Long	Medium	Medium	Medium
TMNR	Medium	Medium	Medium	Medium	Medium
GPSR	Medium	Medium	Medium	Low	Medium
CBF	High	Short	Medium	Medium	Large
CLA	High	Short	High	High	Large

None of the studies above made use of or mentioned the need for bi-directional coupling of both network and traffic simulators. That's why they fail to properly address the need for such integration. It is highly desirable that the developed applications and protocols should be tested under realistic road traffic conditions. By

only using mobility models available in network simulators this condition cannot be fulfilled. However, bi-directionally coupled simulation is a relatively new phenomenon. The first such tool emerged in the first quarter of the year 2009.

A more recent study (J. A. Ferreiro-Lage, C. P. Gestoso, O. Rubiños, & F. A. Agelet, 2009) presents the analysis of unicast routing protocols in VANET scenarios. They study simulated only those routing protocols that come bundled with the NS2 package. DSR, AODV and DSDV are three routing protocols that are simulated in both city and highway scenario. The study fails to give details of the road topology used in the simulation. In This study it was concluded that AODV is a better suited routing protocol for VANETs as compared to DSR and DSDV. The authors have also stressed the need for the use of for bi-directionally coupled simulations.

In addition to these performance evaluation studies, there are some quality survey papers that discuss not only the concept and technology in VANETs in details but also the routing protocols and their issues. In (Y. Toor, et al., 2008) a detailed survey of vehicular ad hoc networks is provided. VANET applications are identified and technical issues are raised. Regarding the routing issues in VANETs, the authors have clearly stressed the need for a study that compares reactive and proactive routing protocols. In addition to these, the authors have discussed issues from MAC layer approaches to security issues in VANETs. The paper provides a great insight into the VANETs and potential research areas.

In (Fan Li, and Yu Wang, 2007), a survey of routing protocols in VANET environment is presented. The authors cover ad hoc, geographic, cluster-based, and broadcast routing protocols and discuss their performance issues. The protocols are categorized by their structure, type, and implementations. However, the authors have

not discussed proactive routing protocols like OLSR. This survey provides a good basic understanding of different routing protocols.

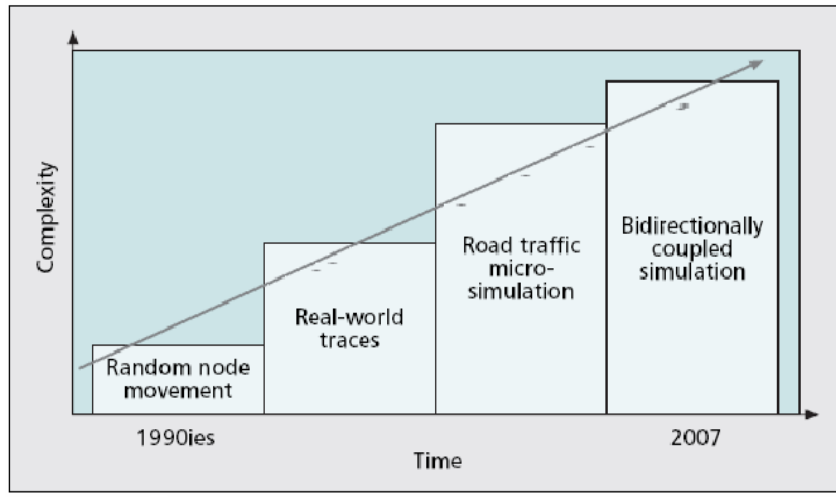
## **2.5 Mobility Models in VANETs**

In the literature, four types of mobility models can be identified for VANET research (C. Sommers, & F. Dressler, 2008). The most basic and earliest mobility model is Random Waypoint Movement (RWM). RWM comes bundled with many network simulators (The Network Simulator on 1<sup>st</sup> October 2009), (Varga, 2001). Researchers in MANET community have extensively used this model. But it is not suitable for VANET research as it is very basic and vehicles do not move in random directions.

Second type of mobility model is Real-World Mobility Traces. These traces are obtained by tracking real vehicles using on-board devices and recording vehicle position at regular intervals. These trace files are then stored and subsequently used in network simulations. However, these traces are costly to obtain and require time as well. The third mobility model is Artificial Mobility Traces, which essentially generates vehicle movement traces artificially instead of using approach of second mobility model. Once these traces are generated variety of scenarios can be obtained by freely changing the parameters. An important drawback of this mobility model is that driver behavior on the road cannot be altered, whenever an emergency event like road side accident occurs.

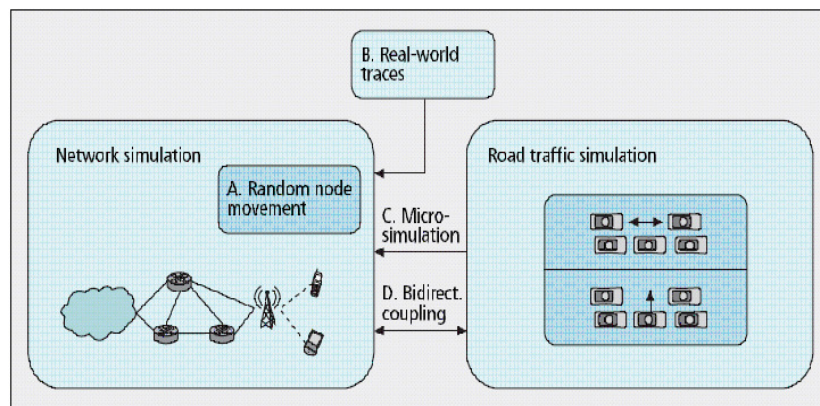
The forth and the most effective mobility model is Bi-Directionally Coupled Simulations. This mobility model is very useful in situations where accident information, danger warning and traffic congestion information is relayed, which results in altering driver's behavior.





**Figure 2. 6: Historical Evolution of Mobility models** (Reproduced from E. Schoch et al., 2008)

To make this happen, two inter-dependent simulators (network and traffic simulator) share data, like vehicle position, speed etc., through a parser. Once an event like an accident is detected, network simulator will share this information with traffic simulator, which in turn will alter the speed of the vehicle, make vehicle to stop or change its lane or compute a new path for the vehicle. Once this information is ready, new data about node speed, position and/or destination of the concerned vehicle will be sent back to the network simulator. The network simulator will model this behavior at the runtime.



**Figure 2. 7: Use of mobility models in simulations** (Reproduced from E. Schoch et al., 2008)

In the literature, we find two such tools which facilitate the bidirectional coupling of network simulator and traffic simulator. One is *Vehicles in Network Simulation* (Veins) (C. Sommer, Z. Yao, R. German & F. Dressler, April 2008), which facilitates the interaction between SUMO and OMNET++. The other tool is *Traffic and Network Simulation Environment* (TraNS) (M. Piórkowski et al., 2008), which facilitates the interaction between SUMO and NS2.

# Chapter 3

## Simulation Setup & Design of Simulation Scenarios

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This chapter describes in detail, the simulation setup used for the evaluation of routing protocols. Two types of simulations are used in this research work

- *Bi-directionally Coupled (BDC) Simulations*
  - In bi-directionally coupled (BDC) simulations, the traffic and network simulators interact with each other at runtime.
- *Offline Simulations*
  - In offline simulations, the traffic simulator is used to generate mobility patterns of nodes beforehand. This information, stored in a file, is used as an input to the network simulator. In this mode, traffic and network simulators do not interact at runtime.

The following two simulation scenarios are considered in both simulation types

- Urban Scenario
- Highway Scenario

The details of these scenarios are presented in subsequent sections.

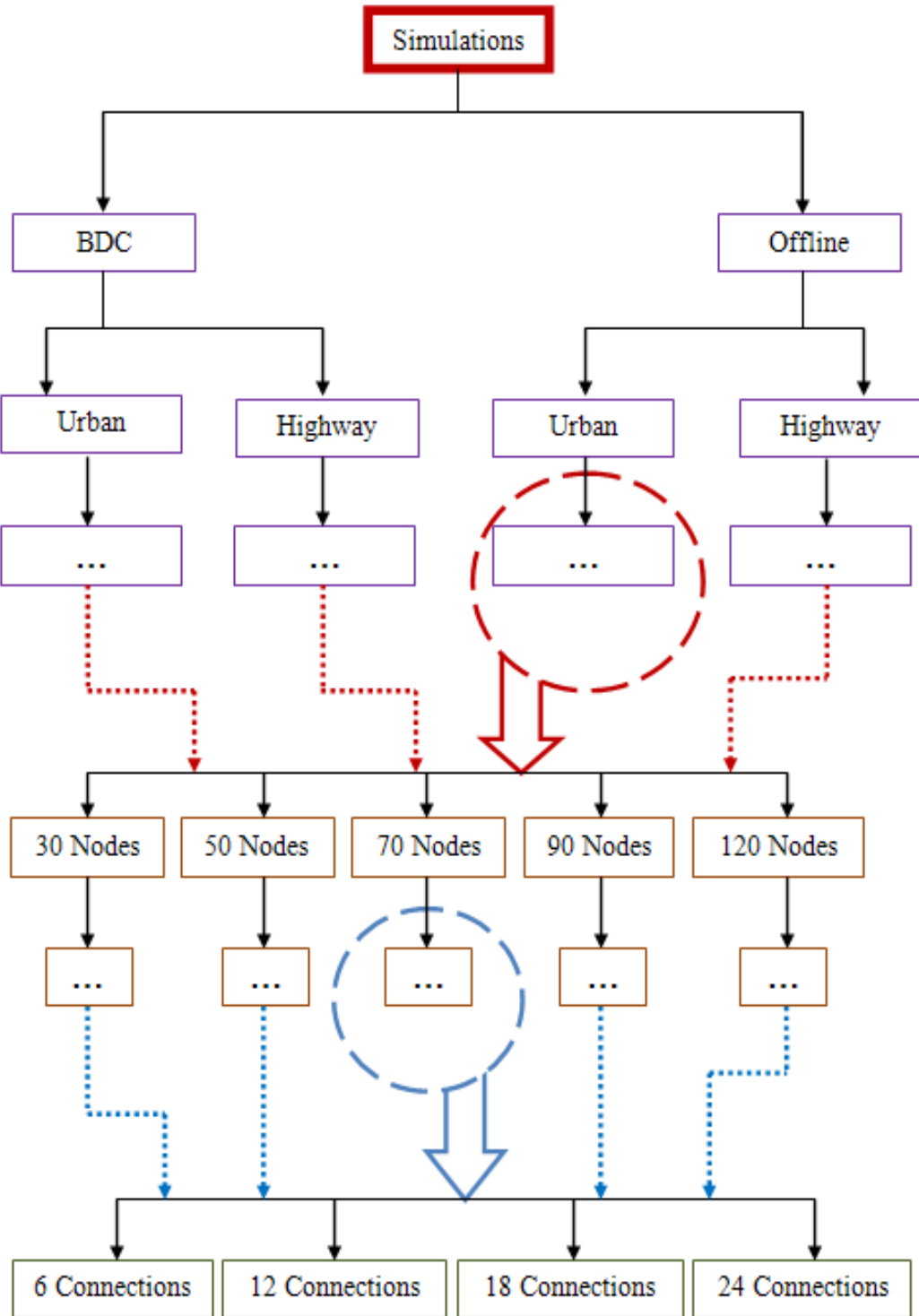
### 3.1 Simulation Setup

Table 3.1 lists the simulation parameters in detail.

**Table 3. 1: Simulation Setup**

<b>OS</b>	Fedora Core 9 64bit
<b>CPU</b>	AMD Athlon Single Core 1.8 GHz
<b>RAM</b>	1 GB DDR-I
<b>NS-2 Version</b>	2.33
<b>AODV Implementation</b>	NS-2 default
<b>DYMO Implementation</b>	DYMOUM
<b>OLSR Implementation</b>	UM-OLSR
<b>MOVE Version</b>	2.64
<b>SUMO Version</b>	0.98
<b>Number of Nodes</b>	BDC – Urban – 15, 30, 45, 60 BDC – Highway – 10, 20, 40, 60 Offline – Urban – 30, 50, 70, 90, 120 Offline – Highway – 60, 75, 90, 120
<b>Number of CBR Sessions</b>	BDC – Urban – 4, 8, 12, 16 BDC – Highway – 4, 8, 12, 16 Offline – Urban – 6, 12, 18, 24 Offline – Highway – 4, 8, 12, 16
<b>Simulation Area</b>	BDC – Urban – 2KM X 3KM BDC – Highway – 8.5KM Offline – Urban - 4KM x 4KM Offline – Highway – 15 KM
<b>Speed</b>	BDC – Urban – 40 kph BDC – Highway – 70 kph, 100 kph, 120 kph Offline – Urban – 40 kph Offline – Highway – 70 kph, 100 kph, 120 kph
<b>Tx Range</b>	300m
<b>Data Type</b>	CBR
<b>Data Packet Size</b>	1000 bytes
<b>MAC Protocol</b>	IEEE 802.11 Overhauled
<b>PHY Standard</b>	IEEE 802.11p
<b>Radio Propagation Model</b>	Nakagami
<b>Total Simulation Time</b>	180 seconds

The Figure 3.1 shows the simulation flow chart for offline urban scenarios. The same setup is used by offline highway, BDC urban & highway scenarios using their respective parameters like number of nodes and communication sessions.



**Figure 3. 1: Simulation Flow Chart**

## **3.2 Bi-directionally Coupled Simulations**

The main idea of using Bi-directionally Coupled (BDC) simulations was to investigate the possibility of using both network and traffic simulators at runtime and make them communicate with each other in an integrated manner. Traffic Control Interface (TraCI) is used to make both network and traffic simulators interact with each other at runtime. Details of TraCI are presented in chapter 2.

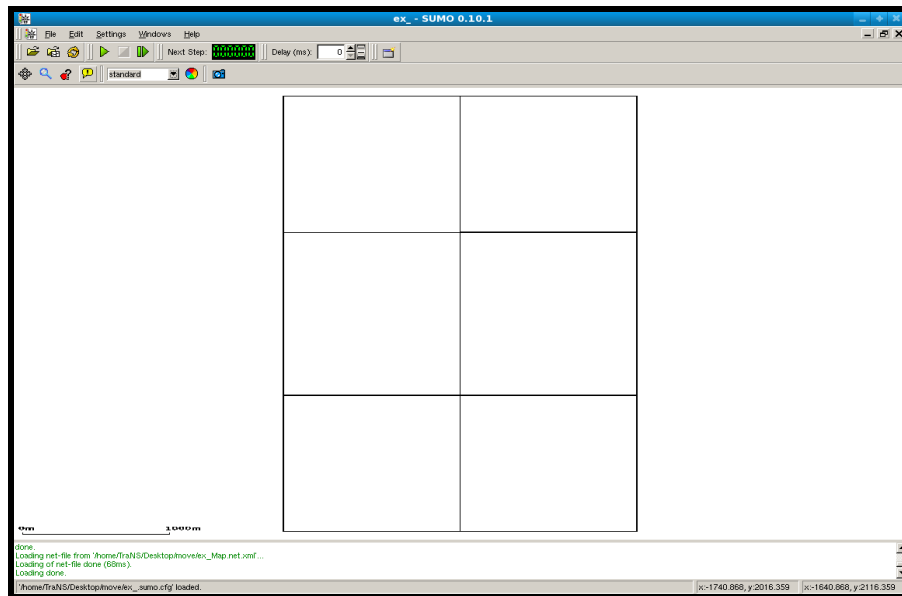
Although many problems were encountered during the integration of network and traffic simulators, a simple configuration setup was created to make simulations with simple scenarios possible. Both network and traffic simulators are evolving constantly but separately. The integration work done between the two simulators is at its initial stage and more effort is definitely required in this direction. This thesis is a research effort that makes use of this integrated approach.

The simulation scenarios designed in BDC simulations are simple and focused. The idea is to investigate whether traffic simulator would be able to exchange commands with network simulator to model emergency scenarios like accidents, etc. These type of scenarios need simpler and focused simulation approach, because accidents usually happen on a single road, so it wouldn't make much sense to use a large topology map that depicts a city or a portion of it.

### **3.2.1 Urban Scenario**

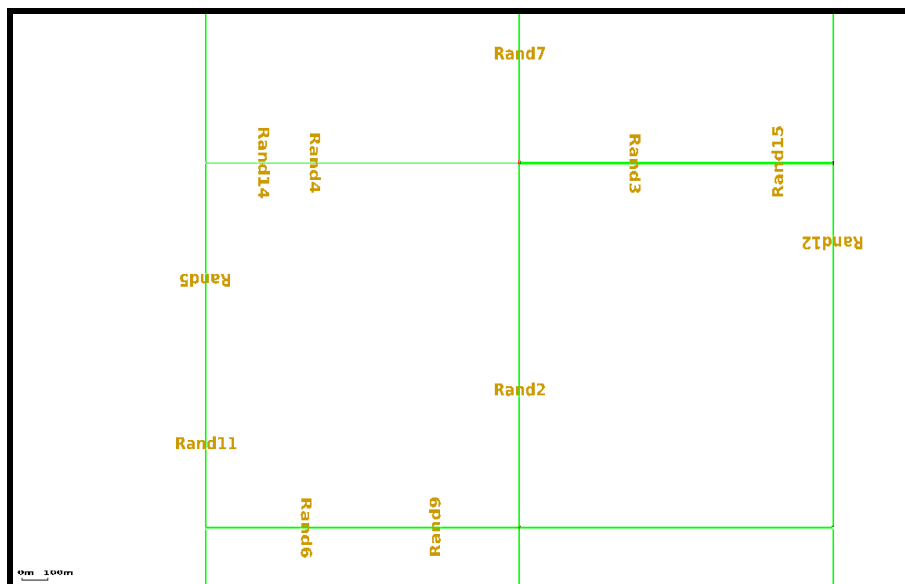
Figure 3.2 shows the urban scenario used for BDC simulations loaded in SUMO editor. This scenario shows the common urban settings found in a city. The two lane roads are created. The white square areas show the empty spaces, buildings etc. It is important to note that NS-2 does not incorporate the obstacle based signal

propagation model. That is why Nakagami propagation model is used to overcome this shortcoming and model channel characteristics realistically.



**Figure 3. 2: BDC Urban Scenario**

Figure 3.3 shows a close up of the movement of vehicles on the topology illustrated in the figure above. This screen shot is also taken from the SUMO editor.



**Figure 3. 3: Movement of Vehicles in BDC Urban Scenario**

### 3.2.2 Highway Scenario

Figure 3.4 shows the highway scenario used in BDC simulations. The scenario depicts a common highway scene. The traffic flow is unidirectional, moving from west to east direction. The speed of vehicles is variable, so slow moving vehicles can also be overtaken by fast moving vehicles.

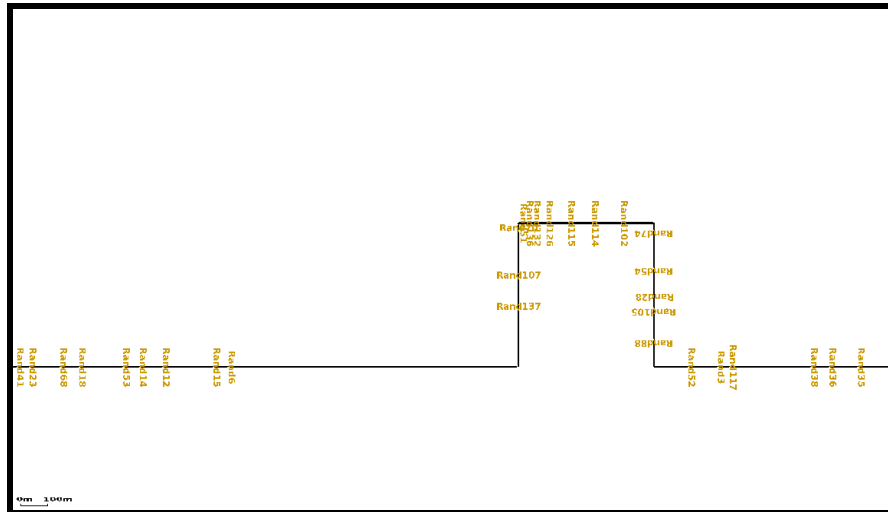


Figure 3. 4: BDC Highway Scenario

### 3.2.3 Accident Scenario

In order to analyze the integration of network and traffic simulators an accident scenario was created in both urban and highway scenarios. The idea was to investigate the performance of routing protocol when such eventuality occurs. Vehicles were randomly selected to have encountered an accident. In simulation, these vehicles were stopped for some duration. TraCI client commands were used to inform traffic simulator about this situation to the TraCI server in SUMO, the TraCI server confirmed the command and the node was stopped at that time. The TraCI server saved information about the stopped node like position, speed and its final destination etc. By using the broadcast mechanism, TraCI client spread message in the entire topology about the stopped vehicle.

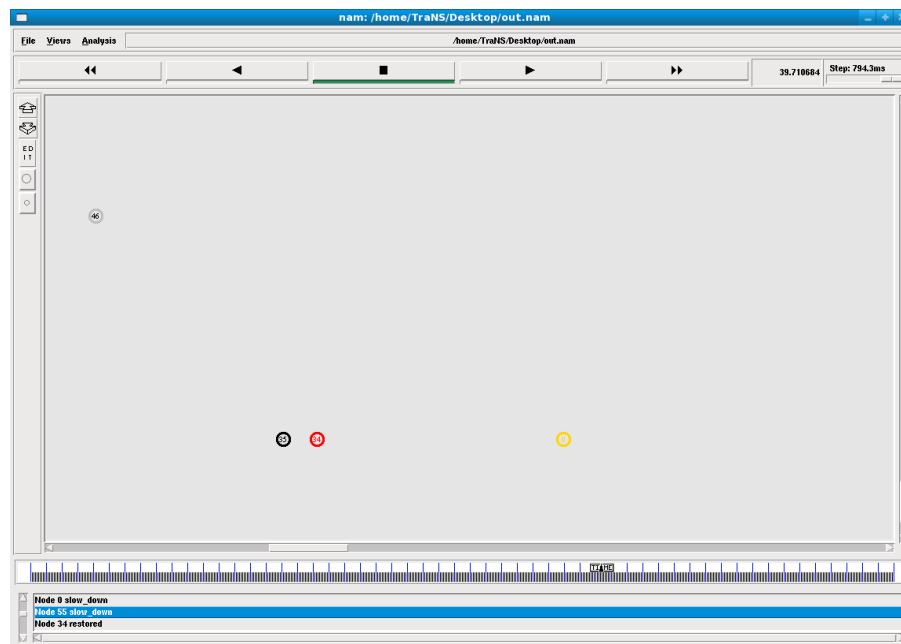


Because the SUMO is responsible for generating movement information of all nodes at runtime, it assures that any vehicle approaching the stopped vehicle must,

*i) Slow down before a certain distance from the stopped vehicle, and*

*ii) Stop when at a certain distance from the stopped vehicle.*

SUMO accomplishes these tasks by using the command exchange between the TraCI server and client. Once the stopped vehicle moves after predefined duration, all its attributes are restored like, speed, destination etc. Figure 3.5 shows this accident scenario during the simulation using Network Animator (NAM).



**Figure 3. 5: Accident Scenario in BDC Simulations**

In the figure above, a vehicle shown is involved in accident and hence is stopped. One vehicle received the emergency broadcast and has slowed its speed. Another vehicle didn't receive the emergency broadcast message and is approaching the stopped vehicle at full speed.

The above mentioned accident scenario was applied to both urban and highway scenarios. Three accident scenarios were created at three different locations in both

the scenarios. Some vehicles that were communicating with other vehicles had accidents; similarly in other instances the vehicles that were not communicating with other vehicles had accidents. Before, during and after the accidents communication was going on between different vehicles.

### **3.3 Offline Simulations**

In offline simulations, no integration of network and traffic simulators was performed. Instead, the movement patterns of vehicles were generated beforehand and used in simulations later. These movement patterns were generated using SUMO, completely randomly. Obviously this eliminated the chances of modeling any emergency event like accidents during the simulations. Despite this fact, the offline simulations allowed us to observe the behavior of routing protocols when vehicles moved and communicated in real life network topologies.

With offline simulations, there is no limit of experimenting with different topologies except for the fact that as the simulation become more complex, a powerful machine with handful of resources, i.e. RAM and processing power, is required. The PC used in this thesis was a modest one in terms of RAM and processing power.

Similar to the BDC simulations, both urban and highway scenarios were simulated in this mode with same attributes like number of vehicles, speed, number of connections, transmission range.

#### **3.3.1 Urban Scenario**

The major difference between the urban scenario of BDC simulations and urban scenario of offline simulation is the use of real world map in the later. The TIGER line map of the state of Alaska of USA was used as an example. These maps of every

US state are available freely over the internet for public use. SUMO easily converts these maps for its use and generates movement patterns of vehicles at every timestamp, according to the layout of the map. Hence, this is the easiest method of obtaining movement patterns of vehicles in real world. Figure 3.6 shows the exact map used in simulations in this thesis.



**Figure 3. 6: Urban Scenario used in Offline Simulations**

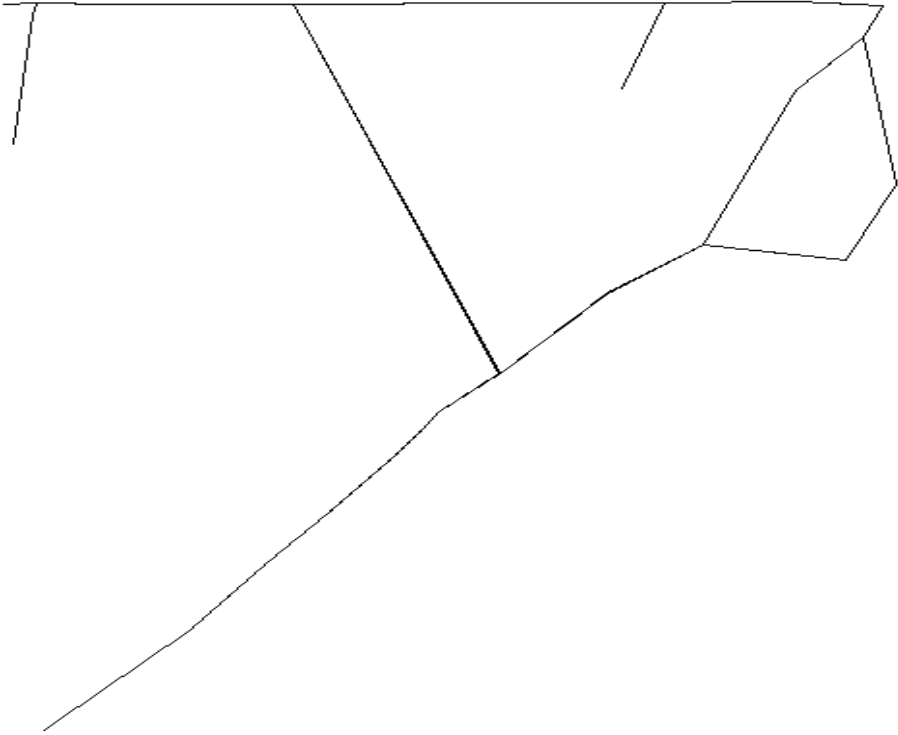
The map above represents the scaled down version of a downtown area. The total area considered is 4KM X 4KM. The map perfectly shows the urban environment found in most metropolitan areas around the world. Using SUMO, movement patterns of variable number of vehicles were generated randomly. Figure 3.7 shows the close up movement of vehicles on the map.



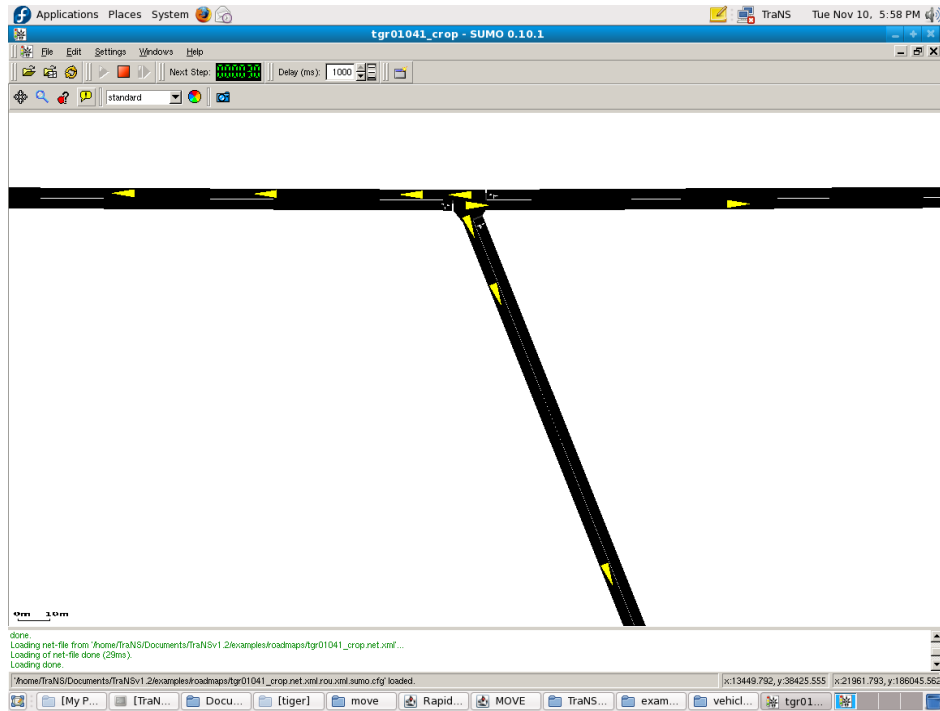
**Figure 3. 7: Movement of Vehicles in Offline Urban Scenario**

**3.3.2 Highway Scenario**

The highway scenario is also generated using Tiger map. It depicts the long highway with wide open spaces. Figure 3.9 show the vehicles on highway in SUMO.



**Figure 3. 8: Highway Scenario used in Offline Simulations**



**Figure 3. 9: Movement of Vehicles in Offline Highway Scenario**

It is important to note that all four scenarios in both simulation types are not comparable with each other. Every scenario has its own distinct characteristics and shortcomings therefore it is not appropriate to compare results of a scenario of bi-directionally coupled simulations with the same scenario of offline simulations.

### 3.4 Simulation Assumptions

In both highway scenarios three types of vehicles moving with different speeds are used. Trucks move with maximum speed of 70kph, small cars move with maximum speed of 100kph and sedans move with maximum speed of 120kph.

**Table 3. 2: Simulation Assumptions**

Simulation scenarios	Road traffic direction	Road lanes	Speed	Environment obstacles
BDC Urban	Multi-directional	2	Uniform	None
BDC Highway	Unidirectional	2	Variable	None
Offline Urban	Multi-directional	2	Uniform	None
Offline Highway	Unidirectional	2	Variable	None

Initially, in both highway and urban scenarios, the vehicles move from standstill and then gain maximum speed after sometime.

In BDC simulations, the vehicles are assumed to have established CBR connections before they encounter an accident. Three different vehicles, at different times and at different locations, encounter accident while either sending or receiving CBR data. The vehicle encountering accident moves after stopping for predefined duration.

### 3.5 Simulation Metrics

The following metrics are used in this thesis to evaluate the performance of AODV, DYMO and OLSR routing protocols.

- ***Packet Delivery Ratio (PDR):***

- This metric gives the ratio of the data packets successfully received at the destination and total number of data packets generated at source.

The following equation is used to calculate the PDR,

$$PDR = (Data_R / Data_S) * 100, \text{ Where}$$

$Data_R$  = Data packets received by the CBR agent at destination node

$Data_S$  = Data packets Sent by the CBR agent at source node

- ***Average End-to-End Delay:***

- This metric gives the overall delay, from packet transmission by the application agent at the source node till packet reception by the application agent at the destination node. The following equation is used to calculate the average end-to-end delay,

$$\text{Average End-to-End Delay} = (T_{Data_R} - T_{Data_S}), \text{ Where}$$

$T_{Data_R}$  = Time data packets received at destination node

$T_{Data_S}$  = Time data packets sent from source node

- ***Normalized Routing Overhead (NRO):***

- This metric indicates the number of routing packets transmitted per data packet delivered to the destination. This includes all routing packet types (request, reply, error) in the network. The following equation is used to calculate the NRO,

$NRO = (CP_{Sent} + CP_{Forw}) / Data_R$ , Where

$CP_{Sent}$  = Control packets sent by all nodes

$CP_{Forw}$  = Control packets forwarded by all nodes

$Data_R$  = Data packets received at the destination node

- ***Average End-to-End Delay of 1<sup>st</sup> Data Packet:***

- This metric gives the overall delay of first data packet, from packet transmission by the application agent at the source node till packet reception by the application agent at the destination node. The following equation is used to calculate the average end-to-end delay of 1<sup>st</sup> data packet,

$Average\ End\text{-to-End}\ Delay\ of\ 1^{st}\ Data\ Packet = (T_{Data_R} - T_{Data_S})$ ,

Where

$T_{Data_R}$  = Time 1<sup>st</sup> data packets received at destination node

$T_{Data_S}$  = Time 1<sup>st</sup> data packets sent from source node

These metrics are most commonly used in the research community to evaluate the performance of different routing protocols.

# Chapter 4

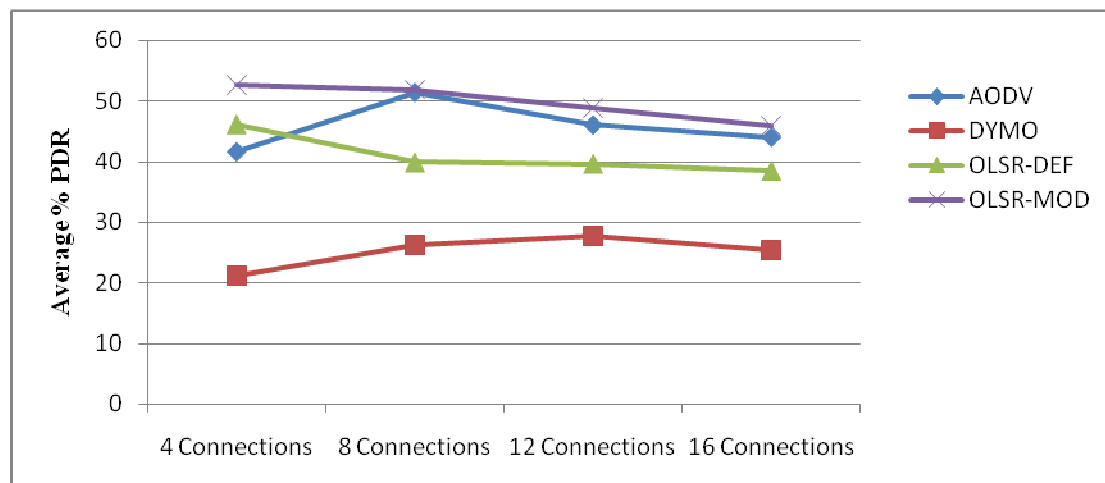
## Simulation Results

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In the following sections the simulation results of all scenarios are presented. It is important to note that in all simulations two variants of OLSR routing protocols are used. In OLSR-DEF the default values of *Hello* and *Topology Control (TC)* message intervals are used, while OLSR-MOD uses modified values of these two messages.

### 4.1 Simulation Results of BDC Urban Scenario

#### 4.1.1 Packet Delivery Ratio of AODV, DYMO and OLSR

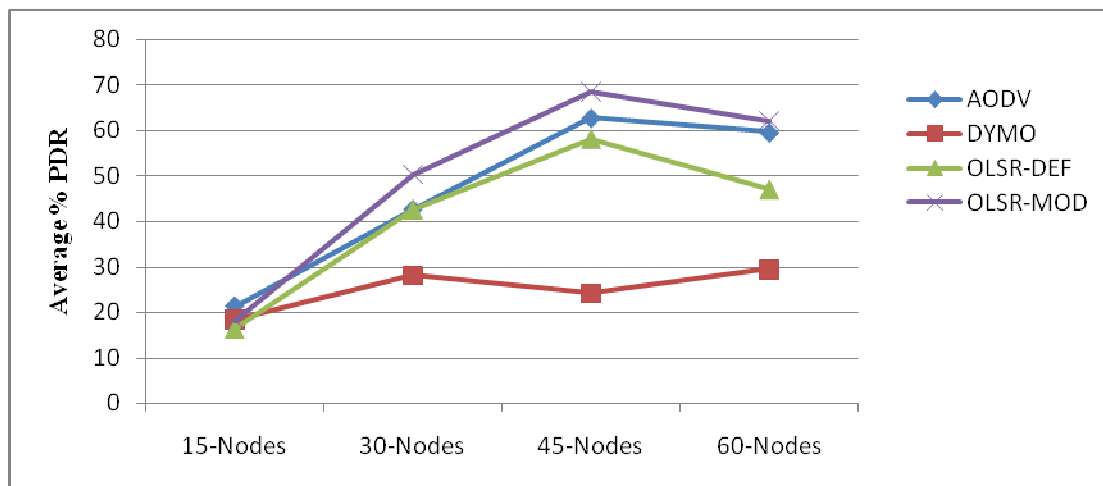


**Figure 4. 1: Average PDR VS Communication Sessions**

Figure 4.1 shows the average PDR of all 3 protocols. The behavior of PDR of every routing protocol with respect to communication sessions is shown. We observe that OLSR-MOD with short interval values is able to give better PDR consistently as compared to other protocols. AODV in this scenario performs well, although in fewer connections its performance is less than both variants of OLSR, but it is able to



outperform OLSR-DEF when number of communication sessions increase. One possible reason could be that due to link breakages, OLSR-DEF was taking too long to update its routing table. DYMO has lower PDR throughout this scenario. The proactive routing protocols have decreasing PDR all the time. Overall it can be concluded that proactive routing protocols with short interval values provide better PDR, as their routing table is updated quickly.

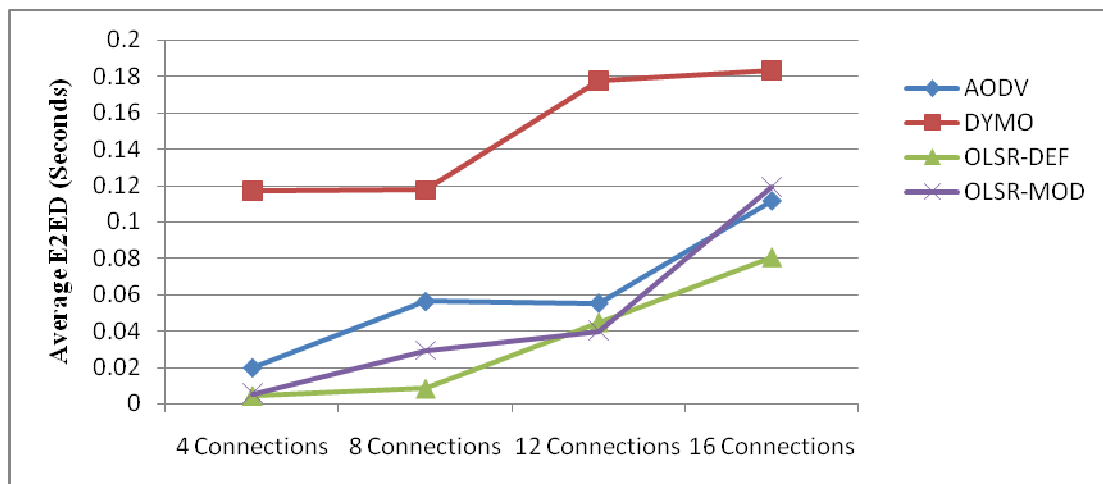


**Figure 4. 2: Average PDR VS Node Density**

Figure 4.2 shows the effects of node density on the PDR of AODV, DYMO and OLSR in BDC Urban scenario. Here again we observe that OLSR-MOD with shorter intervals of control messages is able to give better PDR against the increase in node density. AODV also performs quite well as compared to new DYMO routing protocol. An important observation can be made that in VANET scenarios, the default values of OLSR control messages are not good enough. For highly dynamic topology like VANET, we need quick refresh of topology, however, this results in generating more control traffic thus routing overhead increases.

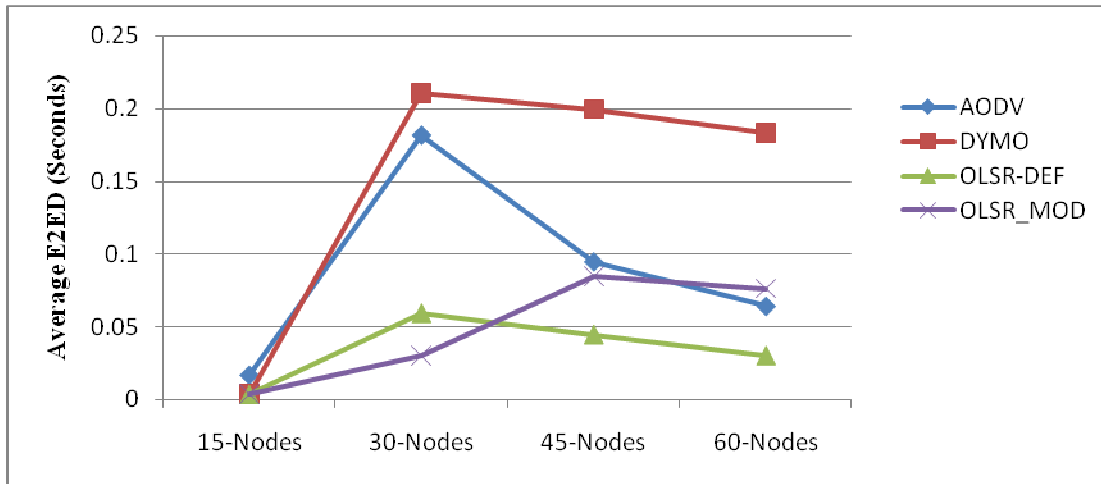
### 4.1.2 End-to-End Delay of AODV, DYMO and OLSR

In figure 4.3 we see the average end-to-end delay of all 3 routing protocols. DYMO appears to have suffered more and therefore has more end-to-end delay than other routing protocols. Both variants of OLSR, being proactive in nature, have less end-to-end delay than both AODV and DYMO on average. Between the two reactive routing protocols, AODV performs better than DYMO. One reason for this could be that DYMO internally set a large value for route delete timeout or the routes learnt to neighboring nodes through path accumulation became quickly obsolete as vehicles took left or right turns and moved away from sending node. But as the vehicles were moving constantly DYMO had to initiate path discovery multiple times.



**Figure 4. 3: Average End-to-End Delay VS Communication Sessions**

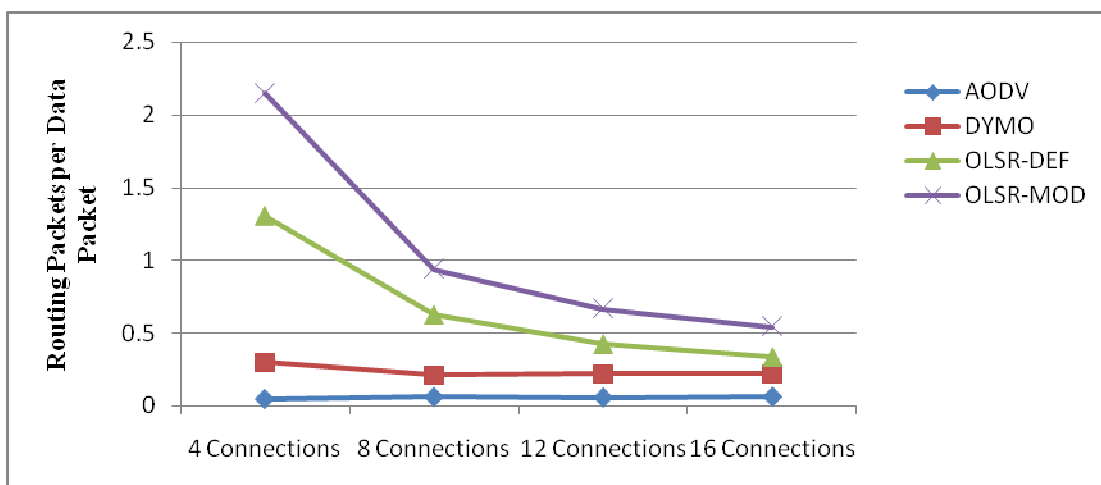
The proactive nature of the OLSR variants allowed them to use predetermined routes, instead of finding new, like in reactive routing protocols, thus saving end-to-end latency. Figure 4.4 shows the end-to-end of AODV, DYMO and OLSR in BDC Urban Scenario against increasing node density. Again we observe that reactive routing protocols have higher end-to-end delay than proactive routing protocols. AODV again outperforms DYMO when the node density increases in this scenario.



**Figure 4. 4: Average End-to-End Delay VS Node Density**

#### 4.1.3 Normalized Routing Overhead of AODV, DYMO and OLSR

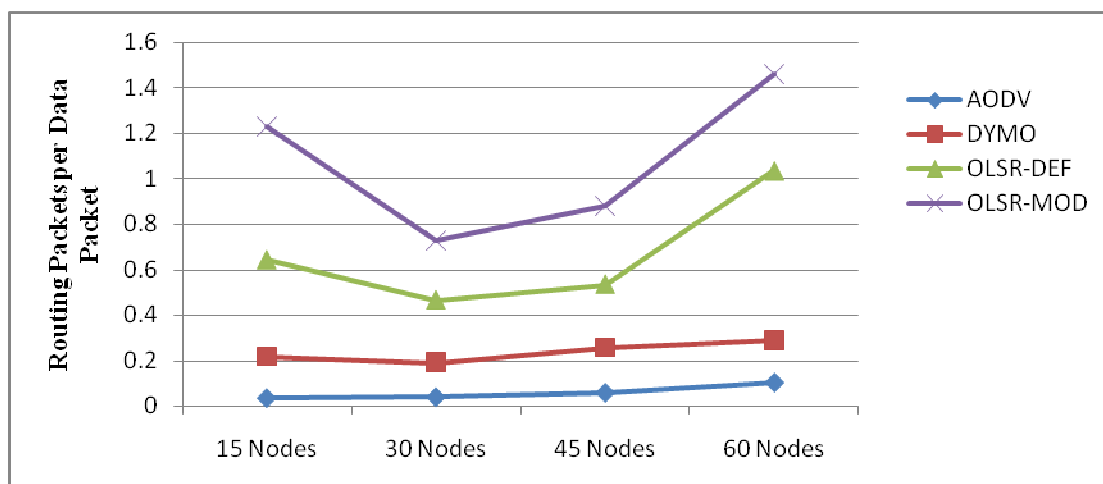
In Figure 4.5, the Normalized Routing Overhead (NRO) is shown. It is observed that both variants of OLSR consistently have more NRO than reactive routing protocols. This is because the proactive routing protocols generate sustained control traffic, in order to have updated information about the topology and routing paths. This process is done irrespective of user communication. On one hand this helps in avoiding initial latency of finding routes, but in return it generates more routing overhead than reactive routing protocols.



**Figure 4. 5: Normalized Routing Overhead VS Communication Sessions**

One important thing to note is that as communication sessions are increasing in number, the NRO of both OLSR-DEF and OLSR-MOD decreases considerably. AODV and DYMO more or less maintain same NRO despite increase in communication sessions. In situations where communication sessions increase over time, OLSR may be a good choice as routing protocol.

Next, Figure 4.6 shows the effects of increase in node density on NRO of AODV, DYMO and OLSR. Here again we see that when there are more nodes in the network, the NRO of both OLSR-DEF and OLSR-MOD increases. Between the two OLSR variants, OLSR-MOD generates more control traffic than OLSR-DEF because of its short intervals between the control packets. This phenomenon holds true irrespective of node density or increase in communication sessions.

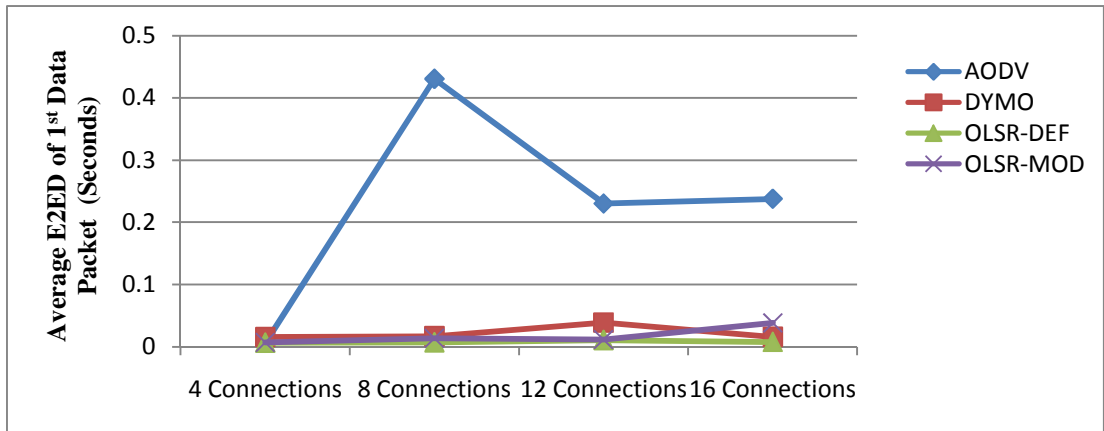


**Figure 4. 6: Normalized Routing Overhead VS Node Density**

#### 4.1.4 Average End-to-End Delay of 1<sup>st</sup> Data Packet

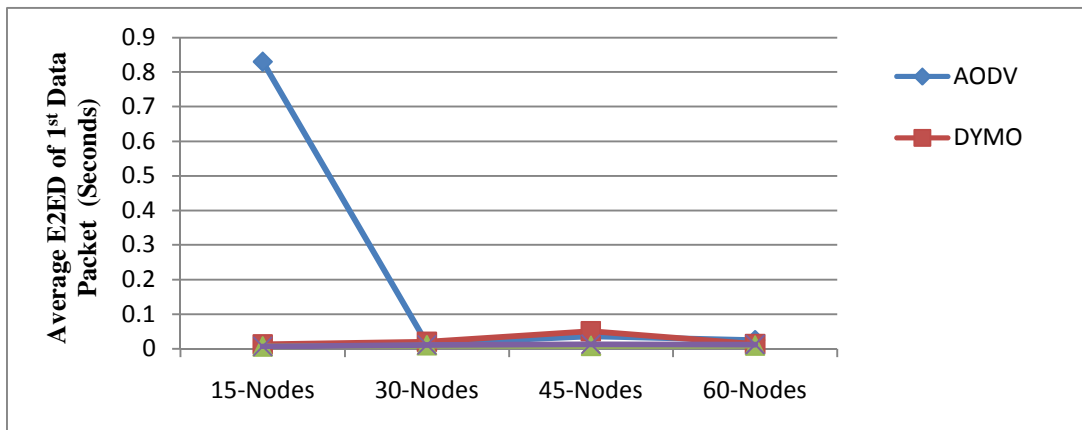
Figure 4.7 show the average end-to-end delay of 1<sup>st</sup> data packet in BDC urban scenario. We observe that using AODV has delayed 1<sup>st</sup> data packet much more than other routing protocols. DYMO performs way better than AODV and takes much less time getting the 1<sup>st</sup> data packet to the destination. Proactive protocols like

OLSR-DEF and OLSR-MOD get the 1<sup>st</sup> data packet to the destination quickly than their reactive counterparts AODV and DYMO.



**Figure 4. 7: Average End-to-End Delay VS Communication Sessions**

Figure 4.8 shows the effects of node density on the delay of 1<sup>st</sup> data packet. Here we observe that except in one instance, AODV and other protocols work likewise. This suggests that in BDC urban scenario the node density does not have any significant effect over initial delay.

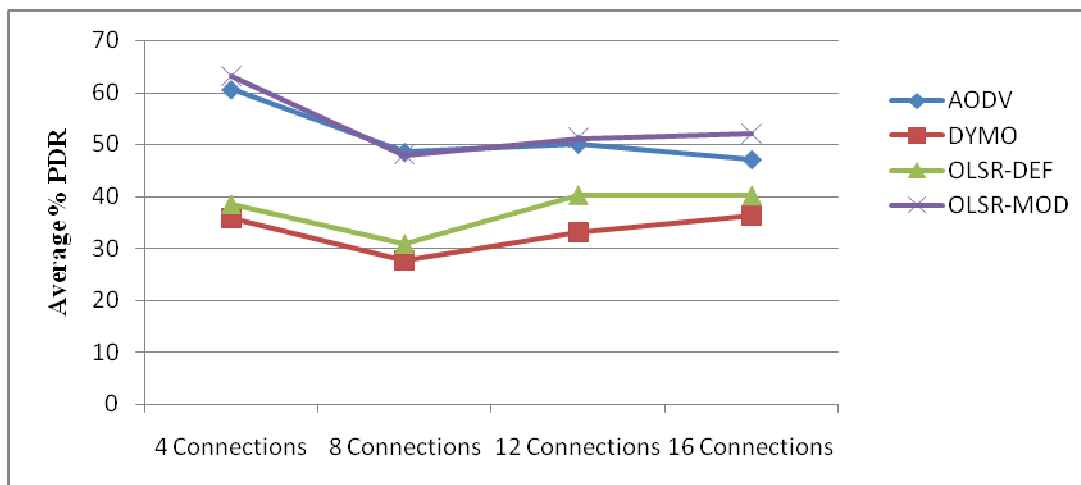


**Figure 4. 8: Average End-to-End Delay VS Node Density**

## 4.2 Simulation Results of BDC Highway Scenario

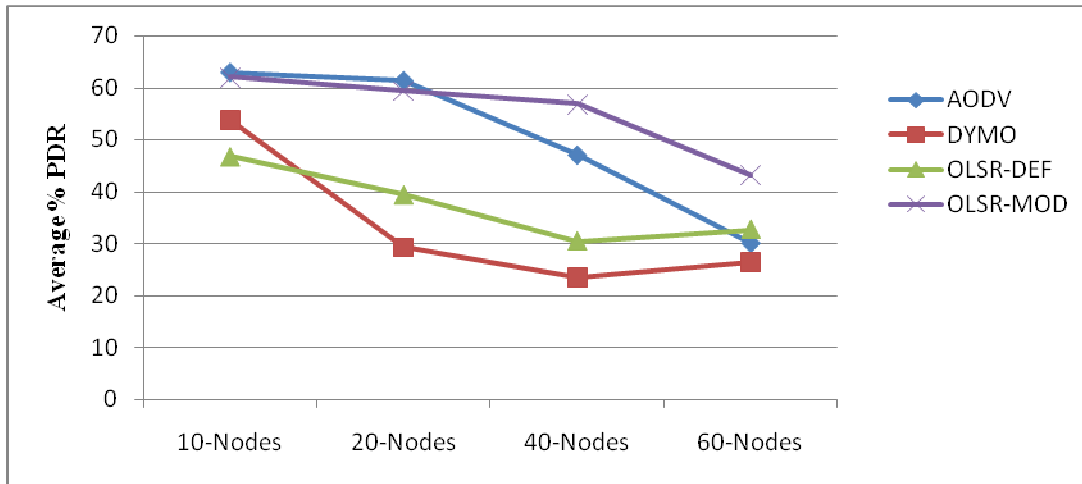
### 4.2.1 Packet Delivery Ratio of AODV, DYMO and OLSR

In Figure 4.9, the average PDR of AODV, DYMO and OLSR is presented. Like urban scenario, we observe that OLSR-MOD and AODV performed very closely to each other, both these protocols performed very much the same. DYMO again loses out to AODV, while OLSR-MOD outperforms OLSR-DEF.



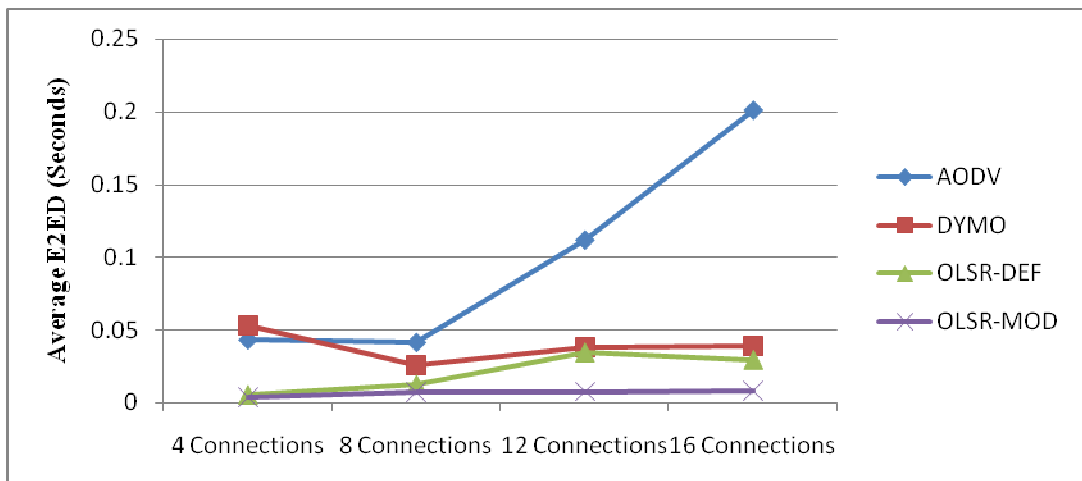
**Figure 4. 9: Average PDR VS Communication Sessions**

In Figure 4.10, the performance of AODV and OLSR-MOD remains almost same initially, but as the number of nodes are increased, PDR of AODV takes a sharp decline and matches the PDR of OLSR-DEF and DYMO. PDR of OLSR-MOD also decreases but still stays considerably above other protocols. Unlike BDC Urban Scenario we've seen previously, the PDR of all these routing protocols decreases as more and more nodes join the network. In urban scenario the area was small and vehicles were present in the neighborhood to aid in ad hoc routing, but on a single road depicting a highway scenario there was less chance of doing so.



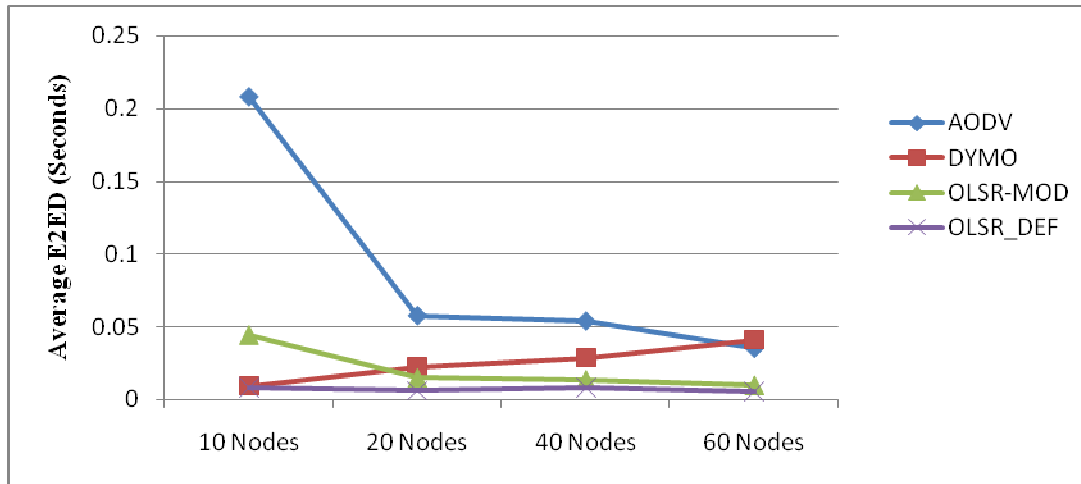
**Figure 4. 10: Average PDR VS Node Density**

#### 4.2.2 End-to-End Delay of AODV, DYMO and OLSR



**Figure 4. 11: Average End-to-End Delay VS Communication Sessions**

Figure 4.11 shows the average end-to-end delay of AODV, DYMO and OLSR in highway BDC scenario. OLSR-MOD performs best and has lowest end-to-end delay on the average as compared to AODV, DYMO and OLSR-DEF. The frequent exchange of control messages enables OLSR-MOD to cope with frequent topology changes. End-to-end delay of AODV increases greatly with the increase in communication sessions.



**Figure 4. 12: Average End-to-End Delay VS Node Density**

In Figure 4.12 we see that AODV again has higher end-to-end delay, but it consistently decreases as the number of nodes increase. Other protocols perform more or less the same way as in figure 4.11.

One interesting observation that can be made about end-to-end delay in BDC urban and highway scenarios is that in urban scenario the least performing routing protocol was DYMO, while in highway scenario the performance of AODV is worst of all. One possible reason for this could be that in urban scenario, DYMO learned the path to neighboring vehicles because of its path accumulation characteristic.

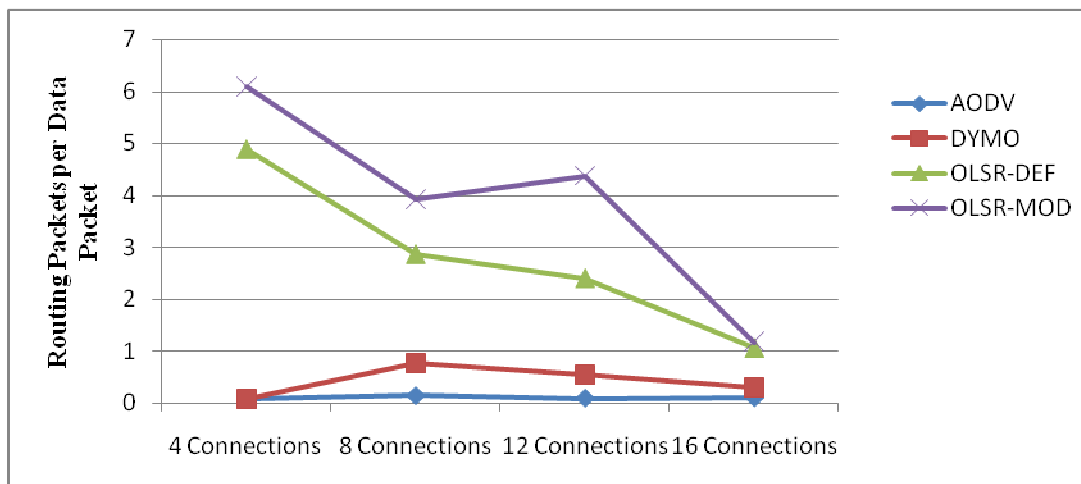
But due to the high mobility and departure of neighboring vehicles DYMO was not able to use the paths learned. So, new route requests would be needed. But in highway scenario, the vehicles moved on single road, so no left or right turns were taken by the vehicles. So in highway scenario the path accumulation worked for DYMO a bit longer. This may be the case for DYMO to outperform AODV in highway scenario. In both scenarios the reactive routing protocols suffered the most, while the variants of proactive routing protocol OLSR performed better. This



observation leads to conclusion that when there is an issue of end-to-end delay, proactive routing protocols are better choice than reactive routing protocols.

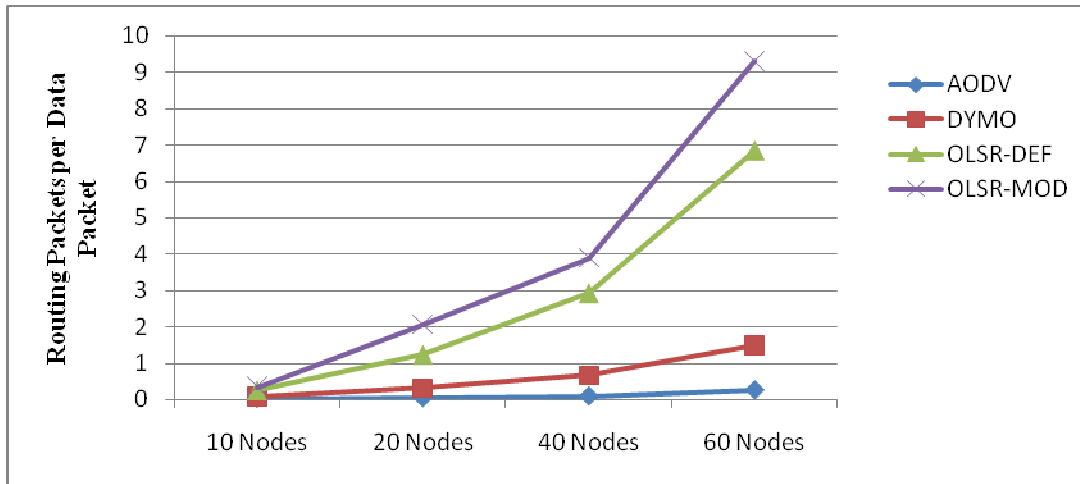
#### 4.2.3 Normalized Routing Overhead of AODV, DYMO and OLSR

The NRO of AODV, DYMO and OLSR for BDC Highway Scenario is presented in Figure 4.13. The results pretty much coincide with the results in section 4.1.3. OLSR-MOD has the highest routing overhead, while AODV has the lowest. The NRO of both OLSR-DEF and OLSR-MOD converges rapidly when number of communication session increase, making them suitable for heavily loaded network.



**Figure 4. 13: Normalized Routing Overhead VS Communication Sessions**

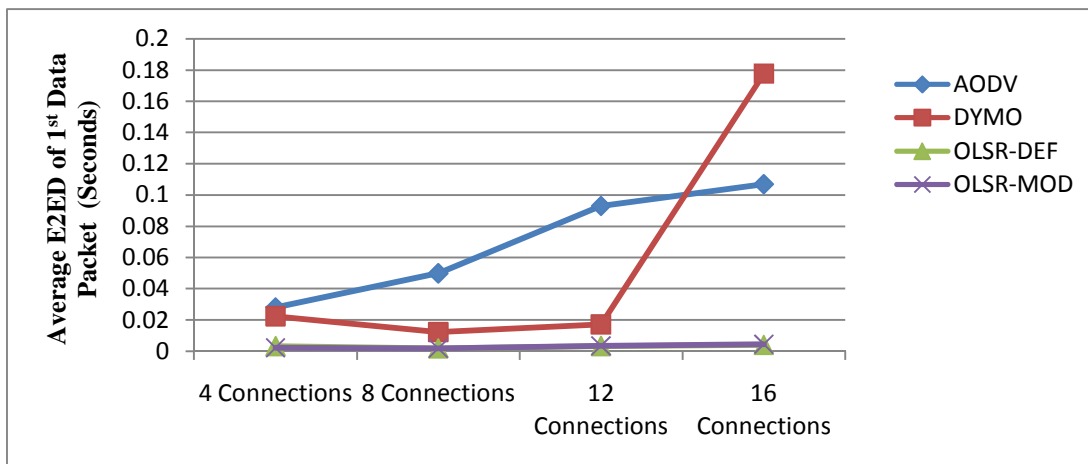
The effects of increase in node density are shown in Figure 4.14. Like previous observation in 4.1.3 the NRO of all protocols increases as node density increases.



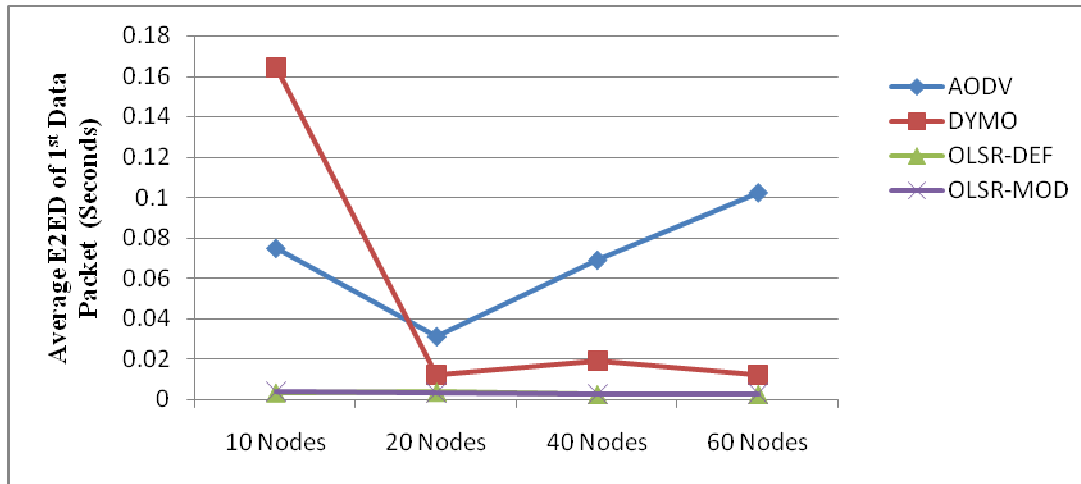
**Figure 4.14: Normalized Routing Overhead VS Node Density**

#### 4.2.4 Average End-to-End Delay of 1<sup>st</sup> Data Packet

In Figure 4.15, it is observed that proactive routing protocols deliver 1<sup>st</sup> data packet very quickly. AODV and DYMO being reactive routing protocols take time while delivering the 1<sup>st</sup> data packet. On the whole as the communication sessions increase in the simulation, DYMO performs slightly better than AODV, as up to 12 connections its delay is clearly well below than AODV.



**Figure 4.15: Average End-to-End Delay VS Communication Sessions**



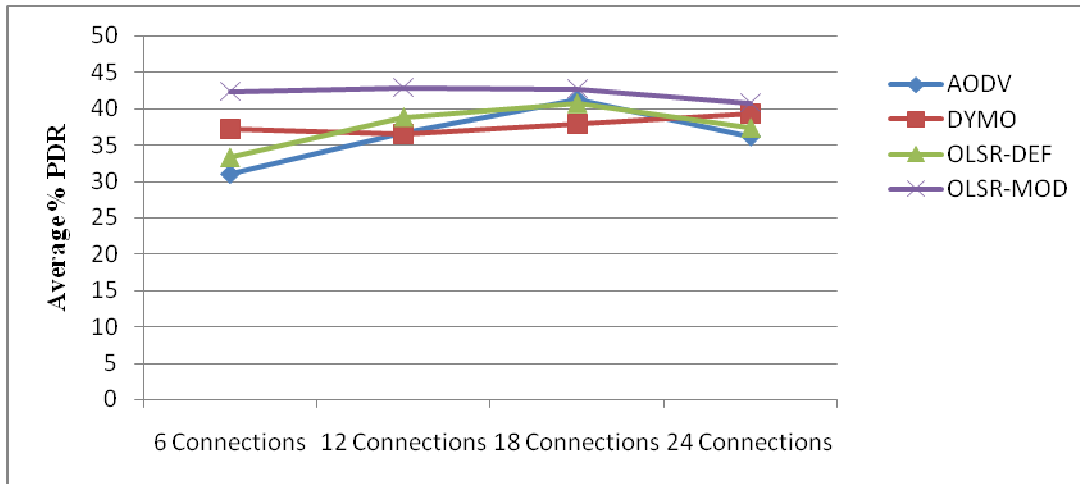
**Figure 4. 16: Average End-to-End Delay VS Node Density**

Figure 4.16 shows the effects of node density on average end-to-end delay of 1<sup>st</sup> data packet. Irrespective of node density the end-to-end delay of 1<sup>st</sup> Data Packet remains almost constant when OLSR is used. However, the node density has its effects on the reactive routing protocols AODV and DYMO. DYMO here again performs slightly better than AODV on the average.

### 4.3 Simulation Results of Offline Urban Scenario

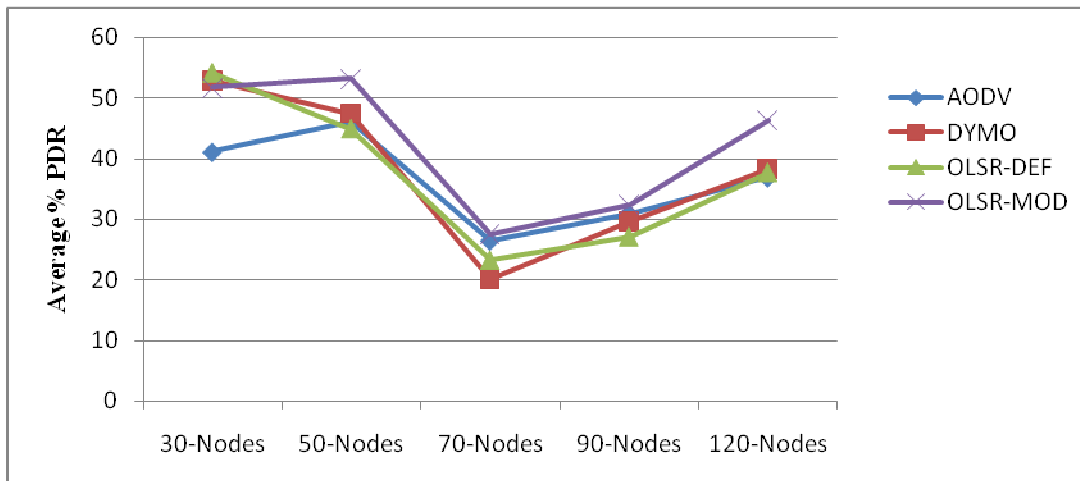
#### 4.3.1 Packet Delivery Ratio of AODV, DYMO and OLSR

Figure 4.17 shows the PDR of all three protocols. Using default values all three protocols perform almost same on the average. But when OLSR is made to use short interval values of its control messages, it provides better PDR than other routing protocols discussed in this thesis. The increase in communication also does not have any effect and OLSR-MOD performs equally well.



**Figure 4.17: Average PDR VS Communication Sessions**

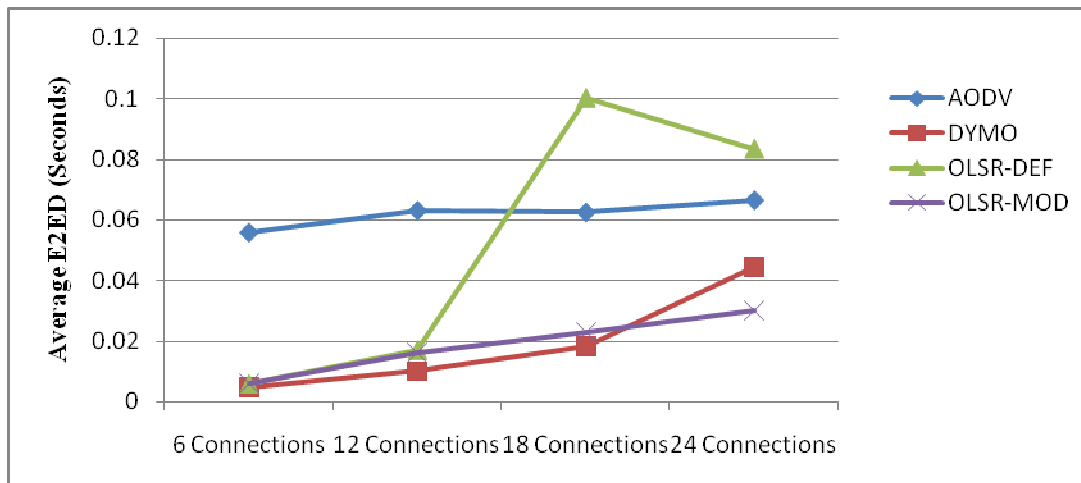
Figure 4.18 shows the effect of node density on the PDR of AODV, DYMO and OLSR routing protocols. Here again we see that AODV, DYMO, OLSR-DEF and OLSR-MOD almost show same trend but OLSR-MOD delivers more packets than its competitors when number of nodes starts increasing in the network. The reason again is that OLSR-MOD, because of its frequent *Hello* and *TC* messages, lost few packets than its counterparts. It has most recent record of network topology.



**Figure 4.18: Average PDR VS Node Density**

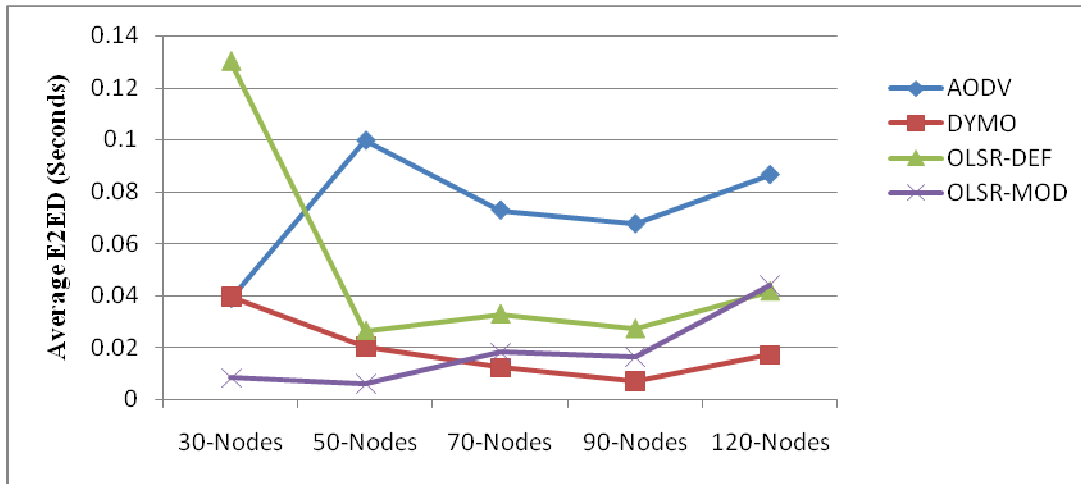
### 4.3.2 End-to-End Delay of AODV, DYMO and OLSR

Average end-to-end delay is shown in Figure 4.19 against number of communication sessions. We observe that end-to-end delay of OLSR-MOD and DYMO is the lowest. In two instances with 18 and 24 connections, the end-to-end delay of OLSR-DEF goes above all routing protocols. On the average its end-to-end delay remains below AODV, which has highest end-to-end delay on the average. We observe that as the number of communication sessions increase over time in, end-to-end delay of all routing protocols increases. But still OLSR-MOD has the lowest end-to-end delay, and then comes DYMO followed by OLSR-DEF and AODV.



**Figure 4. 19: Average End-to-End Delay VS Communication Sessions**

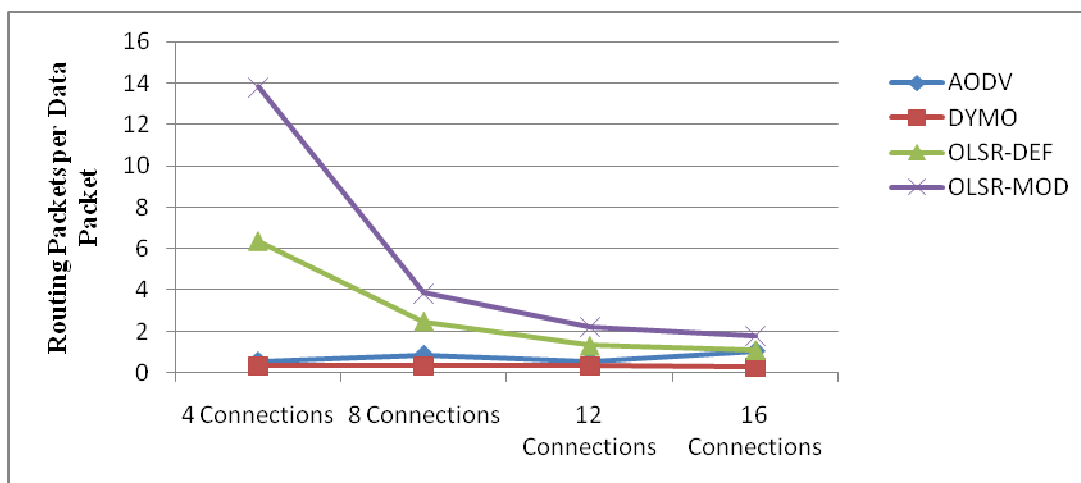
Next in Figure 4.20, the end-to-end delay of these routing protocols is given against node density. AODV has its end-to-end delay increasing over time. DYMO interestingly has its end-to-end delay decreasing when number of nodes increase in the network suggesting that the path accumulation is helpful in such situations. OLSR-MOD and OLSR-DEF also have slight increase in their end-to-end delay as number of nodes increase.



**Figure 4. 20: Average End-to-End Delay VS Node Density**

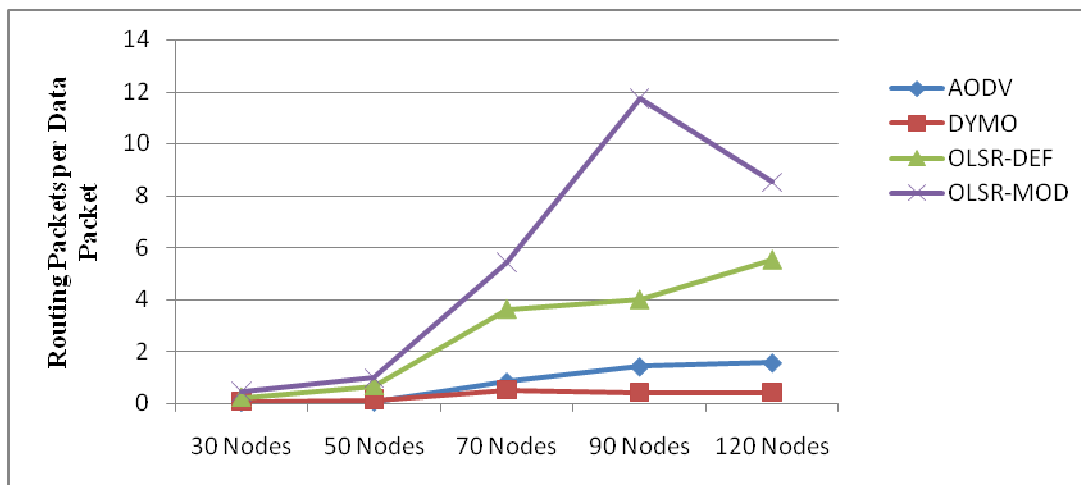
### 4.3.3 Normalized Routing Overhead of AODV, DYMO and OLSR

Figure 4.21 shows the NRO of AODV, DYMO and OLSR. Being reactive routing protocols, both AODV and DYMO have very low NRO compared to variants of OLSR. Between these two, DYMO outperforms AODV with least number of control packets sent for the number of data packet delivered. Initially with least number of communication sessions both variants of OLSR had large values of NRO, but as the number of communication sessions increased with varying number of nodes, their NRO started matching the NRO of DYMO and OLSR.



**Figure 4. 21: Normalized Routing Overhead VS Communication Sessions**

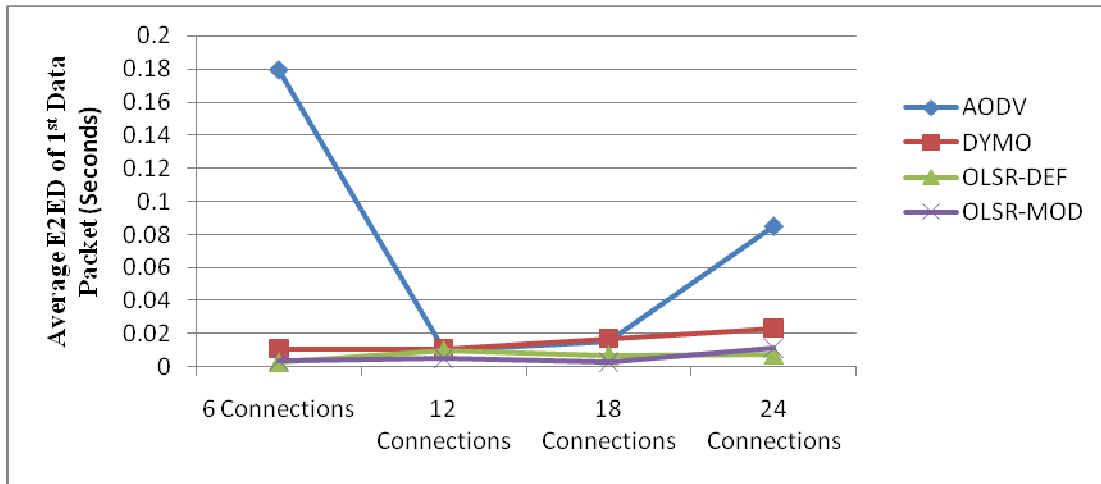
Figure 4.22 shows the NRO of AODV, DYMO and OLSR against the increase in node density. As there are more nodes in the network, the NRO of all routing protocols increases. But the NRO of DYMO and AODV remains well short of NRO of proactive routing protocol OLSR. With proactive routing protocols, as more and more nodes join the network, NRO will tend to increase substantially as these new nodes, not part of any communication, tend to send/receive control messages for protocol functioning.



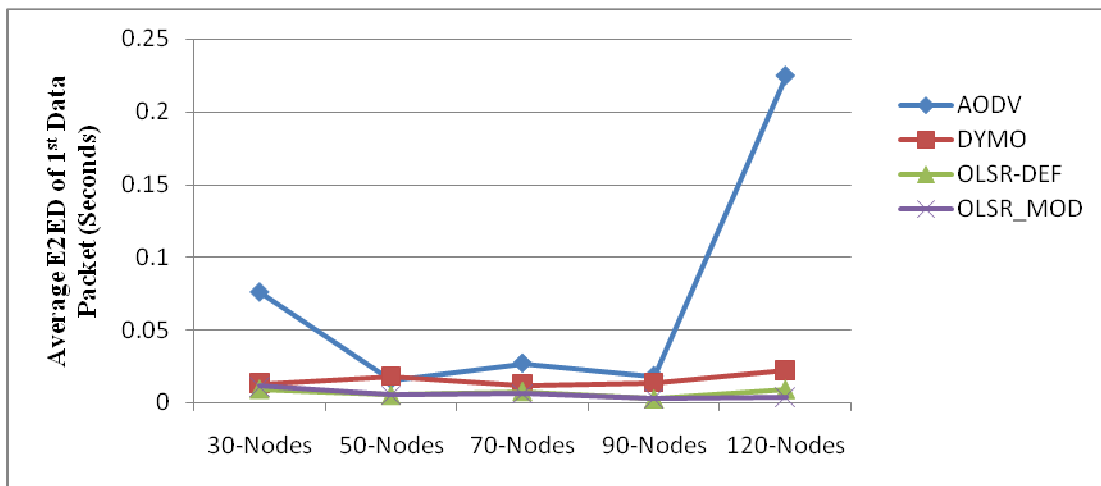
**Figure 4. 22: Normalized Routing Overhead VS Node Density**

#### 4.3.4 Average End-to-End Delay of 1<sup>st</sup> Data Packet

Figure 4.23 shows the end-to-end delay of 1<sup>st</sup> data packet in offline urban scenario. Both variant of OLSR take much less time than AODV and DYMO to deliver first data packet to the destination. AODV does not perform well while end-to-end delay of 1<sup>st</sup> packet using DYMO is steady and increasing. In Figure 4.24, with the increase in node density OLSR-MOD, OLSR-DEF and DYMO have low end-to-end delay, while AODV again has highest end-to-end delay for 1<sup>st</sup> data packet overall. In both circumstances DYMO outperforms AODV, while OLSR performs better than both AODV and DYMO.



**Figure 4. 23: Average End-to-End Delay VS Communication Sessions**



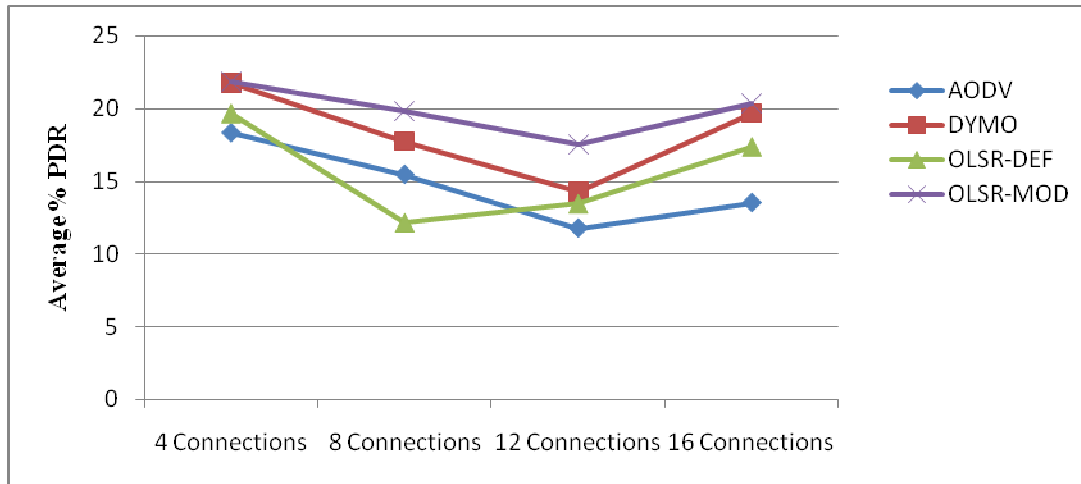
**Figure 4. 24: Average End-to-End Delay VS Node Density**

#### 4.4 Simulation Results of Offline Highway Scenario

##### 4.4.1 Packet Delivery Ratio of AODV, DYMO and OLSR

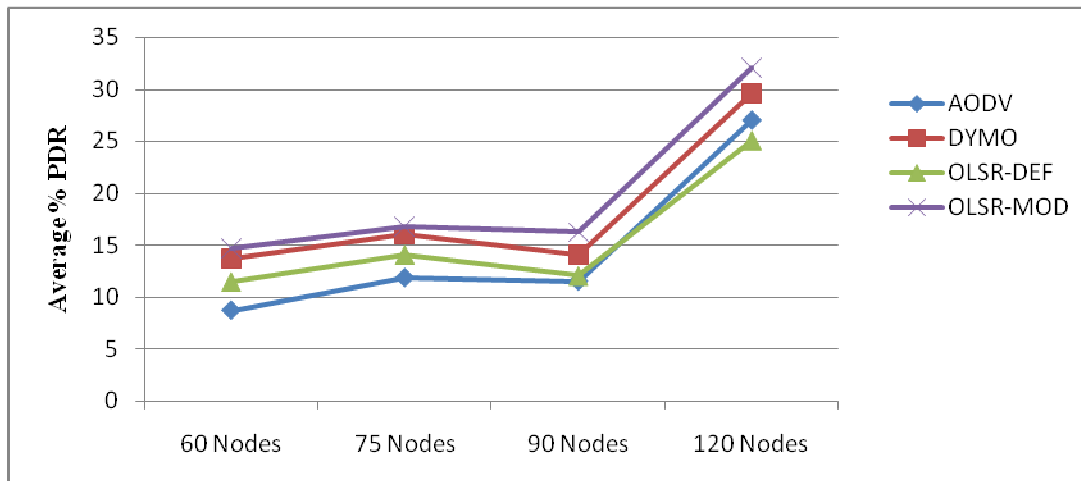
In Figure 4.25, DYMO provides better PDR than AODV and OLSR-DEF. It loses out to OLSR-MOD which uses short interval values of control messages. Between the two reactive routing protocols, DYMO is able to give better PDR than AODV.





**Figure 4. 25: Average PDR VS Communication Sessions**

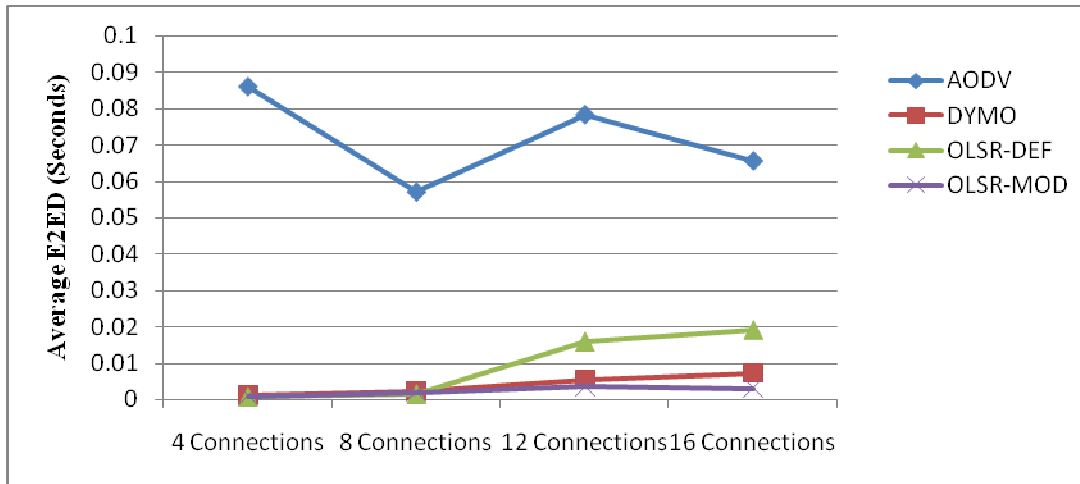
Figure 4.26 shows the PDR against node density. Similar trend is found here with OLSR-MOD providing better PDR than other routing protocols. DYMO closely follows OLSR-MOD and performs better than AODV and OLSR-DEF. It is interesting to find that in urban environments, under realistic channel conditions, AODV performed better than DYMO. While in open space highway scenario, DYMO outperformed AODV.



**Figure 4. 26: Average PDR VS Node Density**

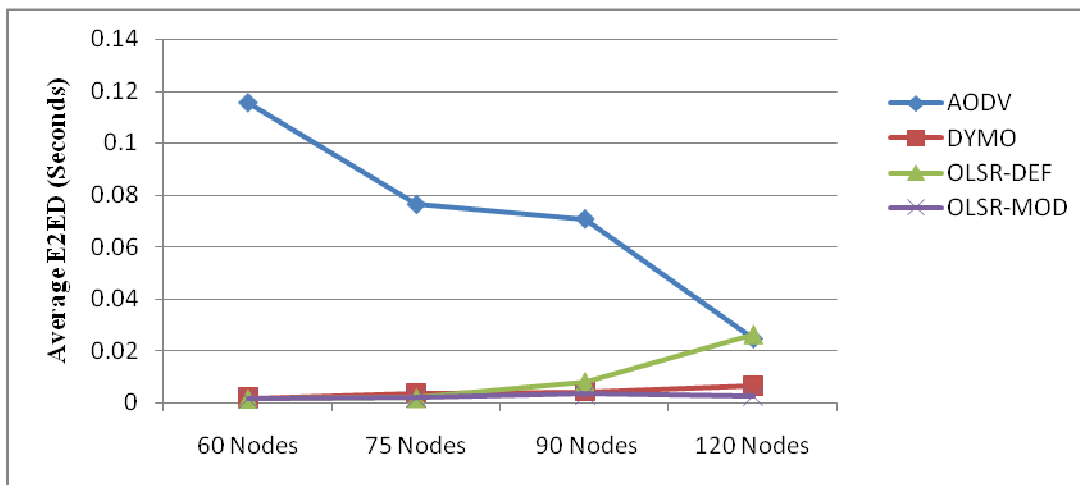
#### 4.4.2 End-to-End Delay of AODV, DYMO and OLSR

Figure 4.27 shows the average end-to-end delay of all three routing protocols.



**Figure 4. 27: Average End-to-End Delay VS Communication Sessions**

AODV does not perform well and has highest end-to-end delay as number of communication sessions increase. The end-to-end delay of OLSR-DEF and DYMO starts increasing as the communication sessions increase. OLSR-MOD gives steady end-to-end delay and the increase in communication sessions has no effect on it.



**Figure 4. 28: Average End-to-End Delay VS Node Density**

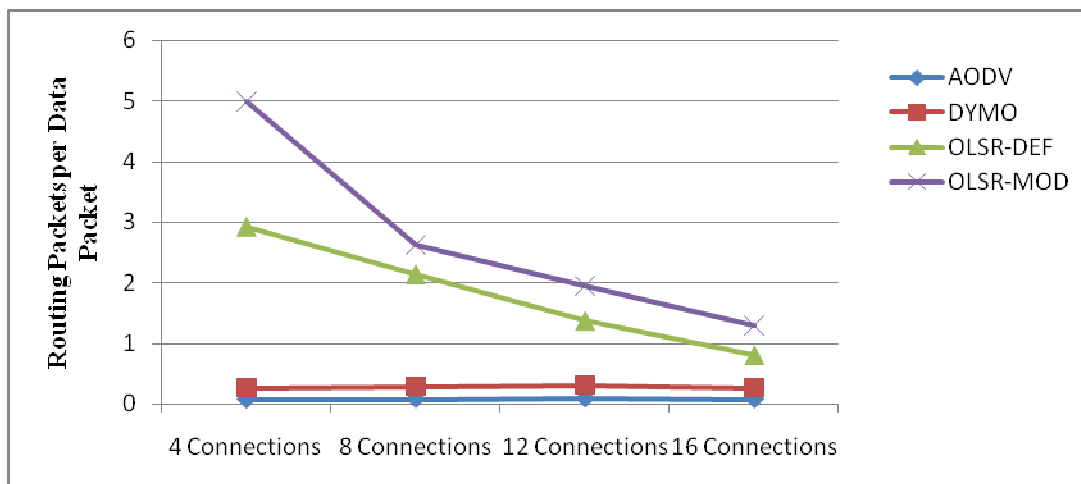
The end-to-end delay of AODV, DYMO and OLSR against node density is shown in Figure 4.28. AODV overall has high end-to-end delay than other protocols, but its end-to-end delay starts to come down as number of nodes increase in the network. End-to-end delay of OLSR-DEF also increases in this scenario when node density

increases. Possible reason for this behavior can be the delayed *Hello* and *TC* messages. However, node density has little effect on the end-to-end delay of both DYMO and OLSR-MOD routing protocols.

#### 4.4.3 Normalized Routing Overhead of AODV, DYMO and OLSR

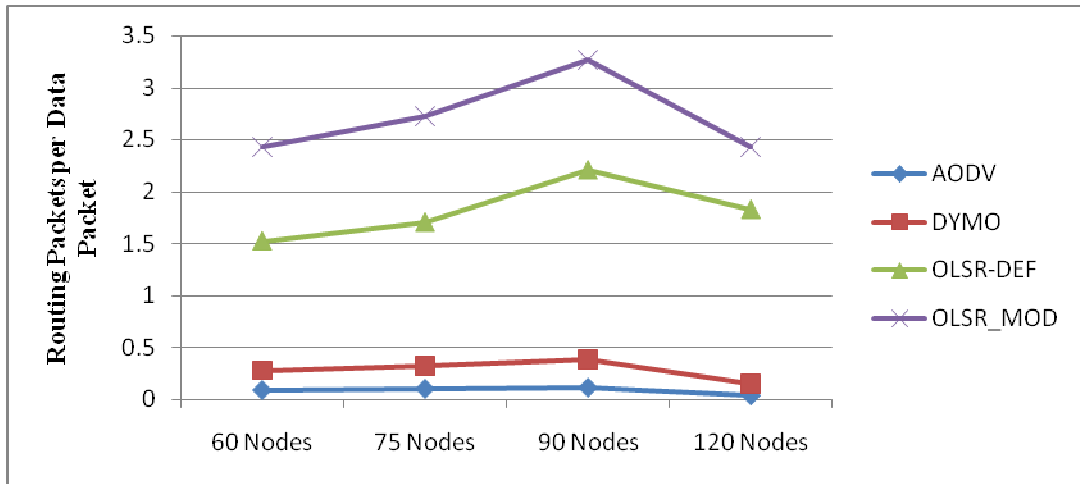
Figures 4.29 and 4.30 show the NRO of AODV, DYMO and OLSR against communication sessions and node density respectively. A similar trend, like previous scenarios, can be found here as well. Proactive routing protocols tend to generate more routing overhead than reactive routing protocols.

But when communication sessions increase in number, the NRO of proactive routing protocols starts to decrease considerably making them acceptable for situations where large number of nodes communicate with each other.



**Figure 4. 29: Normalized Routing Overhead VS Communication Sessions**

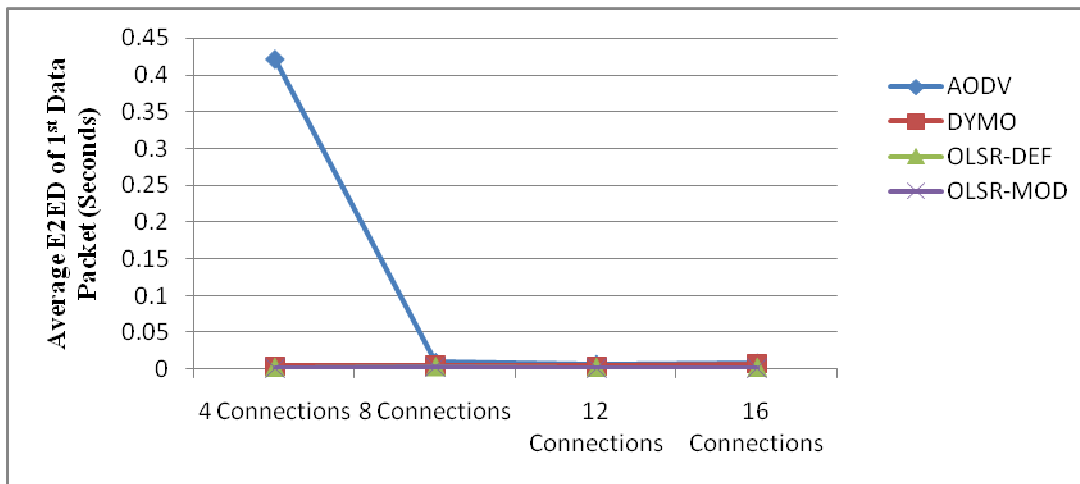
In scenarios where node density increases, like in Figure 4.30, the NRO of proactive routing protocol OLSR increases. Node density has little effect on the NRO of reactive routing protocols. The NRO of AODV is always less than DYMO in offline urban scenario. As DYMO uses path accumulation therefore, it sends more routing information in the network as compared to AODV.



**Figure 4. 30: Normalized Routing Overhead VS Node Density**

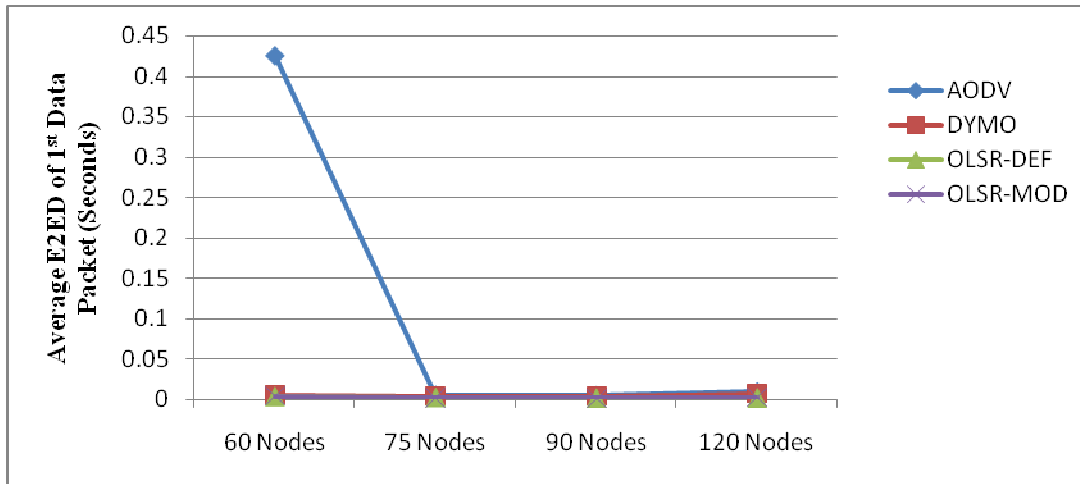
#### 4.4.4 Average End-to-End Delay of 1<sup>st</sup> Data Packet

Figure 4.31 shows end-to-end delay of 1<sup>st</sup> data packet in offline highway scenario.



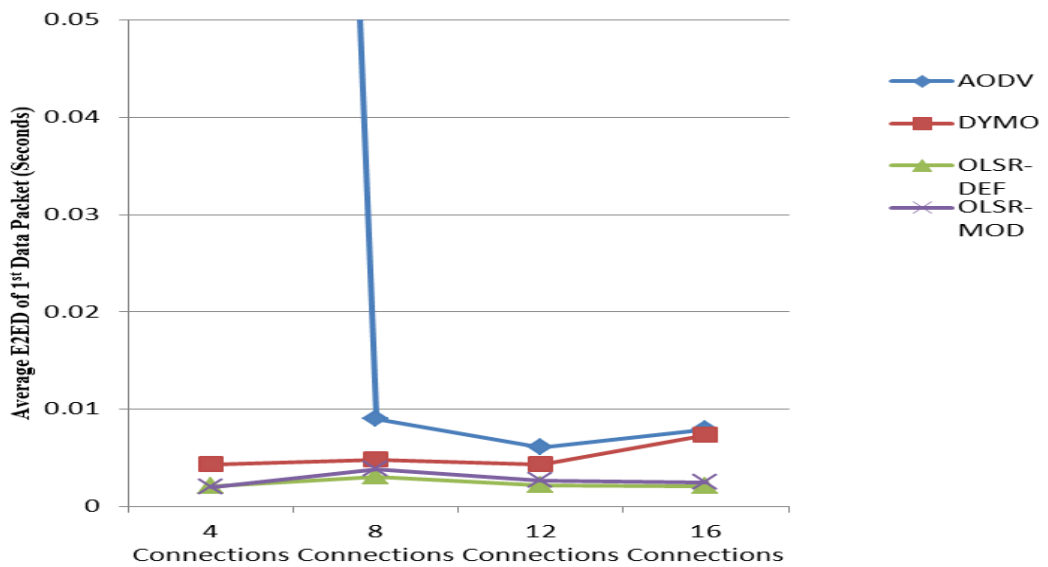
**Figure 4. 31: Average End-to-End Delay VS Communication Sessions**

In this scenario, all protocols almost take similar time to deliver 1<sup>st</sup> data packet to the destination. In one instance where AODV takes 420ms to deliver 1<sup>st</sup> data packet, other than that the time variance between AODV, DYMO, OLSR-DEF and OLSR-MOD for 1<sup>st</sup> data packet is negligible as they are pretty much the same.



**Figure 4. 32: Average End-to-End Delay VS Node Density**

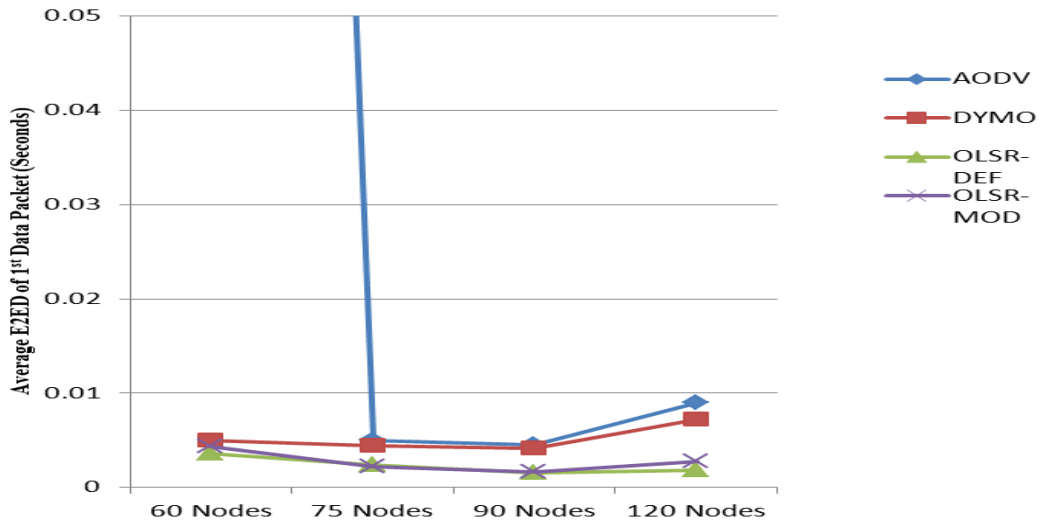
To illustrate the difference between the end-to-end delay of 1<sup>st</sup> data packets of reactive and proactive routing protocols, the figure 4.31 and 4.32 are restructured and shown in figure 4.33 and 4.34.



**Figure 4. 33: Average End-to-End Delay VS Communication Sessions**

Similar observation is made for end-to-end delay of 1<sup>st</sup> data packet when node density increases. In one instance, AODV took 425ms to deliver 1<sup>st</sup> data packet, other than that the performance of all routing protocols for this metric is almost the

same. The end-to-end delay of 1<sup>st</sup> data packet is well below 50 ms for all protocols, suggesting that the source and destination nodes are well within the transmission range of each other hence no need of routing protocols arises for 1<sup>st</sup> data packet.



**Figure 4. 34: Average End-to-End Delay VS Node Density**

In the end it is concluded that over all in all four scenarios OLSR-MOD performed better in terms of packet delivery ratio, end-to-end delay against OLSR-DEF, AODV and DYMO. However its routing overhead was consistently above OLSR-DEF and others, as the rate of its control messages was higher than its competitors.

Because of this high rate of control messages using OLSR-MOD enabled nodes to use most recent routes. This in turn led to higher PDR and lower end-to-end delay. In terms of PDR both DYMO and AODV performed second best. In all scenarios both reactive routing protocols exhibited almost similar performance in terms of PDR.

However, in situations where path accumulation property of DYMO came handy, its performance surpassed AODV. Because when link breakages were frequent, both DYMO and AODV had to initiate route discovery process many times. When

DYMO successfully used routes learned through path accumulation, it provided better PDR and less E-2ED than AODV.

**Table 4. 1: Overall summary of results**

<b>Protocols</b>	<b>PDR</b>	<b>E-2ED</b>	<b>NRO</b>	<b>E-2ED of 1<sup>st</sup> data packet</b>
<b>OLSR-MOD</b> – BDC urban – BDC highway – Offline urban – Offline highway	<b>Highest</b> <i>Highest</i> <i>Highest</i> <i>Highest</i> <i>Highest</i>	<b>Lowest</b> <i>Lowest</i> <i>Lowest</i> <i>Lowest</i> <i>Lowest</i>	<b>Highest</b> <i>Highest</i> <i>Highest.</i> <i>Highest</i> <i>Highest</i>	<b>Lowest</b> <i>Lowest</i> <i>Lowest</i> <i>Lowest</i> <i>Lowest</i>
<b>OLSR-DEF</b> – BDC urban – BDC highway – Offline urban – Offline highway	<b>Low</b> <i>Low</i> <i>Low</i> <i>Low</i> <i>Lowest</i>	<b>Low</b> <i>Lowest</i> <i>Low</i> <i>Low</i> <i>Low</i>	<b>High</b> <i>High</i> <i>High</i> <i>High</i> <i>High</i>	<b>Lowest</b> <i>Lowest</i> <i>Lowest</i> <i>Lowest</i> <i>Lowest</i>
<b>AODV</b> – BDC urban – BDC highway – Offline urban – Offline highway	<b>High</b> <i>High</i> <i>High</i> <i>High</i> <i>Low</i>	<b>Highest</b> <i>High</i> <i>Highest</i> <i>Highest</i> <i>Highest</i>	<b>Lowest</b> <i>Lowest</i> <i>Lowest</i> <i>Low</i> <i>Lowest</i>	<b>Highest</b> <i>Highest</i> <i>Highest</i> <i>Highest</i> <i>Highest</i>
<b>DYMO</b> – BDC urban – BDC highway – Offline urban – Offline highway	<b>High</b> <i>Lowest</i> <i>Low</i> <i>High</i> <i>High</i>	<b>High</b> <i>Highest</i> <i>High</i> <i>High</i> <i>Low</i>	<b>Lowest</b> <i>Low</i> <i>Low</i> <i>Lowest</i> <i>Lowest</i>	<b>High</b> <i>High</i> <i>High</i> <i>High</i> <i>High</i>

In terms of E-2ED AODV suffered the most. Because in case of link breakages AODV has no alternative routes and instead has to initiate route discovery which results in higher E-2ED. This also explains the behavior of AODV in E-2ED and E-2ED of 1<sup>st</sup> data packet graphs. Overall both reactive routing protocols gave highest end-to-end delay, so in VANET scenarios where safety critical applications operate, reactive routing protocols are not suitable choice.

AODV and DYMO give lowest NRO in all simulated scenario. Both variants of OLSR had large NRO, and consumed a part of network bandwidth. Although OLSR-MOD appears to be more suitable for safety critical applications in VANETs, even then its use is a matter of choice. If the consumption of network bandwidth is not an issue then proactive routing protocols with rapid exchange of routing information are more suitable for VANETs than reactive protocols.



# Chapter 5

## Conclusion and Future Work

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In this thesis the performance of reactive and proactive routing protocols is evaluated using two different types of simulations. One is bi-directionally coupled simulation where network and traffic simulators interact with each other at runtime to model complex scenarios like accidents etc. The second is offline simulation in which real world maps are used to model real world topologies using artificially generated movement patterns of vehicles using traffic simulator. In both simulation types urban and highway scenarios are modeled.

In the end it is concluded that traditional approach of using reactive routing protocols in VANETs is not justifiable as proactive routing protocols have performed better than reactive routing protocols in variety of scenarios. OLSR-MOD consistently performed better than all other protocols in all scenarios. It provided better PDR and end-to-end delay than its counterparts. However its routing overhead was, understandably, higher than any other protocol. OLSR-MOD worked with frequent dissemination of control information resulting in higher routing overhead. DYMO performed better in situations where its path accumulation property was used. As vehicles on roads and highways move fast there were frequent link breakages. At times the paths learned by DYMO through path accumulation were lost. Its PDR was comparable to OLSR-DEF and AODV in most scenarios. However its routing overhead was marginally higher than AODV. It was also observed that in VANETs the packet loss ratio is higher than other network types. So applications sensitive to

packet loss will not perform well with both reactive and proactive routing protocols. This case will especially hold true when VANETs are deployed in real world. Initially there will be very few vehicles equipped with VANET capabilities, making it difficult to communicate over large area. However this opens up possibility to explore avenues of either fine tuning the ad hoc routing protocols or looking for new routing paradigms like geographic routing for VANETs.

More research and developmental effort is required for bi-directional coupling of network and traffic simulators. This promising technique has made it possible to explore and model complex simulation scenarios, but as of now this technique is far from perfect. Currently, only three commands out of twelve, supported by TraCI server, are implemented in TraCI client for NS2. This clearly calls for more efforts in extending TraCI for NS2. Performance is also an issue for bi-directionally coupled simulations as they are very slow.

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