
بسم الله الرحمن الرحيم

Adaptive Routing Update Approach for VANET using Local Neighbourhood Change Information

by

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PE-083002

A thesis submitted to the
EE Department
in partial fulfillment of the requirements for the degree of
DOCTORATE OF PHILOSOPHY IN ELECTRONIC ENGINEERING

Faculty of Engineering
Mohammad Ali Jinnah University
Islamabad
April, 2014

This thesis is dedicated to Samia Rasheed (my mother), Asif Rasheed (my brother, late) and Sana Ajmal (my wife), whose continuous prayers and support assisted me to reach at this level

ACKNOWLEDGMENT

This page is intended to thankfully acknowledge Almighty Allah, my parents, Dr Amir Qayyum, my brother Asif Rasheed (late), my wife Sana Ajmal and all members of CoReNeT, who always helped me during all the difficulties while performing this tedious and time consuming research. I am also thankful to Engineer Muhammad Umair, who generously assisted me during simulation working. The completion of this thesis may not be possible without selfless support from all these fellows. The research was done in collaboration with Telecom SudParis, France under the funding platform of STIC-Asie, Government of France, for VANET Program.

ABSTRACT

Recent advances in wireless communications made it possible to consider wireless networks for connectivity at highly scalable rates. Efficiency of any wireless network primarily depends on efficiency of MAC and Routing techniques. The target of routing techniques is to efficiently find a suitable route, update it on availability of better one and then to maintain it on link breakages. Most of the current research is focused on finding and maintaining an efficient route, with very little emphasis on route update. Current route update techniques based upon proactive, reactive and their derivatives for sharing of routing metric, may not provide efficient results for the wireless networks involving large topological changes with high relative mobility and high active node density, e.g. Vehicular Ad-hoc Networks (VANETs). These networks are a specialized type of the upcoming, highly fluent, and mobile wireless networks, which present serious challenges to existing routing techniques.

In this thesis we have evaluated more than fifty routing protocols and grouped them into ten different categories. These categories are based on route determination scheme, coupled with types of routing metric and routing metric sharing schemes. Our study showed that though adaptation has been proposed by many researchers for route determination and selection procedures, routing metric sharing schemes are static in nature. Due to complexity of highly dynamic networks, current predefined and stationary route update strategies cannot work efficiently under varying node densities and fast topology changes.

After proving the justification of adaptive route update, we developed a mathematical model for runtime adaptive route update in VANETs. The model is based on varying node densities within two hop regions. After developing a model, this thesis presents a generic and adaptive route update strategy based upon runtime network conditions. Adaptation is one significant missing characteristic in our current static route update approaches. Regardless of route determination process and routing metrics being used, the proposed adaptive route update strategy can enhance efficiency of all routing protocols.

The fundamental design difference between adaptive and non-adaptive approaches is that the later demands incorporation of different factors according to the runtime network conditions. The adaptation will change the definition of ***Reactive*** by categorizing it based on ***logical conditions*** to find and update the route. Regardless of the baseline routing approach, the adaptive route update strategy can enhance the efficiency of existing routing protocols and will help in better design of future ones.

We also defined different possible VANET scenarios for highway as well as urban / city traffic conditions. We also defined different metrics & factors and showed how they can be used to implement adaptive route update strategy. At the end, we implemented the proposed scheme over Ad hoc On-demand Distance Vector (AODV) routing protocol, and named it as Adaptive AODV (AAODV). We compared AAODV against a few state of the art routing protocols, such as AODVv2, FROMR, OLSRv2 and XORi, for throughput and latency, under both highways and urban / city scenario. From the analysis of theoretical model and subsequent simulations of the proposed approach, promising improvements were observed in comparison to other route update approaches.

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LIST OF ACRONYMS

MAJU	Mohammad Ali Jinnah University
HOD	Head of Department
VANET	Vehicular Ad-hoc Network
MAC	Media Access Control
QoS	Quality of Service
PDR	Packet Delivery Ratio
IP	Internet Protocol
TCP	Transmission Control Protocol
SINR	Signal to Interference plus Noise Ratio
OLSR	Optimized Link State Routing
AODV	Ad-hoc On-demand Distance Vector
DYMO	Dynamic MANET On-demand Routing
AAODV	Adaptive Ad-hoc On-demand Distance Vector
RSU	Road Side Unit
NS2	Network Simulator version 2
NS3	Network Simulator version 3
SUMO	Simulation of Urban Mobility
GPS	Global Positioning System
CSMA	Carrier sense multiple access
Wi-Fi	Wireless Fidelity
DSRC	Dynamic Short Range Communication
RTT	Round Trip Time
ETT	Expected Transmission Time
PBR	Policy Based Routing
GPSR	Greedy Perimeter Stateless Routing for Wireless Networks
CMGR	Connectivity Aware Minimum Delay Geographic routing
VADD	Vehicle-Assisted Data Delivery
HLAR	Hybrid Location-Based Ad Hoc Routing
CAR	Connectivity Aware Routing
AMR	Adaptive Message Routing
SADV	Static-Node-Assisted Adaptive Data Dissemination
PDF	Probability Density Function

Chapter 1

INTRODUCTION

1.1. Overview

Taking into the account growth of data networks in our daily life, reliance on wireless networks is increasing manifold. Specialization and precision for different data communication requirements have changed the dynamics of wireless networks.

Wireless networks, due to their flexibility of design and topology, have thrown a plethora of challenges to the research community. We are slowly migrating to a world of abstraction, from a world where every communicating entity was pre-configured, to communicate with a limited set of other communicating entities.

Wireless ad hoc networks represent a big leap in this direction. Ad hoc is a Latin word which means ***for this purpose***. These networks are created ‘on the fly’ for special purposes, and are usually temporary in nature. The self-configuring nodes communicate directly with each other without the help of any type of infrastructure (such as routers or wireless access points). Multi-hop communication is thus a necessity in such decentralized networks. Each node forwards the data, not intended for it, thus acting as a relay or router for other nodes. Usually the nodes are also free to move around, arranging themselves in any arbitrary topology.

The research into ad hoc networks was initiated by the defence forces, to form robust, mobile and spontaneous networks in any state of affairs. The concept then started penetrating in the industrial and commercial research. The research assumed various forms like wireless mesh networks (WMNs), wireless sensor networks (WSNs), Mobile Ad hoc NETworks (MANETs) and Vehicular Ad hoc NETworks (VANETs), etc.

The research on wireless/ mobile ad hoc networks (MANETs) is fuelled by the fact that MANETs represent the most general type of wireless networks. Almost all other types of networks, including cellular, sensor, vehicular, relay, etc. can be treated as sub types of MANETs [1].

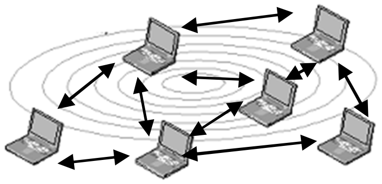

Figure 1.1 Mobile Ad Hoc Network

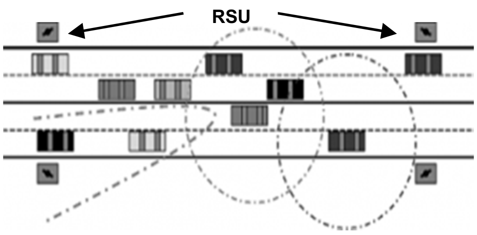

Figure 1.2 Vehicular Ad Hoc Network

Ad hoc networks are not only attractive for their ease, low cost and speed of deployment, but also for their design which makes them robust against failure. Due to non-dependence on any controlling node or infrastructure, the ad hoc networks do not fail, if any node goes out of range or fails to perform its duties.

While the idea of forming networks ‘on the fly’ is attractive, it also poses some formidable challenges to design, optimization and analysis, such as, self-routing, quality of service and distributed scheduling, etc. [1].

With the deployment of wireless infrastructures and involvement of mobility and flexibility, wireless networks are transforming more and more into hybrid networks (ad-hoc nodes using infrastructure). These hybrid networks require resourcefulness and runtime intelligence for efficiency, as compared to pure infrastructure or ad-hoc networks.

VANET uses cars as nodes to create a network. VANET turns every participating car into a wireless node to create a network. As cars may fall out of the communication range and drop out of the network, road side infrastructure units can also be used for assistance.

Most of the concerns in MANET and VANET are common in nature, with difference in details. Rather than moving at random, vehicles tend to move in an organized fashion. The interactions with roadside infrastructures can likewise be characterized fairly accurately. Similarly, most vehicles are restricted in their range of motion, for example by being constrained to follow a paved highway [2],[3],[4],[5].

Never the less, increased mobility has posed serious challenges to existing MAC and routing strategies. Specialized & mixed node deployment patterns and versatile mobility has made the problem more complicated. These network topologies which are highly fluent in nature, also involve large variations in node densities and relative node velocities. Scalability considerations of futuristic networks may require support for several thousands of nodes spanned in very large areas. QoS requirements for such multi-dimensional and complicated networks pose another challenging dimension.

In addition to this, there are many new and unique applications emerging for VANETs, such as traffic management, emergency response services, infotainment, theft detection, law enforcement, military and commercial fleet and convoy management [6],[7] etc.

VANET is one of the examples of the highly fluent wireless networks which incorporate all above stated challenges. Although, many different solutions have been presented by research community to answer the problems, consensus has developed on three major approaches, which are:

- Efficient MAC algorithms
- Efficient routing strategies
- Efficient application designs

On one hand, efficient MAC will provision maximum physical layer resources for upper layers data to provide best QoS. On the other hand, efficient applications and routing will try to use minimum network resources. This two pronged and mutually complimentary strategy, known as cross layer architecture, has opened up new dimensions and possibilities for researchers. One of the key factors for successful VANET deployment and for the effective solutions to the aforementioned problems, is the design and development of efficient routing protocols.

Routing mainly focuses on three major goals, i.e. efficiently finding most suitable route from source to destination, updating the new route at run time on availability of a better one, and lastly maintaining the route in case of route failure. Most of the current research covers the first and third goal, whereas, the second goal is generally considered as logical outcome of first one. To further clarify, we can define these goals as:

- Finding the most suitable route between sender and receiver is the pre-condition to forward any data between both nodes. This goal does not target the need of route, as route can be determined in advance, prior to emergence of need.

- Updating the in-use route to find a more efficient one, with the best route further enhancing the efficiency of any routing protocol. This goal requires determination of new and better route and then shifting to it within the lifetime of the previous route.
- Maintaining the route information on non-availability of existing route or its link breakage, this is another compulsory role of any routing protocol. The new route is determined after the expiry of previous route or due to end-to-end link failure.

To find a route between two nodes, routing algorithms currently focus on three basic questions.

- What information (metrics) should be shared for determination of route?
- How and when the selected information should be shared within the network?
- How route should be determined using the shared metric?

To answer the metric issue, many different metrics for route finding have been identified by the researchers. Subsequently, hundreds of protocols have been proposed using a single or a combination of metrics. Metrics can be grouped as localised, end-to-end and cross layer, etc.

Second issue of how to disseminate the routing information is generally simpler and researchers have considered mainly three types:

- Through sharing of repeated / automated topology beacons regardless of situation change. This approach is called periodic or proactive routing.
- Through sharing of topology updates, either for new route determination or on link breakage only. This approach is also called event triggered or reactive routing.

- Derivatives of above two approaches.

For dissemination of selected metric information from a single node perspective, choices restrict to first two only. The decision between two available choices for sharing the metric to next hop is determined by the role of said node, i.e. source node (for the data packet) or transit node (to provide route to destination). Decision for both of the roles is generally preconfigured without any significant runtime intelligence.

The third goal of how to determine the route is answered by many researchers. In the absence of any deployed VANET architecture, early research on VANET routing was based on simulation scenarios. The main goal of this research was to provide safety information to nearby vehicles. With the advancement in research, the need emerged to incorporate roadside servers and Internet. Such requirement demanded multi-hop communication and more robust routing schemes. Even early research in VANETs which was based on realistic traffic and mobility & communication constraints highlighted the limitations of many routing protocols

Adaptation in routing has also been proposed by researchers through different approaches. These schemes include multiple approaches such as:

- One simple adaptive approach is inclusion or exclusion of specific node from the route according to run time conditions. These runtime conditions include traffic load changes, mobility changes or change in node density.
- Adaptability in reactive routing protocols is also proposed through switching among pre-computed multiple routes according to run time conditions. Although in this approach, routing protocol selects best possible route to destination, however all routes are pre-computed on initial route request.
- Another approach for adaptive routing is through pro-actively updating routes using geographical locations. This approach is getting importance for large scale and rapidly changing networks.

1.2. Statement of Problem

Similar to MANET routing protocols, VANET routing protocols also use same metrics and metric sharing approaches. Hundreds of routing protocols have been proposed by the researchers for fixed as well as wireless networks [3], [4]. Current routing research is primarily focused on routing algorithms with stationary route update policy, using off-time configurations only. Regardless of the technique used for finding most suitable route, all protocols conduct their route determination and maintenance on two predefined conditions, i.e. reactive and proactive metric sharing approaches, independently or in combination of both approaches. Usual protocol behaviour obeys predefined and fixed approaches for route update, instead of analysing runtime situations.

The requirement of route update in the life time of previous route requires updated information of network conditions. For event triggered routing, route is only updated once the old route fails or a new packet exchange is initiated. Thus, considering the definition, route update is technically not possible for this class of protocols. On the other hand, periodic update approach adds significant overheads to the network traffic, owing to its design specifications. Analysis of different situations shows that third approach also does not address efficient route update and fails for highly dynamic networks. In short, the route update mechanism in the current routing approaches is generally fixed and predefined in the protocol, instead of being based on runtime network conditions.

To answer the routing challenges of dynamic networks e.g. VANET, which involve mobile wireless nodes having vast range of node densities with rapid topology changes due to high mobility and scalability, there is a need of new, more flexible and adaptive route update and maintenance strategies. These new route update strategies must work efficiently, supporting a variety of realistic node deployment patterns, mobility scenarios and QoS requirements. Accordingly, rather than maintain a route on link breakages only or updating a route by continuously sharing routing metric, there is a need to find the logical conditions to update the route. These logical conditions will provide localised adaptive strategy to ***HOW OFTEN*** share a routing metric for route update. Hence, regardless of the baseline routing approach, the adaptive route update strategy based upon runtime logical network conditions, will enhance the efficiency of existing & futuristic routing protocols.

1.3. Purpose of the Research

The objective of the research is to show the ***need and viability*** of the adaptive route update approach. In this research, we intend to define different metrics and factors along with their roles for design of adaptive route update strategies in wireless networks. Regardless of baseline routing strategy, these factors will provide a platform for more efficient route update schemes through better use of available resources in wireless networks. The goal of this research is to prove the utility of adaptive route update approach against current approaches, irrespective of how good the adaptive approach is performing.

The research will primarily target highly fluent networks, e.g. VANET. However, being generic in nature, the researched model can also benefit other classes of wireless ad-hoc networks such as Mobile Ad-hoc Networks (MANET), etc.

1.4. Applications of the Research

Our research is not targeted for any specific protocol; rather it is generic with no dependence on any routing algorithm. Regardless of any route finding technique, this research is focused on adaptive route update and maintenance strategies. Considering the fact that very little research is done for route update and maintenance strategies, the proposed modeland studied metrics & factors along with their roles will help to optimize current routing protocols and the design & development of future ones. The research made in the field will not only provide flexibility for the routing protocols, but it will also help researchers and developers to design more realistic, situation aware and adaptive routing protocols for complex mobile wireless networks.

1.5. Theoretical bases and Organization

The rest of the thesis is organized as follows: In chapter 2, the state of the art related to routing strategies is discussed. In chapter 3, we have explained adaptive route update methodology. This chapter explains the theoretical perspective of the researched model. In chapter 4, simulation analysis of adaptive route update strategy is conducted. Comparison of proposed model against some other routing protocols is also presented in this chapter. At the end we have briefly summarized the thesis followed by suggestions for the way forward.

1.6. **Summary**

Efficiency of any wireless network is primarily dependent upon efficiency of MAC and routing technique. Efficient and best route maintenance has become important for future wireless networks involving high mobility with random velocity. There is a need to optimize the route update and maintenance strategies through adaptive and generic schemes for more efficient and reliable communication in future networks.

Chapter 2

CURRENT ROUTING STRATEGIES IN VANETS

Routing protocol is one of the most important subjects of research in the domain of multi-hop networks. Regardless of the approach used, current routing algorithms are challenged by two main issues. First, what to share for topology determination, i.e. the metrics on which routing is to be based. And second, which method to use for sharing the selected information among nodes which determines when and how the routing information and topology would be exchanged.

2.1. Routing Metrics

Many different metrics for route finding have been identified by researchers. Subsequently, hundreds of protocols have been proposed using any single one or a combination of these metrics. Metrics can be grouped into three main types, localised, end-to-end and cross layer, etc. [3], [8].

Localized	End-to-End	Cross Layer	Others
Link Cost	Hop Count	SINR	Hop Count to Cluster Head
Neighbour Count	End to End Throughput	Signal Strength	Historical Flow
Actual Link Throughput	End to End Round Trip Time (RTT)	Node Energy	ETT (Expected Transmission Time)
Link Congestion	Per Hop RTT Time	Node Power	Weighted Cumulative ETT
Link Delay	End to End Jitter	Interference & Channel Switching	Expected Transmission Count
Link Packet Loss Ratio	Node Height	Doppler Shift	Effective Number of Transmissions
Link Life Time	Geographical Positions	Movement Direction	Virtual Ring Predecessor
Theoretical Bandwidth	Inter Node Distance	Node Speed	Per-hop Packet Pair

Table 2.1: Route Determination Metrics

One of the main features observed with routing protocols is that their development is typically done in the context of a particular scenario rather than generically on theoretical perspectives and mathematical models. Most of the routing protocols have been designed to solve a specific network problem or application type. As a result, no single routing approach is suitable to satisfy all network topologies and applications [9], [10], [11]. This situation becomes even more complex when researchers do not share detailed simulation scenarios, preventing open comparison with other techniques [12], [13].

Table 2.1 lists a few commonly used routing metrics. As the name suggests, localized routing metrics determine the next hop node according to metric values of neighbouring nodes only. On the other hand, end-to-end based routing compute the metric values for the entire route. Hence, the next hop node is selected on the route with best metric value. Cross layer routing metrics compute the routing parameters from layers other than network layer as well. The selected metric may have a local or global impact for the selected route. In many cases some additional hardware is required to compute the cross layer metrics. In addition to these simple classifications, a few more complex metrics have also been proposed by researchers, e.g. combination of other types and using probability behaviour of traffic, etc.

2.2. Routing Metrics Sharing Methods

Second issue of how to disseminate the routing information is generally simpler and researchers have considered mainly three types of sharing methods. These include periodic topology sharing, event based topology sharing and their derivatives. However, for dissemination of selected metric information, from a single node perspective, the choice get restricted to the first two only [14], [15]. The decision between two choices for sharing the metric to next hop is determined by role of said node, i.e. source node (for the data packet) or transit node (to provide route to destination). Both of the roles are generally preconfigured against choice decisions without any significant intelligence. The three methods for sharing of routing information are further analysed in following paragraphs.

2.2.1. Periodic Topology Sharing or Proactive Approach

In this technique, topology information metrics are shared periodically regardless of their need. Hence, routes among nodes are always maintained using periodic updates. Each node maintains a routing table using periodic metric updates received from other nodes for ready route determination. This approach has a distinct advantage of round the clock updated routing table; however this comes at the cost of higher overheads. Route maintenance or route update is based on periodic beacons after specific time intervals. The frequency of beacons differs among protocols [3], [15].

2.2.2. Event Triggered Topology Sharing or On demand or Reactive Approach

Contrary to previous approach, this scheme shares the topology information metric on need basis only. On-demand routing protocols calculate the best route on requirement only. Routing table based on shared metric continues to be maintained till requirement lasts, regardless of decrease in its efficiency or change in network topology. This approach has a distinctive benefit of lower overheads, however at the cost of limited network information at the time of need, resulting in additional delays in finding the route to destination. Route maintenance is done on link breakage or change in requirements such as QoS guarantees etc. [3], [15].

2.2.3. Topology Sharing Variants

In addition to above two basic approaches, researchers have proposed minor variations for metric information sharing procedures. The two main variations, i.e. hybrid approach and use of historical data are widely discussed in literature and are defined as following:

- Hybrid [3], [15] topology sharing approach uses combination of both periodic and event based approaches. Each originating node periodically disseminates its updated topology or metric information up to specific predefined distance or zone. Beyond this predefined zone, such information is shared on-demand basis only. The size of zone can be defined in terms of geographical distances as well as hop counts. Researchers have also proposed techniques for adaptive zoning, where zone size for periodic approach is varied according to network conditions. The performance of the protocol improves with adaptability but at the cost of computational complexities on runtime behaviour.

- History [3] oriented topology sharing technique uses different historical data to compute the best possible route. Routes are made as per need using available data for selected metrics. This historical data includes existing ongoing communication among other nodes or route request / reply messages passing through it, etc. In case of absence of relevant data, new route is established as per need using on-demand approach. Route update and maintenance is done on availability of updated data or on existing link breakage.

Protocol Name	Abbreviation	Family	Type	Route Update	Route Metric
Link Life Based Routing	LBR	Reactive	Signal Strength	Link Break	Link Life
Temporally-ordered routing algorithm	TORA	Reactive	Directed Acyclic Graph	Link Break	Node Height
Witness-Aided Routing Protocol	WAR	Reactive	Flow Oriented	Link Break	Hop Count
Adaptive On Demand Distant Vector	AODV	Reactive	Distance Vector	Link Break	Hop Count
Dynamic MANET On-demand Routing	DYMO	Reactive	Distance Vector	Link Break	Hop Count
Ad-hoc Wireless Distribution Service	AWDS	Proactive	Link state	Timed	Expected Transmission Count
Better Approach to Mobile Ad hoc Networking	BATMAN	Proactive	Distance Vector & collective intelligence	Timed	Hop Count
Cluster-Head Gateway Switch Routing Protocol	CGSR	Proactive	Distance Vector & Cluster Head	Timed	Cluster Head Hop Count
Distributed Bellman-Ford	DBF	Proactive	Bellman Ford	Timed	Link Cost
Direction Forward Routing	DFR	Proactive	GPS & Cluster Head	Timed	Cluster Head Hop Count
Destination-Sequenced Distance Vector routing	DSDV	Proactive	Bellman Ford + Sequence Number	Timed	Link Cost
Hierarchical state routing	HSR	Proactive	Hierarchical Routing & Cluster Head	Timed	Hop Count
Intra-zone Routing Protocol	IARP	Proactive	Link state & Zone Radius	Timed	Hop Count
Mobile Mesh Routing Protocol	MMRP	Proactive	Link State & Sequence Number	Timed	Hop Count
Optimized Link State Routing Protocol	OLSR	Proactive	Link State & Multi Point Relay	Timed	Hop Count
Optimized Link State Routing Protocol Version 2	OLSRv2	Proactive	Link State & Multi Point Relay	Timed	Hop Count
Topology Dissemination Based on Reverse-Path Forwarding	TBRPF	Proactive	Link State with differential Data	Timed	Hop Count
Wireless Routing Protocol	WRP	Proactive	Bellman Ford	Timed	Link Cost
Babel		Proactive	Distance Vector	Timed	Expected Transmission Count

Protocol Name	Abbreviation	Family	Type	Route Update	Route Metric
Guesswork		Proactive	Distance Vector & Cluster Head	Timed	Cluster Head Hop Count
Hazy Sighted Link State Routing Protocol	HSLS	Hybrid	Link state	Timed & Link break	Hop Count
Order One Network Protocol	OORP	Hybrid	Hierarchical Routing & Cluster Head	Timed & Link break	Link Cost
Scalable Source Routing	SSR	Hybrid	Source Routing & Virtual Ring Routing	Timed & Link break	Virtual Ring Predecessor
Zone Routing Protocol	ZRP	Hybrid	Zoning	Timed & Link break	Not Specific
Gafni-Bertsekas Routing	GB	Flow	Directed Acyclic Graph & Link Reversal	Automated Flow & Link Break	Node Height
Lightweight Mobile Routing protocol	LMR	Flow	Directed Acyclic Graph & Link Reversal	Link Break	Link Life
Link Quality Source Routing	LQSR		Weighted Cumulative Expected Transmission Time		

Table 2.2: Comparative Study of Ad Hoc Routing Protocols

As a comparison, we performed a study of different MANET routing protocols and their approaches. Although many different routing metrics have been proposed [5], [8], but only a few have actually been considered for practical protocol development and deployment as summarized in Table 2.2.

2.3. Factors Affecting Routing Strategy

The behaviour of routing algorithms varies from fixed / wired network scenarios to wireless network scenarios. The wired networks are much robust in nature due to very limited topological changes, availability of relatively high end-to-end link capacity and negligible link breakages. However, wireless networks, due to their very nature are prone to sudden topological changes, link breakages, changes in node densities and reduction in average link capacities. High and random mobility has also increased the problems manifolds. Due to large variety of wireless network scenarios, same routing protocol may not perform well in all conditions. We have studied and classified different factors which directly influence the routing strategies. The studied factors influence even before the start of route assessment and determination mechanism (routing metric as well as metric dissemination method) in wireless scenarios. As network scenarios are considerably different from each other, hence there evaluation prior to development of routing strategy is important. The factors studied are mentioned below:

2.3.1. Factor-1: Types of wireless networks

Wireless networks can be classified in three different categories according to their control configuration and accordingly have different behaviors [16], [17], [18], [19]. This factor has following sub types:

2.3.1.1.Infrastructure Based Wireless Networks

Most of the current wireless networks lie in this category, e.g. Wi-Fi, cellular data networks, WiMAX networks etc. In this type of network, network policies are mostly determined by infrastructure only. Nodes are generally not allowed to communicate directly to each other and entire communication is routed through infrastructure. Nodes directly communicate with infrastructure through single hop communication.

2.3.1.2.Ad hoc Wireless Networks

These networks are quite complicated as each node in the network enjoys equal status, e.g. wireless sensor networks and MANETs etc. In this type of network, nodes directly communicate with each other without any need of infrastructure. Nodes also provide transit paths to each other for the data dissemination in multi-hop communication. Each node requires a routing protocol to communicate with the destinations which are not directly accessible by the source.

2.3.1.3.Hybrid Wireless Networks

These networks are combination of infrastructure nodes as well as ad-hoc wireless nodes, e.g. VANETs etc. Generally, infrastructures are interconnected through high capacity links. Nodes are allowed to communicate directly as well as through infrastructure. Resultantly, ad-hoc nodes communicate to each other or to the outer world, directly or through infrastructure. Nodes also provide transit service to other nodes like they do in case of ad-hoc networks.

2.3.2. Factor-2: Types of Mobility Patterns

Mobility is a complex phenomenon for the wireless ad-hoc networks, as no single model can define the mobility pattern for all the nodes [12], [13]. Researchers have contributed in the domain through determining probabilistic behavior of the network. In general, we can segregate any node mobility as independent or dependent models [16], [21], as following:

2.3.2.1.Random Models

In this type of movement, nodes adapt absolute random behavior for mobility pattern. However, restrictions on spherical boundaries may be imposed according to practical scenarios, e.g. Random Way Point, Random Walk or movement in large halls, etc.

2.3.2.2.Models with Temporal Dependencies

This is the first type of dependent model in which nodes follow a time restricted pattern through correlation between movements at different time instants e.g. Large Café Hall, etc.

2.3.2.3.Models with Spatial Dependencies

In this second type of dependent model, mobility is adapted according to geographical limitations. Nodes in a geographic location have correlation in their movement accordingly, e.g. soldier movement, etc.

2.3.2.4.Models with Geographical Dependencies

This is the modified form of the models with spatial dependencies. In this type, nodes not only follow geographical correlation, but also remain restricted to geographical limits as nodes are bounded inside geographical areas, e.g. VANET, etc.

2.3.3. Factor-3: Types of QoS Support

The study of QoS is a longtime favorite topic among researchers as all lower layers are dependent upon improved QoS support. Researchers have even proposed cross layer applications and routing algorithms for efficient application design. The combination of QoS requirements makes the situation more complex for network designers. Mainly, QoS revolves around four different metrics [22], [23], as:

2.3.3.1. Throughput

Initial internet design evolved around more and more throughput among different nodes, e.g. data downloading or files transfer, etc. Later, the term throughput was taken over by good-put, which can be defined as throughput at application layer. A network may have good throughput, but may not have much data available for application layer due to overheads being added at lower layers.

2.3.3.2. In-Order Delivery

In addition to throughput, most data sharing applications, e.g. file downloads, demand in order delivery. This requirement is not very stringent for multimedia applications. However, error of even single bit may have serious concerns for file transfer applications.

2.3.3.3. Delay

The introduction of multimedia applications and safety related situations have added significant importance for this factor. Applications such as bidirectional audio streaming using VoIP may not give satisfactory results with significant delay, even with very good throughput. Such delay at both communicating ends may also desynchronize sender and receiver for VoIP based telephony.

2.3.3.4. Bandwidth

Bandwidth or link capacity of any link shows the data capacity which can be transferred over that link within a specific time interval. In a wireless network, bandwidth of any given link varies with change in inter-node distance and interference, etc. [20]. As these parameters vary rapidly within mobile ad-hoc networks, hence it is difficult to measure bandwidth for complete transmission lifetime. Generally, bandwidth relates to the theoretical limit of data that a link can handle on the physical layer, in the absence of any other traffic.

2.3.3.5. Jitter

Increase in multimedia applications using a variety of codec has added complexities in data provisioning with constant delay. Variation in delay (jitter) requires additional buffer space for smooth application handling. Wireless networks are logically prone to jitter due to MAC layer limitations, especially medium access and contention issues.

2.3.3.6. Reliability

Reliability or link stability is usually considered as the MAC layer metric [8]. Although, this information is often not directly available to higher network layers, same can be acquired through maintenance of logs for previous communications. Hence, it is possible to estimate the values for reliability by probing. Researchers have proposed availability of this information through radio card manufacturing standard interfaces [24].

2.3.4. Factor-4 Types of Applications based on Hop Count

The evolvement of Internet from wired domain to wireless domain has increased the need for amalgamation of computer networks to human life. Many new scenarios and applications have evolved demanding close interaction between communicating nodes and living beings. Researchers have developed scenarios where communicating nodes are attached with humans for runtime data sharing, e.g. Body Area Networks (BAN), etc. Evolution of Bio-sensor networks, VANETs, Defense Networks, etc., have given a new dimension to application data sharing approaches [5], [10]. From data dissemination perspective, we can classify the wireless network based applications as following:

2.3.4.1. Single Hop Applications

This type generally shares situation oriented data through control messages or situation updates, e.g. VANET location update etc. The data is required to be disseminated among immediate neighbours for awareness or alert through single hop broadcast. Due to nature of applications, data may have priority implementation. Such priority notification is not only required to be communicated to other end nodes for efficient handling, but to all lower layers for timely delivery to application layer.

2.3.4.2. Geo Hop Applications

The increase in mobility and demand for flexibility has stipulated change in hierarchical network topologies. In most of the scenarios where human lives interact as nodes, e.g. VANETs or BAN, etc., data is restricted to geographical regions only and generally remain within single type of networks. Due to continuous changes in node positions, geographical limitations cannot be mapped to number of hops adding significant complications. In such scenarios, use of hierarchical addressing can cause additional overheads, as hierarchical addressing is not mapped to geographical locations. Increased overheads for mapping of hierarchical addressing to geographical location can significantly reduce the available bandwidth. Researchers have proposed the use of geographical addressing for such specific network designs.

2.3.4.3. Multi Hop Applications

These are the most common type of applications, being used in MANETs. Such applications are not restricted to any number of hops or geographical regions and virtually cover the entire globe. Such applications may involve multiple networks with different resource availability. Currently, no single routing approach provides an end-to-end solution using multiple types of networks. Generally, researchers propose use of different routing approaches within and among different networks.

2.4. Network Simulators and Research Limitations

One of the main benefits of theoretical modelling against simulation studies is its clear definition of upper and lower practical bounds prior to implementation. Most of the research for MAC and routing strategies is based on routing scenarios defined in well-known and especially open source simulators [25], [26], [27]. Network simulators such as NS2, NS3 or NCTUns have peculiar programming related limitations in simulation environments, which confine performance analysis of the actual protocol being simulated. A survey on network simulators [27] identifies many significant limitations in scenarios, environments and protocol patch implementations.

Different protocols have widely been evaluated by researchers using different scenarios and environmental conditions. The fact of simulation limitations is also evident from diverse results even for same scenario and using same simulator [4], [5], [9], [10], [15], [19], [28]. Large variations among graphs for different metrics under same environmental conditions demand clear definitions, e.g. node density, velocity, delay and throughput, etc. These definitions include classifications of simulation scenarios as well as metrics for final evaluation. Lack of such definitions raises questions on viability of results. The major limitations to extreme cases of highly fluent mobile networks can be identified as follows:

2.4.1. High Scalability

The term ***highly scalable*** has now advanced beyond the scope of few hundred nodes for networks such as VANETs [13], [19]. Number of nodes in VANETs and future battle fields can be envisaged up to multiples of thousands, e.g. parking areas etc. Most of the open source simulators, e.g. NS-2[27], face compatibility issues for large scale simulations. On the contrary, ESTINet or NCTUns [27], being specifically developed for VANETs, lack support for many significant routing protocols such as OLSR. Most of the researchers when simulating scalable scenarios have considered nodes up to few hundred only, hence creating limited performance analyses for scalability [5], [27], [29].

2.4.2. High Relative Node Velocity

The term node velocity has either been confused by many or not clearly stated in their research [11], [12], [13], [14], and [15]. The term velocity or speed cannot be compared with relative mobility. Two nodes moving in same direction at high speed can be considered relatively static with respect to each other. Peculiar case of VANET covers the node velocity from as low as less than 10 kmph to 120+ kmph. The bidirectional flow of traffic doubles the relative node speed for nodes moving at same speed but in opposite directions. Flow of traffic in different lanes and specifically in urban and highway scenarios introduces large velocity variation among each other. The simulator limitations and lack of graphical user interface (GUI) and animation support makes the implementation and visualisation of realistic, accurate and high node mobility patterns quite difficult. As a result, researchers restrain themselves to relatively simpler models for simulation of routing behaviours.

2.4.3. High Active Node Density

The active node density can neither be compared with simple node density nor scalability, especially for networks like VANETs [30]. In mobile networks, there can be scenarios with very high node density but very limited number of nodes practically participating in active communication. As a test case, we can make a comparison between road blockade on a major highway and vehicles in parking area of some soccer ground. Considering the average vehicle size and inter vehicle space in static conditions, both the scenarios may have more than thousand nodes in just one kilometre area. Due to very nature of traffic jam and presence of drivers in each vehicle, each node can cause active data traffic. On the contrary, parking area may have negligible data load due to absence of drivers. Active traffic load has a direct impact on processing resources of operating system as well as simulator. Hence true and realistic behaviour of any routing protocol cannot be determined without full understanding of active node density.

2.4.4. Simultaneous Multi Data Type Behavior

For a highly fluent network, such as VANET, there can be different types of data behaviours experienced at MAC layers. Variations of single hop to multi-hop communication and diverse QoS requirements cannot be guaranteed in all scenarios of same network [31]. Similarly, many new MAC protocols support multiple data type priorities. Each data type can have different impact on MAC and especially routing strategies. The multi-type of data flows can be accessed using same resources, which include:

- Broadcast communication, e.g. routing control messages and VANET safety application messages.
- Uni-cast communication, e.g. VANET toll payment messages.
- Multicast communication, e.g. fleet management etc.

True behaviour of any network scenario cannot be ascertained without simultaneously considering data flow of all three types. The diverse nature of the data dissemination needs verification of simulation results through real time test beds or realistic emulations.

2.5. VANET Routing Surveys

Initial concept of VANET revolved around safety applications and emergency alerts for drivers. Resultantly, research for routing in VANETs started with single or few hop communication, [32], [33], [34], [35], and [36], the main goal of which was to provide safety information to nearby vehicles. With the advancement in research, the need emerged to incorporate roadside servers and Internet for management and infotainment purposes. Such requirement demanded multi-hop communication and more robust routing schemes. Accordingly, a large number of VANET protocols emerged to solve different network and application requirements. Many researchers have also performed survey of different routing protocols proposed for VANETs. Summary of a few surveys is as under:

2.5.1. Reliable Routing Protocols in Vehicular Ad Hoc Networks

Authors in [37] have described maintenance of routes as the most critical problem related to VANETs. The paper explains theoretical analysis of different routing classes for VANETs and has explained different protocols under each class.

The paper classifies VANET routing protocols based upon flooding, mobility, infrastructure, location and probability models. The paper also proposed use of different classes for single routing protocol. As a test case, mobility and probability models can be combined for more efficient routing.

Out of five suggested class, connectivity is considered as first and simplest class for routing. It is based upon communication between any pair of transmitter and receiver, e.g. AODV, etc. Flooding is considered simplest form of connectivity. Although flooding is simple to implement and efficient for alert messages, it lacks efficiency and can lead to broadcast storming. Different researchers have proposed modifications to enhance the efficiency of flooding. One of the enhancements relates to limiting broadcast to control messages only. For another enhancement, acknowledgement is used to learn about new nodes before rebroadcasting the packet.

The second proposed class relates to mobility. Mobility based routing protocols require predictive information about neighbours. Mobility based routing protocols suffers from disconnected topologies. One of the modifications proposed to enhance the life time of the link is through use of historical data and predicting accordingly. Use of information related to speed, direction and node position can also help in this regard.

Use of infrastructure for hybrid networks is the third proposed class for routing in VANETs. Authors have commented that infrastructure based routing protocols are most suitable for VANETs. However cost of infrastructure is the major hurdle in this regard. Use of public transport, such as buses etc. is suggested as alternate for infrastructure nodes. Use of roadside units for determination of general locality of other nodes is also suggested for timely sharing of updated route information. Such information is shared among infrastructures for subsequent dissemination to vehicles.

The use of geographical location is the fourth suggested class for VANET routing protocols. The prior information of other node location helps in timely route determination. However, determination of accurate node location under high mobility and its timely dissemination with minimum overheads is a significant problem. Use of road maps grid layouts, signal strength and infrastructure nodes are the modifications proposed in this regard.

Use of probability models, such as mobility models or received signal models is the fifth class for VANET routing. Prediction models are generally based upon some specific conditions; hence routing protocol is required to satisfy the target condition. In the absence of sufficient data to satisfy target conditions (e.g. disconnected topology for mobility based prediction), performance of routing protocol degrades significantly. Moreover, as the prediction is based on events rather than true measurement, such routing protocols may lack optimized solution. Use of multiple prediction models is one of the enhancements proposed in this regard. The paper concludes use of prediction models coupled with infrastructure based routing as the most realistic approach for VANETs.

2.5.2. Uni-cast Routing Protocols for Vehicular Ad Hoc Networks: A Critical Comparison and Classification.

Authors in [38] have described the factors effecting design of VANET routing protocols for uni-cast applications. Authors have considered vehicle to infrastructure (V2I), vehicle to vehicle (V2V) communication, communication paradigms and environmental constraints as the major design factors.

The paper also described the time sequence followed during the development of these protocols. After doing the classification, authors have also compared different protocols qualitatively. The paper has grouped VANET routing protocols into four categories as, MANET routing protocols adapted in VANET, position based, delay tolerant and QoS aware routing protocols. For the qualitative analysis, paper has compared fourteen different protocols for objectives, characteristics and assumptions. Paper provides following analysis from the comparison:

- V2V based routing protocols do not support delay tolerant networks.
- Delay tolerant routing protocols do not offer best route.
- Most of the routing protocols do not support efficient Internet connectivity.
- Routing protocols based on greedy forwarding and delay tolerant behaviours do not offer QoS support.
- Most of the routing protocols do not consider current traffic state while determining their routes.
- No single approach offers efficiency under varying network conditions.
- Different routing protocols can be merged to enhance the efficiency under different conditions.

After performing the analysis, paper has proposed different modifications to enhance the efficiency of VANET, such as:

- Information acquisition and dissemination related to traffic density can be decoupled from routing approaches.

- Use of long range trajectory information acquired through navigation systems can be merged with other routing approaches.

- Use of location services can be useful if added in non-location based protocols.

- Use of geographic markers and road side units can help in accurate location determination and sharing.

- Privacy and security mechanisms can be added into routing protocols for more practical deployment.

The paper mainly deals with uni-cast routing protocols. Other VANET requirements, such as multicast, information hovering, emergency broadcast etc., have not been evaluated. The paper concludes that position based routing works targets dense networks, whereas delay tolerant routing targets sparse topologies. As actual VANET scenario may face both network states simultaneously, amalgamation of different routing approaches can offer routing protocol efficiency under all conditions.

2.5.3. Routing Protocols in Vehicular Ad Hoc Networks: A Survey and Future Perspectives

Authors in [39] have compared different VANET routing protocols designed for uni-cast, multicast, geo-cast, mobi-cast and broadcast applications. Carry and forward approach used for delay tolerant network is an important consideration required in VANET. The paper has categorized VANET routing protocols for carry and forward, multi-hop forwarding and delay bounded routing.

Authors have considered network fragmentation due to rapidly changing topology, and broadcast storm as two major problems for VANET. Authors have commented that solution of these two problems with limited delay and overheads is a major research challenge while designing VANET routing protocols. Paper comments that timely forwarding considers overall network state as compared to greedy forwarding which is based upon local information only. However, timely forwarding faces increased overheads. Paper considered that most of the routing protocols either target dense networks or sparse networks. The authors have proposed that efficient VANET routing protocol must offer low overheads, minimum time cost and adaptability for both dense and sparse network. The following challenges are required to be met to enhance the efficiency of VANET:

- Designing delay bounded routing protocol for sparse networks, incorporating driver behaviour and high interference.
- Simultaneous reduction of delivery delay time packet retransmissions for delay bounded.
- A multi-source multicast/geo-cast routing for multimedia applications.
- Use of relation of messages with network topology for the multicast / geo-cast routing.
- Designing of scalable and efficient broadcast routing for comfort applications and information hovering.

While comparing the VANET routing protocols from the perspective of application requirements, authors conclude that no single routing protocols can work efficiently under dense and sparse network topologies and for different application requirements.

2.5.4. Vehicular Ad Hoc Networks (VANETs): Status, Results, and Challenges

The authors in [5] have presented a detailed review on different aspects of VANETs, such as wireless access standards, current deployments and simulation resources, followed by a few research challenges including routing. The paper analyzed that VANET has gone beyond the scope of vehicles as communicating nodes. Different products related to driver or vehicle itself has also become part of VANETs. Devices like keyless entry, mobile phones or notebooks, etc. will also use VANETs for communication. Resultantly, the communication and routing requirements will grow and become more complex than earlier envisaged.

Limited available resources, disconnected topologies and rapid topology changes have made current MANET routing protocols inefficient for VANET. Resultantly, adaptive and cross layer routing architectures amalgamating different routing approaches are need of the hour.

Broadcasting protocols in VANET environments are required to fulfill default requirement of safety applications.

Current broadcast based routing protocols do not efficiently handle broadcast storms. Moreover, current wireless communication based on IEEE 802.11 MAC is not efficient or broadcast based routing protocols due to increased collision. In addition to these protocols, new routing protocols considering distributed environment for asymmetric communications within nodes are need of efficient VANET deployment.

Efficiency in broadcast routing protocols can be introduced by reducing overheads. However, reduction in overheads leads to some other critical problems like selection of next broadcasting node etc.

2.5.5. A Comparative Study of Routing Protocols in VANET

Authors in [9] have presented analytical comparison of different VANET routing protocols. The paper also highlights different pros and cons of these protocols. It also presents the main motivation for designing these protocols. Paper comments that VANET architecture can adapt infrastructure based, ad hoc or hybrid nature varying network topologies. Authors have categorized different VANET routing protocols, as topology based, position based and broadcast based protocols. Topology and position based routing protocols primarily targets urban scenarios, whereas broadcast protocols support highway scenarios. Authors have summarized the analysis as under:-

- Delay bounded routing protocols use prior forwarding approach while forwarding the packets. On the other hand, all other routing schemes use multi hop method for forwarding the packets.

- Digital maps are necessary part of few of the cluster based routing protocols, as these maps offer traffic statistics, e.g. traffic density and node velocity etc.

- Scalability can be offered through virtual infrastructure nodes to create infrastructure based topologies.

While concluding that no current routing strategy works for all routing scenarios, authors have highlighted few challenges, related to future VANET deployments, as:

- Reliability of routing protocols by reducing packet delivery delay and retransmission.
- Consideration of drive behaviour for delay bounded routing protocols.
- Routing protocols to support comfort applications.

2.5.6. Survey of Routing Protocols in Vehicular Ad Hoc Networks

Authors in [4] have divided VANET routing protocols in two main categories as topology based and position based routing protocols. VANET was initially designed for broadcast based safety applications and have adapted multi-hop uni-cast routing protocols. The paper mainly discusses uni-cast routing protocols. Most of the topology based routing protocols were designed for MANETs. Due to obvious design variation between VANET and MANET routing topologies, most of the MANET routing protocols fail to perform under VANET. The paper has discussed the routing protocol for the roles as:

- To adapt a procedure in establishing a route,
- Decision in forwarding, and
- How to recover from routing failure.

After defining a list of routing protocols, authors have compared different routing protocols based on their type (topology based or position based), sub type (reactive or proactive, etc.), overheads, followed by mobility and propagation models. All position based protocols shared their position beacons in proactive manner. Hence, most of the position based routing protocols can be sub divided into delay tolerant and non-delay tolerant categories. However, topology based routing protocols cannot be used for disconnected topologies or delay tolerant categories.

The paper concludes that VANET routing protocols are generally designed to handle a specific network condition or a problem. Currently, literature lacks any agreed-upon standard or benchmark for performance validation of these routing protocols. Non standardization is not limited to routing protocols, but also includes simulators and simulation environment. Due to large variations in implementation procedures, some parameters cannot be directly compared.

The paper concludes that, even with significant advancement towards routing efficiency, VANET environment still lacks a benchmark routing protocol which could work under all conditions.

2.5.7. Qualitative Based Comparison of Routing Protocols for VANET

Authors in [40] have classified VANET routing protocols into six categories as Topology based, Position based, Geo-cast based, cluster based, broadcast Based and Infrastructure based protocols. Authors have considered safety applications coupled with comfort of passengers as a primary goal for VANETs. Owing to peculiar requirements of VANETs, MANET routing protocols face performance degradation in finding stable routing paths under VANET environments. The performance of any routing protocol not only depends on network topology and network conditions, but is also affected by mobility model and driving environment. Resultantly, designing of a single routing protocol for efficient handling of all applications is quite a tricky task in VANET. Through analytical study, the paper concludes that position, geo-cast and cluster based routing protocols are more suitable for VANETs.

2.5.8. VANET Routing Protocols: Pros and Cons

Authors in [41] have discussed the pros and cons of different routing approaches adapted in VANETs. After dividing the VANET routing protocols into topology based and position based routing categories, pros and cons of both categories have been discussed. The paper provides following analysis:

- The current VANET routing protocols lacks efficiency to answer all practical traffic scenarios.

- Proactive routing protocols offer low latency, but unused paths waste a significant part of the available network resources

- Reactive routing protocols offer higher resource availability, but with higher route finding latency.

- Geographic routing protocols offer simple route discovery and management. However, determination and dissemination of accurate node position is a tricky task. Moreover, sharing of such information through periodic beacons consumes sufficient bandwidth.

2.5.9. On The Performance Evaluation of VANET Routing Protocols In Large-Scale Urban Environments

Authors in [42] have performed simulative analysis of different routing protocols. The paper has discussed the effects of network topology, mobility pattern and different applications on routing protocols. The paper presents the comparison of topology based routing (AODV), position based routing (GPCR [43]), overlay routing (LOUVRE [44]) and carry-and-forward routing (VADD [45]). The comparison is performed under urban scenarios only. The authors have argued that most of the proposed VANET routing protocols are designed to target urban or highway scenarios. However, the evaluation for these protocols has not been done under realistic environments. Authors have also compared their simulation environment with a few other papers for realistic mobility, realistic topology, realistic application, simulation area and node density. The simulation is done using Nakagami propagation model using IEEE 802.11p MAC protocol. The paper presents following results:

- For low data rates, AODV showed lowest packet delivery rate, while VADD being the highest. However, on increasing the data rate, the performance of VADD deteriorated at higher rate than others.

- VADD showed highest end-to-end delay for all data rates, hence failing for applications requiring delay constraints.

- All protocols suffered significantly under disconnected network states.

2.6. **Classification of VANET Routing Approaches**

Considering the research targeted towards VANET routing the routing protocols in VANETs can be classified into the following major categories:

2.6.1. Topology based Routing Protocols

Topology based (link state and distance vector) MANET routing protocols adapted in VANET, such as AODV [46], AODVv2 (DYMO) [47], and OLSRv2 [48] etc., generally perform topology based routing. In many cases, these protocols face performance degradation issues with increased scalability and rapid link breakages [49]. However, adaptive routing with minimum overheads according to change in topology can overcome the limitations of complex networks.

2.6.1.1. Ad Hoc On-demand Distance Vector version 2(AODVv2)

The AODVv2 (formerly named DYMO) is the successor to AODV [46]. It uses on-demand, multi-hop uni-cast routing. It performs route discovery by multicasting a request message to destination. Each retransmitting node also records a route toward the originator and generates a route reply uni-cast towards backward path. Similarly, nodes receiving the route reply message records the path to originator. On link breakage, route maintenance is done through two operations. To maintain active routes, it extends route lifetimes upon successfully forwarding a packet. On link failure, route error is generated and new route discovery is performed.

2.6.1.2. Optimized Link State Routing Protocol version 2(OLSRv2)

The OLSRv2 [48] is the successor to OLSR [50]. It is a cluster head based table driven proactive protocol. It selects two cluster head or Multi Point Relays (MPRs) of its symmetrically connected two hop neighbour routers. First type, also, known as ***flooding MPRs*** is used for reduction of control message flooding. Second type, also known as ***routing MPRs*** is used for reduction of topology information. Reduction in flooding is done through control traffic flooding using hop by hop forwarding. However this flooding is done with a node, which has selected it as a flooding MPR. A router selects both routing and flooding MPRs from among its one hop neighbours connected by symmetric, bidirectional links. The difference between both OLSR versions is the flexibility and modular design using shared components, packet format, neighbourhood discovery and handling of multiple addresses & interfaces.

2.6.2. Broadcast based Routing Protocols

Broadcast based routing protocols typically flood entire networks with data required to be shared. This approach ensures delivery but can only work for small scale networks. Modification of this approach such as V-TRADE and HV-TRADE [51] limits the flooding by reorganizing the network in sub groups. However significant routing overheads for rebroadcast are their major performance limitation.

2.6.2.1.Vector Based Tracing Detection (V-Trade)

V_TRADE [51] is a node location based message broadcasting protocols. It uses GPS to determine the node position. The basic concept of V-TRADE is zoning based routing protocols. This protocol groups its neighbours into different categories according to their position and movement information. Accordingly, a subset of nodes is selected for broadcasting information within a group. Although V-TRADE enhances the efficiency of a network by reducing broadcasted messages, determination of groups and subgroups require additional overheads.

2.6.2.2.DV-CAST: Broadcasting in VANET

Distributed Vehicular Broadcast (DV-CAST) [52] is another position based routing protocol which also targets delay tolerant networks. To make the broadcasting decisions, each vehicle maintains state regarding position of neighbouring vehicles. If a vehicle receives a new broadcast message, it checks for the location of source node before further broadcast. It suppresses further message broadcast towards the position of source by using directional transmission. After broadcasting the message, respective node overhears for a period of time to ensure that the message has successfully reached other neighbours. In case no neighbour is found, message is rebroadcast till it is received by any neighbour. Accordingly, problem of disconnected networks is solved through successful retransmission.

2.6.2.3. AODV-PGB – Preferred Group Broadcasting (PGB)

AODV-PGB [53] modifies standard AODV by reducing broadcast overheads for route discovery, etc. It maintains broadcast group based on the received signal strength. Accordingly, each node determines whether to rebroadcast or not. As the selected group may not adapt the better path towards destination, hence route discovery may adapt longer path. Another drawback in the approach is packet duplication as two nodes in the preferred group can broadcast at the same time.

2.6.3. Cluster based Routing Protocols

Cluster based routing e.g. FROMR [54], XORi [55] & HCB [56] is the combination of above two techniques. In such schemes, each node designates a cluster-head within a subset of nodes. The node designated to be the cluster-head broadcasts the required packet to the cluster members. Although, these protocols answer the scalability issue, additional delays and overhead are incurred while forming and maintaining clusters.

2.6.3.1. Fast Restoration Multipath Routing (FROMR)

FROMR [54] is multipath routing based fast recovery protocol, developed using AODV design. It is targeted for rapid restoration of route through alternate path when the original path is broken. To reduce the control overheads, it divides the geographic region into grids. It selects a grid head according to criteria of longest stay inside grid. Hence it uses combination of topology based and cluster based routing.

2.6.3.2. XOR Based Routing Protocols (XORi)

The XORi [55] is 'XOR' based routing protocol based on combination of topology routing and cluster based routing. It uses the blind routing approach where the information related to the identifiers of the nodes is being used independent of any other metric. It uses variable length identifiers for each node. These identifiers are used as node identity at the network layer for routing. This protocol is targeted to high mobility conditions in VANETs.

2.6.3.3. Hierarchical Cluster Based (HCB) Routing

HCB [56] is a layered architecture, where first layer is based on nodes of same radio interface and second layer is based among nodes with duplicate interfaces. Nodes with duplicate interfaces are called Super nodes (cluster heads). Super nodes are able to communicate with each other through base stations as well. Each node is required to attach to the nearest super node to form clusters. In HCB, cluster heads periodically exchange membership information to enable inter-cluster routing, which is performed independently in each cluster.

2.6.3.4. Cluster Based Routing Protocol (CBRP)

The CBRP [57] uses the amalgamation of cluster based routing and geographic routing. The geographic region is divided into square grids. Using node position, each node selects a cluster head. The cluster head broadcasts coordinates of its grid and its location to its neighbours. RSU is preferred to be selected as a cluster head. Cluster head broadcast leaves a message while leaving the grid. An intermediate node stores it until a new cluster header is selected. Routing is done in two phases. In setup phase, cluster head is selected, whereas in steady state phase routing trees are constructed. Each node maintains a neighbourhood table to store the information about its neighbours.

2.6.3.5. Cluster Based Location Routing (CBLR)

The CBLR [58] uses concept of cluster based routing as an on demand routing protocol using node position. A cluster head in CBLR maintains a routing table to other cluster heads and cluster members. Like any other cluster based routing protocol, each node passes the data to the cluster head for destination nodes outside its own cluster. If the destination node is in the same cluster, source node sends data to the closest neighbour to the destination. Otherwise, the source stores the data packet in its buffer, and starts a timer and broadcasts Location Request (LREQ) packets. CBLR updates the location of the source and destination before each transmission.

2.6.3.6. Cluster-Based Directional Routing Protocol (CBDRP)

The CBDRP [59] uses the concept of cluster head according to movement direction of nodes. The nodes moving in same direction form a cluster. Cluster head is selected using node velocity and movement direction of the nodes. The procedure adapted for cluster head is same as CBRP. Like any other cluster based protocol, communication outside cluster is done through cluster heads.

2.6.4. Location based Routing Protocols

Location based routing protocols e.g. GSR [60] & GPSR [61], are generally claimed to be suitable for VANETs. The information of nodes all along the path reduces delay in route determination. Use of location information instead of hierarchical routing tables significantly reduces routing overheads. However, it can suffer from routing loops and disconnected network topologies. Presence of disconnected topologies towards the destination can cause a packet to travel longer route or form a loop [62]. Although, these protocols address scalability and delay in route determination issues, the lack of updated and exact location of all the nodes can degrade the routing performance [63],[64],[65].

2.6.4.1. Greedy Perimeter Stateless Routing (GPSR)

In GPSR [61], each forwarding node selects its next hop neighbour geographically closer to the destination node, also known as greedy mode. If at any hop there are no nodes in the direction of destination (local maximum) then GPSR utilizes a recovery strategy known as perimeter mode. For perimeter mode, a recovery mode is used to forward a packet to a node that is closer to the destination than the node where the packet encountered the local maximum. The packet resumes forwarding in greedy mode when it reaches a node whose distance to the destination is closer than the node at the local maximum to the destination. This approach is also called *face routing,* as the packet traverses many faces formed by nodes in the network until it reaches a node closer to the destination.

2.6.4.2. Geographic Source Routing (GSR)

The GSR [60] uses urban area street maps along with use of node locations, to overcome the disadvantages of position based routing, as in GPSR. With the help of a static street map and location information of each node, GSR computes a route to a destination by selecting next hop neighbours along the streets. The sender of a message computes a sequence of intersections that must be traversed in order to reach the destination, which is placed in the packet header. The path between the source and destination is computed using Dijkstra's shortest-path algorithm.

2.6.4.3. Greedy Routing with Abstract Neighbour Table (GRANT)

GRANT [66] uses the concept of extended greedy source routing by knowing the position of neighbours' up to a predefined number of hops. Availability of information for multi-hop neighbour allows each node to determine best possible route. The best route is selected based on distance to destination, number of hops, and the weight against shortest path. To reduce the node location overheads, GRANT adapts cluster head approach by dividing the total area into clusters. Upon receiving a location beacon, a node computes the area under cover by the broadcasting node and its immediate neighbours, thus categorizing them into different clusters.

2.6.5. Geo-cast Routing Protocols

Geo-cast routing e.g. BBR [67] is a combination of broadcast routing and position based routing. In this scheme, data is broadcasted within a specific geographical region around the source. This scheme is useful for control and safety information dissemination. However, other schemes can be used for data transmission outside geographical region. The network partitioning and mapping of geographical regions on road layout is one major limitation of this approach.

2.6.5.1. Multicast Protocol in Ad Hoc Networks Inter-Vehicle Geo-cast (IVG)

The IVG [67] protocol is designed for dissemination of safety alert within a geographical region. The *risk* area is determined in terms of driving direction and positioning of nodes. Accordingly, a multicast group is formed within risk area. For message delivery in disconnected network state, periodic rebroadcast is performed.

The rebroadcast period is calculated based on the maximum vehicle speed. IVG adapts the shortest path to risk area, by using the concept of deferring time. Hence, a vehicle which has the farthest distance to source vehicle waits for less deferring time to rebroadcast.

2.6.5.2. Distributed Robust Geo-cast Multicast Routing Protocol

The distributed robust geo-cast multicast routing protocol [68] is targeted to deliver packets to vehicles located in a specific geographical region. Accordingly, two zones as zone of relevance (ZOR) and zone of forwarding (ZOF) is defined for each geo-cast message. Each node within the ZOR is targeted to receive the packet. Whereas, each node in the ZOF forwards the geo-cast messages to nodes in the ZOR. To handle the disconnected topology issue a periodic retransmission mechanism is used.

2.6.5.3. RObust VEhicular Routing (ROVER)

ROVER [69] uses the flooding of control packets, whereas the data packets are sent through uni-cast. Each ROVER node is equipped with a GPS, a digital street map, and possesses a unique Vehicle Identification Number (VIN). ROVER also uses the concept of ZOR and ZOF. The ZOR is defined as a rectangle defined through its corner coordinates. When a message is received by any node, it accepts the message only if, at the time of the reception, it is within the ZOR. Similarly, nodes within ZOF forward the messages to nodes present within ZOR.

2.6.5.4. Spatio-temporary Multicast/Geocast Routing Protocol

The spatio-temporary multicast/geo-cast routing protocol [70] uses time factor as an additional parameter for geo-cast transmission. The distinctive feature of time factor utilization is the delivery of information to all nodes within a specific geographical region at a particular point in time. Emergency alerts based on time factor, e.g. road block etc. can use the concept for efficient handling of data.

2.6.6. Delay tolerant Routing Protocols

Delay tolerant routing e.g. VADD [45] & GeOpps [71] is generally a new concept for the nodes spread in sparse areas. As establishing an end-to-end route may not be possible in the absence of next hop neighbour under disconnected topologies, packets are buffered till availability of next hop neighbour. This approach is generally known as ***carry-and-forward*** and is proposed for highway VANET scenarios, etc.

2.6.6.1. Vehicle-Assisted Data Delivery (VADD)

VADD [45] uses the concept of carry-and-forward based on the predictable vehicle mobility, to improve routing in disconnected networks. Each forwarding node at a junction selects the next forwarding *path* with the smallest packet delivery delay. Each node is equipped with street maps showing traffic statistics such as traffic density and vehicle speed on roads at different times of the day. To keep the data transmission delay low, VADD transmits at maximum level, and if the packet has to be carried through roads, the road with higher speed is selected. The expected packet delivery delay of a path can be modelled and expressed by parameters such as road density, average vehicle velocity, and the road distance.

2.6.6.2. Geographical Opportunistic Routing (GeOpps)

GeOpps [71] uses the node position and movement direction information to select the nodes closer to the destination node. It estimates the arrival time of a packet to a destination by calculating the shortest distance to destination. If, due to mobility, any other node is found to have shorter estimated arrival time than the previous one, packet is forwarded to other node. The minimum delay used by VADD is indirectly obtained by selecting the next forwarding node whose path is closest to the destination. As GeOpps requires navigation information of each node, hence privacy of nodes is an issue, requiring further research.

2.6.7. QoS based Routing Protocols

A Quality of Service (QoS) based routing e.g. PBR [72], generally performs resource reservation prior to start of data transfer. Although such guarantees are difficult for highly dynamic networks, the probabilistic nature of VANETs supports analyses of link reliability using vehicle velocity, position and movement direction of the nodes. The probabilistic nature of nodes moving on roads, especially under highway scenarios, supported research community to propose this scheme for VANETs.

2.6.7.1.Prediction Based Routing (PBR)

The PBR [72] is focussed on providing Internet connectivity to vehicles using mobile gateways with wireless WAN connectivity. Considering the RSU deployment as a long term project, PBR targets mobile Internet gateways specifically on highway scenarios. Using GPS, each node shares its position with other nodes. Using probabilistic movement of nods on highways, PBR predicts the duration and expiration of a route to a mobile gateway. PBR predicts route failure and establishes a new route before a route failure has occurred.

2.6.7.2.GVGrid: a QoS Routing Protocol

To improve delivery delay-time and routing reliability, GVGrid [73] determines a path to destination using grid approach. A street map is divided into several grids. To find a routing path through minimum number of grids, GVGrid delivers RREQ and RREP messages through different grids. A grid is selected for next hop basing upon the direction and the distance between vehicle and street intersection. Accordingly, intermediate grids are recorded in the table if the direction of next grid is the same as current grid or the grid is nearer to the intersection. To forward a packet, a node is selected with minimum disconnections within each grid. On route error, GVGrid finds alternate node in the grid instead of finding complete route.

2.6.7.3.Delay-Bounded Routing Protocol

The delay-bounded routing protocol [74] is based on the carry-and-forward schemes for data delivery to RSU. It uses two separate algorithms D-Greedy (Delay-bounded Greedy Forwarding) and D-MinCost (Delay-bounded Min-Cost Forwarding) to determine traffic information and the bounded delay time. D-Greedy algorithm adapts only local traffic information from the map, to select the shortest path to destined RSU. D-MinCost algorithm considers the global traffic information in a city to achieve the minimum channel utilization within the constrained delay-time.

2.6.8. Overlay Routing Protocols

In overlay routing, the routing protocol operates on a set of representative nodes overlaid over network topology, e.g. GPCR [43] & CAR [75]. In the dense environment (e.g. urban scenarios), it is understandable that nodes use street junctions as decision points for subsequent selection of route. Appropriate selection of overlay map, e.g. junction points, can assist in timely delivery of data using shortest path.

2.6.8.1.Greedy Perimeter Coordinator Routing (GPCR)

The GPCR [43] uses the concept of elimination of node planarization as street map forms a planar graph. This algorithm improves upon GSR by eliminating the requirement of an external static street map for its operation. To avoid potential radio interference e.g. buildings, the typical destination-based greedy forwarding strategy is modified. Each node tries to select the next hop along roads up to junctions. At junctions, decision about next road segment is made considering the proximity to destination position. The modified routing decision keeps packets from being routed to the wrong direction. GPCR provides two heuristics to determine whether a node is a junction or not. The first heuristic uses beacon messages and determines whether a node is located at a junction or not. The second heuristic is derived from a correlation coefficient that relates a node to its neighbours.

2.6.8.2.Connectivity-Aware Routing (CAR)

The CAR [75] is an up-gradation of PGB [53] which is AODV modification for VANET. It limits the broadcast and establishes a routing path from source to destination by setting the anchor points at intermediate junctions. Each forwarding node records its identity, hop count, and average number of neighbours for route request. On return, destination chooses a routing path with the minimum delivery delay time. The nodes at junctions through which reply packet is passed, are set as the anchor points.

2.6.8.3.Landmark Overlays for Urban Vehicular Routing Environments (LOUVRE)

The LOUVRE [44] uses the concept of geo-proactive overlay routing where the sequence of overlaid nodes is determined in advance. It assumes that above a given vehicular density threshold, an overlay link remains connected regardless of the vehicular spatio-temporal distribution. Hence, most routes would partially use the same overlay links, while establishing overlay routes based on the specific density threshold. Resultantly, geo-proactive overlay routing becomes attractive as it guarantees global route optimality and reduces the delay for establishing overlay routes.

2.6.9. Infrastructure based Routing Protocols

Infrastructure or road side unit (RSU) based routing protocols, e.g. RAR [76] and MOVE [77] forms the concept of hybrid networks, where maximum reliance is given to RSU for route to destination. Each RSU, being static in nature, maintains information about other RSUs and mobile nodes directly connected to it.

2.6.9.1. Motion Vector Routing Algorithm (MOVE)

MOVE [77] is delay tolerant routing protocol based upon RSU. It uses node information related to its velocity and movement direction to select the next hop node closest to destination. Algorithm used in MOVE assumes a sparse network where rare opportunistic routing decisions are taken through prediction. In such scenarios, nodes act as a mobile router, which possess intermittent connectivity with other nodes or RSUs. To handle disconnected topology issues, a carry-and-forward approach is used. For such scenarios, MOVE predicts about the success rate of the message delivery to any neighbour at that specific instant.

2.6.9.2. Roadside Aided Routing (RAR) [76]

The RAR is a routing framework for VANETs, rather than a classical routing protocol. It uses the concept of road sectoring using RSUs. Routes are formed using RSUs as well as mobile nodes. In the absence of large scale deployment of RSUs, the performance of these frameworks or routing protocols is not very efficient.

2.7. **Adaptive Routing in VANETs**

In the absence of any deployed VANET architecture, early research on VANET routing was based on simulation scenarios. With further advancement, even research in VANETs came to be based on realistic traffic and mobility & communication constraints, which highlighted the limitations of many routing protocols [53],[78],[79],[80],[81],[82].

In the recent past, researchers have come up with the different proposals to answer the complex requirements of highly dynamic networks, such as VANETs. The salient features of a few state-of-the-art researches for adaptive routing in VANETs are described below.

2.7.1. Connectivity Aware Minimum Delay Geographic Routing with Vehicle Tracking in VANETs

The paper [83] proposes an adaptive Connectivity aware Minimum delay Geographic Routing (CMGR) protocol. Authors have considered delay as a critical metric for routing performance in urban areas, whereas, availability of next hop node is considered as major routing problem in highway communication. The proposed protocol uses delay as routing metric for route to destination under dense networks. The protocol adaptively uses link connectivity information for route selection in sparse and disconnected topologies. The protocol at each node computes a neighbour list using GPS and marks updated neighbour list on pre-loaded digital maps. Incorporation of node locations also supports delay tolerant routing in the proposed algorithm. Protocol also supports adaptive frequency for location update beacons according to node density changes.

2.7.2. ACAR: Adaptive Connectivity Aware Routing for Vehicular Ad-hoc Networks in City Scenarios

The paper [87] is outcome of a doctoral dissertation of one of the authors in the field of routing for VANETs. The authors in their research have tried to target the mobility models with spatial and geographical dependencies being followed in VANETs. The authors claimed that from the overall road map topology, VANET topology consists of one or more sub-graphs. Using the road maps, authors have proposed a scheme to select a route with the highest throughput. The proposed Adaptive Connectivity Aware Routing protocol (ACAR) performs the routing in three steps:

- Gather statistical and real-time density data through an on-the-fly density collection process.

- Within road segments, select an optimal route with the best network transmission quality.
- Select the most efficient multi-hop path in each road segment of the chosen route.

2.7.3. A New Scalable Hybrid Routing Protocol for VANETs

The paper [88] proposes a Hybrid Location-Based Ad Hoc Routing (HLAR) protocol as a combination of greedy forwarding and location information approach with reactive routing. Authors have tried to answer the problem of sudden topology changes in VANETs by using location data. The basis of the proposed approach is the literature analysis of topology based as well as geographical routing approaches. They have analyzed that topology routing may not perform well under sudden topological changes. On the contrary, geographical routing may not perform well without accurate and updated location information. Resultantly, no single approach may work efficiently in all conditions. The proposed scheme tries to follow location based routing. However, with the decrease in location information, the protocol adapts reactive routing. In the proposed approach, GPS data is used in modified AODV routing protocol to provide geographical routing. AODV routing protocol is modified in a manner that each node shares location data through routing control packets. Instead of end-to-end route repair as adapted in standard AODV, local repair is also considered as a better option in the proposed protocol.

2.7.4. Adaptive Message Routing with QoS Support in Vehicular Ad Hoc Networks

The paper [89] proposes a QoS based Adaptive Message Routing (AMR) protocol based upon local topology and location information. The proposed protocol is developed using mathematical model for connectivity probability and delay in urban scenario. Accordingly, route is determined with minimum delay using connectivity probability and hop count threshold. The proposed protocol is based on hybrid (infrastructure & ad-hoc) approach. Targeting the QoS challenges in VANETs, authors have proposed a scheme in which all nodes update their location to local infrastructure node. The routing algorithm uses the cellular design for sharing of location information to a directly or indirectly connected infrastructure node. Each node shares its updated location information with the infrastructure node of its cell. Each infrastructure node maintains the backbone routes whenever a noticeable change in the statistical location of other nodes within its cell boundary is observed. Hence, best suitable infrastructure node for each source is selected to maintain a route to the destination. The immediate location information and route discovery ensures minimum end-to-end delay with desired QoS constraints.

2.7.5. Spatial Distribution and Channel Quality Adaptive Protocol for Multi-Hop Wireless Broadcast Routing in VANET

The paper [90] proposes a distance based Distribution Adaptive Distance with Channel Quality (DADCQ) routing protocol. Authors have considered that broadcast at network or application layer can be critical due to broadcast storm problem [91]. The network environment varies significantly with change in node distribution, density and physical parameters. The proposed algorithm targeted multi-hop wireless broadcasts required for safety applications. The protocol selects next hop nodes basing on adaptive distance thresholds, which are selected according to changing network environment. Authors considered that predefined threshold values cannot perform efficiently in rapidly changing network conditions in VANETs. Improper threshold values can cause reach-ability issues. Low value can directly reduce the broadcast performance. On the other hand, high value can reduce the reach-ability. To solve this problem, authors have developed a mathematical expression for adaptive decision threshold based on neighbouring node count, clustering factor and fading parameters. The Quadrat method of spatial analysis is being proposed for computation of clustering factor.

2.7.6. Adaptive Probabilistic Flooding for Information Hovering in VANETs

The paper [97] presents an adaptive protocol for geo-cast transmission based upon epidemic routing. Instead of simple broadcast beyond geo-cast region, protocol performs probabilistic flooding to minimize the overheads. Authors have considered information hovering as a major problem in many VANET based routing protocols. In many VANET scenarios, specific information within a geo-cast region may be required to be disseminated to all nodes present for specific time duration. Similarly, disconnected nodes within some specific region may require epidemic flooding over large network. However, such scheme will cause large overheads. The protocol uses a novel concept of adaptive computation of rebroadcast probability beyond geo-cast region according to node density within geo-cast region. Bridging concept is also employed to solve the disconnected node topologies. Combination of epidemic routing with probabilistic flooding is considered to provide limited overheads with maximum reach-ability.

2.7.7. SADV: Static-Node-Assisted Adaptive Data Dissemination in Vehicular Networks

The paper [99] introduces a delay tolerant routing protocol for VANETs. As the name suggests, Static-Node-Assisted Adaptive Data Dissemination (SADV) routing protocol is based on an adaptive algorithm. Authors have proposed deployment of static (infrastructure) nodes at road crossings for store and forward concept. In the absence of any mobile node which could establish path to destination, data is stored at infrastructure node. The delayed data is passed to the next mobile node on its availability. According to the ground situations, each mobile node independently decides to pass the data packet to next hop neighbour or to infrastructure node. Each infrastructure node maintains updated QoS statistics for inter-infrastructure node communication. The statistical data is used to optimize the static route according to changing node densities. For the low node density, multipath routing is also supported to reduce the data delivery delay. The proposed protocol uses location information for a geographic-based routing protocol, where the routing decision at each vehicle or static node is based on the knowledge of its position on the street map and its communication with neighbours. Authors have designed SADV in three modules as:

- Static Node Assisted Routing (SNAR)
- Link Delay Update (LDU)
- Multipath Data Dissemination (MPDD)

2.7.8. PVA in VANETs: Stopped Cars Are Not Silent

The paper [100] suggests Parked Vehicles Assistance (PVA) as road side units for routing in VANETs. Authors have considered lack of infrastructure nodes and network portioning as major problem for routing in VANETs. VANET is generally considered free of power constraints due to availability of large sizes of rechargeable batteries. After large scale availability of VANET compliant nodes, inclusion of all VANET equipped nodes in routing processes can significantly solve disconnected networks problem. Similarly, availability of such nodes can provide more stable routes for highly fluent nodes. Deployment of standard road side units will involve huge finances and may take considerable time. The large scale availability of road side parked, garage parked and parking area vehicles can provide sufficient static infrastructure for more stable routes.

2.7.9. Introducing Lane Based Sectoring for Routing in VANETs

The paper [102] proposes a VANET routing scheme based on lane based sectoring. The authors have targeted channel access problem for large number of contending nodes under dense networks. The paper proposes a novel idea for channel access to achieve single node per time slot arrangement. Using the Differential Geographic Positioning System (DGPS), the proposed algorithm divides lane structure into grids for logical assignment of access time slots. Authors have considered that wide roads with multiple lanes can communicate to nodes present in two dimensions. This phenomenon requires logical handling of node layout. Distributing the nodes into grid and assigning time slot among grid sections can virtually remove the node contention. Grids are made in such a manner that one vehicle (maximum) is present in each grid cell. Subsequently, no two grid cells have same back off values. This ensures that only one vehicle forwards the message towards destination.

2.8. **Summary**

This chapter discusses the role of routing protocols with respect to what must be shared for creating routing tables, i.e. routing metrics, and how to share those metrics to update routing tables.

Class	Protocol	Routing approach	Use of Cross layer parameter	Routing metric	Route sharing approach
Topology based	AODV	Multi-hop uni-cast routing		Hop count	Reactive
	AODVv2 (DYMO)	Multi-hop uni-cast routing		Hop count	Modification of AODV
	OLSR	Selection of MPR		Hop Count between cluster heads	Proactive
	OLSRv2	Selection of MPR		Hop Count between cluster heads	Modification of OLSR
Broadcast based	V-TRADE	Zoning based broadcasting	Position & movement direction	Distance to destination	Proactive
	DV-CAST	Broadcast to new nodes	Position, movement direction & directional antenna	Distance to destination	Proactive
	AODV-PGB	Received signal strength	SINR	Hop count	Modification of AODV
Cluster based	FROMR	Grid based adaptive multipath routing	Position & street maps	Hop count	Modification of AODV
	XORi	Blind routing through information of the identifiers		Hop Count between cluster heads	Modification of OLSR
	HCB	Multi-interface transformation	Multiple interfaces	Hop Count between cluster heads	Proactive
	CBRP	Dividing city maps into square grids	Position & city maps	Hop Count between cluster heads	Proactive
	CBLR	Clusters according to node positions	Position	Minimum distance between cluster heads	Hybrid
	CBDRP	Cluster head according to movement direction	node velocity and movement direction	Hop Count between cluster heads	Modification of CBRP
Location based	GPSR	Greedy and face routing	Position	Distance to destination	Proactive
	GSR	Greedy and face routing	Position & city maps	Distance to destination among nodes present on streets only	Modification of GPSR
	GRANT	Extended greedy source routing among clusters	Position & city maps	Distance to destination, number of hops, and the weight against shortest path	Proactive
Geo-cast	IVG	Risk area determination according to node movement	Position, movement direction & city maps	Distance to destination zone	Hybrid
	DRGM	Zone of relevance and	Position & city maps	Distance to destination zone	Hybrid

		zone of forwarding			
	ROVER	Geometrically shaped zone of relevance and zone of forwarding	Position & city maps	Distance to destination zone	Hybrid
	STMG	Time factor based geo-cast	Position city maps & time	Broadcast	Proactive
Delay tolerant	VADD	Carry-and-forward based on the predictable vehicle mobility	Position & street maps	Minimum delay	Proactive
	GeOpps	Estimation of the arrival of time of a packet to destination by calculating the shortest distance to destination	Position & movement direction	Distance to destination	Proactive
QoS based	GVGrid	Division of a street map into several grids	Position & street maps	Inter grid distance & disconnection	Proactive
	DBR	Delay-bounded Greedy Forwarding and Delay-bounded Min-Cost Forwarding	Position	Minimum delay	Proactive
	PBR	Use of mobile gateways with wireless WAN connectivity	Position	Distance to mobile gateway	Proactive
Overlay based	GPCR	Elimination of node polarization	Position & city maps	Distance to road junction	Proactive
	CAR	Anchor Points at road junctions	Position & city maps	Hop count	Modification of AODV
	LOUVRE	Geo-proactive overlay routing	Node density	Overlay node density	Proactive
Infrastructure based	MOVE	Mobility prediction	Position & movement direction	Distance to destination	Proactive
	RAR	RSU and mobile gateways	street maps & RSUs	Distance to RSU	Reactive
Adaptive	CMGR	Use of link connectivity information for route selection in sparse and disconnected topologies	Position & city maps	Minimum delay	Proactive
	ACAR	Use of mobility models with	Position and street maps	Maximum throughput	Proactive

		spatial and geographical dependencies			
	HLAR	Combination of greedy forwarding and location information approach	Position	Minimum hops to destination	Modification of AODV
	AMR	Use of local topology and location information for connectivity probability and delay	Position	Minimum delay	Hybrid
	DADCQ	Adaptive decision threshold based upon neighbouring node count, clustering factor and fading parameters		Adaptive distance thresholds	Reactive
	APFIH	Geo-cast transmission based upon epidemic routing	Position	Broadcast	Proactive
	SADV	Deployment of static (infrastructure) nodes at road crossings for store and forward concept	Position & street maps	QoS statistics	Proactive
	PVA	Parked Vehicles Assistance as road side units	Position	Not defined	Proactive
	ILBS	Use of Differential Geographic Positioning System for division of lane structure into grids	Position	Not defined	Proactive

Table 2.3: Comparative Study of VANET Routing Protocols

Different routing metrics and sharing schemes used in wired and wireless networks have been described in this chapter for detailed evaluation of the end goal. The two basic questions, i.e. what to share, and how to share information related to route determination, are affected by different factors. The study of these factors needs classification for both questions independently. Subsequently, their types in relation to wireless networks have been discussed in detail.

After discussing the behavior of different factors for routing, the research methodology is deliberated. Due to limited test bed support for complex wireless networks, most of the current research is based on network simulators, such as NS2, NS3 and NCTUns etc. These simulators have many inbuilt limitations against realistic scenarios due to design and processing constraints. In addition to limitations related to complex topology writing, limitations related to high scalability, high active node density, nodes with high relative velocity and large variety of data flow types are prominent. The highly fluent network topologies need more directed simulation approach to ascertain the true behavior of complex network. At the end, state of the art in routing for VANETs is discussed in detail.

In this chapter, a detailed survey of VANET classifications and routing protocols is performed. Table 2.3 shows comparative study of different VANET routing protocols. VANET routing protocols can be further classified into ten different categories. However, it can be observed that all protocols share the routing metrics using reactive, proactive or their derivative approach only.

Chapter 3

JUSTIFICATION FOR ADAPTIVE ROUTE UPDATE

3.1. **Effect of Different Factors on Route Update Strategy**

We can divide the routing protocols in many groups / subgroups considering their basic algorithm and modifications proposed against other protocols. However, regardless of the algorithm used for finding most suitable and best route, all routing algorithms primarily perform route maintenance / route update on two predefined conditions only. As already explained, these conditions include repeated / automated beacons regardless of situation change and update beacons on link breakage only. These conditions are not based on network scenarios, but rather are predefined in the protocol as a static behavior, basing on simulation / test results.

Route update and maintenance is affected by many factors, such as node density, relative mobility etc. Strictly considering the route maintenance conditions only, a detailed research was done to study effects of different factors on ***Route Update Strategy***. After classifying different factors which affect routing strategies, we observed effect of different factors on route update and maintenance behavior in absolute isolation. We classified these factors as following:

3.1.1. How Topology Change (TC) Affects Route update

Mobility is the main factor which differentiates MANETs from static networks causing frequent topological changes. The change in topology demands route update to achieve efficiency, even if existing link continues. From topological change perspective, a lot of research has evolved into defining three distinctive scenarios:

- Low topological changes tend the network behaviour to become static in nature. Periodic control overheads become waste for topology changes below some threshold level ***A***. The threshold level ***A*** varies from protocol to protocol, but within this level a protocol appears relatively static. Event based update approach sufficiently maintains efficiency with minimum overheads, for low topology changes.

- Periodic update performs better for topology changes above some threshold level ***B*** but below some threshold level ***C***. In such scenarios, finding new route on emergence of need will delay the application data flow significantly.
- If topological changes are too high i.e. above threshold level ***B***, hybrid approach is suitable in many scenarios as proposed by many researchers [5],[10]. Periodic approach in such scenario will lead to unnecessary flooding in entire network and control messages seriously affects throughput.

B

$$Ru = \begin{cases} Event\ Based\ Approach(Ae),\ TC \leq A \\ Periodic\ Approach(Ap),\ A < TC \leq B,\ \ where\ (A < B), \\ Hybrid\ Approach(Ah),\ TC > B \end{cases} \quad (Eq\ 3.1)$$

3.1.2. How Zone Size Affect Route Update

The zone size within hybrid approach significantly affects route update performance. The separate study of variation in zone sizes is necessary for different factors. Appropriate zone size selection is a tricky task and is dependent on combination of threshold levels.

- Larger zone size supports the network when overall behaviour of the network is biased towards proactive approach.
- On the contrary, smaller zone size supports the network when overall behaviour of the network supports reactive approach.

3.1.3. How Relative Mobility (RM) Affect Route update

Study of ***relativity*** proves that effect of relative mobility cannot be compared with simple mobility. Relative mobility in fluent networks demands more precise evaluation of the issue as follows:

- Event based route update performs better for relative mobility below some threshold level ***C***, i.e. two nodes moving at speed of 120 kmph in same direction will have limited topology changes or static behaviour to each other.

- On contrary, periodic route update performs better for nodes with relative mobility above level ***C*** and below some threshold level ***D***, as topological changes will be too high. Two nodes moving at speed of 120 kmph but in opposite direction will have low link stability, resulting in sudden topological changes.

- Similarly high relative mobility i.e. above threshold level ***D*** will cause high topological changes. Hence, such conditions will support hybrid approach.

Resultantly, we can develop following equation:

$$Ru = \begin{cases} Ae, & RM \le C \\ Ap, & C < RM \le D, \quad where\ (C < D) \\ Ah, & RM > D \end{cases} \qquad \text{(Eq 3.2)}$$

3.1.4. How Node Density (ND) Affect Route update

From the study of queuing theory, one can draw the conclusion that packing phenomenon has direct impact on contention rate [106]. The phenomenon, if applied on MANETs, has direct impact on throughput of any network, as following:

- If network contains limited node density i.e. below threshold level ***E***, frequency of control messages will also be limited. Hence control overheads will not affect network throughput. Resultantly, periodic route update will be a better choice in such scenarios.

- Simple analytical calculations prove that flooding exponentially increases the control traffic. Similarly, increase in node density will also increase the medium contention rate. Both conditions will add delay and reduce good-put for the network. Resultantly, event based route update performs better for node density above threshold level ***E***.

Subsequently, we can develop following equation:

$$Ru = \begin{cases} Ap, & ND \leq E \\ Ae, & ND > E \end{cases} \qquad \textit{(Eq 3.3)}$$

3.1.5. Node Density in Comparison with Relative Mobility

Node density and relative mobility directly affects each other for any network topology. However the relation cannot be ascertained by considering simple mobility only.

- If node density is low e.g. nodes moving on highways, then nodes may adapt mobility at higher rate.
- Mobility tends to zero on increases in node density. Relative mobility also approaches to zero if inter node distance approaches to zero.

Considering the mutual relation of both the points, we can combine both behaviors. Using results from previous two sections, we can conclude that event based route update supports low relative mobility as well as high node density. Similarly, periodic route update supports networks with high mobility as well as low node density.

3.1.6. How Scalability Affect Route update

Regardless of routing approach, scalability or the network size (NS) has impact on control overheads, as following:

- As studied for node density, control traffic remains limited for scalability below some threshold level ***F***. Due to peculiar benefits defined earlier, periodic update performs better for networks where control traffic does not significantly affect the good put.
- On the other hand, control messages also increases with increases in scalability, which affect the overall performance of network. Hence, event based route update performs better for scalability above threshold level ***F***.

Subsequently, we can develop following equation:

$$\mathrm{Ru} = \begin{cases} \mathrm{Ap}, & NS \leq F \\ \mathrm{Ae}, & NS > F \end{cases} \qquad (Eq\ 3.4)$$

3.1.7. How Mobility Pattern Affect Route update

Basing on mobility pattern (MP), nodes can have different behaviors in a network. Although, it is difficult to quantify the randomness in mobility, however, stochastic analysis can be used to determine the same [107]. Accordingly, we can study the effect as:

- Pure random movement or mobility pattern below some threshold probability level ***G*** causes sudden topological changes in network, hence supporting periodic route update approach.

- If nodes are tagging unidirectional probabilistic movement patterns, the overall behaviour of the network will tend to be static with limited topological changes. Such scenarios will support event based route update.

- For nodes following probabilistic movement pattern with geometrical layout, one can guess the link life probability [107]. However, for such mobility pattern, the single node behaviour remains much less probabilistic as compared to overall behaviour, supporting hybrid approach.

Resultantly, we can develop following equation:

$$\mathrm{Ru} = \begin{cases} \mathrm{Ap}, & MP \leq G \\ \mathrm{Ae}, & MP > G, \ \ where\ (MobilityPattern\ =\ Unidirectional) \\ \mathrm{Ah}, & MP > G, \ \ where\ (MobilityPattern \neq Unidirectional) \end{cases} \qquad \textit{(Eq 3.5)}$$

3.1.8. How QoS Requirements Affect Route update

The type of traffic has a direct relation over network resources, which can be classified as:

- Delay and jitter sensitive traffic such as multimedia traffic, demands ready route availability round the clock. Delay in route maintenance may have significant decay in overall performance of such applications. Resultantly, periodic route update performs better for such QoS sensitive applications.

- Throughput sensitive traffic such as data download, demands minimum control traffic to keep maximum network resources for application data. Minimum overheads for event based update logically supports good-put sensitive data.

3.1.9. How Hybrid Networks Affect Route update

Hybrid networks, which are combinations of ad-hoc and infrastructure networks, change their behavior with change in the ratio of both types of networks. The Nature of any network remains ad hoc-in general, if number of infrastructure nodes remain less than the square root of number of ad-hoc nodes ***H***[16],[20], and vice versa.

- The route update strategy will follow the rules of purely ad-hoc network for number of infrastructures nodes (IN) less than threshold level ***H***, as defined in subsequent paragraphs.

- Increase in number of infrastructure nodes from threshold level ***H*** makes the network as a clustered ad-hoc network. As bulk of the flows use the infrastructure node and all nodes will be able to approach infrastructure node in limited number of hops, hybrid route update approach will support this scenario.

- If the number of infrastructures nodes increases more than threshold level ***J***, network behaviour will tend to behave like infrastructure based only. Such a network supports event based routing approach.

Resultantly, we can develop following equation:

$$\text{Ru} = \begin{cases} \text{Determined by Ad hoc network rules}, & IN < H \\ \text{Ah}, & H \le IN \le J, \ \ where\ (H < J) \textit{(Eq 3.6)} \\ \text{Ae}, & IN > J \end{cases}$$

3.1.10. How Application Behavior Affect Route Update

The uni-cast, multicast and broadcast behavior of the application directly affects the control traffic generated by other layers. Applications which require implicit control messages at frequent intervals (e.g. location beacons) may cause propagation conflict with the periodic route updates. Similarly, applications which have high priority data (e.g. safety applications) may conflict with routing updates, causing slow routing dissemination. Both types of applications are highly important for VANETs as well as troops movement in military operations.

3.1.11. How MAC Affect Route Update

Other than Physical layer parameters, Medium Access Control is the major contributor to overall throughput of the network. MAC tries to eliminate the interferers near a receiver consuming a space around a transmission region, as shown in Figure 3.1. Sphere packing, as depicted in Figure 3.2, ensures maximum possible packing of concurrent transmissions into space, such that the SINR constraint is also met. It causes direct effect on transmission capacity or spatial intensity of successful transmissions [16], [17].

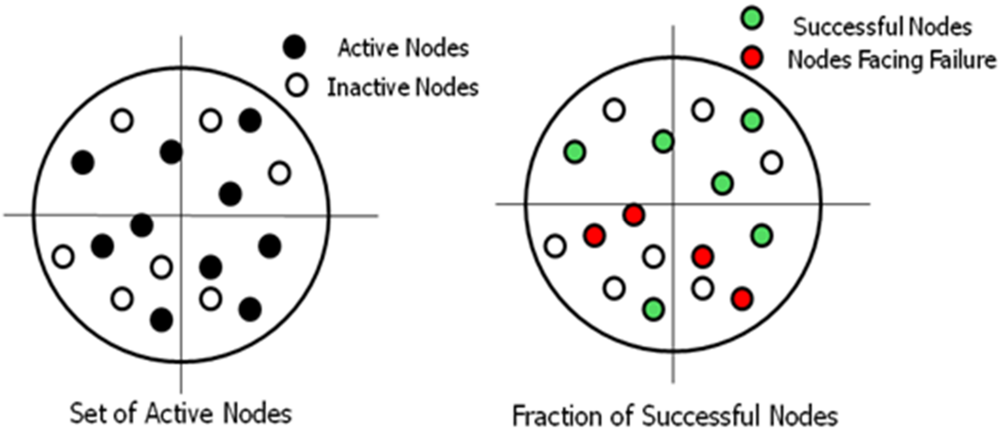

Figure 3.1: How MAC Changes the Node Geometry

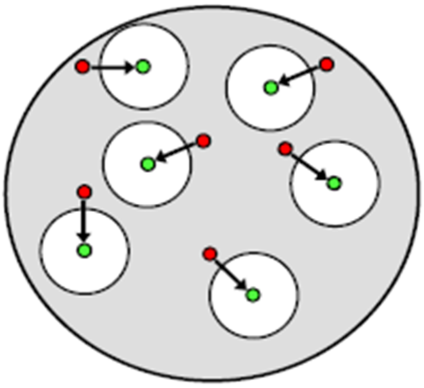

Figure 3.2: Sphere Packing due to MAC

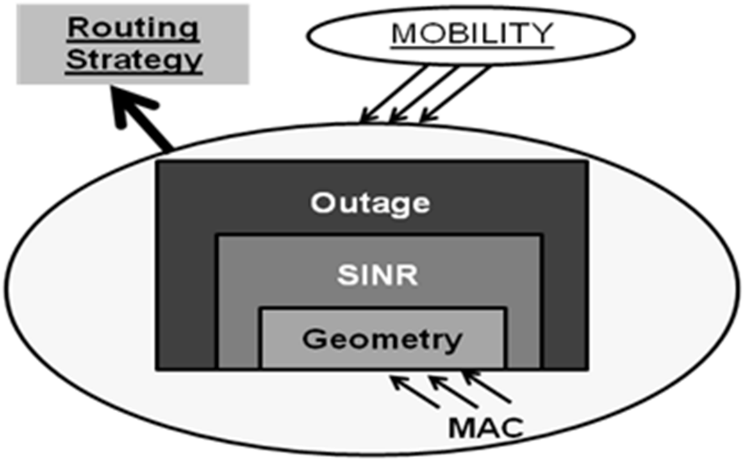

Figure 3.3: Effect of MAC on Routing Strategy

MAC affects the geometry of nodes, through which nodes are allowed to speak or remain silent. This geometry ultimately affects the SINR among the nodes as shown in Figure 3.3. In return, the changed SINR affects the outage probability which is inversely proportional to the link capacity. The mobility generates a new requirement in totality, hence affecting link capacity at the end. The link capacity is a prime network resource available with the nodes which affects upper layer payload including routing strategy.

3.2. Analytical Evaluation of Situational Topologies

Route update strategy is generally considered as the natural outcome of routing strategy. However results prove that the update strategy has very different meanings for different factors. The situation becomes more complex if cross effect of different factors is studied simultaneously. This situation demands more realistic and definite route update strategy for better usage of resources. The dynamic nature of ad-hoc and hybrid networks continuously affects the factors affecting the routing strategy. Hence route update strategy can neither be ignored nor implemented on static factors.

For proof of our claim, we analytically developed a few situations and scenarios. Subsequently, the results against preceding analysis and conclusions were verified. We have considered a highly scalable hybrid wireless network, where nodes are deployed randomly on a geometrical pattern. All nodes are moving at different speeds according to a specific geographical topology and probabilistic mobility pattern (e.g. vehicles moving on a road) with regard to direction of move and speed. All situations are sequential to each other and conditions for each scenario are explained in the subsequent parts accordingly. Our host node is maintaining data connection through infrastructure for throughput and delay sensitivity traffic.

3.2.1. Situation – 1

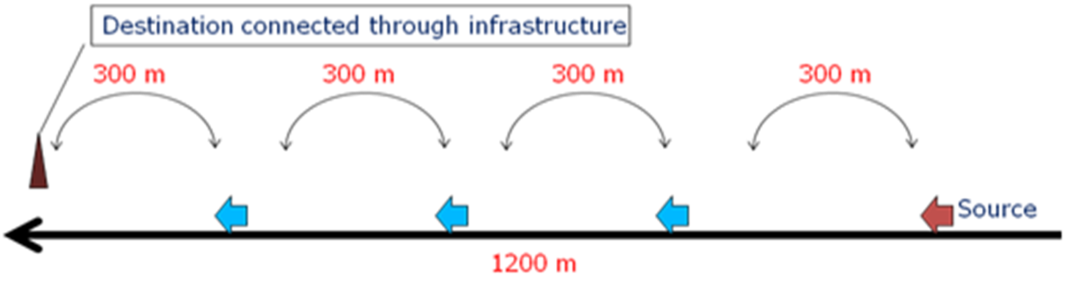

Figure 3.4: Situation 1

This scenario depicted in Figure 3.4, corresponds to a real life scenario of wireless networks having geometrically deployed nodes moving stochastically at random velocity e.g. VANETs or soldiers movement. In defined scenario of a hybrid network, multiple wireless nodes are moving in a straight line with almost constant initial inter-node distance. The velocity for each node has been defined randomly. The source node is communicating to external world through infrastructure. Being out of range of infrastructure node, source node has established a four hop link accordingly.

3.2.1.1. Node Parameters

The parameters of the scenario are as under:

- Type of Network - Hybrid
- Node Deployment - Geometrical+Poisson+Mutual Attraction Distribution
- Mobility Model - Models With Geographical Dependencies
- QoS Requirements - Throughput & Delay
- Application Hop Count- Multi-hop
- Node Velocity - Variable from 30-80 km/hr

- Maximum Hop Range - 300 meters
- Direction of Move - As per direction of Arrow
- Node Density - Low

3.2.1.2. Situation Analysis

Considering the conclusions of section 3.1 especially from source node perspective, analysis of the situation demands periodic or hybrid route update strategy as best suitable for the situation. However considering purely from source node perspective and the design of hybrid approach, initial value will lead to proactive approach, due to following reasons:

- Hybrid (clustered) deployment
- Low node density
- Low relative mobility

3.2.2. Situation – 2

This scenario corresponds to sequential changes from situation 1, where multiple wireless nodes moving on a straight line encountered a temporary blockade in their movement path. We can observe that network parameters are changing rapidly.

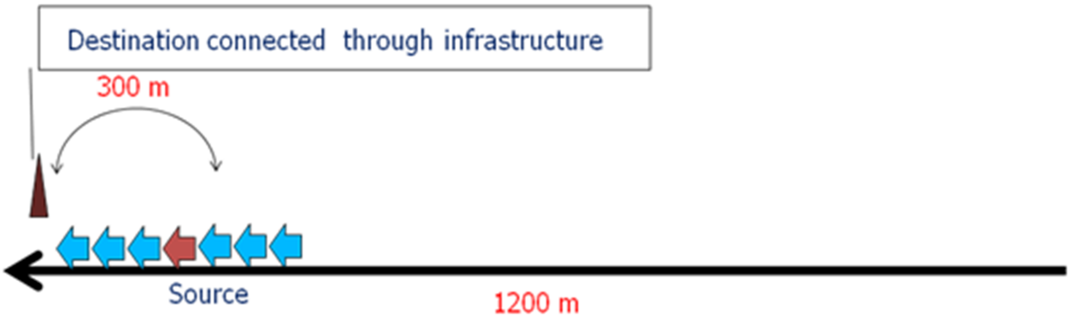

Figure 3.5: Situation 2

Figure 3.5 describes the scenario after the temporary halt being encountered by nodes. The scenario made all nodes to stop their movement gradually while approaching the blockade position. The situation changed the inter-node density due to decrease in node velocity. For a practical world, this scenario can be a traffic signal in the path of vehicles etc.

Due to decrease in inter node distance, more and more nodes are entering in one hop range of the source node. As velocity approached to zero, inter node distance became negligible, and infrastructure node along with all transit nodes in the route to infrastructure fell in direct communication from the source node.

3.2.2.1. Node Parameters

Considering this scenario in isolation from situation 1, parameters of the scenario are as under:

- Type of Network - Infrastructure
- Node Deployment - Geometrical + Mutual Attraction Distribution
- Mobility Model - Static
- QoS Requirement - Throughput & Delay
- Application Hop Count- Single-hop
- Node Velocity - 0 km/hr
- Maximum Hop Range- 300 meters
- Direction of Move - As per direction of Arrow
- Node Density - High

3.2.2.2. Situation Analysis

According to analysis of the isolated situation, event based route update strategy is best suitable for this scenario. Considering the conclusions of section 3.1, especially from source node perspective, following conditions support the decision, as:

- Infrastructure deployment

- Probabilistic movement
- High node density
- Low topological changes

3.2.2.3. Effects of Routing Update Strategy

Regardless of the approach adapted for the route update strategy in the current situation, we can observe that behavior of both periodic and event based route maintenance strategy may not give better utilization of resources. Both conditions may prove much less effective in the race towards best QoS, as under:

- If periodic route update is adapted for the overall scenario, the same strategy for regular update beacon will continue. If there is no change in node topology; periodic route update will cause high medium contention rate due to high node density, resulting drop in throughput and increase in delay. Moreover significant amount of overhead will make the conditions worst for the application.
- Although analysis demands that even based route update strategy is much better than periodic update strategy for the situation 2, but it may prove much less efficient visualizing the effects in comparison to situation 1. If event based route update strategy is adapted for the communication, source node will continue using four hops as no ***event*** has occurred with respect to existing route. The source will continue on the same route even when destination (infrastructure node) is within next hop range or in direct communication.

3.2.3. Situation – 3

This scenario corresponds to a sequential change from situation 2. Multiple wireless nodes which were moving on a straight line and encounter a temporary blockade in their movement path are now again moving on different geometrical directions following predefined paths.

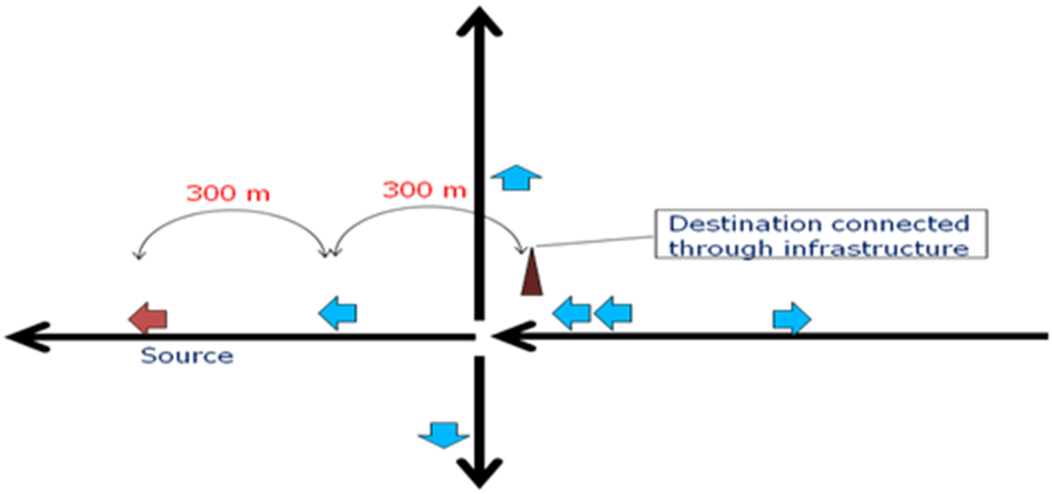

Figure 3.6: Situation 3

Figure 3.6 depicts the scenario which can be mapped to a real life scenario of road conditions immediately after a signal halt. Due to release of blockade, nodes again start moving at high random velocity. The situation again changes the inter-node density due to change in node velocity and different direction of movements.

Due to increase in relative node velocity, the node within next hop range also decreased. Considering the presence of subsequent nodes, source node is again dependent on transit nodes after going out of the range from infrastructure node. The new scenario again demands re-consideration for optimal efficiency.

3.2.3.1.Node Parameters

Considering the scenario in isolation from both of previous situations, different parameters of the scenario are:

- Type of Network - Hybrid (Clustered)
- Node Deployment - Geometrical+Poisson+Mutual Attraction Distribution
- Mobility Model - Geographical Dependencies
- QoS Requirement - Throughput & Delay
- Application Hop Count- Multi-hop

Node Velocity	-	Variable from 30-80 km/hr
Maximum Hop Range	-	300 meters
Direction of Move	-	As per direction of Arrow
Node Density	-	Low

3.2.3.2. Situation Analysis

Considering the conclusions of section 3.1, analysis of the situation dictates hybrid or periodic route update strategy as most suitable, due to following reasons:

- Hybrid deployment
- Low node density
- High relative mobility
- Rapidly changing node topology

3.3. Basic Simulation for Evaluation of Current Routing Strategies

Many researchers have claimed the effectiveness of proactive routing protocols over the reactive routing protocols for VANET [10], [108]. Proactive sharing of routing matrices, may it be hop count or node location, cause timely updates to the network for changes in topology. However, the timely update of routing metrics can cause significant overheads. To test the effectiveness of proactive routing protocols, we analysed famous OLSR [50] and OLSRv2 [48] proactive routing protocols in simple environments. First we evaluated various MAC layers for analytical and simulation analysis. Later we also measured the maximum simulative limits for these two proactive routing protocols.

3.3.1. MAC Layer Analysis

Most of the envisaged highly fluent networks e.g. VANETs are currently in research phase with relatively limited practical deployments [25], [26], and [27]. Resultantly, their implementation analyses are currently dependant on simulation results only. As proof of our claims, we analysed analytical behaviour of few network conditions, which were then affirmed by simulation results. Simple analytical assessment shows that current routing strategies have serious limitations to answer peculiarities of highly fluent networks.

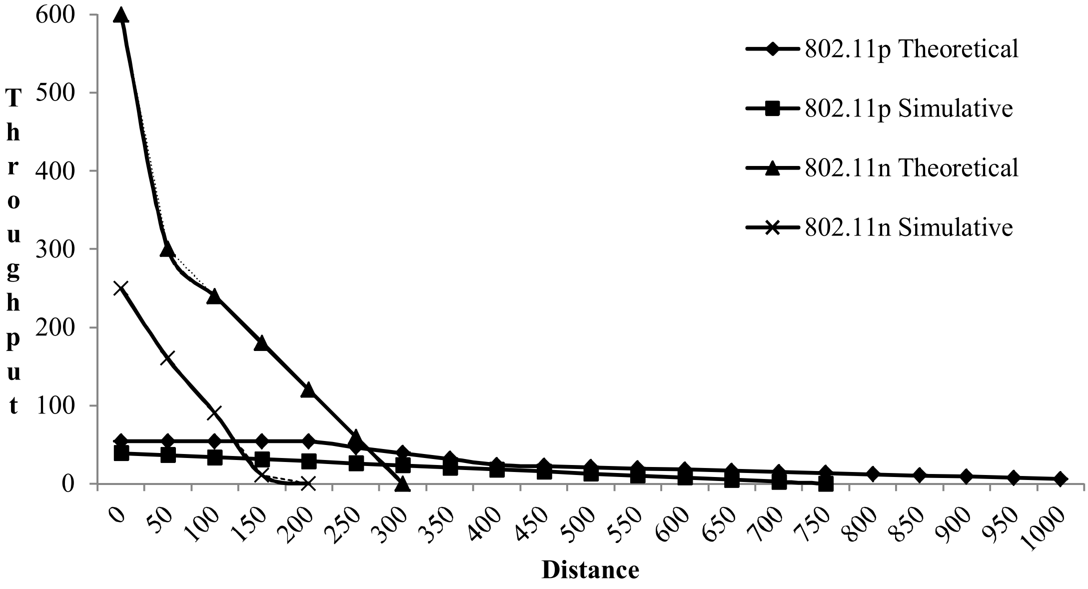

Figure 3.7: 802.11n and 802.11p without Interfering Node

We initially tested the simulation limits of two leading MAC protocols (802.11n and 802.11p) for link throughput against inter-node distance. To achieve maximum throughput, we deployed only two nodes at a distance of 1000 meters, without any interfering node. Subsequently, we moved both nodes to achieve zero distance between them. We tried to study the behaviour of MAC protocol for throughput and speed against time. Other simulation parameters we considered are as under:

- Simulator - NS2
- Initial inter node distance - 1000 meters

- Node speed - 10 kmph
- Node A move direction - Towards node B
- Node B move direction - Towards node A
- Type of traffic - UDP
- 802.11p Channel Bandwidth - 20 MHz
- 802.11n Channel Bandwidth - 40 MHz
- Horizontal Axis - Distance in meters
- Vertical Axis - Throughput in Mbps
- Fading Model - Two Ray Ground Model

Figure 3.7 shows the comparison of 802.11p and 802.11n simulation against their theoretical values [109], [110]. The x-axis shows the distance in meters between two nodes and y-axis shows the throughput in Mbps. It is evident from the situation that throughput drastically reduces with increase in distance. To achieve maximum possible throughput during simulations, node velocity was kept to lowest possible value. It can be observed that the simulation results for 802.11n are much better with respect to throughput, but its suitability for highly fluent networks, such as VANET, is questionable due to short range. On the contrary, 802.11p provides throughput up to 725 meters, however, with very minimal data value of less than 1 Mbps against theoretical limits of 6 Mbps up to 1000 meters.

3.3.2. Network Layer Analysis

For the subsequent analysis of routing protocols, we considered hypothetical ideal conditions for network layer. To test existing routing protocols for the theoretical limit of 6 Mbps at maximum distance of 1000 meters of IEEE 802.11p MAC protocol, we developed analytical model for OLSR and OLSRv2 routing protocols. We assumed highly dense network conditions, e.g. road block or parking area, where no node is communicating to any other node. However, being proactive in nature, each node is generating control traffic after regular intervals.

Hop Distance	**Link Throughput Mbps**	**Lanes**	**Total Nodes**	**Overheads For Each Node (bps)**	**Total Overheads / Hello Interval (Mbps)**	**Overheads / Second (Mbps)**	**Remaining Bandwidth (Mbps)**
300	27	3	180	17,311	3.12	1.56	25.44
300	27	4	240	23,071	5.54	2.77	24.23
600	14	3	360	34,591	12.45	6.23	7.77
600	14	4	480	46,111	22.13	11.07	2.93
1000	6	2	400	38,431	15.37	7.69	-1.68
1000	6	3	600	57,631	34.58	17.29	-11.29
1000	6	4	800	76,831	61.46	30.73	-24.73

Table 3.1 Throughput Models of OLSR & OLSRv2

From the OLSR header [48], each node within one hop region adds 128 bits for each neighbouring node to determine cluster head, also known as Multi Point Relay (MPR). Being proactive in nature, MPR detection is performed periodically according to a configurable timer. For simplicity, we ignored all other messages and application data, and just considered control messages for determination of one hop neighbour. IEEE 802.11p MAC protocol adds 34 bytes of header on each packet by keeping maximum size of 2312 bytes for a packet. To acquire ideal conditions and to keep smooth and sequential transmission of packets, we ignored network and MAC overheads, retransmissions, MAC contentions, back off delays and PHY layer frame errors. The model describes maximum theoretical throughput possible using both protocols which will further decrease significantly incorporating all realistic delays. We have considered a road blockade scenario on a highway with multiple lanes. The road block or traffic signal halt may continue from as low as one minute to hours. The halt delay will impart multiple Hello intervals. Analytical parameters for the scenario are as under:

- MAC Protocol - 802.11p
- Average Vehicle Size - 5 meters

- Hello Interval - 2 Seconds
- Road Lanes - 3, 4, 5
- Hop Distance - 300, 600, 1000 meters

The simple analytical results computed in Table 3.1 clearly show that even normal road signal halts will incorporate significant number of vehicles within next hop range. Such high node density will leave no remaining bandwidth for application data. In real life scenario, any TCP session over OLSR routing protocol will face packet retransmission and subsequently user time out [111] for high node densities, such as road blockades, signal halts and parking areas. Similarly, other proactive routing protocols will generate significant overheads for determination of neighbours under dense networks. MAC protocols with high throughput e.g. 802.11n may perform better under such conditions. However, its shorter range may prove to be a major compromise for low density scenarios such as highways in VANETs.

3.3.3. Maximum Practical Limit for OLSR

To verify the results computed for OLSR protocol under Table 3.1, we simulated the throughput of a simple topology. For the topology, two distant end nodes were deployed at distance of two hops from each other. Subsequently, we moved both end nodes towards each other to bring them in direct communication range. After reaching in next hop range to each other, we subsequently increased the neighbouring nodes causing interference to host nodes. Other simulation parameters were as under:

- Simulator - NS2
- Initial inter-node distance among end nodes - 500 meters
- Final inter-node distance among end nodes - 230 meters
- Node speed - 10 kmph
- Node A move direction - Towards node B
- Node B move direction - Towards node A

- OLSR Hello Interval - 2 seconds
- Type of traffic - UDP
- MAC Protocol - 802.11n
- MAC Protocol Channel Bandwidth - 20 MHz
- Fading Model - Two Ray Ground Model

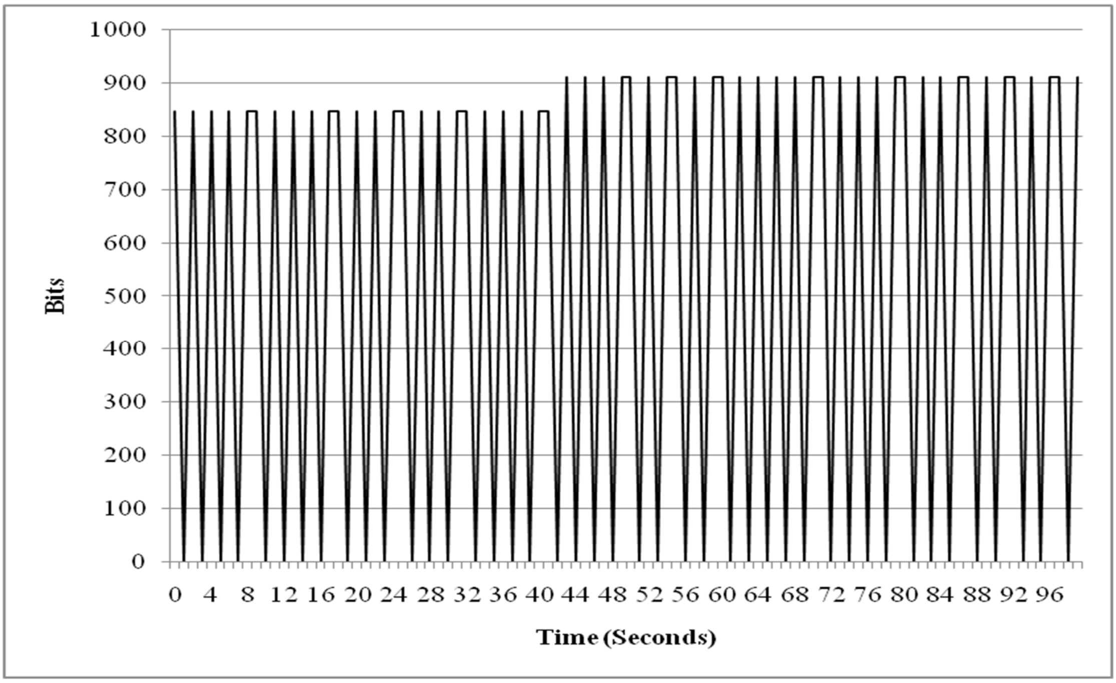

Figure 3.8: OLSR Overheads per Node (2 Nodes)

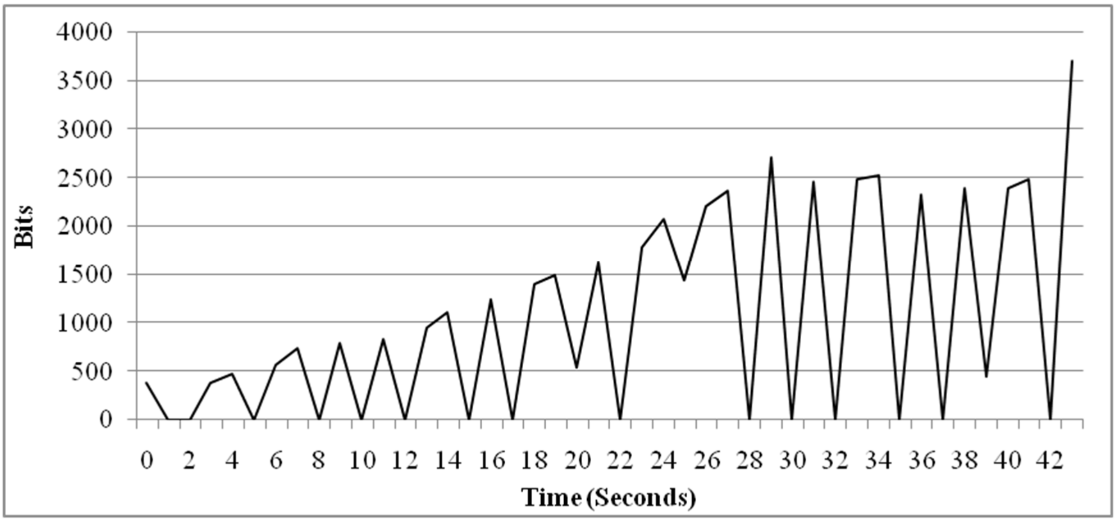

Figure 3.9: OLSR Overheads per Node (68 Nodes)

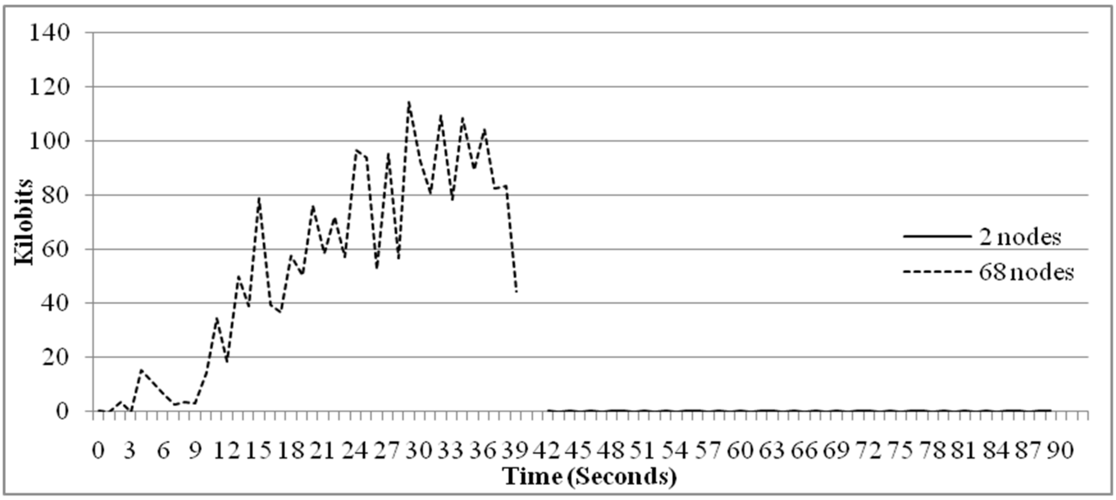

Figure 3.10: OLSR Overheads per Node (2 Nodes vs 68 Nodes)

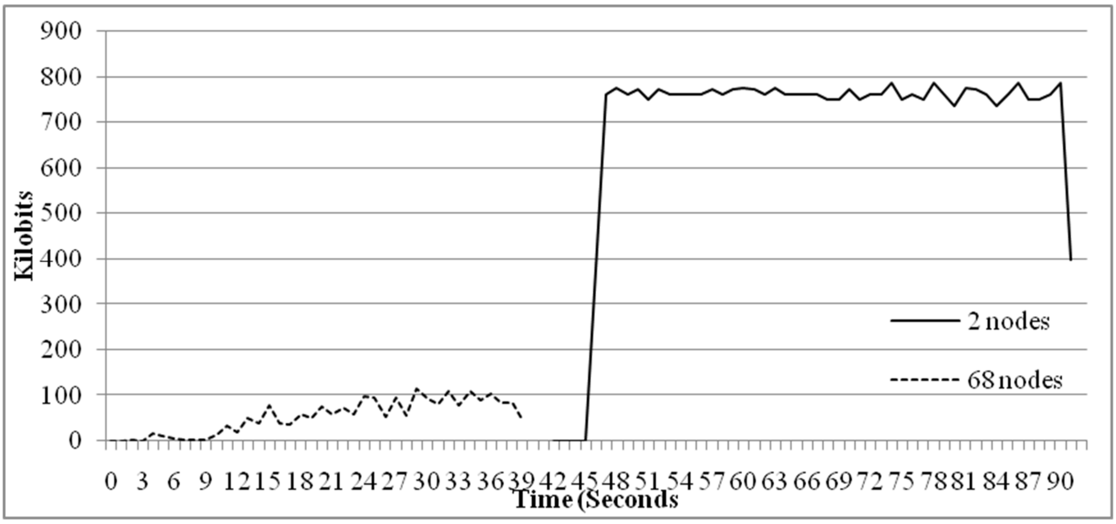

Figure 3.11: End-to-End Throughput for 2 Nodes vs 68 Nodes

Figures 3.8, 3.9, 3.10 & 3.11 show the comparison of throughput and OLSR overheads for 2 neighbours and 68 neighbours. The x-axis shows the time duration in seconds, whereas the y-axis shows overheads / throughput in Mbps. For clarity purposes, we separately studied the effect of routing overheads and total overheads. On increasing the neighbouring nodes between source and destination links, we observed drastic increase for the OLSR overheads as well as total overheads. On reaching a limit of 68 neighbouring nodes, we observed segmentation faults on few of the nodes. The segmentation fault was observed on randomly selected nodes due to lack of communication resources for OLSR packets.

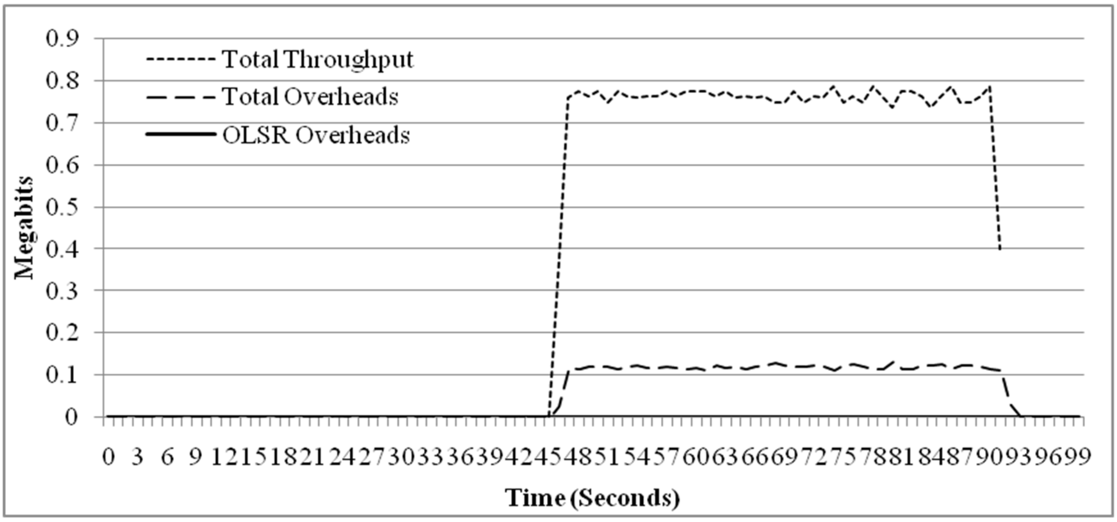

Figure 3.12: OLSR Overheads vs Total Overheads vs Total Throughput (per Node for 2 Nodes)

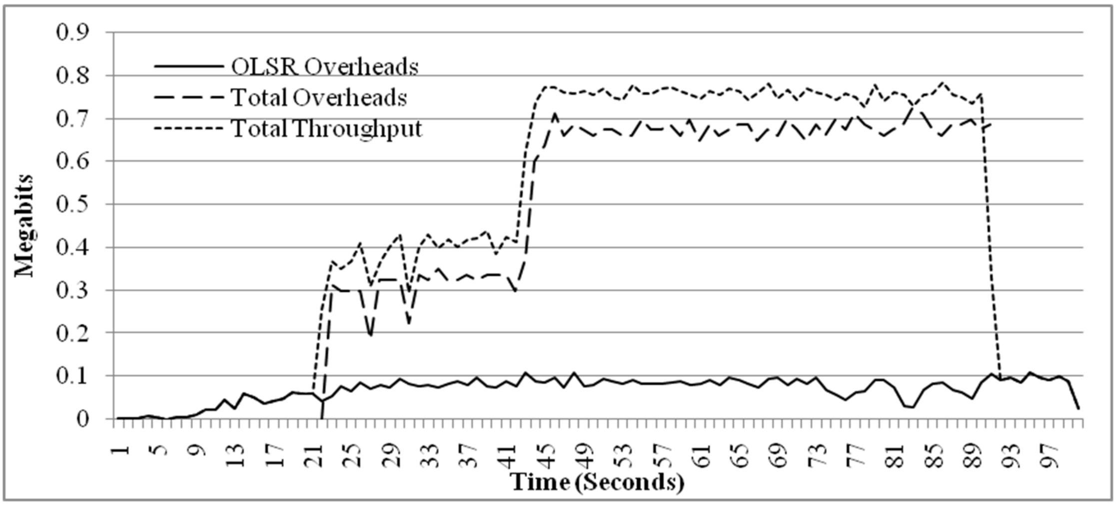

Figure 3.13: OLSR Overheads vs Total Overheads vs Total Throughput (per Node for 68 Nodes)

Figures 3.8 & 3.9 show increase in OLSR overheads with increase in neighbouring nodes. From Figure 3.10, we can observe that OLSR overheads increased approximately 100 times on increasing neighbouring nodes from 2 nodes to 68 nodes. This increase in OLSR overheads coupled with overall overheads significantly reduced the overall per node throughput for the communicating nodes.

Figures 3.12 & 3.13 show the increase of total overheads with increase in OLSR overheads. The increase in total overheads was caused due to increased transmission retires for control packets as well as data packets. Figure 3.12 shows the ratio between

OLSR overheads, total overheads and end-to-end throughput among end nodes. Figure 3.13 shows the same relation for the 68 neighbour nodes scenario. We can observe that total overheads for the 68 neighbouring nodes scenario approached to total throughput between end nodes. This increase in the total overheads for the proactive routing protocol scenario caused communication failure for few of the nodes. Due to high rate of overheads, many nodes even fail to share the control information hence facing segmentation fault in processing.

These simple analytical and simulation studies proved that our current approaches for event based or timed route update may fail badly for the simple VANET scenarios. The routine practical situations like traffic halt at signals may cause complete communication blackout for many successful proactive routing protocols, regardless of metrics (hop count or node position, etc.) being used for route determination.

3.4. **Summary**

In this chapter we highlighted the need of Adaptive Route Update. Through analytical and simulation analysis, we compared performance of different routing strategies under rapidly changing topologies. We also analyzed a few simple but realistic node topologies to ascertain the behaviour of event based and time based routing metrics sharing mechanism. The effect of excessive overheads for periodic approach and non-awareness of updated network state caused both routing protocols to be unsuitable for routing in VANETs. We proved that current static route update strategies, based on any category of routing protocol cannot perform efficiently under complex network topologies such as VANET.

Chapter 4

ADAPTIVE ROUTE UPDATE METHODOLOGY

A VANET node may also face repeated topological changes and approximately static behavior during a single data session. Contrary to the behavior of periodic and event based route update approach, we need to prove the theoretical requirements for adaptive route update. For the efficiency, each node is required to update its onward route towards destination only on two independent conditions, as following:

- When next hop neighbour is about to go out of range, or
- When second hop neighbour comes in range of the current node.

For an in depth study of both of these conditions, we need to study the combined impact of both. To proceed further towards a generic route update strategy, we need to define a simple and practical topology.

4.1. Test Link Topology

To study the need of adaptive route update according to changing topology and to evaluate the node behavior from link stability perspective, we defined a simple topology.

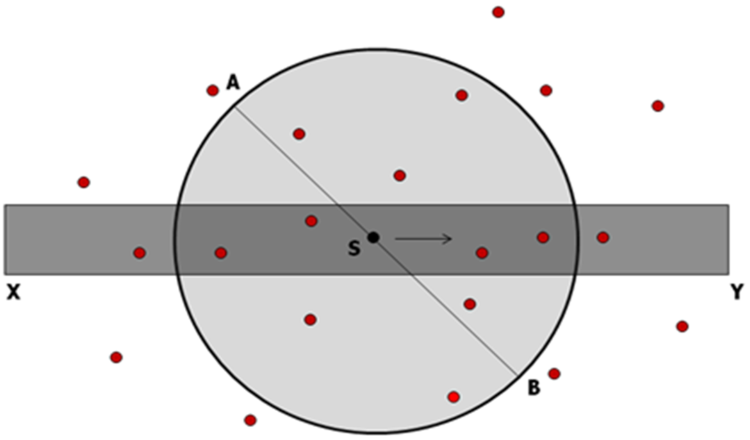

Figure 4.1 Test Nodes Deployment for a VANET Scenario

Figure 4.1 shows a simple ad-hoc network topology where source node ***S*** has next hop communication range defined by area covered by line AB. Node ***S*** exists on a road segment XY. From mobile ad-hoc network perspective, all other nodes within next hop region can be considered as neighbour nodes. Whereas, from VANET perspective, either nodes can only exist on roads or else, the nodes existing on road can be part of communication link. Nodes outside one hop region can act as 2nd or subsequent hop neighbours towards the arbitrary destination node ***D***. Direct communication between any two nodes is dependent on the link stability between them. To develop end-to-end communication link, we first need to define behaviour of two neighbours with respect to link stability.

4.2. Link Stability Conditions

The possibility of any mobile node to remain within communication range of any neighbour node depends upon two factors, as following:

- How much distance next hop neighbour node can cover relative to the host?
- In which direction the neighbour node is moving relative to host?

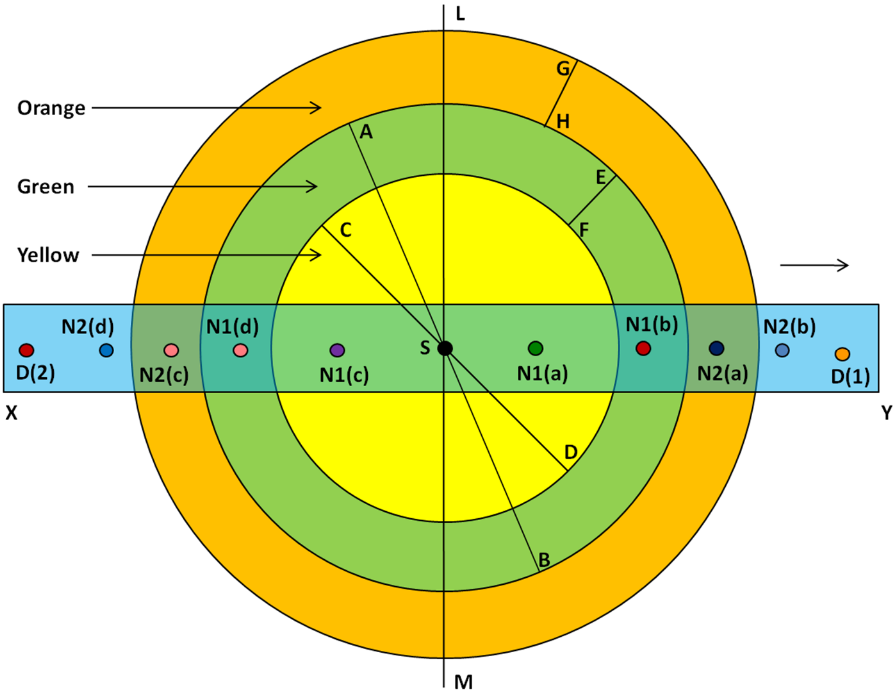

Figure 4.2 Communication Ranges for the Test Topology

Figure 4.2 defines different communication ranges with respect to the host node (source node ***S***). Let ***S*** be the host node which has data to be passed to some destination node. The data with ***S*** can either be its own or received from some previous hop neighbour. For the adaptive route update study, we considered each node to independently choose its subsequent next hop neighbour for the end destination.

From the VANET node mobility perspective, if ***S*** is moving on road segment ***XY***, then its destination can either be towards its movement of direction or against it. Accordingly, for a generic model, we considered two separate destinations according to direction of move of the node ***S***. Let D(1) be the destination node moving towards the direction of move of node ***S*** and D(2) be the destination node moving against its the direction of node ***S***. N1(a, b, c & d) are the next hop neighbours and N2(a, b, c & d) are the second hop neighbours of node ***S***. For further study, we have following assumptions:

- Let ***S*** be the target (source) node moving left to right.
- Line ***AB*** is the diameter of the one hop region of the node ***S***. The colour regions around ***S*** will be defined in subsequent paragraphs.
- The arbitrary destination node is away from source ***S*** involving multi-hop communication.
- We assumed two separate topologies. First topology involves node distribution all around the source as in MANET. Whereas the second topology considers a VANET scenario involving road segment strip ***XY*** carrying all nodes.
- Area under consideration for both topologies contains nodes with uniform density and Poisson Point distribution.
- Considering overall scenario with uniform node density, equal numbers of nodes are present in all lanes. Resultantly, node topology is tagging Gaussian curve for movement pattern.

- To consider maximum nodes according to real life limitations, the road segment ***XY*** has five bi-directional lanes.
- For simplicity, we assumed that all nodes within same lane have equal speed.
- Lanes are numbered as per their node speed and lane speed increases with increasing lane number. Hence, among all lanes, lane 1 as slowest lane and lane 5 is the fastest lane.

According to our assumptions defined above, all nodes can independently adapt static behavior or different velocities according to their lane speeds. Similarly, these nodes can independently follow the movement direction with respect to node ***S***. This independence of speed and direction of movement will create different node behaviors with respect to link stability. Resultantly, we need to separately define effect of the relative distance Δd and relative angle of movement $\Delta\theta$ between 1st and 2nd hop neighbour nodes.

4.2.1. Relative Distance Δd Covered by Neighbour Node with respect to Target Node

The distance Δd depends on relative velocity difference Δv of neighbour node with respect to host node ***S***, within unit time. According to the law of motion of physics, we can define Δd as:

$$\Delta d = \Delta v * t \qquad \textit{Eq 4.1}$$

and

$$\Delta v = v_n - v_s \qquad \textit{Eq 4.2}$$

Where, v_n = Velocity of neighbour node

v_s = Velocity of source node

The effect of relative velocity Δv can be defined as:

- If Δv is the maximum velocity change, then Δd is the maximum distance covered by any neighbour node with respect to node ***S***. It means that during time ***t***, the nodes present within distance Δd from the edges of communication range of node ***S*** will be able to go out of its range. Accordingly, nodes closer to the source may not go out of communication range from source. The area from which a 1st hop neighbour may go out of range of node ***S*** is shown in green colour (arc covered by line EF) in the Figure4.2. On the contrary, nodes in yellow zone (area covered by line CD) will never go out of communication range from source in unit time ***t***.

- Similarly for the second hop neighbours, only the nodes existing within $\boldsymbol{\Delta d}$ distance (orange arc covered by line GH) from the maximum communication range of node ***S*** will have the possibility to enter within its next hop range. Whereas the nodes outside the orange area will not be able to enter one hop region in unit time ***t***.
- As the distance $\boldsymbol{\Delta d}$ depends upon time ***t***, with increasing value of ***t***, the area $\boldsymbol{\Delta d}$ will expand. Due to expansion of $\boldsymbol{\Delta d}$, the probability of next hop neighbour going out of range from the source will increase. Similarly, with increasing value of ***t***, probability of second hop neighbour coming in range from the source will also increase. In both cases, the need for local route update will vary with time contrary to periodic or need based route update approach. However conditions for timely route update may vary with involvement of other relevant factors.

We can compute area of the green and orange zones for communication radius of ***r*** meters, as under,

Green zone area = $\pi r^2 - \pi(r - \Delta d)^2$ *Eq 4.3*

Orange zone area = $\pi(r + \Delta d)^2 - \pi r^2$ *Eq 4.4*

Total area of circular region (green + orange) = $4\pi r \Delta d$ *Eq 4.5*

Total area road segment (green + orange) = $4x\Delta d$ *Eq 4.6*

Where ***x*** is the width of the road, and

The curved edges of road segment ***XY*** can be assumed as straight line according to the ratio of road width and length.

4.2.2. Relative Angle of Movement $\Delta\theta$ of Neighbour Node with respect to Target Node

Inclusion of angular value $\Delta\theta$ will make the Δv a vector. Hence the value of Δv can be computed by modifying equation 4.2 as:

$$\Delta v = v_n \cos\theta_n - v_s \cos\theta_s \qquad \textit{Eq 4.7}$$

$$\Delta v = v_n \cos\theta_n - v_s \qquad \textit{Eq 4.8}$$

Where, θ_s = Angle of movement of source node with respect to itself = 0^0

θ_n = Angle of movement of neighbour node with respect to source node

To consider all possibilities from the $\Delta\theta$ perspective, let line ***ST*** divide the area in two equal halves with respect to movement of direction of node ***S***. Let us consider a unit time ***t***, during which any node can travel maximum distance for half the length of line AB. The effect of different neighbours can be evaluated as under:

4.2.2.1.Area towards the Movement Direction of Source Node

The area on the right of line ST (towards the direction of movement of source) will have simpler differentiation of nodes than the other half. This area will have two extreme possibilities with respect to movement of direction of neighbouring node, as:

- As case 1 of relative angle, a neighbour node with movement direction of $\Delta\theta=0^0$ will have the possibility of going out of range from source node depending on its relative speed with respect to source node ***S***. However the probability of moving out of range from source ***S*** will only exist if the neighbour node has the higher velocity or positive value of Δv. Contrarily, neighbour nodes with negative or $\Delta v=0$ will not go out of communication range in unit time ***t***.

- As case 2 of relative angle, the neighbour node will only be able to cover a maximum distance of half of the communication range, and it will maintain its neighbour link with the node ***S***. Hence, a neighbour node having movement direction of $\Delta\theta=180^0$ will not move out of communication range from node ***S***.

4.2.2.2.The Area Opposite to the Movement Direction of Source Node

The behavior of any node existing in left half area of line ST (opposite to the direction of movement of source) is more complex in general. This area will also have two extreme possibilities with respect to movement of direction of neighbour node, but both extremes will have similarities in node behavior, as:

- As case 3 of relative angle, any neighbour node with movement direction of $\Delta\theta=0^0$ will have the possibility of going out of range from node ***S***, depending on the relative speed. Any such node will have the chance of moving out of range from node ***S*** if the neighbour node has lower velocity or negative value of $\boldsymbol{\Delta v}$. On the contrary, neighbour nodes with positive or $\boldsymbol{\Delta v=0}$ will maintain their communication link during unit time ***t***.

- As case 4 of relative angle, all the nodes moving opposite to source node while in opposite half will have added effect of its own velocity as well as of its target node. A neighbour node with movement direction of $\Delta\theta=180^0$ will have higher probability of moving out of communication range of node ***S***.

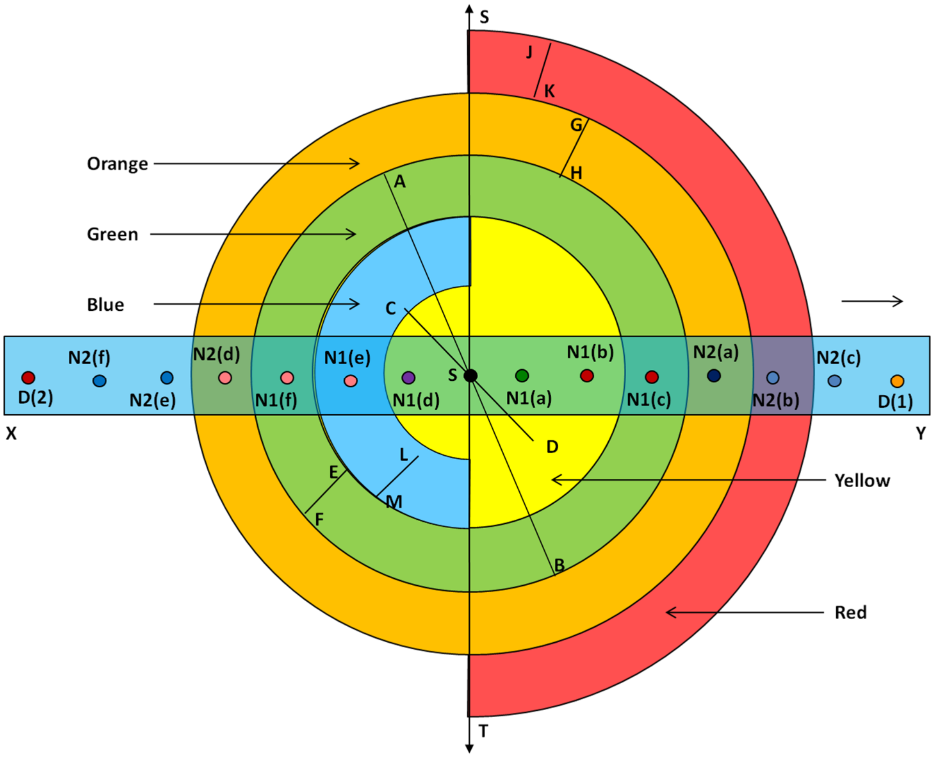

Figure 4.3: Modified Communication Ranges for the Test Topology

The nodes moving in opposite direction even at the same speed will have double the value of dispersion ***Δd*** among nodes. As assumed, a node can cover a maximum of half of hop length in unit time ***t***, and this characteristic will not affect the nodes on right half of line ST. However, the expansion of blue zone (arc covered by line LM) will affect the nodes in left half for route update, as shown in Figure 4.3.

Similarly, the orange zone on right half of line ST will also expand to double of the original size for the second hop neighbours moving towards host node ***S***. The red zone (arc covered by line JK) in Figure 4.3 shows expansion of distance ***Δd*** for 2nd hop neighbour. Resultantly, we can have six zones for positions of different 1st and 2nd hop neighbour nodes, as shown in Figure 4.3. The probability of existence of neighbour node in respective zone will vary according to multiple factors which will be defined in subsequent sections. However, for a generic model, we can consider different probabilities as:

- P(y) is the probability of 1st hop neighbour in yellow zone, e.g. nodes N1(a) & N1(d).
- P(b) is the probability of 1st hop neighbour in blue zone, e.g. nodes N1(b) & N1(e).
- P(g) is the probability of 1st hop neighbour in green zone, e.g. nodes N1(c) & N1(f).
- P(o) is the probability of 2nd hop neighbour in orange zone, e.g. nodes N2(a) & N2(d).
- P(r) is the probability of 2nd hop neighbour in red zone, e.g. nodes N2(b) & N2(e).
- P(w) is the probability of 2nd hop neighbour outside red zone, e.g. nodes N2(c) & N2(f).

Scen-ario	**Node**	**Relation with source *S***	**Desti-nation**	**Existence zone**	**Expected status w.r.t. source *S* in time *t***	**Route update required**
1	N1(a)	1st Hop neighbour	D(1)	yellow zone (area covered by line CD)	will remain in range	No
2	N1(b)	1st Hop neighbour	D(1)	blue zone (arc covered by line LM)	will remain in range	No
3	N1(c)	1st Hop neighbour	D(1)	green zone (arc covered by line EF)	can go out of range	Yes
4	N1(d)	1st Hop neighbour	D(2)	yellow zone (area covered by line CD)	will remain in range	No
5	N1(e)	1st Hop neighbour	D(2)	blue zone (arc covered by line LM)	can go out of range	Yes
6	N1(f)	1st Hop neighbour	D(2)	green zone (arc covered by line EF)	can go out of range	Yes
7	N2(a)	2nd Hop neighbour	D(1)	orange zone (arc covered by line GH)	can come in range	Yes
8	N2(b)	2nd Hop neighbour	D(1)	red zone (arc covered by line JK)	can come in range	Yes
9	N2(c)	2nd Hop neighbour	D(1)	outside red zone (arc covered by line JK)	will remain out of range	No
10	N2(d)	2nd Hop neighbour	D(2)	orange zone (arc covered by line GH)	can come in range	Yes
11	N2(e)	2nd Hop neighbour	D(2)	red zone (arc covered by line JK)	will remain out of range	No
12	N2(f)	2nd Hop neighbour	D(2)	outside red zone (arc covered by line JK)	will remain out of range	No

Table 4.1: Test Topology

4.3. Combined Effect of *Δd* & *Δθ* on Route Update Strategy

For subsequent analysis of zones defined in Figure 4.3, we need to separately evaluate each zoning case. According to presence of any neighbour node in different zones, different possible 1st and 2nd hop neighbour nodes of node ***S*** can be considered.

For best route calculation, the route update needs to be according to expected status of 1st and 2nd hop neighbours is defined in Table 4.1. Accordingly, 12 different scenarios have been defined considering expected behavior of neighbour node. 1st column of the Table 4.1shows the scenario identity number. 2nd, 3rd and 4th columns list the respective node identity and its relation to the source according to the destination.

Last three columns define the need of route update according to possibility of change of topology due to mobility.

In the light of above study, we can conclude that only scenarios 3, 5, 6, 7, 8 & 10 listed in Table 4.1 are of our interest for adaptive route update. Whereas remaining six scenarios do not require any route update within unit time ***t***.

Along with neighbour node locations with reference to host node, we can redefine our cases of interest after introduction of ***Δθ***. By introducing combination of ***Δθ*** and ***Δd***, we can further conclude that only following cases will have direct effect on route update strategy and will be our cases of interest, as:

- Scenario 3 with nodes moving at relative angle $\Delta\theta=0^0$.
- Scenario 5 with nodes moving at relative angle $\Delta\theta=180^0$.
- Scenario 6 with nodes moving at relative angle $\Delta\theta=0^0$.
- Scenario 6 with nodes moving at relative angle $\Delta\theta=180^0$.
- Scenario 7 with nodes moving at relative angle $\Delta\theta=0^0$.
- Scenario 7 with nodes moving at relative angle $\Delta\theta=180^0$.
- Scenario 8 with nodes moving at relative angle $\Delta\theta=180^0$.
- Scenario 10 with nodes moving at relative angle $\Delta\theta=0^0$.

The combined effect of ***Δd*** & ***Δθ*** can change the behaviour of any node. Though complex, the same effect can significantly assist in the adaptive route update decision. Combined effect of ***Δd*** & ***Δθ*** is evaluated in following sections.

Region	**Percentage of Number of Nodes**							
	t= 1sec	t= 2sec	t= 4sec	t=8sec	t=16sec	t=32sec	t=64sec	t=128sec
Circular Region (r=250m, Δv=2 kmph)	0.88%	1.76%	3.52%	7.04%	14.1%	28.16%	56.32%	112.64%
Circular Region (r=1000m, Δv=120 kmph)	13.3%	26.7%	53.3%	106.6%				
Road Segment (x=50m, Δv=120 kmph)	14.5%	29.0%	58.0%	116.0%				

Table 4.2: Possible Number of Mobile Nodes Involved in Topology Change

4.3.1. Δd Analysis

To compute the practical effect of Δd on route update, we can consider two MAC layer protocols i.e. IEEE 802.11a/b/g/n and 802.11p. MANET MAC protocol IEEE 802.11 a/b/g/n has theoretical communication range of 250 meters [110]. On other hand, VANET MAC protocol IEEE 802.11p has maximum theoretical range of 1000 meters. By using the equation 4.5&4.6, we can compute the maximum possible nodes going out from or coming in to communication range of any host node.

Table 4.2 defines the expected number of nodes involved in topology change for MANET and VANET. MANET nodes are deployed in circular region with relative node velocity of 2 kmph, whereas VANET nodes are deployed over 50 meter wide road with node velocity of 120 kmph. Interestingly, we can observe from Table 4.2 that only a limited number of nodes are involved in change of status within a unit time. The percentage value of possible nodes involved in change of link status is directly proportional to the node speed and time lapsed. The current route update strategies based on periodic or event based route update do not consider this important conclusion while updating their routes. Current approaches either do not perform route update or perform route update on all nodes regardless of their involvement in topology change. Resultantly, these protocols work fine for limited scenarios and fail for the complicated scenarios involving variable and high node densities and varying values of Δv.

The next most important factor for route update calculation is the probability of existence of next hop neighbour in green or blue zone or second hop neighbour in orange or red zone. As both events are independent, hence their combined probability should be considered independently.

Let's consider P(g) and P(b) as the probabilities of 1st hop neighbour in green and blue zone respectively. Similarly, P(o) and P(r) is the probability of 2nd hop neighbour in orange and red zone respectively. Generic computation of both the probabilities is a complex task as both probabilities are dependent on the routing strategy in addition to involvement of node position. Routing protocols with routing strategy of maintaining minimum hop path will have higher value of P(g) than a protocol targeted for maximum link life. Similarly, the value of P(g) will vary among other routing strategies, such as minimum delay, minimum cost, load balance, etc. In many cases, the value of P(o) will behave inversely as compared to P(g), owing to routing behavior. As a test case, we can consider the example of routing strategy of minimum hop count towards the destination. This approach will have higher value of P(g) as each node will try to find the next hop neighbour closest to its communication boundary. The same approach being adapted by the first hop neighbour will tend to select 2nd hop neighbour also at farthest distance. This intention will cause much lower value of P(o) for second hop neighbour. On the other hand, the behavior of a routing strategy based on maximum stable link will have lower P(g) and higher P(o). However, this behavior may not stand true for strategies which do not depend on node distance, such as minimum cost or load balance, etc.

4.3.2. $\Delta\theta$ Analysis

To evaluate short listed scenarios in previous section, incorporating $\Delta\theta$ along with Δd, we can formulate different mathematical expressions. These expressions can further define the behavior of any 1st or 2nd hop neighbour node for the adaptive route update as described below.

4.3.2.1.Nodes Moving in Same Direction i.e. $\Delta\theta=0^0$(Scenario 3)

We can consider different practical scenarios against assumptions of multiple two way lanes, nodes of uniform density and Gaussian mobility pattern. For a generic scenario, any node can either exist on any lane or remain stationary. VANET architectures recommend use of all vehicles to act as communicating node, whether moving on the road, halted at signals or parked at any location. It is quite difficult to determine the exact probability of current status of any vehicle, i.e. moving, halted or parked, for different cities, vehicle types and traffic conditions. Hence, probability of status of host and neighbor node can be determined using weight (W_S) assignment.

While existing on any lane, a node can either move towards or inline to host node. However only nodes with $\Delta\theta=0^0$ will be of our interest under scenario 3 as shown in Table 4.3. Table 4.3 defines different possibilities related to behavior of two neighbour nodes communicating to each other with in green zone.

Lane Count	**Target Node Lane**	**1^{st} Hop Neighbour Node Lane**	**$\Delta\theta$ (degrees)**	**Δv**	**Possibility of Link Breakage**	**Probability of Link Breakage**
1	0 (static)	0 (static)		0	No	1/3
	0 (static)	1	0	+ve	Yes	
	0 (static)	1	180	-ve	No	
	1	0 (static)	0	-ve	No	0
	1	1	0	0	No	
	1	1	180	-ve	No	
2	0 (static)	0 (static)		0	No	2/5
	0 (static)	1	0	+ve	Yes	
	0 (static)	1	180	-ve	No	
	0 (static)	2	0	+ve	Yes	
	0 (static)	2	180	-ve	No	
	1	0 (static)		-ve	No	1/5
	1	1	0	0	No	
	1	1	180	-ve	No	
	1	2	0	+ve	Yes	
	1	2	180	-ve	No	
	2	0 (static)		-ve	No	0
	2	1	0	-ve	No	
	2	1	180	-ve	No	
	2	2	0	0	No	
	2	2	180	-ve	No	
3	0 (static)	0 (static)		0	No	2/7
	0 (static)	1	0	-ve	No	
	0 (static)	1	180	-ve	No	
	0 (static)	2	0	+ve	Yes	
	0 (static)	2	180	-ve	No	
	0 (static)	3	0	+ve	Yes	
	0 (static)	3	180	-ve	No	
	1	0 (static)		+ve	Yes	3/7
	1	1	0	0	No	
	1	1	180	-ve	No	
	1	2	0	+ve	Yes	
	1	2	180	-ve	No	
	1	3	0	+ve	Yes	
	1	3	180	-ve	No	
	2	0 (static)		-ve	No	1/7
	2	1	0	-ve	No	
	2	1	180	-ve	No	
	2	2	0	0	No	
	2	2	180	-ve	No	
	2	3	0	+ve	Yes	
	2	3	180	-ve	No	
	3	0 (static)		-ve	No	0
	3	1	0	-ve	No	
	3	1	180	-ve	No	
	3	2	0	-ve	No	
	3	2	180	-ve	No	
	3	3	0	0	No	
	3	3	180	-ve	No	

Table 4.3: Link Breakage Probabilities for Scenario 3

Lane Count	**Target Node Lane**	**1^{st} Hop Neighbour Node Lane**	**$\Delta\theta$ (degrees)**	**Δv**	**Possibility of Link Breakage**	**Probability of Link Breakage**
1	0 (static)	0 (static)		0	No	0
	0 (static)	1	0	+ve	No	
	0 (static)	1	180	-ve	No	
	1	0 (static)		-ve	No	1/3
	1	1	0	0	No	
	1	1	180	-ve	Yes	
2	0 (static)	0 (static)		0	No	0
	0 (static)	1	0	+ve	No	
	0 (static)	1	180	-ve	No	
	0 (static)	2	0	+ve	No	
	0 (static)	2	180	-ve	No	
	1	0 (static)		-ve	No	2/5
	1	1	0	0	No	
	1	1	180	-ve	Yes	
	1	2	0	+ve	No	
	1	2	180	-ve	Yes	
	2	0 (static)		-ve	No	2/5
	2	1	0	-ve	No	
	2	1	180	-ve	Yes	
	2	2	0	0	No	
	2	2	180	-ve	Yes	
3	0 (static)	0 (static)		0	No	0
	0 (static)	1	0	-ve	No	
	0 (static)	1	180	-ve	No	
	0 (static)	2	0	+ve	No	
	0 (static)	2	180	-ve	No	
	0 (static)	3	0	+ve	No	
	0 (static)	3	180	-ve	No	
	1	0 (static)		+ve	No	3/7
	1	1	0	0	No	
	1	1	180	-ve	Yes	
	1	2	0	+ve	No	
	1	2	180	-ve	Yes	
	1	3	0	+ve	No	
	1	3	180	-ve	Yes	
	2	0 (static)		-ve	No	3/7
	2	1	0	-ve	No	
	2	1	180	-ve	Yes	
	2	2	0	0	No	
	2	2	180	-ve	Yes	
	2	3	0	+ve	No	
	2	3	180	-ve	Yes	
	3	0 (static)		-ve	No	3/7
	3	1	0	-ve	No	
	3	1	180	-ve	Yes	
	3	2	0	-ve	No	
	3	2	180	-ve	Yes	
	3	3	0	0	No	
	3	3	180	-ve	Yes	

Table 4.4: Link Breakage Probabilities for Scenario 5

The first column defines the total number of available lanes. Second and third columns define the relative position of both neighbour nodes with reference to the road lane. The next two columns explain the effect of relative velocity and possibility of going out of range from each other. The last column on the right states the probability of link breakage with reference to node position in different lanes.

Observing the probability of link breakage and its relation with number of lanes in Table 4.3, we can formulate the mathematical expression for probability of neighbour node from green zone going out of range of host node under scenario 3, as:

$$P(N1(out)_g = \frac{\Sigma(\mathrm{l-z})}{\mathrm{l(l+1)+(l+1)^2}} \qquad \textit{Eq 4.9}$$

$$where z = 0,1,2 \dots\dots, (l-1)$$

As P(g) is the probability of node existence in green zone, hence probability of 1st hop neighbour node existence in right half of green zone and going out of range from host node is,

$$P(N1(out))_3 = \left(\frac{1}{2}\right) W_s * \mathrm{P(g)} * \left(\frac{\Sigma(\mathrm{l-z})}{\mathrm{l(l+1)+(l+1)^2}}\right) \qquad \textit{Eq 4.10}$$

where:

$\mathrm{z} = 0,1,2 \dots\dots, (\mathrm{l}-1)$,

l = number of lanes, W_s is the combined weight for host and neighbor node status, and

$P(N1(out))_3$=Probability of 1st hop neighbour going out from communication range of host node under scenario 3

4.3.2.2.<u>Nodes Moving in Opposite Direction i.e. Δθ=180^0 (Scenario 5)</u>

Similarly, like scenario 3, we can consider the possibilities of nodes going out of range from host node under scenario 5.

Table 4.4 defines the different possibilities related to behavior of two neighbour nodes communicating to each other under scenario 5. Contrary to previous case, only the nodes moving opposite to each other will be able to go out of range. Resultantly, we can formulate the mathematical expression for probability of neighbour node going out of range of host node from blue zone under scenario 5, as:

Lane Count	**Target Node Lane**	**1st Hop Neighbour Node Lane**	***Δθ* (degrees)**	***Δv***	**Possibility of Link Breakage**	**Probability of Link Breakage**
1	0 (static)	0 (static)		0	No	1/3
	0 (static)	1	0	+ve	No	
	0 (static)	1	180	-ve	Yes	
	1	0 (static)		-ve	Yes	2/3
	1	1	0	0	No	
	1	1	180	-ve	Yes	
2	0 (static)	0 (static)		0	No	2/5
	0 (static)	1	0	+ve	No	
	0 (static)	1	180	-ve	Yes	
	0 (static)	2	0	+ve	No	
	0 (static)	2	180	-ve	Yes	
	1	0 (static)		-ve	Yes	3/5
	1	1	0	0	No	
	1	1	180	-ve	Yes	
	1	2	0	+ve	No	
	1	2	180	-ve	Yes	
	2	0 (static)		-ve	Yes	4/5
	2	1	0	-ve	Yes	
	2	1	180	-ve	Yes	
	2	2	0	0	No	
	2	2	180	-ve	Yes	
3	0 (static)	0 (static)		0	No	3/7
	0 (static)	1	0	-ve	No	
	0 (static)	1	180	-ve	Yes	
	0 (static)	2	0	+ve	No	
	0 (static)	2	180	-ve	Yes	
	0 (static)	3	0	+ve	No	
	0 (static)	3	180	-ve	Yes	
	1	0 (static)		+ve	Yes	4/7
	1	1	0	0	No	
	1	1	180	-ve	Yes	
	1	2	0	+ve	No	
	1	2	180	-ve	Yes	
	1	3	0	+ve	No	
	1	3	180	-ve	Yes	
	2	0 (static)		-ve	Yes	5/7
	2	1	0	-ve	Yes	
	2	1	180	-ve	Yes	
	2	2	0	0	No	
	2	2	180	-ve	Yes	
	2	3	0	+ve	No	
	2	3	180	-ve	Yes	
	3	0 (static)		-ve	Yes	6/7
	3	1	0	-ve	Yes	
	3	1	180	-ve	Yes	
	3	2	0	-ve	Yes	
	3	2	180	-ve	Yes	
	3	3	0	0	No	
	3	3	180	-ve	Yes	

Table 4.5: Link Breakage Probabilities for Scenario 6

$$P(N1(out))_5 = \left(\frac{1}{2}\right) * Ws * \mathrm{P(b)} * \left(\frac{\mathrm{l}^2}{\mathrm{l(l+1)+(l+1)^2}}\right) \qquad Eq\ 4.11$$

Where:

P(b) = Probability of existence of any node in blue zone,

l = Number of lanes, W_s is the combined weight for host and neighbor node status, and

$P(N1(out))_5$ = Probability of 1st hop neighbour going out from communication range of host node under scenario 5

4.3.2.3. Nodes Moving in Both Directions i.e. $\Delta\theta=0^0\&180^0$ (Scenario 6)

Similar to above cases, the Table 4.5 defines the different possibilities related to behavior of two neighbour nodes communicating to each other under scenario 6.

Resultantly, we can formulate the mathematical expression for probability of neighbour node going out of range of host node from green zone under scenario 6, as:

$$P(N1(out))_6 = \left(\frac{1}{2}\right) * \ Ws * \mathrm{P(g)} * \left(\frac{\sum\mathrm{(l+y)}}{\mathrm{l(l+1)+(l+1)^2}}\right) Eq\ 4.12$$

$where$:

$y = 0,1,2 \dots\dots, l,$

P(g) = Probability of existence of any node in green zone,

l =Number of lanes, W_s is the combined weight for host and neighbor node status, and

$P(N1(out))_6$= Probability of 1st hop neighbour going out from communication range of host node under scenario 6

4.3.2.4. Nodes Moving in Both Directions i.e. $\Delta\theta=0^0\ \&180^0$ (Scenario 7)

Similar to the first hop neighbours, second hop neighbours reciprocate the behavior with respect to host node, where scenario 7 reciprocates scenario 6. Resultantly, we can formulate the mathematical expression for probability of neighbour node from orange zone coming in range of host node under scenario 7, as:

$$P(N2(in))_7 = \left(\frac{1}{2}\right) * \ Ws * \mathrm{P(o)} * \left(\frac{\sum(\mathrm{l}+\mathrm{x})}{\mathrm{l}(\mathrm{l}+1)+(\mathrm{l}+1)^2}\right) Eq\ 4.13$$

$where$:

$x = 0,1,2 \dots \dots , l$

P(o) = Probability of existence of any node in orange zone,

l =Number of lanes, W_s is the combined weight for host and neighbor node status, and

P(N2(in))$_7$= Probability of 2nd hop neighbour coming in communication range of host node under scenario 7

4.3.2.5.Nodes Moving in Opposite Direction i.e. Δθ=180^0 (Scenario 8)

Similar to previous case of scenario 7, Scenario 8 reciprocates scenario 5. Resultantly, we can formulate the mathematical expression for probability of neighbour node from red zone coming in range of host node under scenario 8, as:

$$P(N2(in))_8 = \left(\frac{1}{2}\right) * Ws * \mathrm{P(r)} * \left(\frac{\mathrm{l}^2}{\mathrm{l}(\mathrm{l}+1)+(\mathrm{l}+1)^2}\right) Eq\ 4.14$$

$where$:

P(r) = Probability of existence of any node in red zone,

l =Number of lanes, W_s is the combined weight for host and neighbor node status, and

P(N2(in))$_8$= Probability of 2nd hop neighbour coming in communication range of host node under scenario 8

4.3.2.6.Nodes Moving in Same Direction i.e. Δθ=0^0 (Scenario 10)

Similar to previous cases of scenario 7 & scenario 8, scenario 10 reciprocates scenario 3. Resultantly, we can formulate the mathematical expression for probability of neighbour node from orange zone coming in range of host node under scenario 10, as:

$$P(N2(in))_{10} = \left(\frac{1}{2}\right) * Ws * \mathrm{P(o)} * \left(\frac{\sum(\mathrm{l}-\mathrm{w})}{\mathrm{l}(\mathrm{l}+1)+(\mathrm{l}+1)^2}\right) Eq\ 4.15$$

$$where:$$

$$w = 0,1,2 \dots \dots, (l - 1),$$

P(o) = Probability of existence of any node in orange zone,

$\boldsymbol{l}$ =Number of lanes, W_s is the combined weight for host and neighbor node status, and

$P(N2(in))_{10}$= Probability of 2nd hop neighbour coming in communication range of host node under scenario 10

4.4. **Combined Probability for Need of Route Update**

For any individual node, the requirement of route update at optimal timings occurs, as previously stated, on any of the following two conditions.

- When first hop neighbour of current node is about to go out of range, or
- When second hop neighbour of current node comes in communication range of the current node.

To compute the overall probability of route update requirement, we need to compute separate probabilities of two independent events followed by combined probability for occurrence of any of the events.

4.4.1. Probability of 1st Hop Neighbour Going Out of Range from Target Node

The probability of 1st hop neighbour going out of range from host node ***S***, incorporating all possible cases will be the sum of equations 4.10, 4.11&4.12, hence:

$$P\big(N1(out)\big) = P(N1(out))_3 + P(N1(out))_5 + P(N1(out))_6$$

$$P\big(N1(out)\big) = \left(\frac{1}{2}\right) * \mathrm{P(g)} * \left(\frac{\sum(\mathrm{l} - \mathrm{z})}{\mathrm{l(l + 1) + (l + 1)^2}}\right) + \left(\frac{1}{2}\right) * \mathrm{P(b)} * \left(\frac{\mathrm{l}^2}{\mathrm{l(l + 1) + (l + 1)^2}}\right) + \left(\frac{1}{2}\right) * \mathrm{P(g)} * \left(\frac{\sum(\mathrm{l} + \mathrm{y})}{\mathrm{l(l + 1)(l + 1)^2}}\right)$$

$$P(N1(out)) = \left(\frac{1}{2}\right) * \left(\mathrm{P(g)} * \left(\frac{\sum(\mathrm{l}-\mathrm{z}) + \sum(\mathrm{l}+\mathrm{y})}{\mathrm{l}(\mathrm{l}+1) + (\mathrm{l}+1)^2}\right) + \mathrm{P(b)} * \left(\frac{\mathrm{l}^2}{\mathrm{l}(\mathrm{l}+1) + (\mathrm{l}+1)^2}\right)\right) Eq\ 4.16$$

$where$:

$z = 0,1,2 \ldots\ldots, (l-1), y = 0,1,2 \ldots\ldots, l,$ and

P(N1(out)) = Probability of 1st hop neighbour going out from communication range of host node

4.4.2. Probability of 2nd Hop Neighbour Coming in Range of Target Node

The probability of 2nd hop neighbour coming in range of host node ***S***, incorporating all possible cases will be the sum of equations 4.13, 4.14&4.15, hence:

$$P(N2(in)) = \mathrm{P(N2(in))_7} + \mathrm{P(N2(in))_8} + \mathrm{P(N2(in))_{10}}$$

$$P(N2(in)) = \left(\frac{1}{2}\right) * \mathrm{P(o)} * \left(\frac{\sum(\mathrm{l}+\mathrm{x})}{\mathrm{l}(\mathrm{l}+1) + (\mathrm{l}+1)^2}\right) + \left(\frac{1}{2}\right) * \mathrm{P(r)} * \left(\frac{\mathrm{l}^2}{\mathrm{l}(\mathrm{l}+1) + (\mathrm{l}+1)^2}\right) + \left(\frac{1}{2}\right) * \mathrm{P(o)} * \left(\frac{\sum(\mathrm{l}-\mathrm{w})}{\mathrm{l}(\mathrm{l}+1)(\mathrm{l}+1)^2}\right)$$

$$P(N2(in)) = \left(\frac{1}{2}\right) * \left(\mathrm{P(o)} * \left(\frac{\sum(\mathrm{l}+\mathrm{x}) + \sum(\mathrm{l}-\mathrm{w})}{\mathrm{l}(\mathrm{l}+1) + (\mathrm{l}+1)^2}\right) + \mathrm{P(r)} * \left(\frac{\mathrm{l}^2}{\mathrm{l}(\mathrm{l}+1) + (\mathrm{l}+1)^2}\right)\right) \qquad \mathrm{Eq\ 4.17}$$

$where$:

$w = 0,1,2 \ldots\ldots, (l-1),$

$x = 0,1,2 \ldots\ldots, l,$ and

P(N2(in)) = Probability of 2nd hop neighbour coming in communication range of host node

4.4.3. Combined Probability for Route Update

From the theory of probability, the combined probability for optimal route update condition using equation 4.16&4.17 will be:

$$P\big(N1(out)orN2(in)\big) = P\big(N1(out)\big) + P\big(N2(in)\big) - \Big(P\big(N1(out)\big)\& \, P\big(N2(in)\big)\Big)$$

$$\begin{aligned}
&P\big(N1(out)orN2(in)\big) \\
&\qquad = \left(\frac{1}{2}\right) W_{h,n} \\
&\qquad * \left(\left(\mathrm{P(g)} * \left(\frac{\sum(\mathrm{l}-\mathrm{z}) + \sum(\mathrm{l}+\mathrm{y})}{\mathrm{l}(\mathrm{l}+1) + (\mathrm{l}+1)^2}\right) + \mathrm{P(b)} * \left(\frac{\mathrm{l}^2}{\mathrm{l}(\mathrm{l}+1) + (\mathrm{l}+1)^2}\right)\right)\right. \\
&\qquad + \left(\mathrm{P(o)} * \left(\frac{\sum(\mathrm{l}+\mathrm{x}) + \sum(\mathrm{l}-\mathrm{w})}{\mathrm{l}(\mathrm{l}+1) + (\mathrm{l}+1)^2}\right) + \mathrm{P(r)} * \left(\frac{\mathrm{l}^2}{\mathrm{l}(\mathrm{l}+1) + (\mathrm{l}+1)^2}\right)\right) \\
&\qquad - \left(\frac{1}{2}\right) \\
&\qquad * \left(\left(\mathrm{P(g)} * \left(\frac{\sum(\mathrm{l}-\mathrm{z}) + \sum(\mathrm{l}+\mathrm{y})}{\mathrm{l}(\mathrm{l}+1) + (\mathrm{l}+1)^2}\right) + \mathrm{P(b)} * \left(\frac{\mathrm{l}^2}{\mathrm{l}(\mathrm{l}+1) + (\mathrm{l}+1)^2}\right)\right)\right. \\
&\qquad * \left(\mathrm{P(o)} * \left(\frac{\sum(\mathrm{l}+\mathrm{x}) + \sum(\mathrm{l}-\mathrm{w})}{\mathrm{l}(\mathrm{l}+1) + (\mathrm{l}+1)^2}\right) + \mathrm{P(r)}\right. \\
&\qquad \left.\left.\left. * \left(\frac{\mathrm{l}^2}{\mathrm{l}(\mathrm{l}+1) + (\mathrm{l}+1)^2}\right)\right)\right)\right) Eq\ 4.18
\end{aligned}$$

$where$:

$z = 0,1,2 \ldots \ldots, (l-1),$

$y = 0,1,2 \ldots \ldots, l,$

$x = 0,1,2 \ldots \ldots, l,$

$w = 0,1,2 \ldots \ldots, (l-1),$and

P$(N1(out)orN2(in))$ = Probability of 1st hop neighbour going out from, or 2nd hop neighbour coming in communication range of host node

4.5. **Probability Curve Behavior**

From the assumption of uniform node density, we know that number of nodes ***n*** is directly proportional to the number of lanes ***l***.

$$n = al \qquad Eq\ 4.19$$

Where ***a*** is the proportionality constant

For the worst case scenario, where each lane may have only one node i.e. ***a=1***, we can get an expression using equation 4.18 in simplified equation 4.19, as following:

$$\begin{aligned} &P(N1(out)orN2(in)) \\ &= W_s\left(\frac{1}{2*(\mathrm{n}*(\mathrm{n}+1)+(\mathrm{n}+1)^2)}\right) \\ &*\left(\left((\mathrm{P(g)}+\mathrm{P(o)})*\left(\left(\sum(\mathrm{n}-\mathrm{z})+\sum(\mathrm{n}+\mathrm{y})\right)\right)+(\mathrm{P(b)}+\mathrm{P(r)})\right.\right. \\ &\left.*\,\mathrm{n}^2\right)-\left(\frac{1}{2*(\mathrm{n}*(\mathrm{n}+1)+(\mathrm{n}+1)^2)}\right) \\ &*\left(\left(\mathrm{P(g)}*\left(\left(\sum(\mathrm{n}-\mathrm{z})+\sum(\mathrm{n}+\mathrm{y})\right)\right)+\mathrm{P(b)}*\mathrm{n}^2\right)\right. \\ &\left.*\left(\mathrm{P(o)}*\left(\left(\sum(\mathrm{n}-\mathrm{z})+\sum(\mathrm{n}+\mathrm{y})\right)\right)+\mathrm{P(r)}*\mathrm{n}^2\right)\right)\right) Eq\ 4.20 \end{aligned}$$

$where$:

$z = 0,1,2 \ldots\ldots, (n-1)$,

$y = 0,1,2 \ldots\ldots, n$,

n = Number of nodes in one hop region, and

P($N1(out)orN2(in)$) = Probability of 1st hop neighbour going out from, or 2nd hop neighbour coming in communication range of host node

The values of different probabilities ***P(region)*** according to neighbour location in different regions (i.e. P(g), P(b), P(o) & P(r)) are the function of different parameters as :

- Node Distribution
- Relative velocity ***Δv***
- Time ***t*** during which value is computed
- Routing protocol approach ***R(approach)***

Hence we have,

$$P(\text{region}) = f(\text{node distribution}, \Delta v, t \ \& \ R(\text{approach}))$$

Routing approach tags on a variety of curves according to selected shared metrics. The exact value of P(region) is beyond the scope of this research. However, to get a more realistic picture, and to observe the behavior of equation 4.20, we selected different common probability curves, as:

4.5.1. Minimum Hop Count

Minimum hop count is one of the widely used routing metrics. The main idea in this approach is to select route towards destination with minimum hop count. Resultantly each node selects farthest node towards the destination as a next hop neighbour. However, the route is selected with minimum hop count in end-to-end perspective. The selected approach makes its metric dependent on inter-node distance.

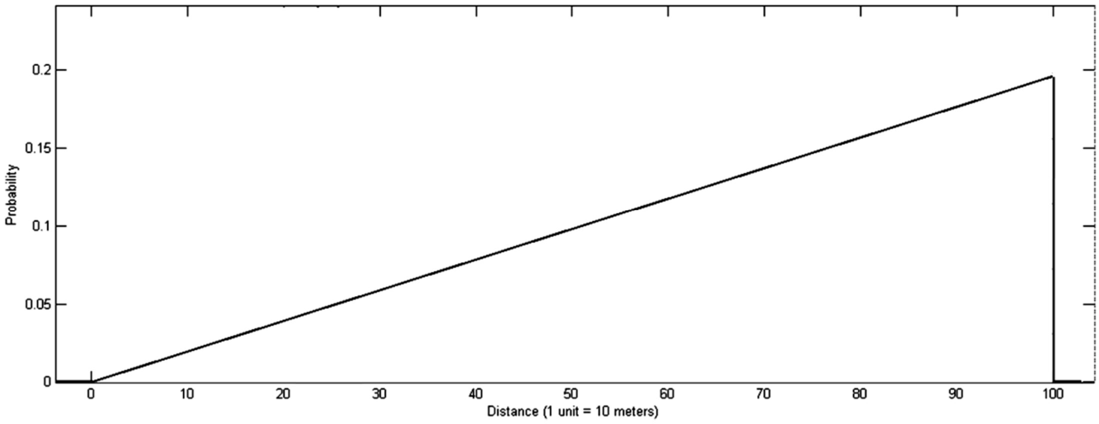

Figure 4.4: Probability of Next Hop Node Distance for Minimum Hop Count

Figure 4.4 shows the Probability Density Function (PDF) curve of Linear Distribution. The probability of the selection of next hop neighbour node increases with increases in distance. The selected curve follows the highest probability for the nodes lying at the edges of the one hop range. Similarly, neighbour nodes closer to the host nodes will have lesser chance of selection as next hop neighbour.

4.5.2. Minimum Hop Count with Aggressive Approach

Minimum hop count with aggressive approach also uses the same routing approach as previous one. However, the curve follows a more aggressive approach for the selection of next hop neighbour closer to the edges. The main difference of this approach from previous one is the selection of next hop neighbour according to localized state. Whereas in the previous approach, the next hop neighbour is selected by keeping minimum hop count according to end-to-end state.

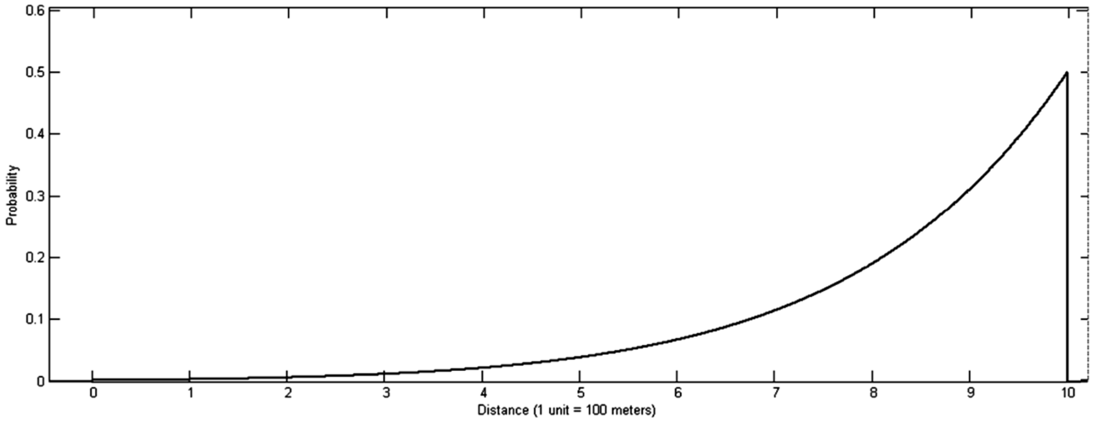

Figure 4.5: Probability of Next Hop Node Distance for Minimum Hop Count with Aggressive Approach

Figure 4.5 shows the PDF curve of Reverse Centralized Pareto Distribution with ***k=0, σ=2 and θ=0***. The probability of selecting next hop neighbour increases aggressively, along with the increase in distance between neighbouring nodes. Similarly, neighbour nodes closer to host node may have lesser probability of selection as next hop neighbour.

4.5.3. Maximum Stable Link

The maximum stable link approach is opposite to last approach, where next hop neighbour is selected closest to host node. Similarly, decision for next hop neighbour is based upon local conditions, where each node tries to maintain next hop link for maximum duration by selecting nearest next hop neighbour. Hence, this approach is also a distance dependent approach like the previous two approaches. This approach can also adapt many different curves, e.g. linear, aggressive and mild etc.

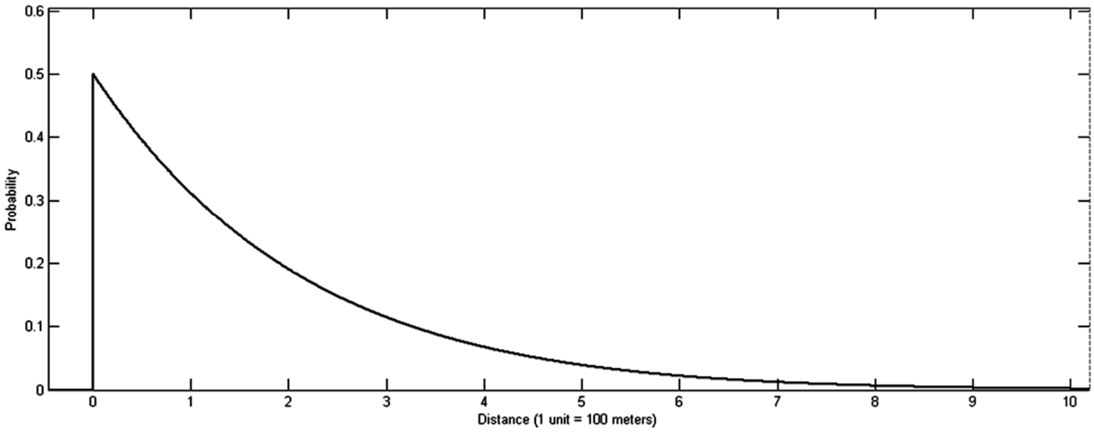

Figure 4.6: Probability of Next Hop Node Distance for Maximum Stable Link

Figure 4.6 shows the PDF curve of Centralized Pareto Distribution with ***k=0, σ=2 and θ=0***. This curve in the figure tags the aggressive approach to maintain the established link. Resultantly, the probability of selecting a different next hop neighbour decreases aggressively with increase in distance between neighbouring nodes. Similarly, probability to select next hop neighbour close to edge remains negligible.

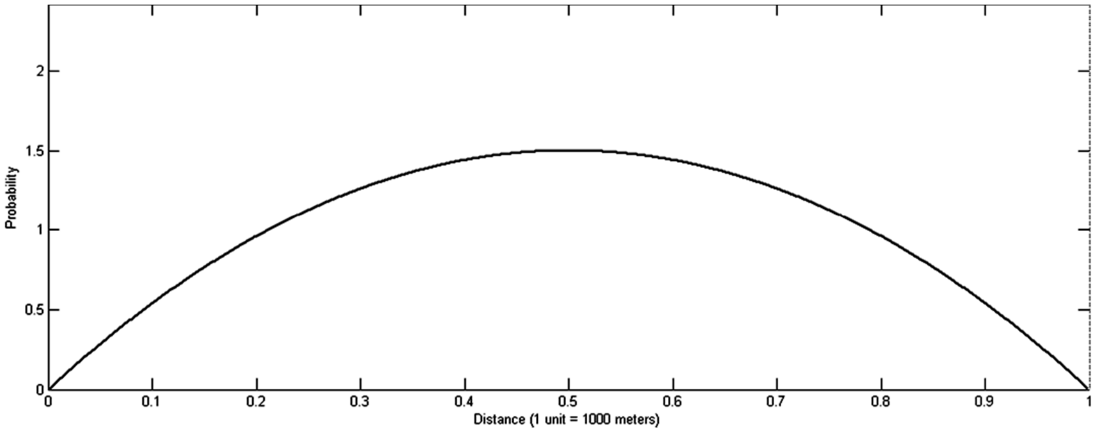

Figure 4.7: Probability of Next Hop Node Distance for Optimized Balanced Load

4.5.4. Optimized Balanced Load

Optimized balance load routing approach is the combination of minimum hop approach with some other routing metric such as load balancing or minimum cost. Due to use of a combination of metrics, this approach tries to select next hop neighbour satisfying both of the metrics, by compromising state of any single metric.

Hence, the effort to satisfy both metrics may lead to compromise the condition of ideal minimum hop count. Resultantly, probability of next hop neighbour remains highest at middle distance. This routing approach more closely adapts the widely spread curve then the previous three approaches.

Figure 4.7 shows the PDF curve of Beta Distribution with $\alpha = \beta = 2$. This type of curve maintains the behaviour all along the next hop distance by satisfying the other selected metric. However, due to design limitations, probability remains highest at centre distance. Moreover, the probability to select next hop neighbour decreases by increasing or decreasing the inter-node distance.

4.5.5. Normalized Load

Normalized routing approach is a modified form of the Optimized Balanced Load, where emphasis is given to load balancing and link stability while keeping minimum hop count as a secondary metric. Hence, the behavior of normalized load curve is generally independent of inter node distance. However, similar to the previous curve, this routing approach also follows a variety of distribution curves.

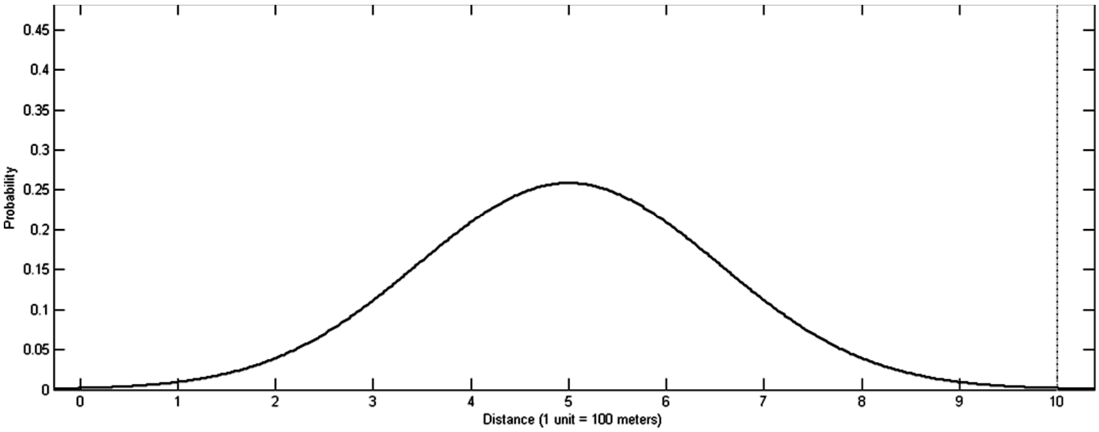

Figure 4.8: Probability of Next Hop Node Distance for Normalised Load

Figure 4.8 shows the pdftex curve of Normal Distribution with $\mu=5$ and $\sigma=1.545$. This type of curve generally keeps next hop neighbor between 30-70% of the total hop distance to maintain the normalised load among all neighbours. Selection of next hop neighbour according to minimum hop count or maximum stability may lead to compromise on primary metric. Hence, the probability curve shows sudden decrease in value for the nodes closer to the host as well as the link boundary.

4.5.6. Maximal Load Distribution

Maximal load distribution is the classical form of routing approach without inter-node distance dependency. This approach follows non inter-node distance metrics such as load balance or minimum cost, etc. Hence all nodes share equal probability to be selected as next hop neighbour when compared against inter-node distance. These curves are ideally suited for data networks where QoS parameters are not of prime importance such as Delay Tolerant Networks.

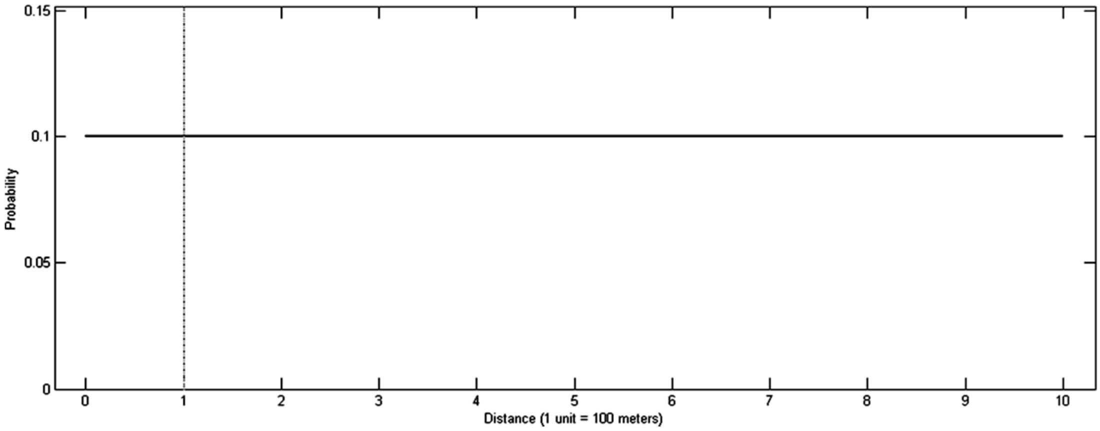

Figure 4.9: Probability of Next Hop Node Distance for Non Distance Algorithm

Figure 4.9 shows the pdftex of Uniform Curve with ***Minima = 0 and Maxima =10***. As evident from the curve, the value of probability remains constant all along the distance based on non-distance metrics.

In addition to the probability curve for first hop neighbour node, the computation of probability of second hop neighbour node can also be quite tricky. As for the static routing approach, same computation is performed at each node. This concept enables replication of selected pdftex curve for computation of any hop neighbour. For simplicity purposes, we computed second hop neighbour probability as the replication curve of first hop neighbour for maximum distance as well as at the distance from peak distance value.

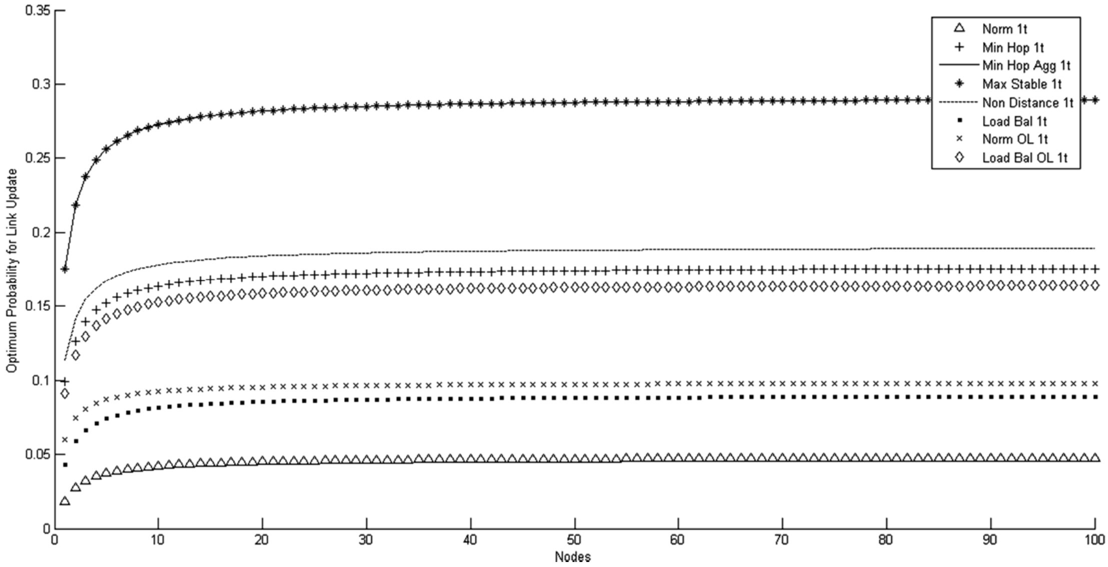

Figure 4.10: Probability of Change for Need of Link Update for Different Routing Algorithms in One Unit Time Duration

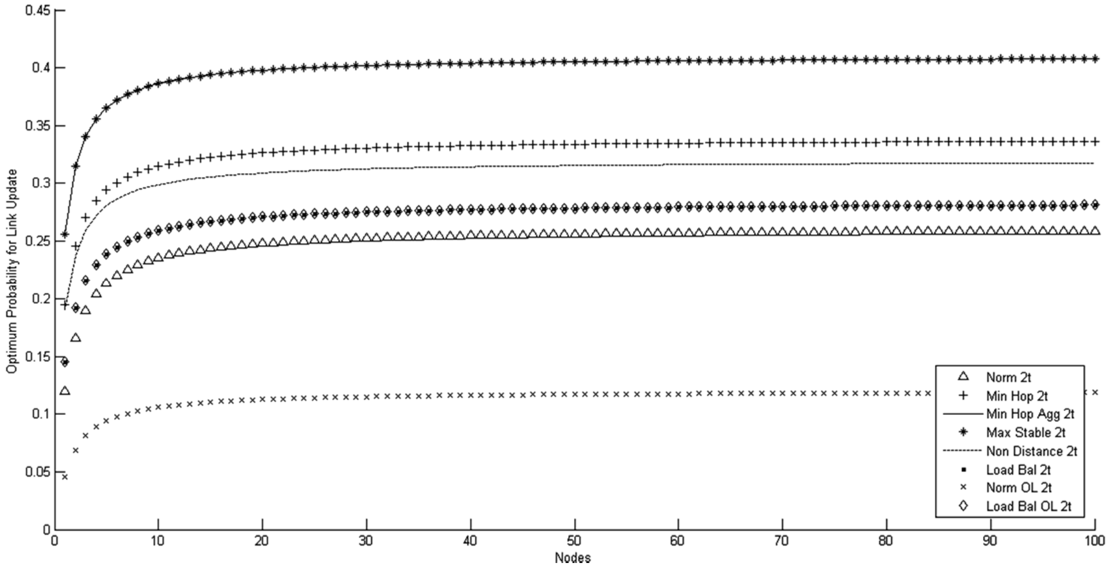

Figure 4.11: Probability of Change for Need of Link Update for Different Routing Algorithms in Two Units Time Duration

Figures 4.10 & 4.11 show the probability curve of equation 4.20 for different R(approach). The x-axis shows the number of nodes, whereas, y-axis shows the probability of change for need of link update. For the computation of combined probability of equation 4.14, different parameters were used as:

- ***t=1*** second for Figure 4.10 and ***t=2*** second for Figure 4.11
- Δv=120 kmph & Maximum hop distance, x = 1000 meters

- $\Delta\theta = 0^0$& 180^0

The combined probability of equation 4.20 was computed for different values of ***P(region)*** using eight different pdftex curves for probability distribution, as:

- Normalized load
- Minimum hop count
- Minimum hop count with aggressive approach
- Maximum stable link
- Maximal load distribution
- Optimized balanced load
- Normalized load with overlapping curve from the distance of peak pdftex value
- Optimized balanced load with overlapping curve from the distance of peak PDF value

As we can observe from the Figure 4.10&4.11 that all curves independently follow the same pattern. We can find two important results from those figures, which areas follow:

- By keeping the neighbour nodes constant, the probability of change in network for timely route update increases with increase in the update interval ***t***.
- By keeping the update interval ***t*** constant, the probability of change in network for timely route update increases with increase in number of neighbour nodes.

The above stated conclusions are the baseline factors for our adaptive route update strategy. The modification of current routing protocols by introducing adaptive route update can significantly improve the efficiency of the network. Hence, we can conclude that irrespective of route finding approach, the requirement for timely route update increases with increase in number of neighbour nodes and time interval ***t***.

We know that link status change probability is directly proportional to change in topology, as static nodes will have no change in their status and vice versa.

$$P(ch) = B * \%age\ T(ch)$$

Where:

P(ch) = Probability of change in link status

B = Probability constant

%age T(ch) = percentage change in topology or network parameters

For our interest, probability of change in link status is the probability of 1st hop neighbour going out from, or 2nd hop neighbour coming in communication range of host node, hence

$$\text{P(ch)} = \text{P}(N1(out) or N2(in)) = \text{B} * \text{\%age T(ch)} \qquad \textit{Eq 4.21}$$

Equation 4.20&4.21 leads to a very important conclusion that the probability of 1st hop neighbour going out, or 2nd hop neighbour coming in, the communication range of host node is proportional to change in network status. Moreover, threshold value for both of the above stated factors increases with increase in node density and time interval ***t***. Similarly increase in node density needs more change in the network environment for the state where 1st hop neighbour is about to go out from, or 2nd hop neighbour has come in communication range of host node. However, the timely route update condition may be computed using status change of different metrics among two hop neighbours.

4.6. **Metrics for Adaptive Route Update Conditions**

In the previous sections, we have discussed the simple analytical and empirical model of different factors and subsequent mathematical model, followed by the comparison of different practical situations affecting routing strategies. The results prove that current approach of predefined route update algorithms is not always efficient. We have emphasized that two fundamental questions related to routing strategies need to be answered before going for more generic and realistic solutions, which are:

- Which metric or combination of metrics should be shared for route determination and should it be fixed or adaptive as per network state?
- Should the selected metric or combination of metrics be shared through predefined and stationary approach or adaptively as per network conditions?

First question is answered by many researchers and new solutions are still being proposed. However, the second question needs to be looked at again according to demands of highly fluent networks.

To utilize the results achieved through equation 4.20&4.21, we propose the term ***adaptation*** for route update strategy. Adaptation is one significant missing characteristic in our current static routing approaches. The fundamental design difference between adaptive and non-adaptive approaches is that the later demands incorporation of different factors according to runtime network conditions. The adaptation will change the definition of ***Reactive*** by categorizing it to ***logical conditions*** to find and update the route.

4.6.1. Adaptation in Route Update Strategy

Adaptation means use of different metrics and factors considering their impact on route update strategy. Although the adaptation will make the software design a bit complicated, it will however overcome the limitations of existing approaches. We need to segregate the role of different metrics for route determination and route update & maintenance. However, from the design perspective and based on the preceding discussion, we can conclude that a single metric may not remove the limitations in current approach. Through an in depth study for selection of metrics (or their combination), we present their effect in the next section.

4.6.2. Metrics for Route Update Strategy

As a preliminary study, effect of few metrics related to need for adaptive route update is described in Table 4.6. The change of each metric has been evaluated from the sending node perspective for four different conditions, as:

- Effect on network when metric value increases from previous value
- Effect on network when metric value decreases from previous value
- Effect on network when metric value approaches to maximum theoretical value
- Effect on network when metric value approaches to minimum theoretical value

Metric	**If Changing from Low to High**	**If Changing from High to Low**	**If Approaching Max Value**	**If Approaching Min Value**
SINR	Node density is decreasing	Node density is increasing	No other node is communicating in one hop range	Link is about to break
	Next hop node is approaching nearer	Next hop node is going far		Node density is high
Received power	Next hop node is approaching nearer	Next hop node is going far	Next hop node is just aside	Link is about to break
Geographical distance	Next hop node is going far	Next hop node is approaching nearer	Link is about to break	Next hop node is just aside
Average geographical distance	Node density is increasing	Node density is decreasing	No other node is communicating in one hop range	Node density is too high
Next hop throughput	Immediate node density is decreasing	Immediate node density is increasing	Next hop node is just aside	Link is about to break
	Next hop node is approaching nearer	Next hop node is going far		Node density is too high
End to end throughput	Over all node density is decreasing	Over all node density is increasing	Node density is too low	Link is about to break
	Inter node distances are decreasing	Inter node distances are increasing	End node is just aside	Overall node density is high
Channel bandwidth	Node density is decreasing	Node density is increasing	No other node is communicating	Node density is high
End to end Delay	Over all node density is increasing	Over all node density is decreasing	Link is about to break	Node density is too low
	Inter node distances in each hop is increasing	Inter node distances in each hop is decreasing	Overall node density is high	End node is just aside
	Some intermediate link is about to break			
End to end Jitter	Over all node density is increasing	Over all node density is decreasing	Overall node density is high	Overall node density is high
	Inter node distances in each hop is increasing	Inter node distances in each hop is decreasing	Nodes are using bursty traffic	Topology is maintained
	Network topology is changing rapidly	Network topology is becoming static	Topology is random	Network is almost static
	Network is facing burst traffic	Network is avoiding burst traffic		
Packet loss	Over all node density is increasing	Over all node density is decreasing	Link is about to break	Node density is too low
	Inter node distances in each hop is increasing	Inter node distances in each hop is decreasing	Overall node density is high	End node is just aside
Frame loss	Node density is increasing	Node density is decreasing	Link is about to break	Node density is too low
	Next hop node is going far	Next hop node is approaching nearer	Overall node density is high	End node is just aside

Metric	**If Changing from Low to High**	**If Changing from High to Low**	**If Approaching Max Value**	**If Approaching Min Value**
Egress queue length	Node density is increasing	Node density is decreasing	Link is about to break	Node density is too low
	Next hop node is going far	Next hop node is approaching nearer	Overall node density is high	End node is just aside
Node speed	Immediate node density is decreasing	Immediate node density is increasing	Node density is low	Node density is high
	Next hop node is going far or coming nearer	Next hop node is going far or coming near		
One hop neighbours	Node density is increasing	Node density is decreasing	Node density is high	Node density is low

Table 4.6: Metrics Affecting Routing Information Sharing

Table 4.6 categorizes different metrics according to their use for adaptive route update strategy. For the local route update and maintenance, classification of different metrics using the existing flow of traffic and local parameters is defined. Each sending node, whether it is an originator or transit node, needs to assess the network state independently. Accordingly, the runtime computation of defined metrics on each node, regardless of its status in an end-to-end route, can help in determination of change in network status from last route update. Resultantly, each node can initiate route update request considering the updated state of the network.

4.7. Summary

This chapter discussed two basic questions: what information to share related to route determination, and how to share it. The answers to both of these questions are governed by various factors and metrics. We have identified different factors for further study which can help answer these questions in a better way.

Table 4.7 summarizes the comparative effects of different factors on route update strategy. It clearly shows that no single approach can be optimal in all network scenarios. The limitations of current route update approaches can also be ascertained using analytical study of different sequential scenarios.

We have formulated a mathematical relation between timely route update probability with respect to time interval and number of neighbouring nodes. We can conclude that irrespective of route finding approach, the requirement for timely route update has direct relation with change in network environment and number of nodes. Increase in number of neighbouring nodes leads to higher value of change in environment before route update. However, the route update conditions may be computed using status change of different metrics among two hop neighbours.

Factor	**Sub Factor**	**Periodic Route update**	**Event based Route Update**	**Hybrid Route Update**
QoS	Throughput Sensitive		√	
	Jitter Sensitive	√		
	Delay Sensitive	√		
Application Behavior	Applications with control messages		√	
	Broadcast Applications		√	
Deployment	Purely Ad hoc	√		
	Hybrid (Clustered Oriented)			√
	Hybrid (Infrastructure Oriented)		√	
Node Density	High Node Density		√	
	Low Node Density	√		
Scalability	High Scalability		√	
	Low Scalability	√		
Mobility Model	Random Movement	√		
	Probabilistic Movement (Uni Directional)		√	
	Probabilistic Movement (Non Uni Directional)			√
Relative Mobility	Very High Relative Mobility			√
	High Relative Mobility	√		
	Low Relative Mobility		√	
Topological Changes	Very High Topology Changes			√
	High Topology Changes	√		
	Low Topology Changes		√	

Table 4.7: Route Update Strategy Comparison

Route update strategy is dependent on different factors which vary according to network topology and conditions. Resultantly, no single approach can perform optimally in all conditions.

Chapter 5

ADAPTIVE ROUTE UPDATE STRATEGY EVALUATION

After discussing the need for adaptive route update and mathematical model towards the solution, this chapter provides the implementation model followed by simulation results. It is to be noted that our work is not restricted to any specific protocol; rather it is generic with no dependence on any routing algorithm. As already mentioned, Table 4.6 provides the guidelines for future research to utilise these metrics accordingly. Considering the fact that very little research is done for route update strategies, the proposed analysis will provide the basis for optimization of existing routing protocols and efficient design of future ones. The research made in the field will hopefully provide flexibility for the routing protocols and it will also help researchers and developers to design more realistic, situation aware and adaptive routing protocols. However, the option remains open to the researcher to either select the same or different metrics for route determination and adaptive route update.

5.1. Simulation Framework

Our target for this exercise is to establish a comprehensive model for route update strategy, incorporating different factors and metrics to best answer how to share route update metrics. The different threshold values for each metric or combination of metrics, computed on runtime, can develop adaptive route update approach. The proposed approach using multiple metrics may add complexity for processing resources, but may perform the route update without adding overheads to the network resources. Availability of sufficient processing resources and power assurance in wireless networks, like VANETs, will also help in designing complex but network friendly protocols. Similarly, availability of high-end processors in mobile nodes may also eliminate processing limitations. On the other hand, better network resource utilization will surely add a significant edge in the overall performance of any mobile network. Hence, the proposed model will help researchers to develop more practical, situation aware and network friendly routing protocols for future networks.

5.1.1. Some Significant Routing Metric Types

The study of networks proves that localized route repair performs better than end-to-end repair due to involvement of minimum number of nodes [112]. Resultantly, a localized metric can show more promising results as compared to end-to-end metric for local route repair. Analysis of networks with large topology changes emphasizes use of three different types of metrics for efficient routing strategy. These routing metrics which are also cross layer in design, independently define changes in network topology. However, routing strategies with multi-metric schemes have also been proposed by the researchers. The three selected domains of cross layer metrics are:

5.1.1.1.QoS Related Metrics

QoS related metrics such as throughput, delay and packet pair delay are often used in routing schemes. Considering the use of local route repair, QoS metrics for next hop perform better in realistic situations, than end-to-end metrics, such as next hop throughput, next hop delay and next hop packet pair delay [8].

5.1.1.2.Position Related Metrics

The use of position related metrics [113] have taken significant importance for networks such as VANETs. These metrics include list of neighbouring nodes, average node distance and number of neighbours, etc. Due to involvement of geographical location sharing, these metrics have received special attention by researchers for geo-cast communication.

5.1.1.3.Physical Layer Related Metrics

With the advancement in cross layer design, the use of physical layer metrics such as SINR and received power etc., is gradually emerging [114], [115]. Although these metrics require more complicated computation algorithms, their usefulness for more stable routes is proven.

5.1.2. Metrics Used in the Simulation

Considering the importance of above mentioned QoS related metrics, position related metrics and PHY layer metrics; we selected one metric from each domain considering its importance and simplicity for implementation:

5.1.2.1.Next Hop Throughput

Although QoS metrics such as next-hop throughput, next hop delay and packet pair delay have different interpretations, but they have more or less the same computing technique. Next hop throughput can be computed at the Data Link layer using the amount of duly acknowledged data sent to next hop neighbour. Similarly, next hop delay or packet pair delays can also be computed using the MAC layer acknowledgements. Accordingly, for our simulations, we selected next hop throughput from the QoS family as the first metric for implementation of adaptive route update strategy model.

5.1.2.2.One Hop Neighbour List

Every routing algorithm broadcasts HELLO messages on periodic basis to determine one hop neighbours. The geographical locations among the neighbours can be computed using GPS or non GPS techniques [115]. Due to nature of node topology in VANETs, the number of nodes entering and leaving one hop region adapts Gaussian distribution. As nodes observe probabilistic mobility pattern due to two way movement under geometrical mobility constraints (roads, streets, etc.), we can fairly assume that traffic moving in both directions at any reference point is equal in number. Hence, neighbour count value may not provide true picture for change in the topology. For highly fluent networks like VANETs, list of one hop neighbours provides a more realistic picture for change in network topology as compared to average neighbour count or average neighbour distance. Change in neighbour list describes the state of nodes entering or leaving any specific area. Resultantly, we selected one hop neighbour list as second metric for adaptive local route update strategy.

5.1.2.3. SINR

Throughput analysis clearly shows degradation of link capacity with decrease in received power which is inversely proportional to the inter-node distance. The received signal at far end node is the transmitted signal affected by combination of noise and interference caused by neighbouring nodes. Retrieval of transmitted signal from the received signal is one of the important topics among physical layer researchers. Change in received signal power can show the change in either signal strength or in noise plus interference strength. Being a combination of received signal strength, noise and interference, SINR provides more realistic results than received signal strength only. Resultantly, SINR provides a more promising view for the change in network state. Hence we selected SINR as third metric for implementation of proposed model.

5.1.3. Metric Values Computation for Simulations

With regard to selected metrics for our simulation study of adaptive local route update i.e. next hop throughput, one hop neighbour list and SINR, the method to determine the value of these metrics in real world is beyond our scope. We assume that the nodes using these metrics are equipped with the requisite hardware support. For simulation purposes, we selected NS2 after necessary changes in routing protocol codes for all three metrics. The values for each metric will be computed after predefined time intervals. The initial value will be compared against current metric values and the route will be updated if the difference in both values is observed up to a threshold level. The values can be computed as:

- Throughput is computed using the number of bits transmitted by one node and received correctly by next hop node and duly acknowledged at MAC layer. Hence no overhead is required for computation of throughput.
- Node position can be computed using ***posx*** & ***posy*** functions of NS2. The values can be disseminated among nodes using already available ***Hello*** messages or some special message. Each node will maintain a table containing identification and respective position of each node.

Most of the MAC protocols create sphere packing under the guard zone concept around each transmitting and receiving node, (e.g. MACA). The IEEE 802.11 protocols use the RTS/CTS concept, which is also like creating guard zones around the communicating nodes. Guard zones reduce interference around the receiver. However significant interference from other nodes can be observed in many scenarios, such as:

- While contending for channel access
- When one already transmitting mobile node may enter into guard zone of another node

The value of SINR for our simulation framework can be computed using the existing position of each node. SINR is the function of path loss which is dependent on inter-node distances. The path loss is the distribution of distance between the transmitter and receiver and between the interferers and the receiver. Each node can compute SINR value around itself using formula [20].

$$SINR = \frac{S}{N+I} = \frac{P_t * h_t * l(r)}{N + \sum_{i \epsilon \phi_S} (P_i * h_i * l * K * |x_i^{-a}|)} Eq \quad 5.1$$

Where, P_t = Transmitted power (constant)
h_t = Channel gain of transmitter
P_i = Transmitted power from I^{th} node (constant)
r = distance between transmitter and receiver
x_i = distance between I^{th} interfering node and receiver

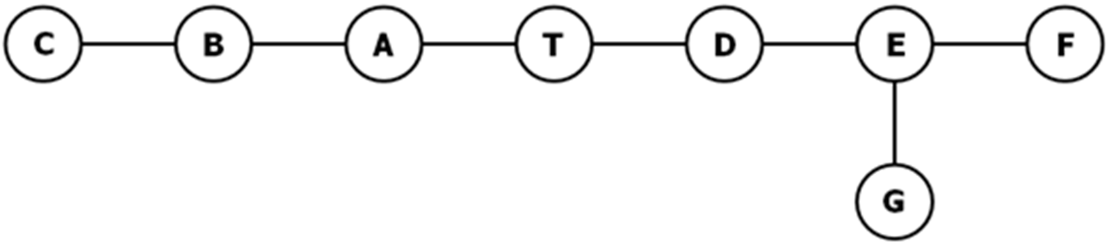

Figure 5.1: Example Topology for the Framework

5.2. Framework Flow Chart

Figure 5.1 shows the simple example of MANET topology involving eight nodes. Let us consider node ***T*** as the host node for the example case. Subsequently, nodes ***A*** and ***D*** are the one hop neighbours of node ***T***. Nodes ***B*** and ***E*** are the two hop neighbours, whereas node ***C***, ***F*** & ***G*** are the three hop neighbours of node ***T***.

Destination	Next Hop	Cost (Hop Count)
A	A	1
B	A	2
C	A	3
D	D	1
E	D	2
F	D	3
G	D	3

Table 5.1: Generic Routing Table at Node ***T***

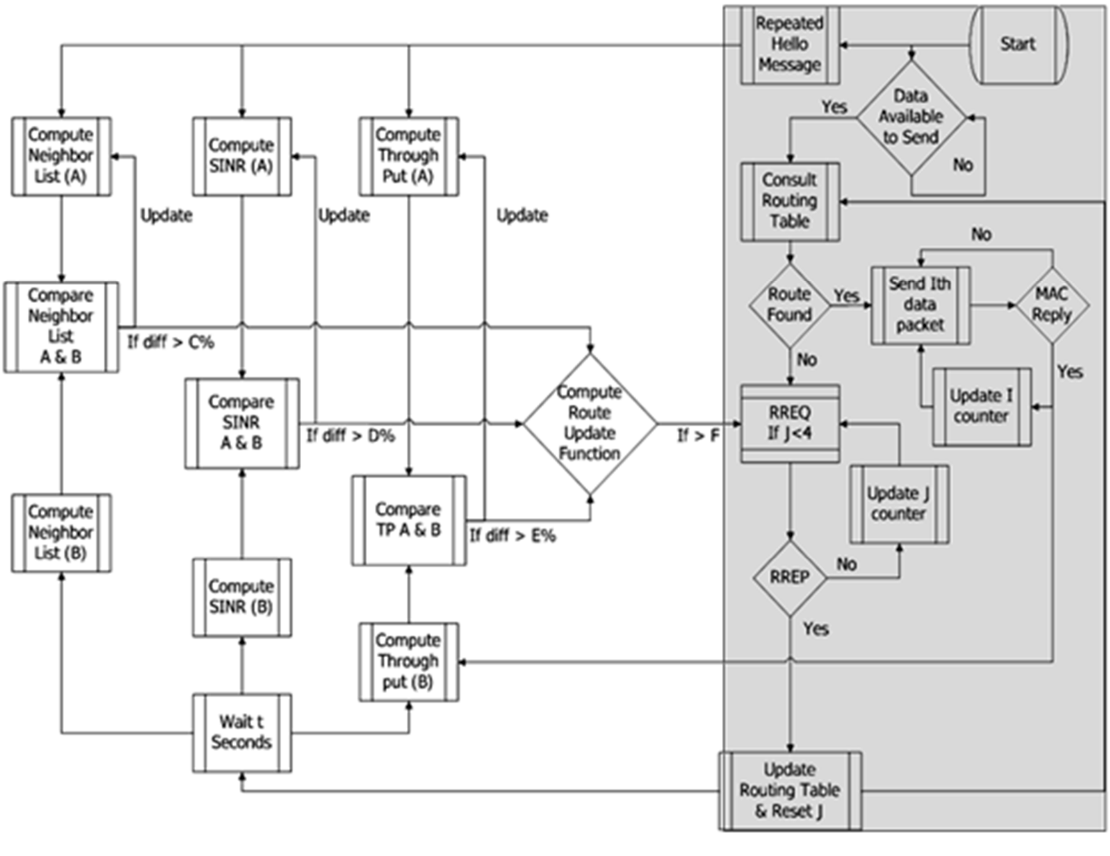

Figure 5.2: Framework Work Flow

Regardless of the routing algorithm, each protocol maintains the routing table containing columns for destination, next hop node and the cost. The generic adaptive route update process will run on each node. Let us consider the different procedures and states according to host node T. Table 5.1 shows the generic routing table at node T.

Based on the description of our frame work and method for metric values computation for simulation, we defined a simulation model as depicted in Figure 5.2. The shaded portion shows the generic route update mechanism for a routing protocol. Whereas, remaining non-shaded portion shows the adaptive update framework for three selected metrics. The variables ***C, D, E & F*** are the threshold values of neighbour list, SINR, next hop throughput and wait time respectively. To compute the two states (previous & current), we defined a generic process to be run on each node as defined in following section.

Node	SINR(A)	Neighbour List (A)	Throughput (A)
A	A	B	c
D	a'	b'	c'

Table 5.2 Example Table (Initial)

5.2.1. Initialization

- Initialization of two separate tables (previous) and (current). Table (previous) will contain initial or previous values, whereas table (current) will contain current values of the selected metric.
- Computation of current value of SINR (A), NeighbourList (A) and Throughput (A) of all the one hop neighbours for the starting process.
- SINR and Throughput are dependent on the next hop neighbour nodes. These factors will be computed sequentially for all relevant nodes. However, Neighbour List is independent of next hop neighbour node and can be computed once at any specific time interval incorporating all neighbours.
- Logging of all metrics against all next hop neighbours present in routing table.

Table 5.2 shows a few of entries of the table (previous) for the host node ***T***. First column of the table shows the next hop neighbour node, whereas SINR (A), Neighbour List (A) and Throughput (A) show the table(previous)'s values of SINR, neighbour list and throughput respectively.

- Computation of current value of SINR (B), Neighbour list (B) and Throughput (B) of all the next hop neighbours for the starting process. At start of the process, table(current) will have the same values as of table(previous).

5.2.2. Initiation of ***Update Flag***

- Marking of the ***Update Flag*** if difference in value for each independent metric in table(current) and table(previous) is greater than the defined threshold values ***C, D & E***. At start of the process, table(previous) and table(current) will have equal values; hence ***Update Flag*** column will have zero values.

Node	**SINR(B)**	**Neighbour List (B)**	**Throughput (B)**	**Update Flag**
A	A	B	C	0
D	a'	B	c'	0

Table 5.3: Example Table(Current)

Node	**SINR (B)**	**Neighbour list (B)**	**Throughput (B)**	**Update Flag**
A	D	e	f	0
D	d'	e	f'	0

Table 5.4: Example Updated Table(Current)

Table 5.3 shows a few entries of the table(current) for host node ***T***. First column of the table shows the next hop neighbour nodes, whereas SINR (B), Neighbour List (B) and Throughput (B) show the table(current)'s values of SINR, neighbour list and throughput respectively. Update Flag field shows the current state of update flag for the respective neighbour node.

- Waiting for the time interval ***t*** before computation of next updated values for table(current).

- Re-computation of SINR (B), Neighbour list (B) and Throughput (B) of all the next hop neighbours present in next hop column of the routing table.

Due to involvement of mobility, we assumed continuous change in network topology. The updated topology caused changes in SINR, neighbour list and throughput for host node ***T***. Table 5.4 shows the updated state of table(current) for the host node ***T***. We can observe that values of SINR, Neighbour List and Throughput have changed from initial state of table(previous) for node ***T***.

5.2.3. Computation of Update Threshold

- Computation of percentage difference of SINR, Neighbour List and Throughput, recursively for all next hop neighbour nodes.
- Computation of ***Update Factor (UF)***, as

UF (SINR) = scaling factor (Z) * % change in SINR

Node	SINR (B)	Neighbour List (B)	Throughput (B)	Update Flag
A	D	e	F	1
D	d'	e'	f'	0

Table 5.5: Example Updated Table(Current) as per Update Factor

UF (Neighbour List) = scaling factor (Y) * % change in Neighbour List

UF (Throughput) = scaling factor (X) * % change in Throughput

- If UF>C/D/E for any next hop neighbour present in Next Hop column, Mark ***Update Flag*** as ‘1’.

Table 5.5 shows the example of updated state of table(current) after the computation of Update Flag (UF). We can observe that ***Update Flag*** for node ***A*** has been marked ***set***, whereas there is no change in its value for node ***D***.

5.2.4. Packet Delivery

After initialization of different tables and computation of ***Update Flag*** according to runtime states of the network, following action will be taken on arrival of any packet (upper layer or from neighbour node):

- Transmission of available data as per routing table.

- Checking of the ***Update Flag*** for the targeted destination. Initiate local route repair for the said destination, if the ***Update Flag*** is set for the destination node and the destination is not in the one hop neighbour list.

- Copying table(current)'s values i.e. SINR (B), Neighbour List (B) and Throughput (B) to table(previous) as SINR (A), Neighbour List (A) and Throughput (A) for that specific next hop neighbour, e.g. tables for node 'A' will be updated, as:

Node	SINR(A)	Neighbour List (A)	Throughput (A)
A	d	e	f
D	a'	b'	c'

Table 5.6: Example Updated Table (Previous)

Node	SINR (B)	Neighbour List (B)	Throughput (B)	Update Flag
A	d	e	f	0
D	d'	e'	f'	0

Table 5.7: Resetting of Update Flag after Local Repair

Table 5.6 shows the example of updated state for table(previous) after local route repair involving node ***A***. We can observe that all values of table(previous) for the node ***A*** have been replaced with values of table(current). Whereas, values of the table(previous) for node ***D*** have not been changed.

- Resetting ***Update Flag*** for that specific one hop neighbour in table(current).

Table 5.7 shows the example of updated state of table(current) after initiation of local route repair for destinations involving node ***A***. We can observe that ***Update Flag*** for the node ***A*** has been reset, whereas there is no change in other values till completion of time interval ***t***.

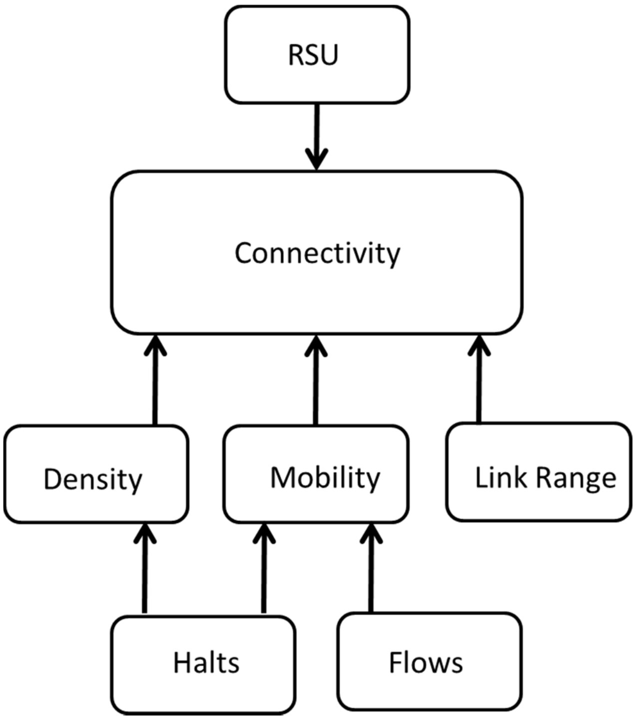

Figure 5.3: Connectivity in VANET

5.3. VANET Scenarios

Topologies and scenarios within any specific environment are governed by the connectivity state among nodes. As discussed in detail in previous sections, connectivity among nodes is affected by different factors. Accordingly, routing is governed by the inter-node connectivity. Figure 5.3 summarizes different factors which need to be considered to study inter-node connectivity.

To further analyze the propose model of adaptive route update, we performed simulations for different possible connectivity scenarios of the VANET. These scenarios include high and variable active node density and changing node mobility, etc. There can be a number of connectivity scenarios according to type of traffic, hour of the day, physical area, etc. However, from VANET perspective, topologies can be grouped in two main categories, i.e. Highway scenarios and Urban or City scenarios, as under:

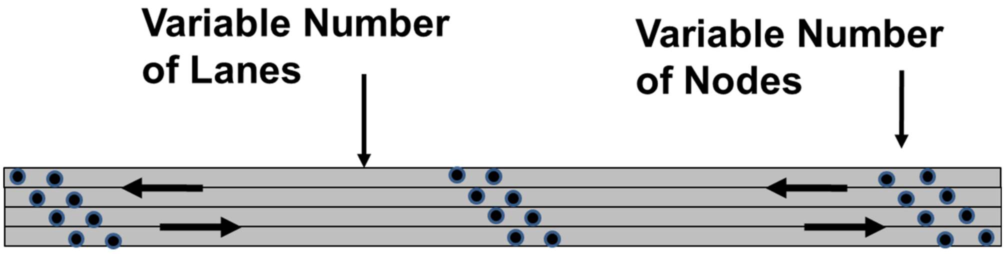

Figure 5.4: Mobile Nodes on a Straight Rode Depicting Highway Scenario

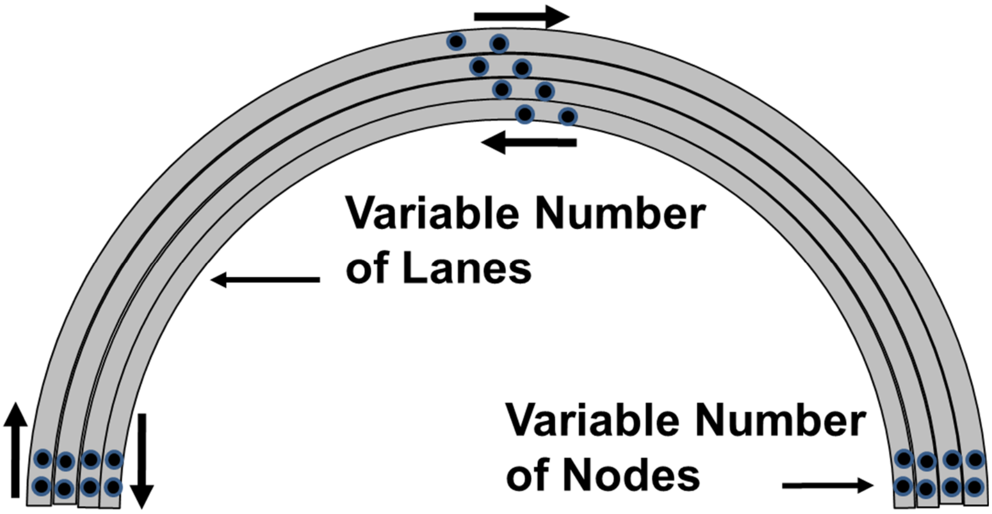

Figure 5.5: Mobile Nodes on a Curve

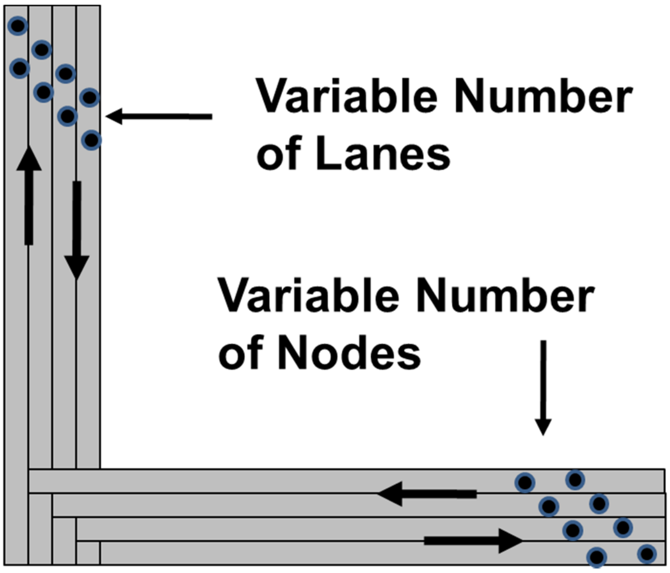

Figure 5.6: Mobile Nodes on a Road Bend

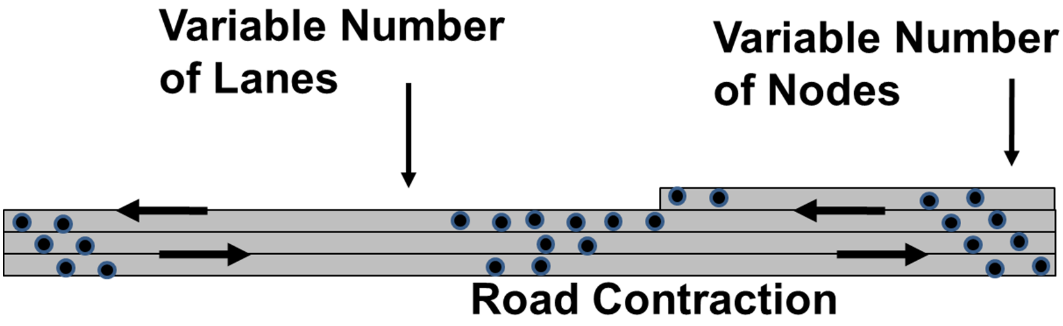

Figure 5.7: Mobile Nodes on a Road Contraction

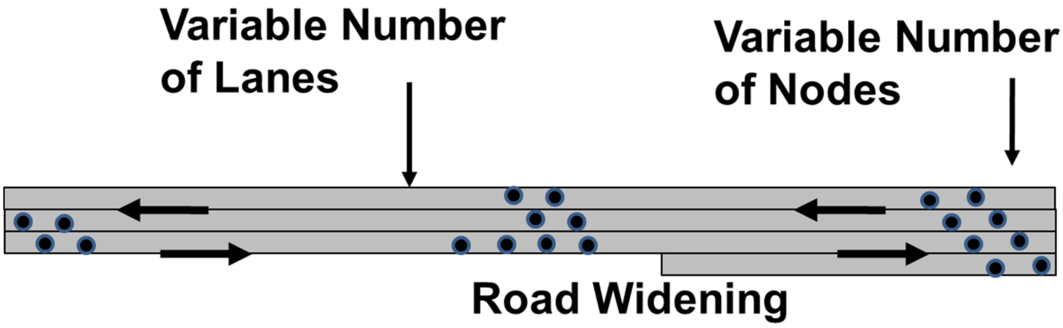

Figure 5.8: Mobile Nodes on a Road Widening

5.3.1. Highway Scenario

A highway scenario generally consists on straight road with relative low node density and fast moving nodes. Fig 5.4 depicts a simple highway with multiple lane scenario. Node mobility is relatively simple involving just two opposite directions, i.e. $\theta=0^0$ or $\theta=180^0$. Hence, link life is significantly higher for all the nodes moving in same direction. On the other hand, nodes face frequent disconnections if next hop node is moving in opposite direction. There can be a few variations in the road topologies, as described below.

5.3.1.1.Road Curve

Figure 5.5 shows a curved road segment on a highway. Such road segments may cause minor speed variations to all nodes. However, no significant topology changes occur due to such curves. Figure 5.5 can be summarised as:

- Initial Mobility : High

- End Mobility : High
- Initial Node Density : Low
- End Node Density : Low
- Initial Topology Change : Low
- End Topology Change : Low

5.3.1.2. Road Bend

Figure 5.6 shows a road bend on a highway. Such bends are not very common on highways in plains, however are common in mountains. As, such segments cause significant decrease in node speed, nodes face increase in node density while approaching to road bend. On the other hand, nodes face reduction in node density while going away from road bend. Accordingly, nodes face minor but gradual topology changes. Figure 5.6 can be summarised as under:

- Initial Mobility : High
- Mid Mobility : Medium
- End Mobility : High
- Initial Node Density : Low
- Mid Node Density : Medium
- End Node Density : Low
- Medium Node Density Duration: Short
- Initial Topology Change : Low
- End Topology Change : Low

5.3.1.3. Road Contraction

Figure 5.7 shows a road contraction e.g. bridges and defiles. Similar to previous case, nodes face significant increase in node density while approaching contraction point. Contrary to road bend, higher node density continues for subsequent path. Such narrowing causes temporary halt for the nodes due to reduction in space. The change in node density reduces topology changes for subsequent section. Resultantly, nodes face higher link life on the path. Figure 5.7 can be summarised as under:

- Initial Mobility : High
- End Mobility : Low
- Initial Node Density : Low
- End Node Density : High
- High Node Density Duration : Medium
- Initial Topology Change : High
- End Topology Change : Low

5.3.1.4. Road Widening

Figure 5.8 shows a road widening, e.g. exit point of a bridges or defiles. The situation in this scenario is absolutely opposite to the previous case, where nodes face significant decrease in node density while leaving widening point. Contrary to previous case, nodes face sudden acceleration, hence decrease in node density. Such widening allows nodes to move at higher speed due to availability of space. Lower node density causes sudden change in link topology, which continues for subsequent path. Higher topology changes cause repeated link breakages. Figure 5.8 can be summarised as under:

- Initial Mobility : Low
- End Mobility : High

- Initial Node Density : High
- End Node Density : Low
- High Node Density Duration : Short
- Initial Topology Change : Low
- End Topology Change : High

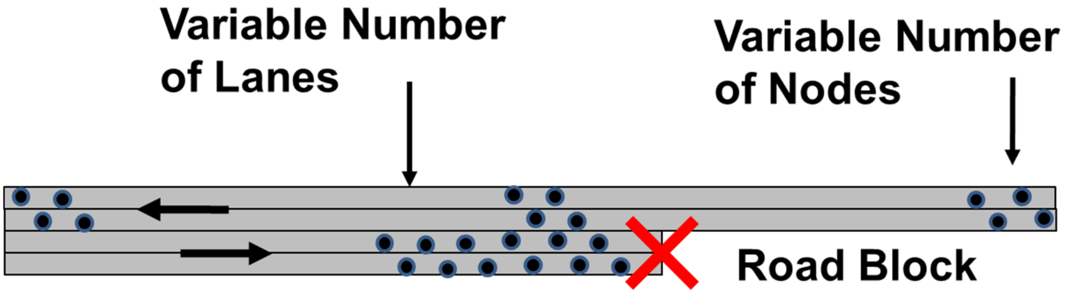

Figure 5.9: Mobile Nodes on a Road Blockade

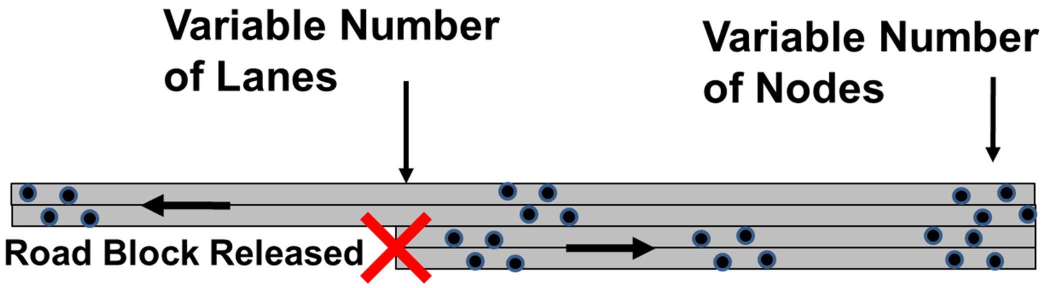

Figure 5.10: Mobile Nodes after Release from Road Blockade

5.3.2. City Scenario

Contrary to highway scenario, an urban scenario is generally a complex case involving different situations. These situations include straight roads, road bends, road halts, crossings etc. Contrary to highway scenarios, nodes within urban region observe rapid topology changes due to sudden acceleration and deceleration; mobility in different directions due to layout of roads and road crossings. Resultantly, link life is significantly lower as compared to highway scenarios. However, use of infrastructure nodes can help to increase link life and reduce number of hops. In addition to different cases defined in highway scenario, there can be a few variations in the road topologies, as described below.

5.3.2.1. Road Blockade

Figure 5.9 shows a road blockade scenario. These blockades are generally pre-coordinated and planned (e.g. signal halts) and sometimes are unplanned, (e.g. traffic disruption, congestion or landslides etc.). Accordingly, these halts may prolong from few seconds to hours. These halts cause high node density within halt region and nodes face almost static behaviour. Accordingly, fast moving nodes face very low topology changes while approaching and staying at halt region. Figure 5.9 can be summarised as under:

- Initial Mobility : High
- End Mobility : Low
- Initial Node Density : Low
- End Node Density : High
- High Node Density Duration : Long
- Initial Topology Change : High
- End Topology Change : Low

5.3.2.2. Road Clearance

Contrary to previous scenario, Figure 5.10 shows a road clearance after a road blockade scenario. Similar to previous scenario, these clearances are generally pre-coordinated and planned (e.g. green lights at signal halts) and sometimes are unplanned, (e.g. traffic release after disruption, congestion or landslides etc.). At such clearing points, nodes tend to move with high acceleration causing link breakages. Figure 5.10 can be summarised as under:

- Initial Mobility : Low

- End Mobility : High
- Initial Node Density : High
- End Node Density : Low
- High Node Density Duration : Short
- Initial Topology Change : Low
- End Topology Change : High

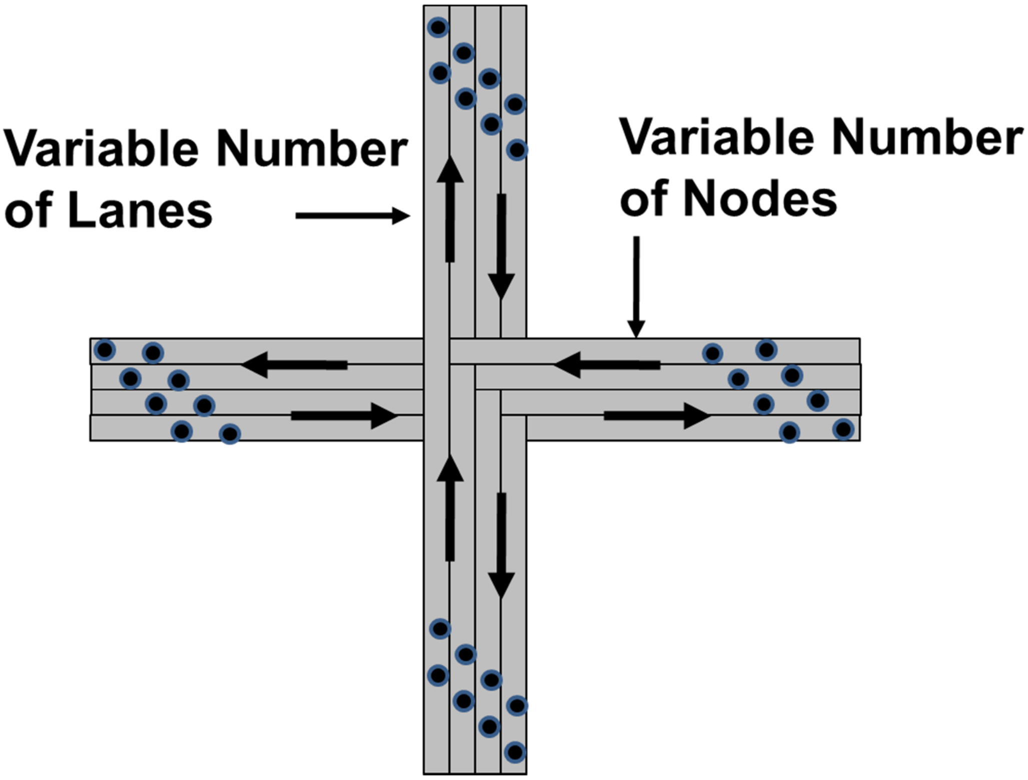

Figure 5.11: Mobile Nodes on a Road Crossing

5.3.2.3. Road Crossing

Figure 5.11 shows a road crossing involving signal halts. Such crossings are very common within city scenarios. This scenario is a combination of multiple road bends, blockades and clearances. Contrary to simple road bend, road crossing coupled with signal halts creates a complex topology. Fast moving nodes from different directions will face gradual reduction in speed while approaching to signal halt. Such halts can be as long as multiple minutes. Signal halts allow node movement from one side at a time. Resultantly, there can be only one side of the road with moving nodes. Rest of the three road segments will face a temporary halt, hence facing very high node density. High node density scenario will continue for quite a long duration according to signal timings. After staying at signal halt with very low topology changes, nodes move in different directions on green signal. Rapid acceleration and variable movement direction cause sudden topology changes and link breakages. For the clarification purposes, Figure 5.11 can be summarised as under:

- Initial Mobility : High
- Mid Mobility : Low
- End Mobility : High
- Node Density : High at signal halt
- High Node Density Duration : Long
- Initial Topology Change : Low
- End Topology Change : High

5.4. Simulation Parameters

To make the simulations and comparison more realistic, a detailed study of the simulation parameters was conducted. We selected NS2 network simulator for verification of our adaptive route update approach. After comprehensive verification of our proposed scheme, we compared it against other routing protocols. As a test platform for the adaptive route update approach, we modified standard AODV routing protocol and named it as Adaptive AODV (AAODV). Accordingly, different parameters were considered as under:

- Simulator - NS2, version 2.34
- Topology Writer - NSG version 2.1

- Fading Model - Two Ray Ground Model
- OLSR Hello Interval - 2 seconds
- AAODV update Interval - 1 second
- QoS Parameter - Net throughput

5.4.1. Initial Simulations

We started our simulation with a simple topology involving five nodes only. For any data session, we considered the end nodes as active nodes, while other nodes involved in data relaying through routing are considered passive nodes. In the initial topology, we considered two active and three passive nodes.

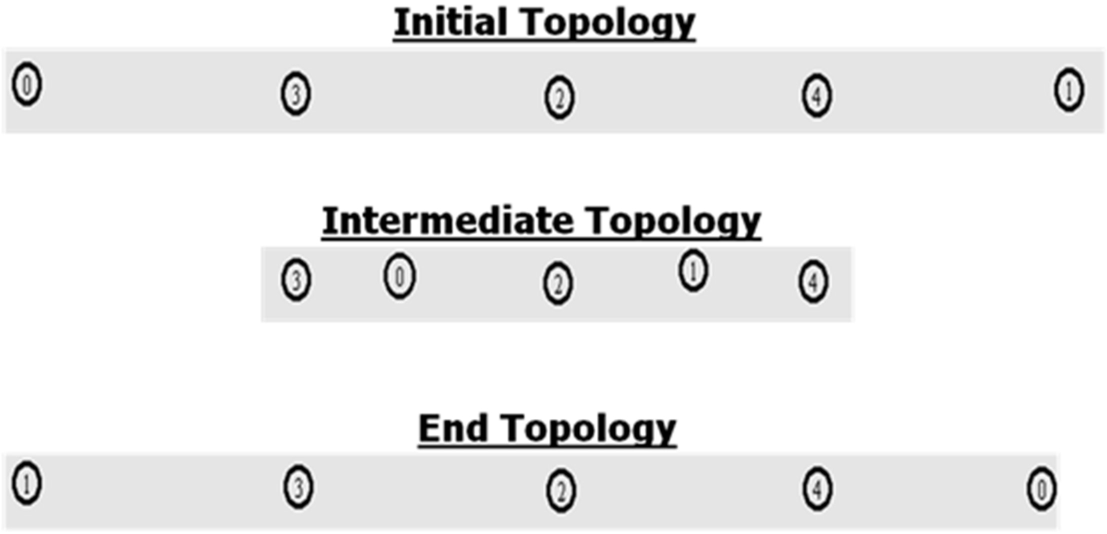

Figure 5.12: Initial Node Topologies for Simulation According to Node Mobility

We considered each node as one hop distance away from the other node, making the two end nodes at 4 hops distance from each other as shown in Figure 5.12. Initially, the end nodes started moving towards each other while having an end-to-end FTP application running on both end nodes. In the second phase, our nodes approached a topology where end nodes stayed static after reaching one hop distance from each other. In the end, both end nodes again continued to move in opposite direction from each other, while involving multi-hop communication. We simulated the situation using AODV, DYMO, OLSR, DSDV and AAODV (the proposed adaptive approach over AODV). We used the percentage change in the SINR as the metric value for adaptive update factor.

For the initial simulation, additional parameters used are shown below:

- Number of Active Nodes - 2
- Number of Passive Nodes - 3
- MAC Protocol - IEEE 802.11a
- Inter-node Distance - 230 meters
- Initial Inter-node Distance among Active Nodes - 500 meters
- Final Inter-node Distance among Active Nodes - 500 meters
- Node Speed - 10 kmph
- Number of Lanes - 1
- Type of Data Traffic - FTP over TCP

5.4.2. Detailed Simulations

As a second part of our simulation, we considered the amalgamation of low active node density with very high active node density. We considered scenario for convergence of highly mobile nodes moving on different roads with variable velocity. All nodes moving on roads were defined as active nodes running combination of TCP and UDP based applications. We simulated seven different topologies by varying the number of nodes from 8 active and 18 passive nodes to 128 active and 18 passive nodes under different scenario conditions.

During these simulations, we also measured throughput by keeping different threshold values of all three metrics. Different threshold values for change in neighbour list, SINR and throughput were set to find the threshold values under different node densities.

For the detailed study, 259 different simulations were run for 10 repetitions each. During the simulation, the nodes faced sudden change in the metric values, e.g. change in throughput from few bits per second to Megabits per second. Resultantly, large threshold values for SINR and throughput were observed. The parameters considered for the simulations were as under:

- Number of Topologies- 7
- Number of Active Nodes- varied from 8, 16, 32, 56, 64 & 128 active nodes
- Number of Passive Nodes- 9 & 18
- MAC Protocol - IEEE 802.11p
- Number of Lanes - 2, 4 & 8
- Node Speeds - from 16, 32, 50, 65, 80, 96, 112 & 130 kmph
- Type of Data Traffic - UDP & TCP
- Type of Metrics - 3 (Neighbour List, SINR & Throughput)
- Thresholds for change in Neighbour List (%)-10, 20, 30, 40, 50, 60, 70, 80, 90, 91, 95, 99
- Thresholds for change in SINR (%)- 25, 50, 75, 100, 200, 500, 2000 (2k), 5k, 10k, 50k, 100k, 1000,000 (1m), 10m, 100m & 1000,000,000 (1b)
- Thresholds for change in Throughput(%)- 80, 100, 1000 (1k), 10k, 50k, 100k, 1000,000 (1m), 10m, 100m & 1000,000,000 (1b)

5.4.3. Comparative Simulations

After finding the threshold values of all three metrics for different node densities, we simulated adaptive route update against other protocols. Standard AODV was further modified to optimize AAODV to be used for the comparison with other routing protocols. All seven topologies simulated under detailed study were tested against standard routing protocols. From the family of MANET routing protocols suggested in VANET, we selected AODVv2 (DYMO) and OLSRv2 routing protocols. Whereas from classic VANET based routing protocols, we selected FROMR [54] and XORi [55] routing protocols. These two protocols were carefully selected considering their utility, design, comparative results claimed by their authors and use of runtime network information. A little description highlighting their design criteria is given in following paragraphs

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5.4.3.1.XORi

As described in chapter 2, XORi is the modification of cluster based routing approach, coupled with XOR approach. The major problem with any proactive protocol is its overhead. In such protocols, in the beginning of the routing table building process a node starts to query all its neighbors about the required information to fill its buckets. This is not a good practice in wireless networks, since it decreases the network capacity. XORi modifies the protocol's information gathering process to accommodate the specific dynamic nature of VANETs topology. XORi maintains the same rationale as XOR algorithm. However, instead of starting to query to all neighbours, a node only interrogates Broadcast Group Leader (BGL) selected by the node that originates the Query. A node only interrogates all its neighbors when it has not previously selected a BGL node.

5.4.3.2.FROMR

FROMR is the combination of cluster based routing, geographical routing, adaptive multipath routing and topology based routing. FROMR is basically an extension of AODV by adding multi-path discovery from source to destination in every route discovery. Multipath routing is used to provide enhanced robustness in case of link failures. FROMR relaxes the requirement for link disjointedness as it allows alternate path disjoint from each other. The main design property of the FROMR is the grouping of vehicles into geographical clusters as a grid. To reduce the overheads, only grid leaders are responsible for route discovery, maintenance and restoration, as used in cluster based routing.

For the comparative study of different routing protocols against optimized AAODV, 28 different simulations were run for 10 repetitions each. 7 different topologies were tested for 5 protocols. The parameters considered for the simulations are as under:

- Number of Topologies - 7
- Number of Active Nodes - 4, 8, 16, 32, 56, 64 & 128
- Number of Passive Nodes - 9 & 18
- MAC Protocol - IEEE 802.11p
- Number of Lanes - 2, 4 & 8
- Node Speeds - 16, 32, 50, 65, 80, 96, 112 & 130 kmph
- Type of Data Traffic - UDP & TCP
- Number of Comparative Protocols- 4 : AODVv2 (DYMO), OLSRv2, FROMR & XORi

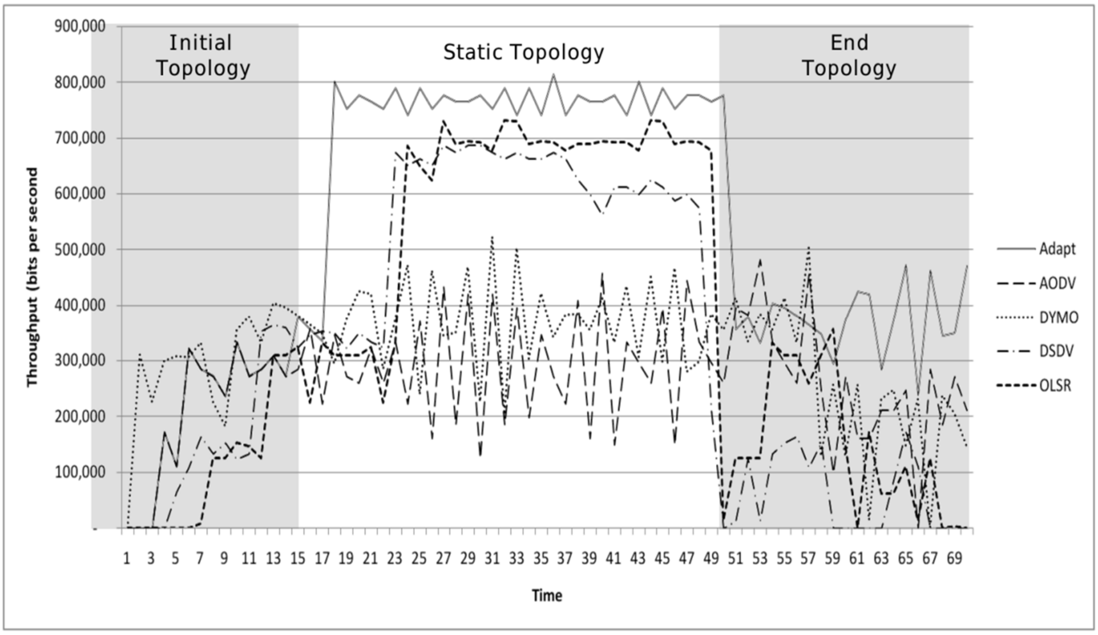

Figure 5.13: Throughput of Various Routing Protocols against Proposed Approach

5.5. **Simulation Results and Analysis**

For the detailed analysis of the proposed adaptive route update strategy, following simulations were conducted.

5.5.1. Initial Simulations

Considering the limited number of nodes, route update was performed on any change in neighbour list. Although the selected route update condition may not perform well for all network topologies, however, the simulation provided significant improvements against other routing protocols. For this simulation, we considered start of data sessions at the start of simulation.

Figure 5.13 shows the net throughput graph of the node topology shown in Figure 5.12. The x-axis shows the time scale which goes up to 70 seconds. The y-axis shows the net throughput in bits per second for all the sessions. For clarity, different topology events have been shaded accordingly. The first shaded segment shows the initial topology, where active nodes started data sessions while at the distance of four hops from the other end node. It can be observed that AAODV is performing like AODV as there is no change in the neighbour list for any node. During this segment, reactive protocols (AODV & AODVv2 (DYMO)) performed better than other protocols due to fast route determination than DSDV & OLSR. The route finding for proactive routing protocols is the function of hello interval and multiple hello intervals were involved to find the initial route to destination. As data sessions started immediately with the start of simulation, proactive routing protocols took significant time to find the route to destination.

After the initial segment, the end nodes approached closer to each other and entered in a temporary topology with static node positions. During this phase, AAODV along with both proactive protocols outperformed reactive protocols by timely updating their routing tables. Reactive protocols continued on old route without incorporating change in topology as old route was still available. Although Proactive protocols updated the route on change in topology, they continued updating it even when there was no change in topology. Such routing topology messages caused additional overheads. AAODV updated the route only after change in topology, without any additional overheads. Although proactive protocols have apparently performed better than reactive protocols, but study in chapter 3 shows degradation in performance of proactive protocols with increase in node density.

During third phase, AAODV approach performed better than both reactive and proactive routing protocols. In this phase, AAODV route update was performed even prior to link breakages. Whereas, reactive routing protocols faced sudden repeated link breakages and maintained the route after link breakage only. The performance of proactive routing protocols remained worst among all as these protocols updated the route after consuming multiple hello intervals. Due to involvement of mobile nodes, significant topology changes had occurred before determination of new route through hello messages. Resultantly, for nodes moving at high speed, hello interval become too large to adapt a new route.

5.5.2. Detailed Simulations

After ascertaining the initial results, detailed simulations were performed for study of metric behavior on adaptive route update strategy. Averages of ten repetitions for seven different topologies against three selected metrics were computed during simulations. Subsequently, the behavior curves for all selected metrics, i.e. Neighbour List (nl), SINR (si) and Throughput (tp) were drawn. For the simulation, standard AODV was modified to adaptively update local route. The local route update was performed if the change in current metric value is greater than the threshold level from the metric value at last local update.

Before defining the levels for local route update, we computed repeated simulations for all the topologies and recorded the occurrences for all three metrics. Accordingly, different threshold values were defined for significant change levels, as:

- Neighbour List - 12 levels
- SINR - 15 levels
- Throughput - 10 levels

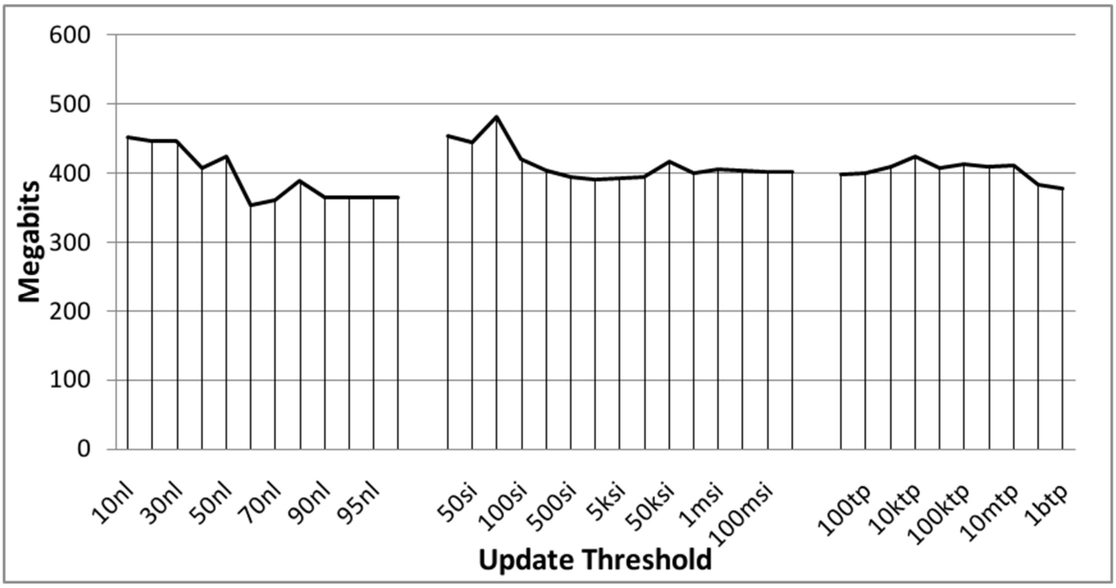

Figure 5.14: Data Transfer of 8 Active and 18 Passive Nodes

5.5.2.1.8 Active and 18 Passive Nodes

Figure 5.14 shows the average of 10 repetitions for total data transferred per active node for 8 active and 18 passive nodes. The x-axis shows the threshold values (in percentage) for all three metrics. Different markings shown at x-axis are the threshold values coupled with metric names, e.g. 10nl shows results for neighbour list change at 10% threshold value. The y-axis shows the average of 10 repetitions for total transferred data bits per active node during the simulation.

The first portion of the curve shows the data transfer values for the neighbour list changes. Whereas, the middle portion shows the data transfer for SINR change and end portion shows the data transfer for throughput change. We can observe that there can be multiple threshold values for which the data transfer is the maximum. However, the curve for 12 different threshold values shows that net data transfer decreases with increase in threshold value for neighbour list change. Similarly, net data transfer also decreases with increase in threshold value for SINR change and throughput change. We can observe the slight peaks of the curve at the lowest threshold values for all three metrics. This curve behaviour is more conclusive for the SINR change, followed by neighbour list change. However, the curve behaviour for throughput change is relatively inconclusive. On the other hand, minimum data transfer rate can be seen for the maximum threshold values of all three metrics. Contrary to peak value, the lowest dip is more conclusive. The higher values can be recorded as 10-30% for neighbour list change, 25-75% for SINR change and 80-10M% for throughput change. Similarly, the lower values can be recorded for 60% onward for neighbour list change, 200% onwards for SINR change and 100M% onwards for throughput change.

The simulation was run for 234 seconds. During the simulation, maximum data transfer per active node was 481 Mb when local route update was performed based on SINR change. For the same metric, the lowest data transfer per active node was observed at 390 Mb. Similarly for neighbour list change and throughput change, maximum data transfer per active node was 451 Mb and 423 Mb respectively. The lowest data transfer per active node for both metrics was observed at 353 Mb and 378 Mb respectively.

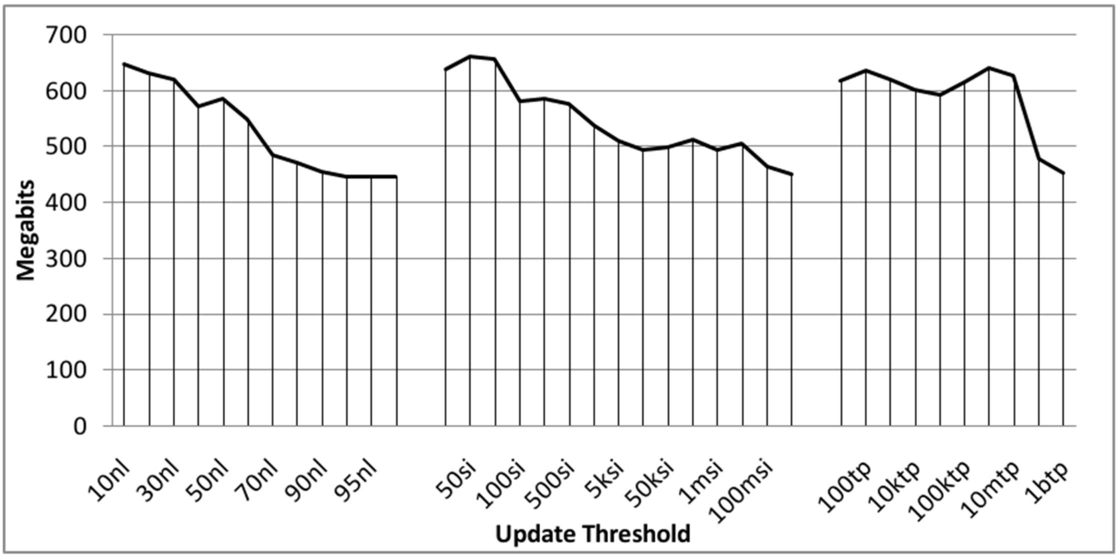

Figure 5.15: Data Transfer of 16 Active and 9 Passive Nodes

5.5.2.2.16 Active and 9 Passive Nodes

Figure 5.15 shows the average of 10 repetitions for total data transfer per active node for 16 active and 9 passive nodes. The x-axis and y-axis representations are same as Figure 5.14. We can observe that peak values for data transferred are seen closer to lowest threshold values for all metrics. For the neighbour list change, the curve again shows the peak for lower threshold values. The peak for neighbour list change, SINR change and throughput change are at 10%, 50% and 100% respectively. The data transfer values decrease with subsequent increase in threshold values. The data curve for SINR change shows little shift in its peak value. Similarly, throughput change curve also shows the shift in its peak value. Similar to Figure 5.14, the data curves for neighbour list change and SINR change are more conclusive than throughput change curve.

The data transfer rate decreases with increase in threshold value for all metrics. However the curve for throughput change remains flat for longer duration then other two metrics. Similar to previous curve, minimum data transfer rate can be seen for the maximum threshold values of all three metrics with more conclusive behaviour. We can also observe that the curve is smoother than curve in Figure 5.14. The higher values can be recorded similar to previous curve as 10-30% for neighbour list change, 25-75% for SINR change and 80-10M% for throughput change. The lower values can be recorded for 40% onward for neighbour list change, 100% onwards for SINR change and 100M% onwards for throughput change.

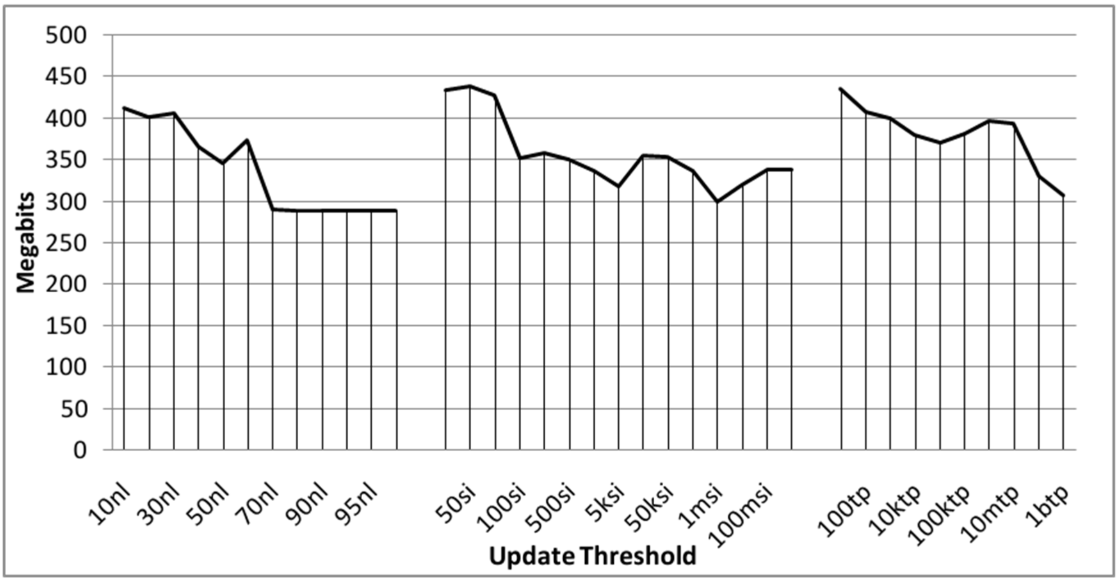

Figure 5.16: Data Transfer of 16 Active and 18 Passive Nodes

Similar to previous simulation, this simulation was also run for 234 seconds. After increasing the number of active nodes and decreasing the passive nodes, data transfer per active node per second was observed higher than 8 active and 18 passive nodes. As total nodes remained almost constant for both the simulations, the increase in data transfer per active node was due to less number of contending nodes for the channel access. For the simulation, maximum data transfer per active node was 661 Mb when local route update was performed based on SINR change. For the same metric, the lowest data transfer per active node was observed at 450 Mb. Similarly for neighbour list change and throughput change, maximum data transfer per active node was 647 Mb and 640 Mb respectively. The lowest data transfer per active node for both metrics was observed at 447 Mb and 443 Mb respectively.

5.5.2.3.16 Active and 18 Passive Nodes

Figure 5.16 shows the average of 10 repetitions for total data transfer per active node for 16 active and 18 passive nodes. The x-axis and y-axis representations are the same as in previous figures. The curve in the figure follows the same behaviour as of previous curves. However, the peaks for all three metrics are seen flatter than the previous ones. Similar to the curves for neighbour list change and SINR change, the curve for throughput change is also more conclusive than previous curves. The peak values for data transfer are closer to lowest threshold values for all metrics like previous curves. The peak for neighbour list change, SINR change and throughput change are at 10%, 50% and 80% respectively. The data transfer values also decreased with increase in threshold values. However, the data curve for SINR change shows little shifts in its peak value. Similarly, throughput change curve also shows the shift in peak value. For overall analysis, the higher values can be recorded similar to previous curves as 10-30% for neighbour list change, with a sudden fall from 60% onwards. SINR change curve shows higher values at 25-75% whereas throughput change curve shows higher values at 80-100%. Lower values can be recorded for 60% onward for neighbour list change, 100% onwards for SINR change and 1K% onwards for throughput change.

Like previous simulations, this simulation was again run for 234 seconds. Comparing previous two results, per active node per second data transfer was observed lowest for all three metrics after increasing the active nodes. The decrease was caused by more number of nodes contending for the same channel resources causing more delay in next channel access for each node. For the simulation, maximum data transfer per active node was 439 Mb when local route update was performed based on SINR change. For the same metric, the lowest data transfer per active node was observed at 300 Mb. Similarly for neighbour list change and throughput change, maximum data transfer per active node was 413 Mb and 436 Mb respectively. The lowest data transfer per active node for both metrics was observed at 289 Mb and 308 Mb respectively.

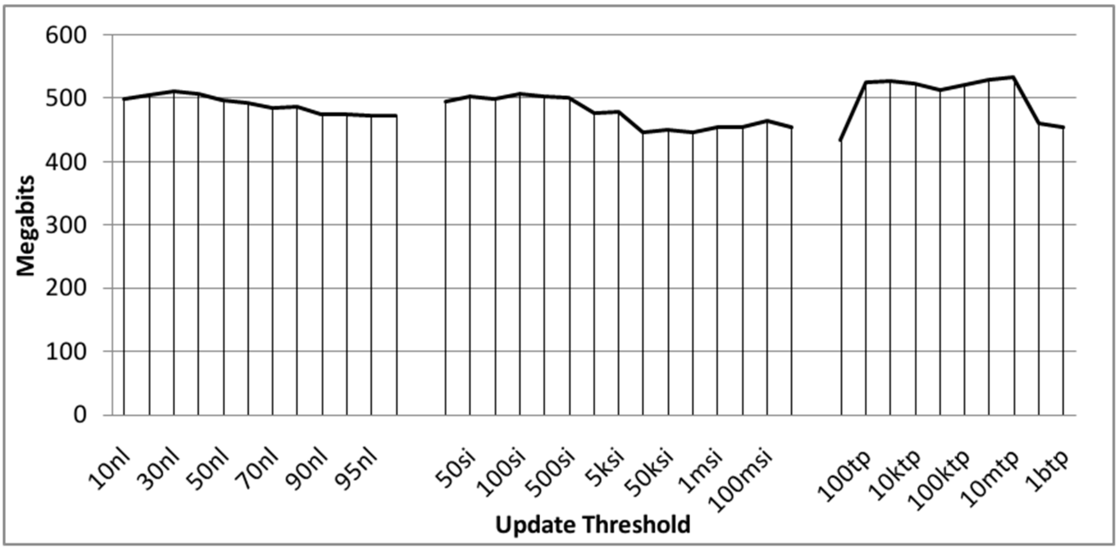

Figure 5.17: Data Transfer of 32 Active and 18 Passive Nodes

5.5.2.4.32 Active and 18 Passive Nodes

Figure 5.17 shows the average of 10 repetitions for total data transfer per active node for 32 active and 18 passive nodes. The x-axis and y-axis representations are same as in previous figures. As observed in the Figure 5.14, the data curve in the figure shows shift in peak values for all of the metrics. The peak for neighbour list change, SINR change and throughput change are at 30%, 100% and 1000% respectively. However, the curves generally follow the same behaviour as of previous curves. Contrary to previous curves, the curve in the Figure 5.17 also shows a dip at lowest threshold values for all metrics. The flatness of the peak with its shifted values can be observed in the curves. The curves for neighbour list change and SINR change are more conclusive than the curve for throughput change, which shows a long flat peak as seen in Figure 5.15. However, the curve for neighbour list change and SINR change is flatter at the peaks than in previous figures. The trend for decrease in data transfer values continues like previous curves, however the variation in the values is lesser than previous curves. For analysis, the higher values can be recorded with little shift from previous curves as 30-40% for neighbour list v, at 50-200% for SINR change and 100-10M% for throughput change.

Due to increase in number of nodes, more speed variations were introduced for the topology. Resultantly the simulation was run for 294 seconds, which is 60 seconds more than previous three simulation. Although the per active node data transfer value increased from last simulation, but per active node per second data transfer was decreased. The increased value was due to increased simulation time. After increasing the total node density as well as number of active nodes, data transfer per active node for the simulation decreased gradually. Increase in active nodes caused more contention for the same channel resources causing more delay and decrease in net throughput. For the simulation, maximum data transfer per active node was 534 Mb when local route update was performed based on throughput change. For the same metric, the lowest data transfer per active node was observed at 435 Mb. Similarly for neighbour list change and SINR change, maximum data transfer per active node was 512 Mb and 509 Mb respectively. The lowest data transfer per active node for both metrics was observed at 473 Mb and 448 Mb respectively.

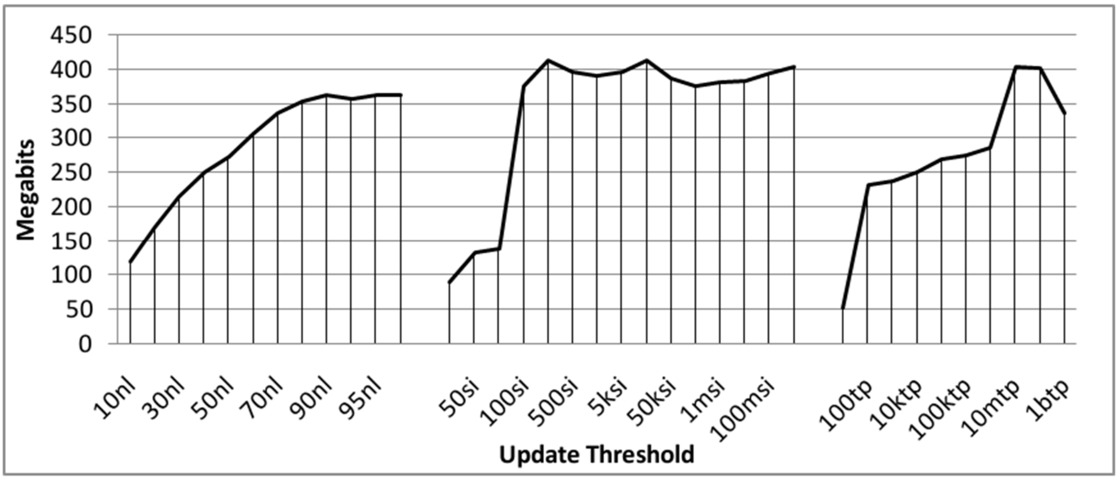

Figure 5.18: Data Transfer of 56 Active and 18 Passive Nodes

5.5.2.5.56 Active and 18 Passive Nodes

Figure 5.18 shows the average of 10 repetitions for total data transfer per active node for 56 active and 18 passive nodes. The x-axis and y-axis representations are same as in previous figures. The data curves show an interesting continuation of the previous results.

After the significant increase in node density, the curve peaks for all three metrics have shifted significantly towards higher threshold values. Contrary to previous curves of the same type, the curves for neighbour list change and throughput change are more conclusive than the curve for SINR change. During the simulation, we also observed enhancement in range for threshold values. New threshold values beyond 1 Billion% were observed for SINR change as well as for throughput change in the log file. However for comparison purposes, we did not change update threshold values beyond 1B%.

As previously observed, any metric curve may have multiple peaks and dips. The same phenomenon is observed in the curve for SINR change in Figure 5.18. However, comparing all the peaks, the curve for SINR change shows the same trend as for other two metrics. The peaks for neighbour list change, SINR change and throughput change are at 90%, 500% and 10,000,000% respectively. The flatness of the curves continued towards the higher threshold values. Resultantly, the dips are observed at lower threshold values for all three metrics. After a significant dip at initial threshold values, the curves rose gradually and attained a peak. For the analysis, the higher values can be recorded with little shift from previous curves as 90-99% for neighbour list change, at 500-10k% for SINR change and 10-100M% for throughput change.

Similar to previous topology, the simulation was run for 294 seconds. As expected, the gradual decrease in per active node per second data transfer continued after increasing the total node density as well number of active nodes. For the simulation, maximum data transfer per active node was 412 Mb when local route update was performed based on SINR change. For the same metric, the lowest data transfer per active node was observed at 89 Mb. Similarly for neighbour list change and throughput change, maximum data transfer per active node was 363 Mb and 403 Mb respectively. The lowest data transfer per active node for both metrics was observed at 118 Mb and 52 Mb respectively.

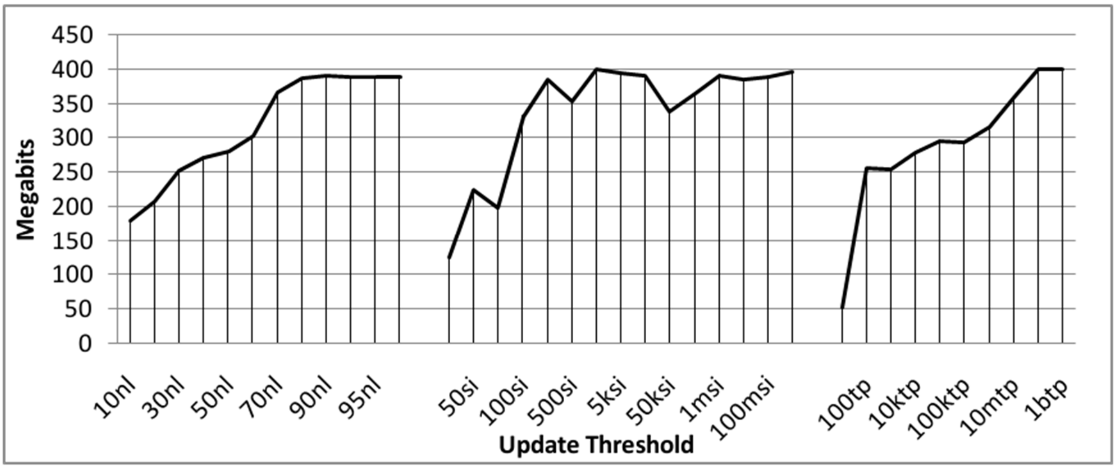

Figure 5.19: Data Transfer of 64 Active and 18 Passive Nodes

5.5.2.6.<u>64 Active and 18 Passive Nodes</u>

Figure 5.19 shows the average of 10 repetitions for total data transfer per active node for 64 active and 18 passive nodes. The x-axis and y-axis representations are same as in previous figures. As observed during simulation of 56 active and 18 passive nodes, enhancement in range for threshold values beyond 1 B% for SINR change and throughput change was also observed during the simulations. Similar to previous case, threshold values beyond 1B% were ignored. The data curves show the exact continuation of the previous results, where the peaks for all three metrics have further shifted towards higher threshold values. Further increase in node densities has skewed the peaks towards our selected maximum threshold values for all three metrics.

Considering the minor change in node density from 56 active to 64 active nodes, the curve for 64 active nodes resembles closely with the curve of 56 active nodes. Although duplicate peaks were again observed for SINR change, the curve for SINR change shows the same trend as for other two metrics. Similarly, the flatness of the curves continued towards the higher threshold values with dips at lower threshold values for all three metrics. The peaks for neighbour list change, SINR change and throughput change are at 90%, 2,000% and 100,000,000% respectively. For the analysis, the higher values can be recorded with little shift from previous curves as 90-99% for neighbour list change, at 2k-5k% for SINR change and 100M-1B% for throughput change.

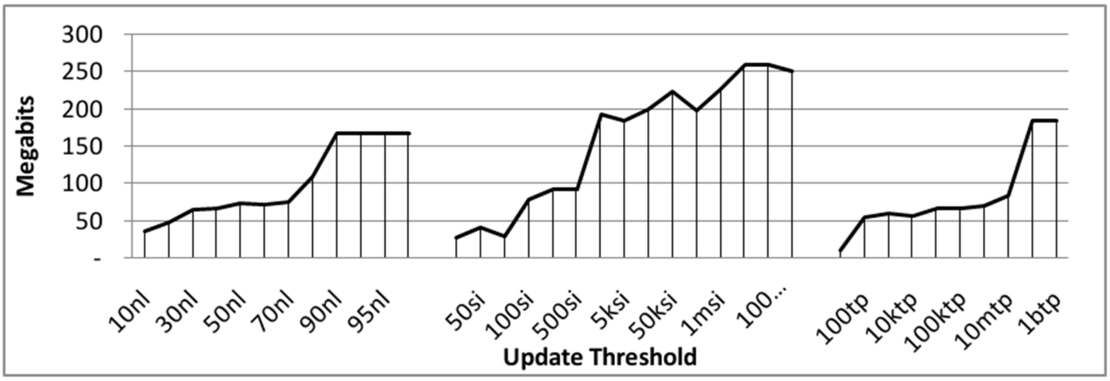

Figure 5.20: Data Transfer of 128 Active and 18 Passive Nodes

Similar to previous topology, this simulation was also run for 294 seconds. And similar to previous results, the gradual decrease in per active node per second data transfer continued after increasing the total node density as well number of active nodes. For the simulation, maximum data transfer per active node was 401 Mb when local route update was performed based on SINR change. For the same metric, the lowest data transfer per active node was observed at 125 Mb. Similarly for neighbour list change and throughput change, maximum data transfer per active node was 391 Mb and 400 Mb respectively. The lowest data transfer per active node for both metrics was observed at 180 Mb and 53 Mb respectively.

5.5.2.7. 128 Active and 18 Passive Nodes

Figure 5.20 shows the average of 10 repetitions for total data transfer per active node for 128 active and 18 passive nodes. The x-axis and y-axis representations are same as in previous figures. The data curves for significantly higher node density, where 146 nodes were in direct communication to each other, showed continuation of the same results. Similar to previous two simulations, enhancement in range for threshold values beyond 1 B% for SINR change and throughput change were also observed. However, the threshold values beyond 1B% were again not considered. As a significant continuation of previous results, the peaks for data curve further skewed towards maximum scale for threshold values for all three metrics.

Considerable increase in node density showed a smooth curve without any duplicate peak for all three metrics. The flatness of the curves also reduced significantly, making the results more conclusive with dips at lower threshold values for all three metrics. The peaks for neighbour list change, SINR change and throughput change were at 95%, 10,000,000% and 1,000,000,000% respectively. For the analysis, the higher values can be recorded with little shift from previous curves as 90-99% for neighbour list change, at 2k-5k% for SINR change and 1B% for throughput change.

After a significant increase in number of nodes, higher numbers of lanes were introduced for the topology. Increase in lanes caused more speed variation among nodes. To cater for increased speed variations, the simulation was run for 324 seconds. Regardless of increase in simulation time, the gradual decrease in data transfer per active node per second continued for the topology. For the simulation, maximum data transfer per active node was 259 Mb when local route update was performed based on SINR change. For the same metric, the lowest data transfer per active node was observed at 28 Mb. Similarly for neighbour list change and throughput change, maximum data transfer per active node was 167 Mb and 184 Mb respectively. The lowest data transfer per active node for both metrics was observed at 35 Mb and 10 Mb respectively.

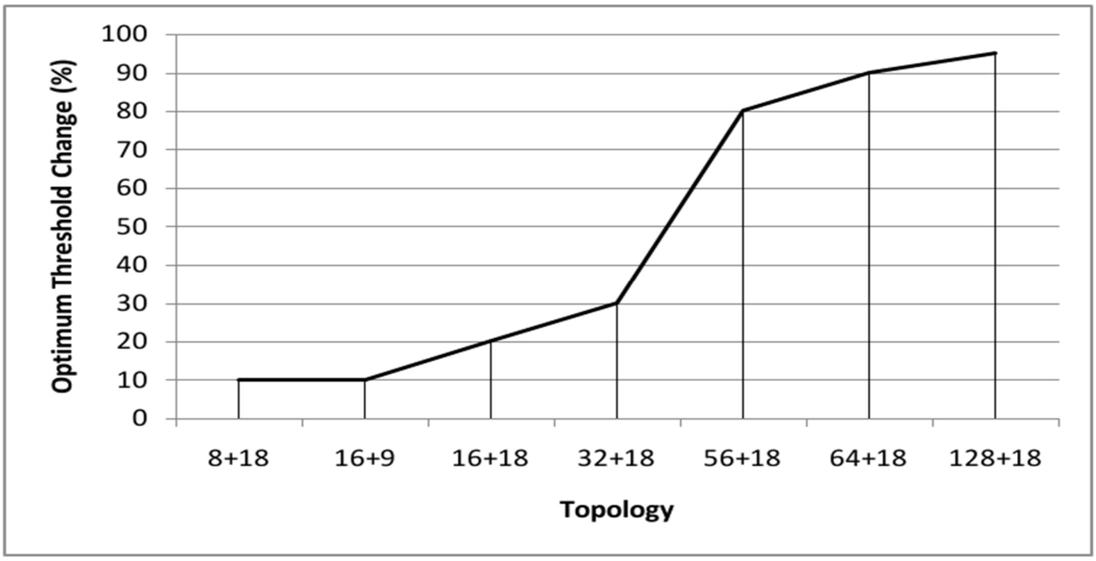

Figure 5.21: Threshold Value of Change (%) for Neighbour List

5.5.3. Comparative Simulations

The goal of this research is to prove the utility of adaptive route update approach against current approaches. Hence the objective of the research is to show the ***need and viability*** of the adaptive approach rather than how good the adaptive approach is performing. Therefore, the optimization of the adaptive route update i.e. optimized values for the three selected metrics can be a subject of future research. Nevertheless, to find more conclusive results, all of the above computed data curves were combined.

After simulating different topologies for variable node densities at variable node speeds, the coarse grained threshold values of all three metrics were drawn for various node densities.

Figure 5.21 shows the graph of percentage change in neighbour list for which local route update achieved maximum throughput. The x-axis of the graph shows the combination of different active + passive node densities. Whereas, y-axis shows the values of percentage change in neighbour list at which local route update provided maximum data transfer for the topology. Threshold value of change increased with increase in the node density. The minimum value of 10% was observed for 8 active and 18 passive nodes topology. Whereas, the maximum value of 95% was recorded for 128 active and 18 passive nodes topology. After increasing the active nodes from 8 active and 18 passive to 16 active and 9 passive, no change in threshold value is observed. This result shows that the threshold is dependent on ***total*** number of nodes involved in data transfer. As defined in the test topologies, both active and passive nodes are virtually active nodes being involved in channel access for subsequent data transfer.

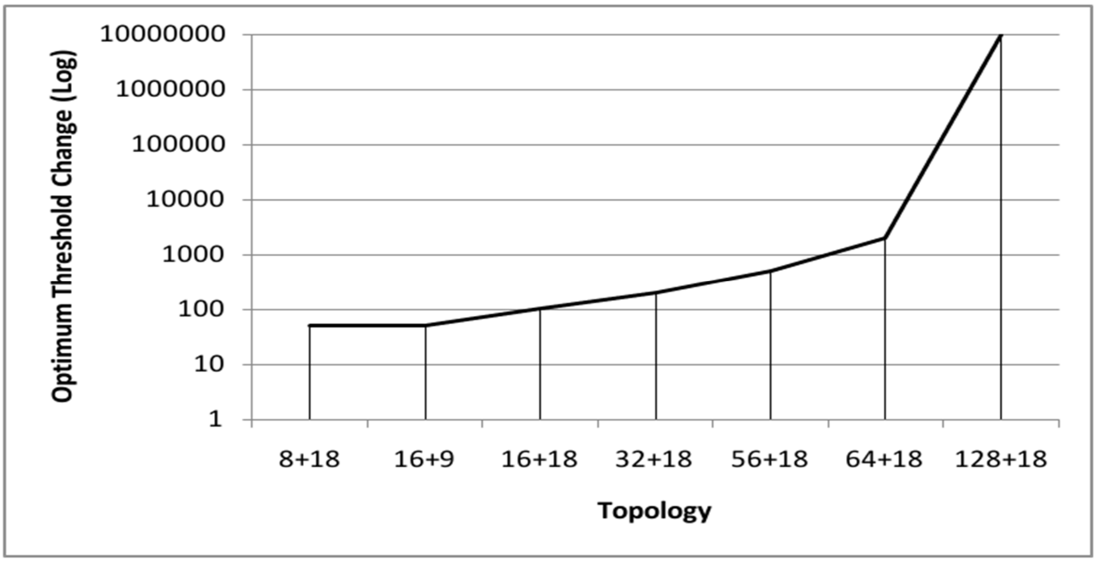

Figure 5.22: Threshold Value of Change (% in Log Scale) for SINR

We can also observe that the threshold curve is nonlinear in nature and follows the pattern of exponential curve. The curve starts from the lower values and reaches the top on increasing the node density. After reaching the top, the monotonically increasing curve flattens in nature. Interestingly, the threshold curve for the neighbour list follows the same pattern as of the mathematical model curves drawn in the last chapter (Figure 4.10&4.11). In all the curves, we can observe that the difference in threshold values for sparse topologies is more as compared to the dense topologies. All the curves are monotonically increasing. After attaining the higher threshold values for higher node densities, the change in threshold values decreases significantly.

Figure 5.22 shows the graph of percentage change in SINR for which local route update achieved maximum throughput. The x-axis of the graph shows the combination of different active + passive node densities. Whereas y-axis shows the values of percentage change in logarithmic scale for SINR change at which local route update provided maximum data transfer for the topology. As the difference between lowest and highest threshold value is too large, the logarithmic scale was selected for better analysis of the curve.

Similar to previous graph, threshold value of change increases with increase in the node density. The minimum value of 50% was observed for 8 active and 18 passive nodes topology. Similar to previous curve, there is no change in threshold value for initial two topologies. This result confirms the analysis that threshold value is dependent upon virtually active nodes within a given area. The maximum value of 10M% was recorded for 128 active and 18 passive nodes topology. Similar to previous curve, this curve also started from the lower values and monotonically increased subsequently.

Similarly, the behavior of this curve also followed the same pattern as the mathematical model curves drawn in the last chapter (Figure 4.10&4.11). This curve is also monotonically increasing and the difference in threshold values for sparse topologies is more as compared to dense topologies.

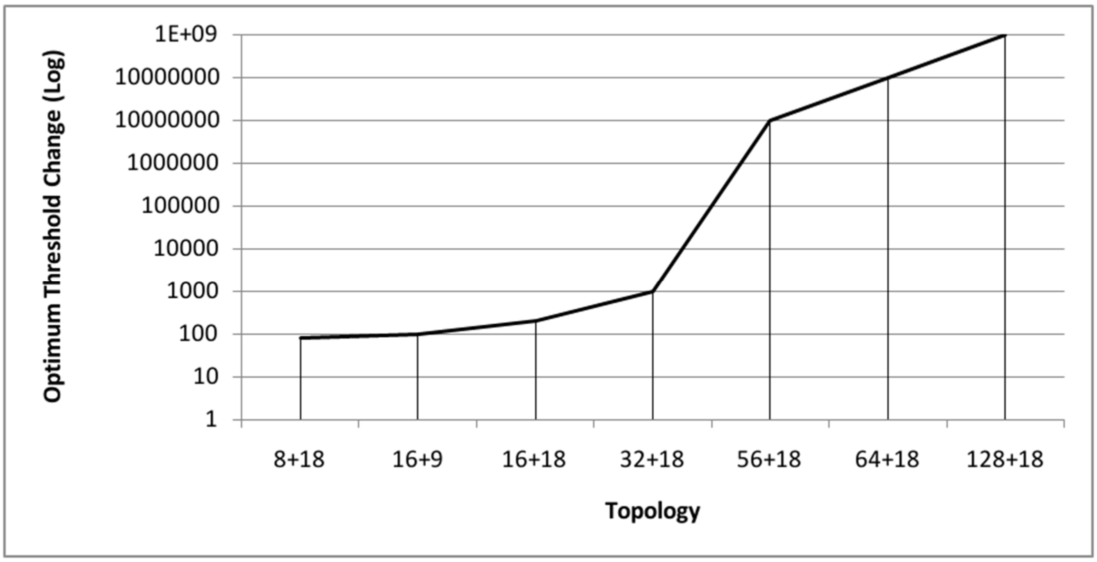

Figure 5.23: Threshold Value of Change (% in Log Scale) for Throughput

Figure 5.23 shows the graph of percentage change in throughput for which local route update achieved maximum throughput. The x-axis and y-axis representations are same as in previous figure. Comparable to previous two curves, the throughput threshold change also increased with increase in the node density. The minimum value of 80% was observed for 8 active and 18 passive nodes topology. Contrary to previous two curves, there is minor increase in threshold value among initial two topologies. Comparing the overall scale, the difference between thresholds for both topologies is negligible. Hence, our analysis for relation between threshold value and virtually active node stood confirmed.

For the maximum threshold value, 1B% was recorded for 128 active and 18 passive nodes topology. Contrary to the previous curve, the shape of this curve is smoother in nature. This curve also started from the lower values and monotonically increased subsequently. Analogous to previous curves, the pattern of the mathematical model curves (Figure 4.10&4.11) is also seen in this curve.

After assessing the data transfer curves for all 7 topologies, and subsequently by doing their comparison, we can draw the logical conclusions as under:

- Data transfer per second per active node, decreases with increase in node density.

- Threshold value for any metric starts from lower values and then increases to achieve some maximum value.

- After attaining the higher threshold values for higher node densities, the change in threshold values decreases significantly and the curve becomes flat.

- The threshold curve flattens for large node densities, and even though very low, but still the increasing trend continues for all values.

- All the curves match the general behaviour of mathematical model shown in Figure 4.10&4.11.

- Neighbour list change provides more conclusive threshold values for the test topologies and is the easiest to implement among all selected metrics.

- Adaptive route update on SINR change provides best results for data transfer rate among all the test metrics. Although its curve is less conclusive as compared to the curve for Neighbour List change.

5.5.3.1. Comparative Simulations Highway Scenario

After attaining the coarse grained threshold values of selected test metrics for route update, the comparison of optimized AAODV with other standard protocols was done. All eight topologies were simulated for cross comparison of optimized AAODV.

For the simulation under a multiple lane highway scenario, we simulated Figures 5.4 & 5.5 by keeping nodes with variable speed according their lane position. The number of lanes and the corresponding speed varied from scenario to scenario. For clarification purposes, we considered road lanes approaching at the road crossing as well as outgoing lanes. Nodes moved at same velocity in each lane of a single road. However, lanes are classified according to their speed as Slow, Medium, Fast and Super Fast. To simulate node overtaking scenario, nodes were allowed to switch from one lane to other. The lane speed varied from as low as 16 kmph to as fast as 130 kmph.

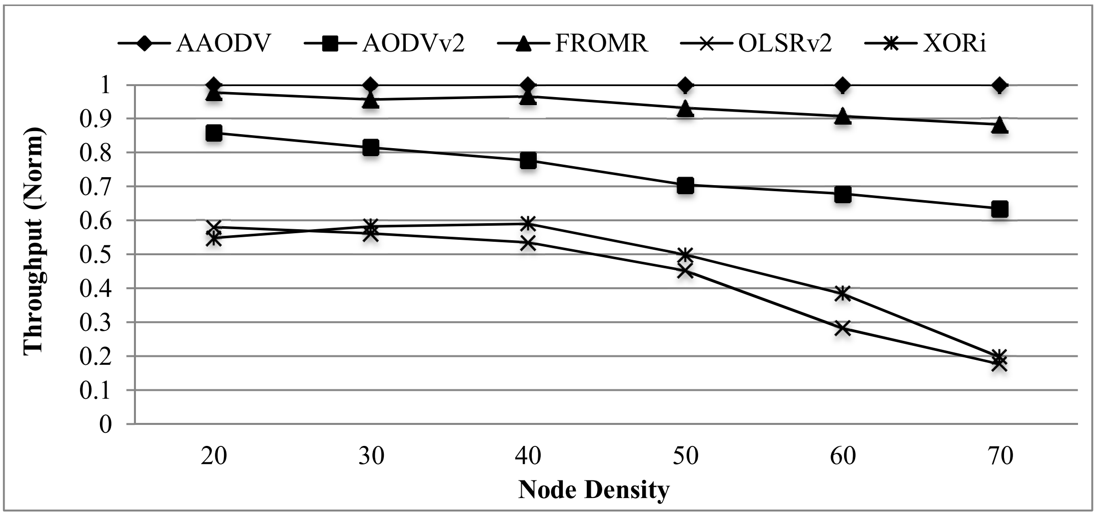

Figure 5.24: Throughput (Normalized) Comparison of Different Protocols against Adaptive Route Update in Highway Scenario

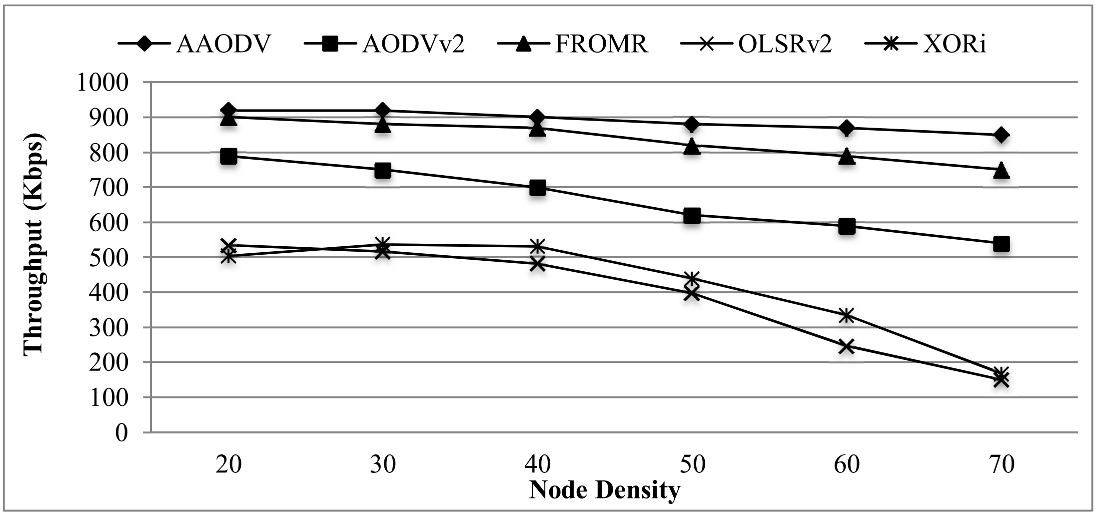

Figure 5.25: Throughput Comparison of Different Protocols against Adaptive Route Update in Highway Scenario

Figures 5.24 and 5.25 show the comparison of optimized AAODV against other selected protocols for throughput in highway scenario. The x-axis of the graph shows the combination of different active + passive node densities. The y-axis of the graph shows the average normalized throughput of other routing protocols against AAODV.

During the simulation, it was observed that nodes did not face frequent topology changes for neighbours moving in same direction as host. However, link life among neighbours moving in opposite direction was significantly low. Relatively low mobility behaviour among nodes moving in same direction caused higher link stability and link life. Such circumstances supported simple reactive protocols as compared to proactive protocols.

From the graph, we can observe that for all node densities, FROMR performed better than other protocols and remained close to Adaptive AODV. Though, AODVv2 showed better results than OLSRv2 and XORi, remained inefficient against FROMR and AAODV. Interestingly, on increasing node density, the gap between FROMR / AODVv2 and AAODV started increasing. Both FROMR and AODVv2 opt to select next hop neighbour towards destination which can offer minimum hop count. Accordingly, both protocols tend to select next hop neighbour closest to their maximum hop range. As proved previously, probability of availability of next hop closest to maximum hop range increases with increase in node density. However, selection of next hop neighbour closest to maximum hop range decreases the link life due to involvement of lower ***Δd*** value. Accordingly, at higher node density, nodes faced relatively higher rate of link breakage. Resultantly, AAODV showed more improvement at higher node densities.

OLSRv2 and XORi showed worst performance against all other protocols at all node densities. Performance of both protocols further degraded at higher node densities. Though stable links were available, both protocols continuously updated their routing tables. Such updates caused significant overhead all node densities. The effect was more prominent at higher node densities.

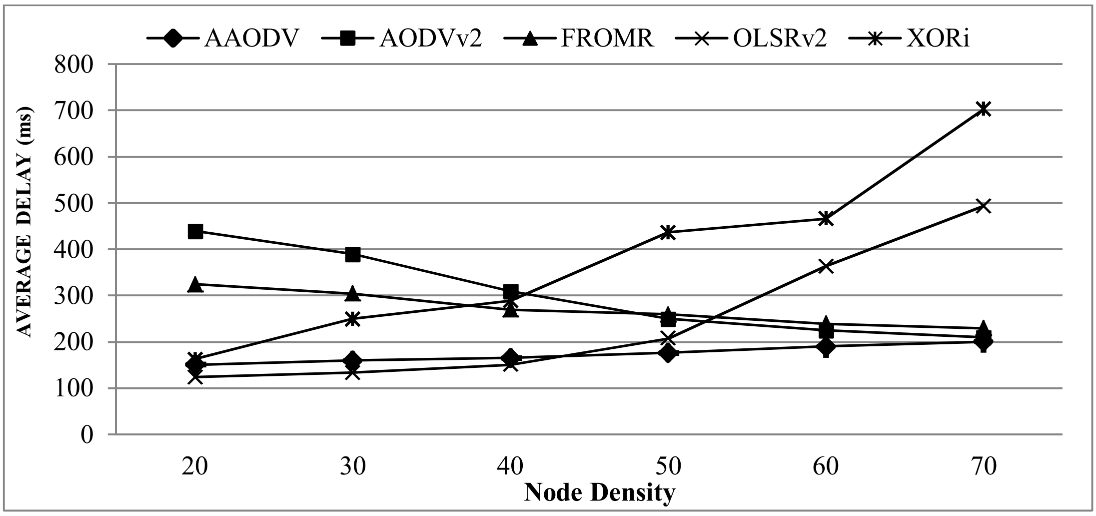

Figure 5.26: Delay Comparison of Different Protocols against Adaptive Route Update in Highway Scenario

Figure 5.26 shows the comparison of optimized AAODV against other selected protocols for average delay. The x-axis of the graph shows the combination of different average node densities. The y-axis of the graph shows the average delay of other routing protocols against AAODV.

Delay graph shows that OLSRv2 offered minimum delay at low node densities. As overhead is not a significant problem at low node density, proactive protocols supported the scenario. Proactive design of OLSRv2 allowed timely update of routing information. Similarly, XORi being proactive in nature showed low delay than other reactive protocols. For low node densities, AODVv2 showed slightly higher delay as compared to XORi and OLSRv2. AODVv2 and FROMR showed higher latency being reactive in nature. As FROMR uses the concept of Adaptive Multipath Routing coupled with location update, it showed better performance than AODVv2. Simple reactive design of AODVv2 forced new route request in case of link failure, hence causing highest latency.

On increasing the node density, the increased overheads caused significant increase in end-to-end latency for both proactive protocols, i.e. XORi and OLSRv2. Though, FROMR showed better latency than XORi and OLSRv2, regular location updates caused relatively higher overhead than AODVv2. Accordingly, due to minimum overheads AODVv2 showed best results as compared to FROMR XORi and OLSRv2. However, delay in new route request in case of link failure caused higher average latency as compared to AAODV. In comparison to AODVv2, AAODV timely updates its route prior to link failure. Hence, for the overall comparison, AAODV showed smoother behavior as compared to all other protocols with overall best latency values.

5.5.3.2.Comparative Simulations Urban Scenario

For the simulation of urban or city scenario, we considered the amalgamation of low active node density with very high active node density, by converging highly mobile nodes moving on different roads with variable velocity, to a single road crossing. The convergence scenario increased the road density by bringing all nodes in one hop communication zone. After staying for a while in this state like the initial simulation, all nodes continued their move on different roads indifferent directions. We considered four long roads of 5 kilometers approaching to a road crossing.

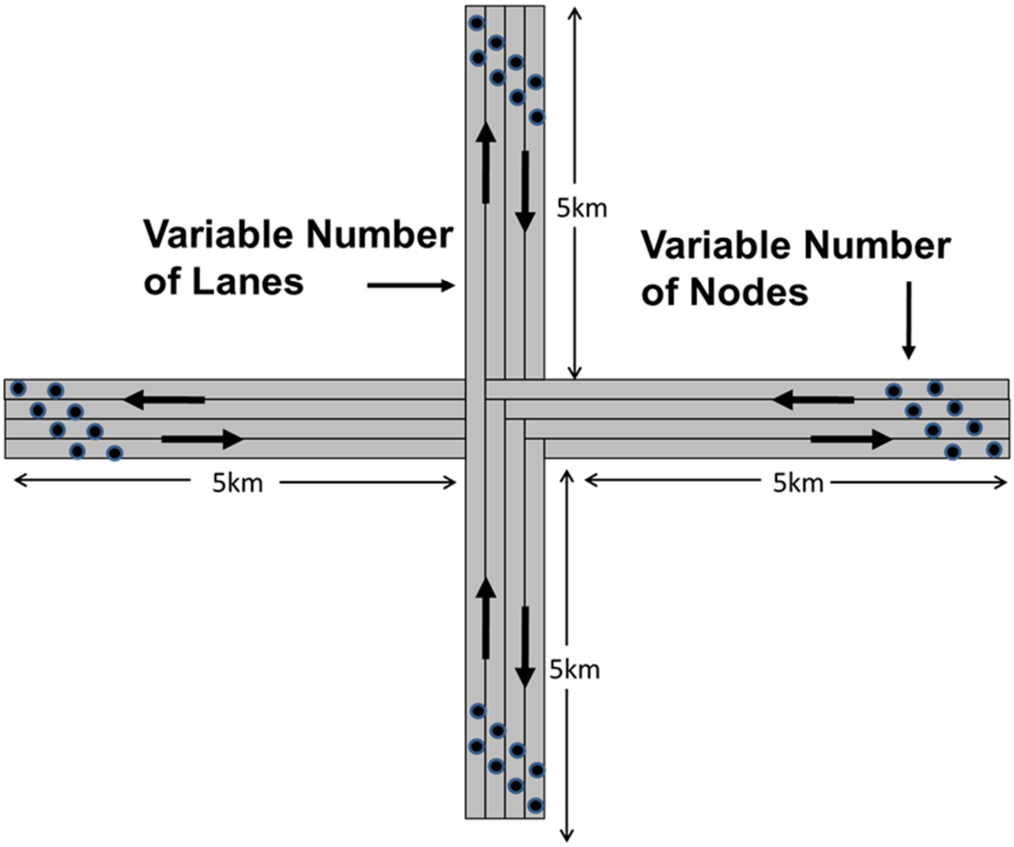

Figure 5.27: Combination of Highway and Urban Scenarios

Figure 5.27 depicts mobile nodes moving on a multi-lane road as the combination of all urban scenarios shown at Figures 5.4 – 5.11. We considered convergence of all four roads at a road crossing (center of the Figure 5.27). The stripes show different lanes with circular nodes (cars) moving in the direction of the arrow. The number of lanes and the corresponding speed varied from scenario to scenario. For clarification purposes, we considered road lanes approaching at the road crossing as well as outgoing lanes. Nodes moved at same velocity in each lane of a single road. However, lanes are classified according to their speed as ***Slow***, ***Medium***, ***Fast*** and ***Super Fast***. The lane speed varied from as low as 16 kmph to as fast as 130 kmph.

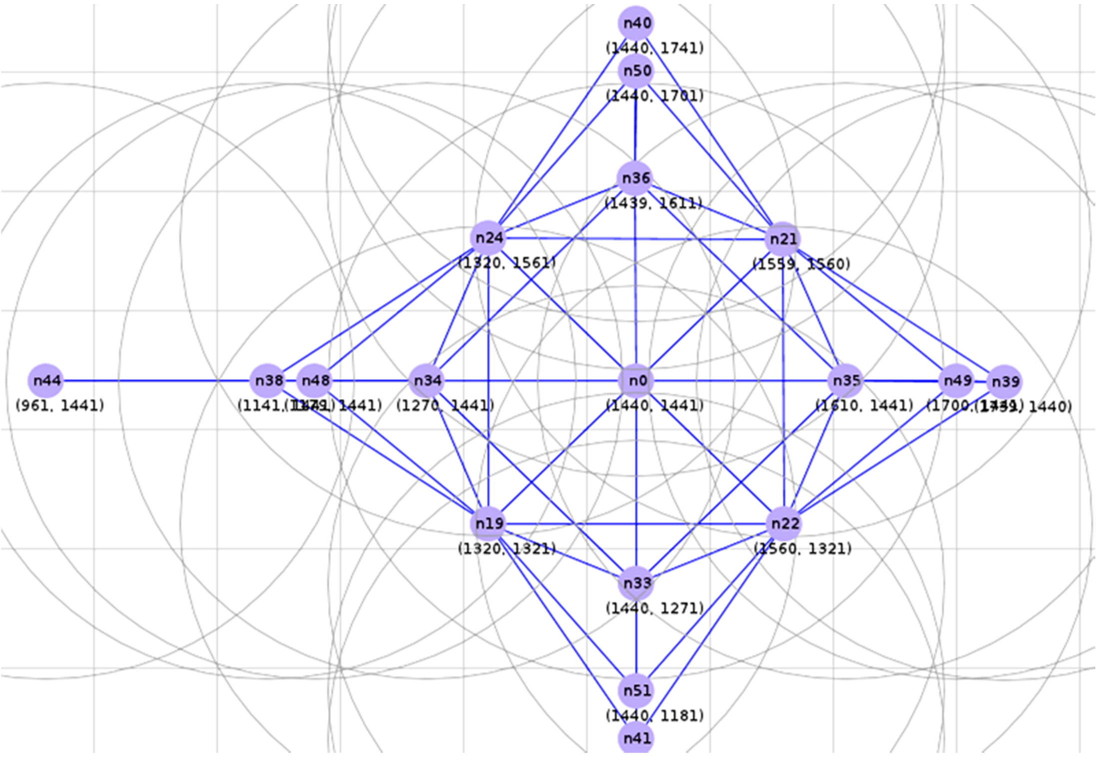

Figure 5.28: Passive Static and Mobile Nodes at Road Crossing

Figure 5.28 shows the node deployment at the road crossing area. All the nodes at the initial position of road crossing were passive nodes. The small circular nodes depict the road side units or stationary nodes at the road crossing region. The straight lines show the direct connectivity range among different nodes. The large circles around each node show its one hop communication range. The digits inside the nodes show their identity, whereas digits around the nodes show their position coordinates. After reaching a road crossing, all nodes observed the road signals, and halted or moved further according to clearance of road signals. To create maximum node density, we assumed that all nodes are in next hop range of each other while stopping at a road signal.

All eight topologies were simulated for cross comparison of optimized AAODV with AODVv2 (DYMO), FROMR [54], XORi [55] and OLSRv2 routing protocols. FROMR is a multipath routing based fast recovery protocol, and concentrates on rapidly building an alternate path when the original path is broken. XORi uses the information related to the identifiers of the nodes, independent of any other metric.

AODVv2 and OLSRv2 were selected from state of the art MANET routing protocols adapted in VANET. Whereas FROMR and XORi were selected as state of the art

VANET routing protocols. The rate of normalized throughput and delay of all selected protocols against AAODV were computed for each topology.

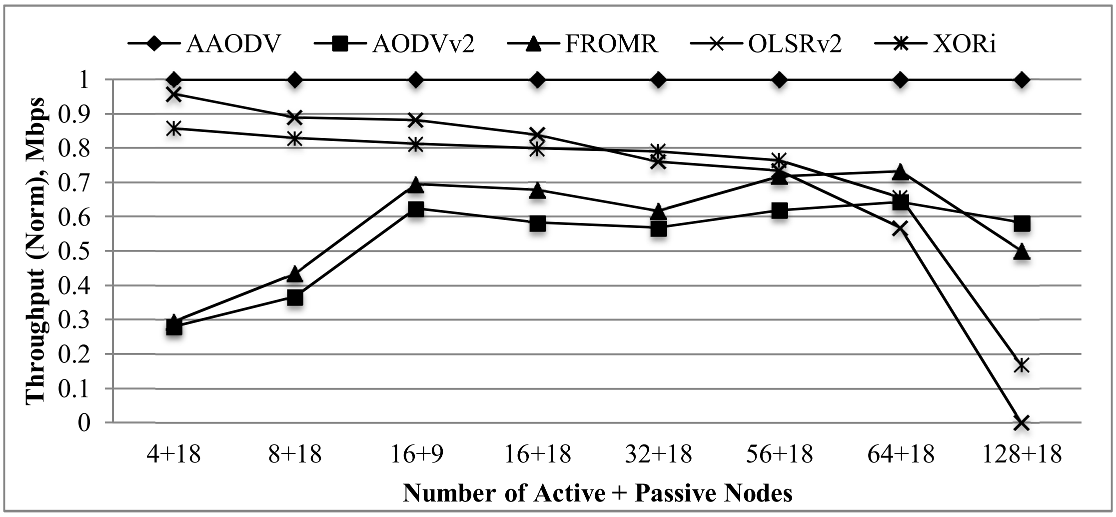

Figure 5.29: Throughput (Normalized) Comparison of Different Protocols against Adaptive Route Update in Urban Scenario

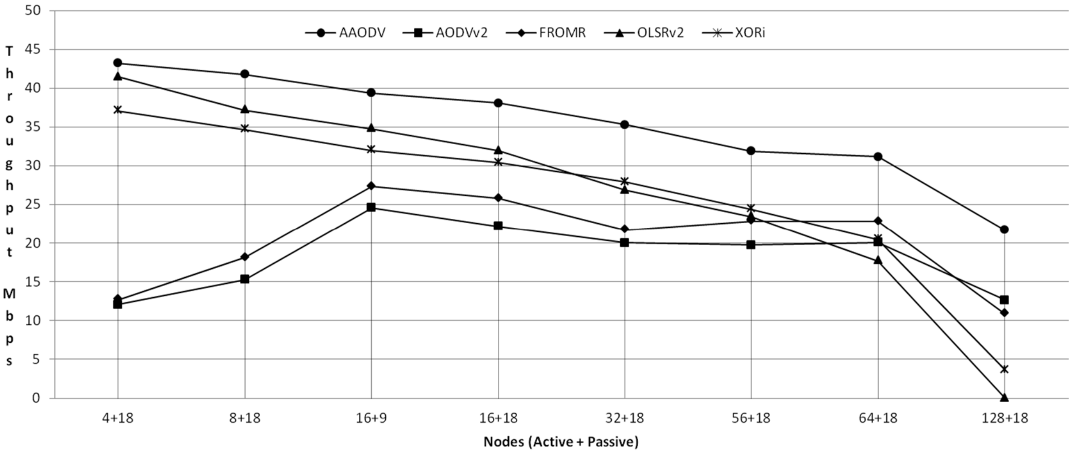

Figure 5.30: Throughput Comparison of Different Protocols against Adaptive Route Update in Urban Scenario

Figures 5.29 and 5.30 show the comparison of optimized AAODV against other selected protocols for throughput. The x-axis of the graph shows the combination of different active + passive node densities. The y-axis of the graph shows the average normalized throughput of other routing protocols against AAODV.

From the graph, we can observe that for low node densities, initially OLSRv2 performed better than XORi and remained close to Adaptive AODV. The close match of OLSRv2, XORi with Adaptive AODV at low node density was observed due to low overhead and timely update of route. However, on increasing the node densities, we can observe the deterioration in performance of both XORi and OLSRv2 protocol. At higher densities, although OLSRv2 tried to optimize the selected route, the increased overhead caused decrease in net throughput. A complex case was observed by increasing the node density from 64 active and 18 passive nodes. On reaching the value of 68 active nodes with 18 passive nodes, we observed that nodes started facing zero application data transmission (goodput). The error was observed due to repeated MAC layer retries and increased routing overheads. The zero goodput was observed randomly at different nodes and caused ***segmentation fault*** for the NS-2 network simulator. The phenomenon confirmed the conclusions drawn from our analysis in section 4.5 ante.

On increasing the node densities, XORi started performing better than OLSRv2. The behavior was observed due to design specification of XORi which controls the overheads through network segmentation. However, the performance of XORi significantly degraded under dense network conditions.

From the curves of reactive routing protocols, we can observe that initially both FROMR and AODVv2 performed similar to each other. On increasing the node densities, FROMR performed better than AODVv2 due to use of alternate path from already computed available routes. However, we can observe from comparison of both protocols against Adaptive AODV that our proposed approach outperformed both protocols.

For low node densities, both protocols did not optimize their routing tables on availability of more suitable paths. However, on increasing the node density, the gap between curves of both protocols and Adaptive AODV started decreasing. On detailed analysis, we observed that improvement in performance of both routing protocols occurred due to unintentional route error messages. On increasing node densities, both protocols faced increased congestion resulting in transmission errors. The increased MAC layer retries caused repeated route error messages. These unintentional route error messages caused new route requests in the presence of existing route. As the new route request is sent after change in topology, hence new and more suitable route is selected than the previous one. Although the unintentional route error messages caused improvement in overall throughput, but increased MAC layer retransmissions caused throughput deterioration. Furthermore, such route updates cannot provide guaranteed performance in all scenarios. Moreover, the performance of Adaptive AODV significantly outperformed both protocols at higher node densities as well.

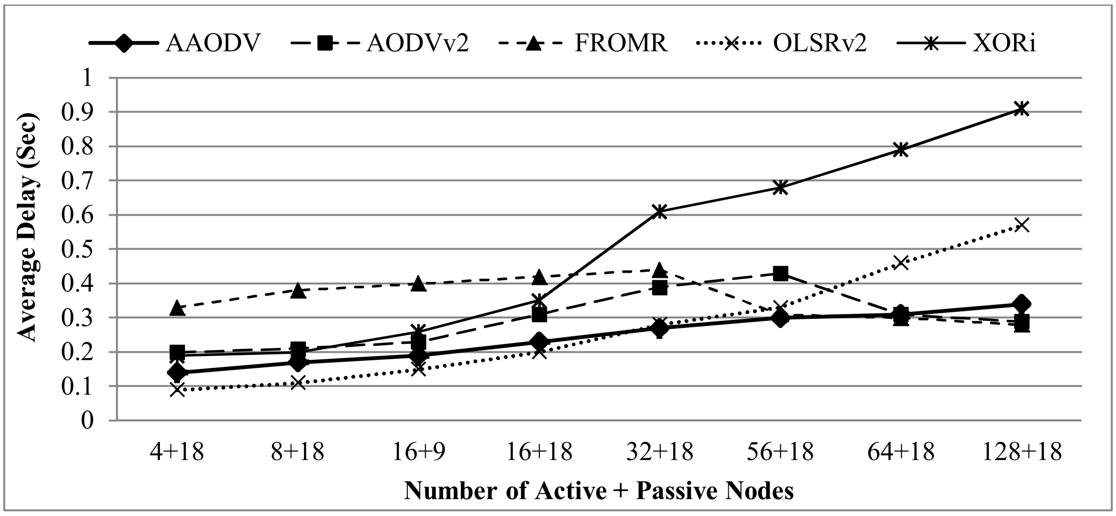

Figure 5.31: Delay Comparison of Different Protocols against Adaptive Route Update in Urban Scenario

Figure 5.31 shows the comparison of optimized AAODV against other selected protocols for average delay. The x-axis of the graph shows the combination of different active + passive node densities. The y-axis of the graph shows the average delay of other routing protocols against AAODV.

We can observe that for low node densities, OLSRv2offered minimum delay owing to its simple proactive design. XORi showed more delay than OLSRv2 but better than AODV, being proactive in nature. On increasing the node density, the increased overheads caused significant increase in end-to-end delay for both XORi and OLSRv2. For low node densities, AODVv2 showed higher delay as compared to XORi and OLSRv2. Although FROMR computes multiple paths, however in our case, alternate path is again suboptimal. Resultantly, FROMR showed the highest latency at low node densities due to additional overheads. AODVv2 and FROMR showed better performance at higher node densities, due to reduced overheads as compared to other two protocols. At higher node densities, AODVv2 showed minimum delay due to its pro-active design and false route update, as already explained. For the overall comparison, AAODV showed smooth behavior as compared to all other protocols with overall best delay figures.

With the above analysis of reactive and proactive routing approaches against optimized AAODV, we can conclude the following:

- Regardless of baseline routing approach, adaptive route update can make a routing protocol more efficient than a routing protocol with static route update approach.
- Different metrics can be used for adaptive route update.
- Optimization of adaptive route update can be performed on different node densities and types of networks.
- The threshold level for optimized adaptive route update may vary by changing the type of network.

5.6. **Summary**

In this chapter we identified different metrics useful for adaptive route update. We observed that localized route repair performs better than end to end repair due to involvement of minimum number of nodes. Resultantly, a localized metric can show more promising results for local route repair as compared to end-to-end metric. Subsequently, we shortlistedQoS related metrics, position related metrics and physical layer related metrics for implementation of the adaptive route update strategy.

With the advancement in cross layer design, the use of these metrics is emerging. These metrics may require more complicated algorithms, but their usefulness towards more stable routes is proven. Subsequently we selected one metric from three domains considering its importance and simplicity for implementation. Next hop throughput from QoS metrics, one hop neighbour list from position related metrics and SINR from physical layer metrics were selected for simulation purposes.

After developing the model for adaptive route update, it was compared with other routing protocols for verification of concept. Initially, simple topologies were compared with AODV and AODVv2 (DYMO) from the reactive family, and OLSR from the proactive family of routing protocols. After basic level testing, the proposed model was implemented over AODV routing protocol. Update levels for all three metrics were refined after detailed simulations. We considered the case of amalgamation of low active node density with very high active node density. Mobile nodes with variable velocity moving on different roads were converged to a single road crossing. The convergence scenario increased the road density by bringing all nodes in one hop communication zone.

During these simulations, we also measured throughput by keeping different threshold values of all three metrics. Different threshold values for change in neighbour list, SINR and throughput were set to find the threshold values under different node densities. Averages of 10 repetitive simulations for 7 different topologies against 3 selected metrics were computed accordingly. Subsequently, the behavior curves for all selected metrics were drawn. Repeated simulations were performed for all the topologies and the occurrences for all three metrics were recorded. Accordingly, different threshold values were defined for all significant change levels.

After finding the threshold values of all three metrics for different node densities, standard AODV was further modified to optimize AAODV to be used for the comparison with AODV, AODVv2 (DYMO) and OLSR routing protocols. After assessing the data transfer curves for all topologies, and subsequently by doing comparison of reactive and proactive routing approaches against proposed approach, we concluded the following:

- Data transfer per second per active node decreases with increase in density.
- Without incorporating adaptive route update, existing protocols can provide satisfactory results for networks with limited topology changes and limited number of nodes. However, for large scale networks or networks involving rapid topology changes, current routing strategies will face performance issues.
- Regardless of baseline routing approach, adaptive route update can enhance the efficiency of a routing protocol.
- Different metrics can be used for adaptive route update.

- Optimization of adaptive route update can be performed on different node densities and types of networks.

- The threshold level for optimized adaptive route update may vary for different types of networks.

- Best threshold value for any metric starts from lower values and then increases to achieve some maximum value.

- After attaining higher threshold values for higher node densities, the change in threshold values decreases significantly and the curve becomes flat.

- The threshold curve flattens for large node densities, and although very low, but the increasing trend continues for all values.

- All curves match the general behaviour of the proposed mathematical model.

- Neighbour list change provides more conclusive threshold values for the test topologies and is the easiest to implement among all selected metrics.

- Adaptive route update on SINR change provides best results for data transfer rate among all the test metrics. Although its curve is less conclusive as compared to the curve for neighbour list change.

Chapter 6

CONCLUSION

Wireless networks are growing at a high rate in our daily life. Due to involvement of more and more data based applications, dependence on mobile networks is increasing with time. Desire of data connectivity everywhere and round the clock has caused emergence of new and specialized data communication types. These types have changed the dynamics of data networks, especially wireless networks. High mobility and scalability are the prime factors for globalization in data networks. These factors have led to increased network sizes with complex topologies. Specialized topologies and complicated movement patterns have made wireless networks more fluent in nature. Highly fluent network topologies also involve large variations in node densities and relative node velocities. Scalability requirements to incorporate thousands of nodes deployed in large span areas challenge the QoS support. Highly scalable networks have peculiar problems of disconnected topologies, sudden changes in active node densities, broadcast storms and dissemination of data in a particular region for longer durations. Resultantly, researchers have proposed a variety of routing protocols for such highly fluent wireless networks.

Routing deals with three important goals. First, efficiently finding the most suitable route from source to destination, second, updating the new route at runtime on availability of a better one, and third, maintaining the route in case of route failure. Most of the routing protocols generally target first and third goals, with little emphasis on the second one. While using different techniques to find best route to destination, routing protocols perform route maintenance using following two approaches:

- Through sharing of repeated topology beacons. This approach is also called periodic or proactive routing.
- Through sharing of topology update on link breakages. This scheme is also called event triggered or reactive routing.

The goal of route update on availability of a better one requires updated information of network conditions. Considering the definition, route update is technically not possible for the event triggered routing. While periodic routing approach will add significant overheads for increased scalability. The decision for approach selection is generally not based on runtime network conditions, but are rather fixed and predefined in the protocol according to simulation / test results. Analysis proves that both periodic or event triggered route maintenance may not work efficiently for highly fluent networks. These complex networks require more flexible, generic and adaptive route update and maintenance strategies.

Behaviour of any routing algorithms differs for fixed and wireless network scenarios. Contrary to fixed networks, mobile wireless networks suffer from sudden link breakages due to topological changes, change in node densities and reduction in average link capacities. Resultantly, any single protocol may not perform well under all scenarios and conditions. Routing protocols can be divided into many categories according to the algorithm and modifications proposed against other protocols. Using different metrics, routing protocols can be grouped into three categories according to routing metric sharing method. These types include periodic topology sharing, event based topology sharing and their derivatives (hybrid and history oriented). However, from a single node perspective and for dissemination of selected metric information, choices get restrict to the first two only. We observed that no single routing scheme can satisfy all possible topologies of complex networks. Although proactive protocols have the ability to adapt according to changes in topology, but their performance rapidly degrades by increasing node density.

A VANET node may face repeated topological changes or approximately static behaviour during a single data session. Rather than a static periodic or event based route update approach, we proposed adaptive route update based on runtime network conditions.

To achieve routing efficiency, all nodes are required to perform local route update as localized route maintenance performs better than end-to-end repair due to involvement of minimum number of nodes. Adaptive route repair is required on two independent conditions:

- When link with next hop neighbour is about to break, or
- When second hop neighbour enters in next hop range.

For the overall analysis, study of the combined impact of both conditions is necessary. However, the possibility of any neighbour node to affect the host node depends upon two factors:

- How much distance a neighbour node can cover relative to the host node.
- In which direction the neighbour node is moving relative to host node.

We developed a mathematical model to describe the behaviour of changes in network conditions. The curves of the model provide a very interesting result: the probability for route update is directly proportional to time interval and node density. Although the rate of change decreases with increase in node density, however, the increasing trend continues for all node densities. We also observed that irrespective of route finding approach, the requirement for route update increases with increase in node density. Similarly, increase in node density requires more change in the network conditions for a network topology, where either next hop node is about to face link breakage or 2nd hop node has already entered in next hop range. These important inferences directly lead to adaptive route update strategy, which can significantly improve any routing protocol.

Considering the mathematical model, we proposed an adaptive route update scheme which is independent of baseline routing algorithm. The adaptation will eliminate the terms of reactive and proactive routing and will categorize them based on logical conditions to find and update the route. The proposed approach using multiple metrics may add complexity for processing resources, but will perform the route update without adding overheads to the network resources. However, availability of sufficient processing resources and power may not be a constraint for networks like VANETs.

Through simulations, we implemented and tested route update strategies incorporating different metrics. We simulated proposed approach using neighbour list, SINR and throughput, as metrics to perform adaptive route update. Initially, we refined the adaptive update levels and later we compared proposed model against other routing protocols. After assessing the data transfer curves for all test topologies, and subsequently by doing comparison of reactive and proactive routing approaches against proposed approach, we concluded the following:

- Data transfer per second per active node decreases with increase in node density.
- Without incorporating adaptive route update, existing protocols can provide satisfactory results for networks with limited topology changes and limited number of nodes. However, for large scale networks or networks involving rapid topology changes, current routing strategies will face performance issues.
- Regardless of baseline routing approach, adaptive route update can make a routing protocol more efficient than a routing protocol with static route update approach.
- Different metrics can be used for adaptive route update.
- Optimization of adaptive route update can be performed on different node densities and types of networks.
- The threshold level for optimized adaptive route update may vary for different types of networks.
- Best threshold value for any metric starts from lower values and then increases to achieve some maximum value.
- After attaining the higher threshold values for higher node densities, the change in threshold values decreases significantly and the curve becomes flat.
- The threshold curve flattens for large node densities, although, very low but increasing trend continues for all values.
- All the curves match the general behaviour of the developed mathematical model.

- Neighbour list change provides more conclusive threshold values for the test topologies and is the easiest to implement among all selected metrics.
- Adaptive route update on SINR change provides best results for data transfer rate among all the test metrics. Although its curve is less conclusive as compared to the curve for neighbour list change.

As a future work, we suggest optimization of different metrics to develop an adaptive route update strategy. The optimization process will require incorporation of a variety of metrics. Literature review supports consensus of the research community to use cross layer metrics for routing in VANET. The optimization of time interval for sharing of different cross layer metrics is a tricky task and need a lot of deliberation.

As our proposed model is independent of any base layer approach or selected metric, it can be used with any routing protocol. Resultantly, any existing protocol can be modified for adaptive route update or new protocols can be designed incorporating the proposed concept. The protocols may include routing protocols for delay tolerant networks, geographical routing protocols, QoS aware routing protocols and hierarchical routing protocols, etc.

In future, we intend to optimize route update mechanism of different routing protocols based on cross layer metrics (e.g. XORi etc.), specifically from VANET perspective. The route update optimization of these routing protocols require detailed analysis through theoretical models, computer simulations and practical testing under realistic conditions.

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