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DESIGN AND ANALYSIS OF A SPEED-AWARE ROUTING PROTOCOL

FOR MOBILE AD HOC NETWORKS

by

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ABSTRACT

The flexibility of movement for the wireless ad hoc devices, referred to as node mobility, introduces challenges such as dynamic topological changes, increased frequency of route disconnections and high packet loss rate in Mobile Ad hoc Wireless Network (MANET) routing. This research proposes a novel on-demand routing protocol, Speed-Aware Routing Protocol (SARP) to mitigate the effects of high node mobility by reducing the frequency of route disconnections in a MANET. SARP identifies a highly mobile node which forms an unstable link by predicting the link expiration time (LET) for a transmitter and receiver pair. When the nodes have high relative velocity, the LET calculated is a small value; this means that the link is predicted to disconnect before the successful transmission of a specific demand. SARP omits such a packet-sending node from the link route during the route discovery phase. The omission of such unstable links helps SARP limit the flooding of control packets during route maintenance and reduces the overall control overhead generated in on-demand routing protocols. NS2 was used to implement the SARP with ad hoc on-demand vector (AODV) as the underlying routing algorithm. Extensive simulations were then conducted using Random Waypoint Mobility model to analyze the performance of SARP. The results from these simulations demonstrated that SARP reduced the overall control traffic of the underlying protocol AODV significantly in situations of high mobility and dense networks; in addition, it showed only a marginal difference as compared to AODV, in all aspects of quality-of-service (QOS) in situations of low mobility and sparse networks.

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1. INTRODUCTION

Until recently, connectivity among mobile wireless devices has relied largely on underlying infrastructures such as wireless access points and base transceiver stations (BTS). However, increasing demands for mobile services demand the expansion of the infrastructure globally. The time and resources required for such expansion have driven the development of an alternative means to maintain network connections and access information. One such alternative means led to the realization of Mobile Ad hoc Networks (MANETs).

MANETs are complex distributed systems comprising wireless mobile devices called MANET nodes that can freely and dynamically self-organize into arbitrary and temporary ad hoc network topologies. In MANETs, nodes internetwork seamlessly in areas with no pre-existing communication infrastructure (e.g., in tactical military networks, disaster recovery environments) providing a new and easily deployed wireless communication medium.

1.1. EVOLUTION OF WIRELESS COMMUNICATION

Worldwide sales of smart phones, laptops, and PDAs have increased exponentially each year since their introduction. According to a report by Gartner Inc., smart phone sales increased in the first quarter of 2010 by 13.8%, this growth is the result of integration with applications like music, email and internet browsing (Rappaport 2002). Currently, the communication between these wireless devices is achieved via fixed infrastructure-based service provider, or private networks. For example,

connections between two cell phones are setup using base station controllers (BSC) and mobile switching centers (MSC) in cellular networks; laptops are connected to Internet via wireless access points which are supported by the cellular infrastructure (Public Workshop: The Mobile Wireless Web, Data Services and Beyond: Emerging Technologies and Consumer Issues 2002). While infrastructure-based networks provide a great way for mobile devices to get network services, it takes time and potentially high cost to set up the necessary infrastructure. Furthermore, there are situations where a user required networking in areas with no prefixed infrastructure. Some examples of such situations are a military application where a tactical network is required but in the battlefield, typically in a foreign land, one may not rely on the existing infrastructure; also disaster struck regions (e.g., the Japan tsunami 2010) where the existing infrastructure is damaged. In these situations, establishing infrastructure is not practical in terms of expenditure and the time consumed. Hence, providing the needed connectivity and network services becomes a real challenge.

More recently, new alternative ways to deliver the services have been emerging. These are focused around having the mobile devices connect to each other through automatic configuration, setting up an ad hoc mobile network that is also flexible (Perkins and Royer 1999) (Lenders, Wagner and May 2006). In this way, not only can mobile nodes communicate with each other, but can also receive Internet services through Internet gateway node, effectively extending Internet services to the non-infrastructure area. Such networks are called Mobile Ad hoc Networks (MANETs). MANETs not only provide dynamic infrastructure networks but also allow the flexibility of wireless device mobility. Mobility is an important characteristic of MANETs since

emerging wireless services are necessarily targeted to a highly mobile workforce (Rappaport 2002). Thus, development of any wireless technology including MANETs must support users' mobility (Chlamtac, Conti and Liu 2003).

Initially, MANETs were used primarily for tactical network applications to improve battlefield communications or survivability. More recently, however, the introduction of new technologies such as the Bluetooth, IEEE 802.11, and HiperLAN has laid foundation for commercialization of MANET. MANET deployments have begun taking place outside the military domain (Varshney U. 2000) (Tonguz and Ferrari 2006). These recent innovations have generated a renewed and growing interest in the research and development of MANETs.

1.2. A BRIEF INTRODUCTION OF MANET

A MANET is a network of mobile wireless devices capable of connecting and communicating with one another using limited-bandwidth radio links. Mobile wireless devices otherwise referred to as MANET nodes, within the transmission range connect with one another through automatic configuration and set up an ad hoc network. A MANET node may be a PDA, laptop, mobile phone, and other wireless device mounted on high-speed vehicles, mobile robots, machines, and instruments; thus, the network topology is highly dynamic. The MANET nodes have computational power and routing functionality that allow them to function as sender, receiver, or an intermediate relay node or router.

1.2.1. Applications of MANETS. In the past, wireless ad hoc paradigms were implemented only in military applications (Chlamtac, Conti and Liu 2003). However,

advances in mobile computing and wireless devices, and the growth of support for ubiquitous computing, have led to exponential growth in the application and deployment of MANETs. With the rapid proliferation of wireless technologies such as Bluetooth, Hyperlan, WiMax, and the IEEE 802.11 series, MANETs have found myriad applications ranging from disaster relief, battlefield operations, and industrial and commercial purposes to information sharing and personal networking. Several industrial and commercial MANET applications have been proposed (Gerla and Raychaudhari 2007), some of them are:

1. A wireless sensor network is one of the most significant applications of MANETs, which have been widely used for domestic and environmental applications. Significant environmental applications include data tracking and remote sensing for weather forecasting.

2. MANETs provide a flexible method of establishing communications (Gerla and Raychaudhari 2007) for disaster relief efforts and rescue operations in areas where no network infrastructure exists, or where the infrastructure has been damaged.

3. The rapid deployment and self-configuration capabilities of MANETs make them suitable for relaying information creating situational awareness, as in a military network (Chlamtac, Conti and Liu 2003).

4. Business colleagues, conference participants, and students have begun to use MANETs for networking among themselves so that they can share documents, presentation materials, and so on.

In addition to those listed above, many other applications were discussed in (Chlamtac, Conti and Liu 2003).

1.2.2. Functioning of a MANET.

As discussed earlier, MANETs do not rely on a static infrastructure including base stations and routers. The nodes have unconstrained mobility, and they can organize themselves arbitrarily, creating a dynamic topology that can change rapidly and unpredictably.

The nodes within a MANET have varying capabilities (like battery life, level of computational intelligence and multi-path links with varying capacities), the network formed is Heterogeneous in nature. Heterogeneity of the network injects uncertainty in predicting or analyzing the functioning of MANETS. To maintain simplicity in simulations, we assume that the networks are homogeneous in nature.

Once a MANET is deployed, the network is formed in an on-demand fashion when the nodes come within transmission range of each other. The nodes dynamically self-organize into a temporary, multi-hop network topology, allowing nodes to internetwork seamlessly. This facilitates communication within the network.

When two nodes are within transmission range of each other, they are said to be at a one-hop distance from one another. When two nodes requiring a communication network are not within direct wireless transmission range of each other, in other words, not at one-hop distance, they forward packets through other nodes which acts as an intermediate relay node (i.e., a router); each link thus formed is counted as a hop and the distance between the transmitter and receiver is the number of hops a packet has to cross in order to reach the receiver. The intermediate node receives the packets, modifies it depending on the routing algorithm employed and forwards the packet to its one-hop

neighbor. Therefore, a node participating in a MANET operates not only as a host, but also as an intermediate relay node (i.e., a router).

Consider a topology illustrated by figure 1.1; wireless nodes 0-3 are required to communicate by forming a MANET. Assume node 0 and node 3 are the transmitter and receiver respectively. Node 0 floods a routing request (RREQ) to its one-hop neighbors; it is node 1 here. Node 1 receives the RREQ and in turn floods the RREQ which is received by its one-hop neighbors, nodes 2 and 3. Since node 3 is the destination, the communication between the sender and receiver pair is two-hops, one hop 0-1 and the other 1-3.
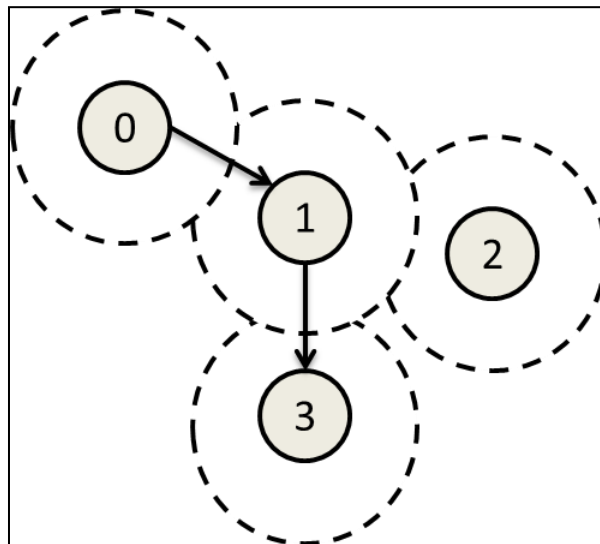
Figure 1.1. Functioning of a MANET

An increase in node population within the topology or the number of transmitter-receiver pairs results in an upsurge in the number of potential routes. The routing now

involves a series of decisions including the information a packet may carry and choosing the effective path, thus complicating the MANET routing procedure. This complexity is solved by a MANET routing protocol. In other words, the algorithm used in handling the organization of a MANET is facilitated by the MANET routing protocol employed.

1.2.3. Ad hoc Routing Protocols. The general algorithm for routing in MANETs is dependent on two key factors – the range of transmission of the individual MANET nodes (d) and the threshold sensing power (P) at the receiving node. When a mobile node moves out of range of a transmitting node, the packets are dropped and eventually the link breaks. Similarly, when the received signal power received at a node is less than the threshold power, the link breaks. Routing protocols are designed to handle both the scenarios with poise.

A MANET routing protocol allows communicating nodes to discover multi-hop paths through the network to desired nodes. It operates as an autonomous system or as a component of other larger networks. The protocol governs all node activities concerned with network configuration, route discovery, communication establishment, and local route maintenance; therefore, dynamic and adaptive.

Routing protocols are ideally classified into three categories - proactive protocols, reactive protocols and hybrid protocols. Proactive (table-driven) protocols are the protocols that enable the nodes to maintain fresh topology information using periodic updates. The periodic updates include frequent distribution of one's routing table throughout the network. A structure of a routing table is specific to the employed protocol, but it generally contains information regarding various destinations and their routes within the network. With the frequent updates, proactive protocols tend to generate

high amount of control traffic for route maintenance and also react slow to restructuring in case of link failures. Destination-sequenced distance vector routing protocol (DSDV), Optimized link state routing protocol (OLSR) and Wireless routing protocol (WRP) are some of the popular and widely used proactive ad hoc routing protocols.

A reactive (on-demand) protocol finds a route when there is a demand for the formation of the route. Whenever a node wants to form a route, it sends out routing packets called route requests (RREQ). The RREQs are transmitted in the network exponentially till it reaches the destination or an intermediate node with an existing route to the destination. This node sends route reply (RREP) progressively till it reaches the source node and thus, a route is discovered. This algorithm eliminates the high control overhead generated by the proactive protocols. However, reactive protocols have two major disadvantages: they invest high latency time in route discovery and have the potential to cause excessive flooding which might lead to network clogging. Ad hoc on-demand routing protocol (AODV) and Dynamic source routing (DSR) are the most extensively employed reactive protocols.

Hybrid protocols combine the advantages of both proactive and reactive protocols. The routing is initially established with some proactively discovered routes and then link failures or topological changes are served with on-demand routing from additionally activated nodes through reactive flooding. The choice for one or the other method is specific to the application of the protocol and the typical case in which it is employed. Though these protocols promise better routing than the proactive and reactive ones, the advantage depends heavily on the number of nodes activated. Also, the reaction of these protocols to varying traffic demands depends on the gradient of volume of the

traffic. Hence, these protocols are developed and effective for specific routing scenarios. Some of the popular hybrid protocols are Zone routing protocol (ZRP) and Temporally-ordered routing algorithm (TORA).

MANETs require a robust routing protocol which can accomplish routing with minimal control traffic and high link reliability. In this research, low control traffic generation for routing is of high prominence. Hence, reactive protocols are chosen as the subject of the study as they promise lower control traffic than proactive protocols.

1.3. MANET DESIGN CHALLENGES

MANETs have offered connectivity and network services in areas with no pre-existing infrastructure. They are inexpensive, and they require limited network resources. Their mobility makes them flexible and widely available. They are also considered robust wireless communication network due to their ease of deployment and configurability. The advantages of MANETs have made them attractive for both military and commercial applications (Nikkei Electronics Asia 2009) (Macker 1999). With greater reliability and a higher quality of service (QOS), MANETs offer a sound alternative for future generations of wireless networks.

MANETs, however, come with complications. In addition to the complexities of traditional wireless networks, they present challenges such as dynamically changing topology, a multi-hop nature, bandwidth constraints, energy constrained operations, network scalability and a lack of pre-existing infrastructure. These create design challenges specific to a MANET (Chlamtac, Conti and Liu 2003). This research addresses challenges and design constraints in context to ad hoc routing and mobility.

Ad hoc Routing and Mobility. Unlike conventional wireless protocols, MANET protocols must maintain complex network functionalities and logical operations that determine reliable routes in a highly dynamic environment. MANET performance depends largely on multi-hop routing governed by routing protocols. A MANET node performs all operations required for route acquisition and local route maintenance. Several factors affect the performance of a routing protocol; among these mobility is significant (Akunuri, Guardiola and Phillips 2010) (J. Mullen October 10–13, 2005) (Lenders, Wagner and May 2006).

Mobility has been a major hindrance to the smooth operation of a MANET protocol (Lenders, Wagner and May 2006). It increases link disruption and, consequently, higher network activities, exerting pressure on protocol performance. Increased network operation forces protocols to generate more control packets; thereby increasing the control overhead. Thus, a robust protocol capable of routing effectively within a highly mobile environment and without compromising its inherent attributes is vital to successful deployment of a MANET. In other words, a protocol must maintain information about the speed of the intermediate nodes and use this information to determine a stable routing path with minimal overhead.

1.4. RESEARCH OVERVIEW

The research presented in this thesis sought to optimize MANET network design using a new routing mechanism based on node mobility. A popular and widely-employed MANET routing protocol, ad hoc on-demand vector (AODV), was modified to drop packets when node mobility does not permit a node to form a link for the necessary amount of time. This new routing protocol is called the Speed-Aware Routing Protocol,

referred to as SARP here forth. Network simulator, ns-2.33, was used to implement SARP and design and perform a variety of experiments to ensure that SARP fulfills the need to incorporate speed-awareness in a MANET's route discovery mechanism. In addition, simple empirical simulations similar to those used in (Akunuri, Guardiola and Phillips 2010), (Paudel and Guardiola July 2009), (S. R. A. Aziz March 2009), (Nikkei Electronics Asia 2009) and (Tonguz and Ferrari 2006)including random movement and traffic scenarios were run to perform a comparative study to analyze the performance of SARP against the established AODV.

The objective of this research is to accomplish MANET on-demand routing by incorporating speed-awareness within the routing algorithm in order to reduce control overhead and increase link reliability. The tasks undertaken to achieve this objective were:

1. Designing SARP algorithm

2. Implementing SARP using the established routing algorithm AODV

3. Simulating realistic assumptions in ns2 (The ns Manual 2009) to analyze SARP and AODV

4. Perform a comparative study between SARP and AODV to ensure the objective of the research is achieved.

In (Akunuri, Guardiola and Phillips 2010) and (Paudel and Guardiola July 2009), a comparative study was conducted on the established reactive MANET protocols AODV, DSR, and DYMO. That study concluded that the protocols have shown a fairly similar performance under small-scaled networks with less traffic and moderate mobility; however, the protocols' capabilities might not be sufficient to achieve the performance demands

imposed by high node mobility. High mobility of the nodes results in frequent link disconnections including loss of priority information. A significant number of applications including mobile medical facilities and tactical warfare require highly reliable communication links. Hence, present research proposes the need for SARP, to incorporate speed-awareness so as to eliminate the fast nodes from consideration as potential intermediate nodes during the route discovery mechanism.

Though the effect of mobility of a wireless node on MANET's performance is closely tied to multi-path fading effects (Haenggi July 2006) (I.G. Guardiola 2007) (M. Lindhe 2007), to maintain the simplicity of simulations within this research, studying the impact of multi-path fading on the performance of SARP has been left out of scope of this study and is intended for future analysis of the effectiveness of SARP.

1.5. THESIS ORGANIZATION

This section lists the organization of the thesis. The thesis is organized as follows:

Section 2 discusses the challenges posed by mobility and its impact on MANET quality of service (QOS). It also elaborates the impact of network density on the performance of a MANET routing protocol. The mobility models have also been discussed briefly.

Section 3 explains the problem addressed by this study. It discusses the proposed solution SARP and elaborates how it attempts to mitigate the effect of high node mobility. It introduces the SARP decision parameter – Link Expiration Time (LET). The SARP algorithm implementation is explained using the demand-supply optimization. It also lists the limitations of SARP implementation.

Section 4 describes the methodology used to implement SARP into an existing MANET routing protocol, AODV. It demonstrates the calculations involved in the implementation. It closes with a discussion with a validation experiment conducted to ensure that the SARP algorithm incorporates speed awareness.

Section 5 describes the environment for the randomized simulations conducted for the performance analysis of SARP and AODV. It explains the assumptions on which this environment is based and defines the performance metrics.

Section 6 analyzes the simulation results using the performance metrics defined in section 5. It discusses the comparative study between SARP and AODV.

Section 7 concludes the thesis by listing the findings of the study. It also states the future work required to further analyze and improve SARP.

1.6. SECTION SUMMARY

MANETs have the potential to provide reliable communication services across areas with no pre-existing infrastructure. They ensure flexibility and convenience by supporting unconstrained mobility. They have the desirable features of a future generation network. However, MANETs have inherent limitations. Dynamic topology and the lack of a fixed infrastructure present serious protocol design challenges. Amongst these challenges, mobility is considered significant; it compromises the reliability of the communication link, reducing overall network performance. This research attempts to mitigate the effect of mobility by incorporating speed-awareness within the routing algorithm. Section 2 discusses some of the challenges posed by mobility in MANETs, emphasizing the impact of mobility on overall network performance.

2. MOBILITY IN MOBILE AD HOC NETWORKS

The dynamic and unpredictable movement of the nodes in a network and the heterogeneous propagation conditions make routing information obsolete; these frequent changes result in continuous network reconfiguration. The random node movements result in frequent exchange of routing packets over the limited networks' communication channels. Mobility also directly impacts the number of link failures within the network. It also causes an increase in network congestion while the routing protocol responds to the topological changes caused by independent node mobility. The impact of mobility and the accompanying factors like network density and links with varying capacities are discussed in this section.

2.1. IMPACT OF NETWORK DENSITY

Ideally, with an increase in network density, the throughput of the network is expected to increase. However, when this increase in network density is very large, the protocol performance degrades. In (Huda Al Amri Dec 2007), it is concluded that an increase in network density drastically affects the performance of MANETs because of various factors like increased path length, additional burden on intermediate nodes and increased packet collisions; it also complicates the protocol routing activity.

In a sparsely-populated network, the nodes are highly distributed reducing the number of possible connections between any two nodes. This distributed nature of nodes results in the formation of lengthy routes thus creating unstable links. The higher the distance between the nodes forming a link, the greater is the possibility of packet loss

(Guardiola 2007). It also causes a high end-to-end delay and increases the possibility of link disconnections.

As the network size is expanded, the average number of forwarding intermediate nodes increases (Guardiola 2007). As the number of intermediate nodes increase, the probability for packet loss at these multi-hop links increases. When an intermediate node receives a routing packet, it processes the packet, sets up a forward path and updates its routing table. Depending on the availability of a fresh reverse route in its routing table, it either floods the network with more routing packets or replies to the source node with a reverse route. This processing at each intermediate node adds to high end-to-end delay in the network. Also, the growing number of forwarded routing packets by the additional nodes would lead to network congestion. The network congestion, in turn, causes increased packet collisions resulting in high packet loss. Thus, increased network density has been known to deter end-to-end performance of MANETs.

Many routing strategies have been proposed to improve the performance of existing protocols or design new ones to improve network scalability. One such attempt was the design of an Adaptive Cell Relay routing protocol (ACR) in (D. Xiaojiang 2006). It was designed to handle different network densities to achieve high scalability. It uses two different routing strategies: the cell relay (CR) routing for dense networks, the large cell (LC) routing for sparse networks. It monitors the network density changes to determine the most effective routing strategy to apply according to the network density.

Most existing routing protocols have not been able to satisfy both scalability and mobility. Apart from network density, several problems in MANETs arise due to the mobility such as high end-to-end delay and low packet delivery ratio. Hence, node

mobility is considered to be highly crucial in achieving high stability and reliability in a MANET.

2.2. IMPACT OF NODE MOBILITY

The ad hoc and mobile nature of the node imposes a number of restrictions on a MANET. Some of the restrictions are the limited battery power, restricted bandwidth allocation, limited transmission power and hence, limited communication range. This in turn restricts the nodes' involvement in the routing activity. A MANET node should, hence, be utilized in an efficient way with a smart routing mechanism. Node parameters like transmission power, battery life have been studied extensively in (Chlamtac, Conti and Liu 2003), (J. Broch 1998) (S. R. A. Aziz March 2009); however, there has been limited focus on the impact of node mobility on the performance of a MANET routing protocol.

Node mobility, coupled with physical layer characteristics, determines the status of link connections. Link connectivity is an important factor affecting the relative performance of MANET routing protocols (Ingo Gruber 2002) (William Su 2001) (R. Oliveira 2010) (Lenders, Wagner and May 2006). From the perspective of the network layer, changes in link connectivity triggers routing events such as routing failures and routing updates. These events affect the performance of a routing protocol, for example, by increasing packet delivery time or decreasing the fraction of delivered packets, and lead to routing overhead (e.g., for route discovery or route update messages) (Chlamtac, Conti and Liu 2003) (William Su 2001) (R. Oliveira 2010).

In (Lenders, Wagner and May 2006), the impact of mobility on connectivity and lifetime route distributions was explored to isolate breakage from mobility or signal interference; this analysis supports the notion that for small route lifetimes, the link breakage is attributable to packet collisions and intermodal interference, and for longer lasting routes, the breakage is a consequence of node mobility (Cheng-Lin Tsao 2006) (R. Oliveira 2010). It can also be stated that larger the amount of data that has to be transmitted between any arbitrary receiver-transmitter pair, the larger would be the impact of node mobility (William Su 2001).

Amongst various fields of MANET routing, node mobility has so far grabbed comparatively little research emphasis. The two applications that captured majority of the work that involved node mobility were designing realistic mobility models or the usage of node mobility to improve the link connectivity time. In (D. Xiaojiang 2006), (Athanasios 2006) and (S. Mueller April 2005), different strategies have been implemented to satisfy different degrees of mobility. Also, much research has been focused on designing competitive mobility models for the simulators; as seen in (Fan Bai 2003) (X. Hong, T. Kwon, M. Gerla, D. Gu, G. Pei January 2007) (Yasser Kamal Hassan Nov. 2010) (F. Bai 2007).

2.3. EFFECT ON MANET QOS

The effect of mobility on the performance of practical ad-hoc wireless networks has been proven deleterious (Varshney U. 2000) (Lenders, Wagner and May 2006) (Gerla and Raychaudhari 2007). The unpredictable movement of intermediate nodes in a MANET environment dynamically changes the network topology thereby causing a

disruption in the established communication links. As the links break, a large amount of data packets that were being transmitted through those links, are dropped. This reduces the overall throughput of the network.

Once the link disconnects, the network forces the underlying protocol to repair the broken links or initiate search for new routing paths resulting in a continuous reconfiguration of the network (Gerla and Raychaudhari 2007). The reconfiguration of the network for a routing protocol denotes route maintenance. Route maintenance includes the transmission of routing packets like route disconnections (RERR), route replies (RREP), route requests (RREQ) and possible HELLO packets (i.e., in case of on-demand routing). The cumulative number of routing packets generated is represented by overall control overhead generated by the network. Frequent route disconnections due to high node mobility and frequent topological changes lead to heavy route maintenance; this causes high control overhead which causes high network traffic load.

The increase in network traffic load due to node mobility will result in otherwise avoidable resource reservation and bandwidth occupancy; it also increases congestion and contention.

2.4. MOBILITY MODELS

As discussed earlier, mobility models have been the focus of study in the field of mobility in MANETs. Currently MANETs are not deployed on a large scale and hence, research in this area is mostly simulation based. The mobility model is an important simulation parameter in determining the protocol performance in MANETs (L. Breslau May 2000). Thus, it has been proven essential to study and analyze various mobility

models and their effect on MANET protocols. This section offers a briefing on popular mobility models proposed in the recent research literature.

The mobility model is designed to describe the movement pattern of mobile nodes, and how their location, velocity and acceleration change over time. Since mobility patterns may play a significant role in determining the protocol performance, it is important for mobility models to imitate the movement pattern of targeted real life applications in a reasonable way. Otherwise, the observations made and the conclusions drawn from the simulation studies may be misleading. Hence, it is necessary to choose the proper underlying mobility model when evaluating MANET protocols.

In (F. Bai 2007), mobility models were categorized based on their specific mobility characteristics. The categories are illustrated in figure 2.1.
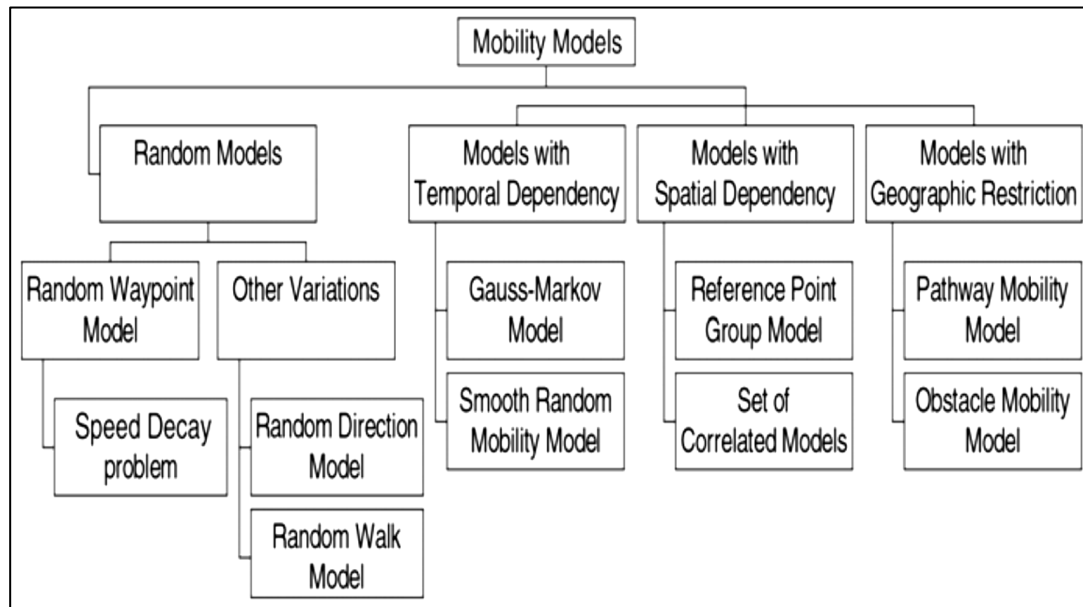
Figure 2.1. The Categories of Mobility Models in MANET

Starting from the right, the class of models with geographic restrictions are the models where movement of nodes is bounded by geographic locations like streets, lanes or obstacles. In some mobility scenarios, the mobile nodes tend to travel in a correlated manner; these models are referred to as mobility models with spatial dependency. Models with temporal dependency are the class of models where the mobility of nodes follows a certain trend or is dependent on its movement history.

In random-based mobility models, the mobile nodes move randomly and freely without restrictions (i.e., the destination, speed and direction are all chosen randomly and independently of other nodes). This class of mobility models has been a popular choice with the simulations since they depict random node mobility which is closer to the real environment.

One frequently used mobility model, the Random Waypoint model, has been chosen for this research since it depicts the closest to reality movement pattern in nodes. The nodes in Random Waypoint model behave quite differently as compared to nodes moving in groups (J. Broch 1998). To generate the node trace of the Random Waypoint model the 'setdest' tool from the CMU Monarch group is used. This tool is included in the network simulator ns-2 (L. Breslau May 2000).

In the Random Waypoint model, maximum allowable velocity for a node 'V_{max}' and pause time 'T_{pause}' are the two key parameters that determine the mobility of nodes. If V_{max} is small and pause time T_{pause} is long, the topology of the ad hoc network becomes relatively stationary. Conversely, if V_{max} is small (i.e., the node moves fast) and the pause time T_{pause} is small, the topology is expected to be highly dynamic. Varying these two parameters, especially the V_{max} parameter, the Random Waypoint model can generate

various mobility scenarios with different levels of node mobility. The choice of the V_{max} for the simulations is elaborated under section 5.1.3.
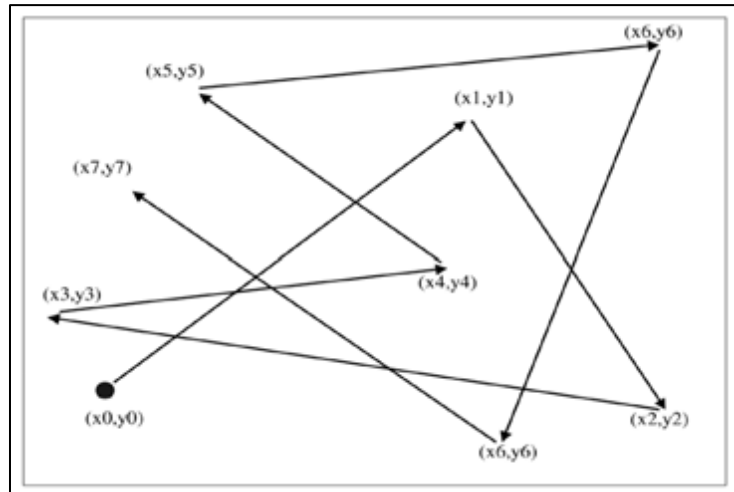
Figure 2.2. Example of node movement in the Random Waypoint Mobility model

Much research had been focused on developing efficient and effective mobility models. In (Athanasios 2006), a mobility-sensitive routing strategy was introduces in which a metric was used to classify the nodes into mobility classes; the mobility class determines the best routing technique for any pair of origin and destination. In (S. Mueller April 2005), (Fan Bai 2003) and (X. Hong January 2007), different mobility models such as random mobility, group mobility, freeman and Manhattan mobility models were simulated using multiple protocols and their performance was evaluated.

2.5. SECTION SUMMARY

The effect of mobility and network density on MANETs was elaborated. With increasing values of network density and level of mobility, the protocol routing activity becomes complex. This complexity introduces various challenges like link disconnections and packet loss. The QOS of the MANET is also adversely affected by mobility. Due to its simplicity and proximity to realistic environment, random waypoint mobility model was chosen for the simulations conducted during this study. Section 3 addresses the problem statement for the thesis and elaborates the proposed solution.

3. PROBLEM STATEMENT

The research presented in this thesis is designed to validate a new routing algorithm SARP, focused towards establishing reliable routes and reducing control overhead generated by the underlying routing protocol. This approach uses the well-established and readily available Global Positioning System (GPS) to acquire node position and velocity information of the network participants. It then uses this information to decide whether the sender should participate in a particular route between a pair of nodes that have propagated a communication demand. This decision ceases the use of such unreliable links within a route by ensuring that all communication satisfies the transmission demands of the network and remains uninfluenced by the nodes' movements. Such a mechanism demands statistical interpretation which is elaborated under section 4.

The research developed a new routing protocol that promises to dramatically increase the reliability of link routes during the connectivity period. The establishment of routes with unreliable links is a major factor in diminishing the end-to-end performance of established protocols (Chlamtac, Conti and Liu 2003). This unreliability often causes lapses in the connectivity during the critical period of data packet transmission. Such a loss in connectivity immediately leads to maintenance activities and the subsequent rediscovery of routes, and thus creating excessive overhead and system congestion. Hence, the research proposes the exclusion of unreliable links in the potential routes using the nodes' GPS information. This capability is achieved for reactive protocols by utilizing basic link expiration time (LET) calculation in the route discovery phase. This

calculation determines which nodes should participate or remain passive in a potential route. A detailed study about the impact of node mobility and network scalability on the network performance, route stability and reliability of communication links is provided within the following sections.

3.1. THE CHALLENGE AND THE PROPOSED SOLUTION

MANET characteristics complicate protocol design. These characteristics must be taken into account, however, to ensure that the protocol is reliable, and perhaps more importantly, robust. Ad hoc networks have several significant attributes, including dynamic topologies, asymmetric links, multi-hop communication, decentralized operations, bandwidth-constrained variable capacity links, energy conservation, and mobility (Guardiola 2007). This research lays emphasis on increasing route reliability in a network by ceasing the receiver nodes to form unreliable routes with highly mobile transmitter nodes. Although the research is application specific, it does well to explain each of the mentioned issues and characteristics of the MANET.

Contrary to the popular belief, reactive protocols do not always have low control overhead (Lenders, Wagner and May 2006) (M. Lindhe 2007) (S. R. Das March 2000). The control overhead for reactive protocols is more sensitive to the traffic load, in terms of the number of active link connections, and mobility, in terms of link connectivity changes, than other protocols. Therefore, reactive protocols have been considered as the primary focus of this research.

The inherent and most prominent characteristics of a MANET - node mobility and frequent topological changes have been discussed in the previous sections. These characteristics are responsible for the frequent link disconnections in a network. The

diminished link connectivity deteriorates the QOS performance of the routing protocol by increasing the control traffic flow, forming unstable routes and reducing available bandwidth.

The new routing algorithm, SARP, proposes to restrict the formation of unreliable routes resulting from highly mobile intermediate nodes. During a route discovery phase, a node sends out routing packets. When a neighboring node receives this packet, it determines whether a node is too fast to form a reliable route. If the node indeed is too fast, the neighbor rejects the sender node as a potential one-hop link. This method helps is eliminating nodes with high mobility and perhaps more importantly, less reliable routes from the routing activity thereby promising comparatively lower control overhead.

Consider a MANET consisting of four nodes 1 – 5 illustrated in figure 3.1. Figures 3.1a, 3.1b and 3.1c represent the network topologies for a non-SARP protocol at times t, t+1 and t+2, respectively. Figures 3.1d, 3.1e and 3.1f narrate the expected network topologies for SARP at times t, t+1and t+2, respectively.

Node 5 and Node 1 are assumed to be sender and receiver nodes respectively. The dotted line represents the active link and the arrow represents the direction of motion for the nodes. The network requires each node to have a relative velocity between [-20, +20m/s] to form a stable link. A non- SARP protocol would use route 5-4-2-1 with nodes 4 and 2 as the intermediate routing nodes. Say node 2 is moving away from node 1 with a relative velocity outside the acceptable range and once it moves out of the transmission range of either node 1 or node 4, either of the links 1-2 or 4-1 break. This event initiates route maintenance activity which results in heavy control traffic generated by node 4 and node 1 in an attempt to revive the broken link but in vain. After exhausting MAC maximum retires to recoup the broken link, it forms route 5-4-3-1 to retain the network data transmission. Apart from high control

traffic generated, the active transmission of data through these links during a link disconnection results in loss of data packets.
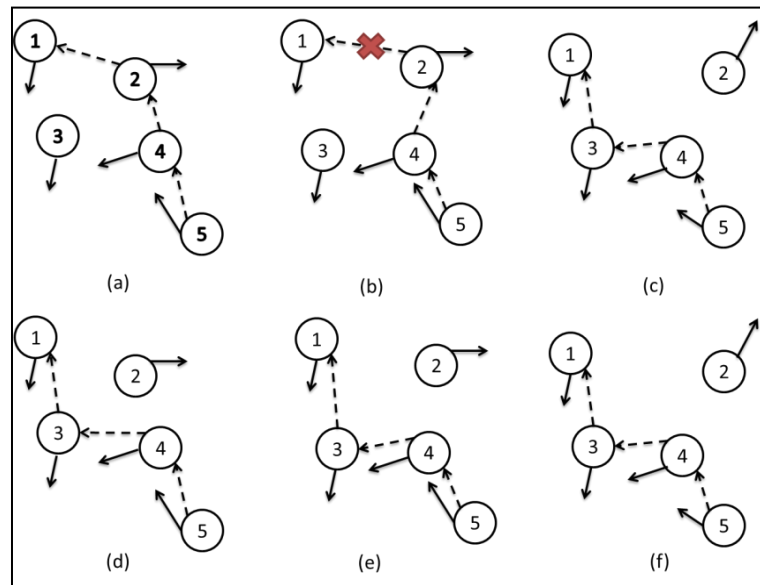
Figure 3.1. The Proposed Solution – SARP

Both the excess control overhead generated to revive the broken links and the data packet loss could have been avoided if a more reliable route 5-4-3-1 was formed instead of 5-4-2-1. This can be achieved with the implementation of SARP routing algorithm in the underlying routing protocol. With SARP, the fast moving node, node 2, is eliminated from route discovery process by node 1 and the routing protocol forms the route through node 3 instead. This link survives through the data transmission and thus, eliminates the control overhead generated by the non-SARP to resuscitate a link breakage. Thus, SARP promises to restrict the number of unreliable routes based on node mobility.

The decision-making parameter for SARP is the route reliability. In this research, route reliability is measured by the amount of time two nodes can be connected without a link disconnection. The link connectivity is determined using the link expiration time (LET).

3.2. LINK EXPIRATION TIME

When certain amount of data is required to be transmitted using a MANET, some data is lost due to the handoffs and/or link breakages. To avoid this loss of data, a secure link should be formed; this link must survive the time required to transmit the given data size at a particular data rate supplied by the network. This would ensure the given block of data to be transmitted efficiently. The measure used in this research to represent uninterrupted link time is the link expiration time (LET).

LET between two nodes could be defined as the predicted connectivity time between the nodes (R. Oliveira 2010). In other words, it is the time two nodes are predicted to have an active route without a disconnection. The LET is calculated using the Global Positioning System (GPS) information (El-Rabbanny 2002) (El-Rabbany 1994) of the nodes (A. Rhim 2009).

In (S. S. Manvi 2010), a Zone and Link Expiry based Routing Protocol (ZLERP) was proposed for MANETs. This proactive protocol forms the most reliable links using the received signal strengths from neighboring nodes at periodic time intervals; the determination of which considers node mobility as a key factor. In both (Song Guo April 2005) and (Ingo Gruber 2002), the node mobility was used to predict a connectivity time between two nodes; however, the connectivity times have been used to form backup

routes or multicast routing. Nevertheless, the idea of employing the predicted link connectivity time to establish reliable routes initially has not been exploited yet. In (A. Rhim 2009)], during the route maintenance phase, the MANET nodes were made capable of predicting the remaining connectivity time with their neighbors in order to avoid disconnections. However, no key progress has been achieved where node mobility was used to establish stable routes.

In (Ingo Gruber 2002), LET was introduced as a statistical derivation to forecast the average distance the relay is within the scope of the nodes. This mobility prediction method utilizes the location and mobility information provided by GPS. Initially, a free space propagation model is used, where the received signal strength solely depends on its distance to the transmitter. It is also assumed that all nodes in the network have their clock synchronized. Therefore, if the motion parameters of two neighboring nodes like speed, direction, radio propagation range are known, the duration of time these two nodes will remain connected can be determined. Assume two nodes i and j within the transmission range of each other. Let (x_i, y_i) be the coordinates of node i and (xj, yj) be the coordinates of node j. Let vi and vj be the speeds, θ_i $(0 \leq \theta_i)$ and θ_j $(\theta_j \leq 2\prod)$ be the directions of motion for nodes i and j, respectively. Then, the amount of time two mobile hosts will stay connected, is predicted by the formula given by equation (3.1):

$$LET = \frac{-(ab+cd)+\sqrt{(a^2+c^2)r^2-(ad-bc)^2}}{a^2+c^2}. \tag{3.1}$$

The parameters a, b, c and d are determined using the formulae illustrated by equations (3.2), (3.3), (3.4) and (3.5).

Parameter 'a' is the relative velocity of the receiver node with respect to the sender node along Y-axis. It is determined using equation (3.2).

$$a = V_r \text{ Cos}\theta - V_s \text{ Cos}\theta. \tag{3.2}$$

'b' is the parameter used to determine the distance of the receiver node from the sender node along X-axis and is determined using equation (3.3).

$$b = X_r - X_s. \tag{3.3}$$

The third parameter used to determine LET is 'c'. Parameter 'c' is the relative velocity of receiver node with respect to the sender node along Y-axis. Equation (3.4) gives the formula to determine 'c'.

$$c = V_r \text{ Sin}\theta - V_s \text{ Sin}\theta = V_{Yr} - V_{Ys.} \tag{3.4}$$

'd' is the distance of the receiver node from the sender node along Y-axis. This parameter is determined using the formula given in equation (3.5).

$$d = Y_r - Y_s. \tag{3.5}$$

The algorithm of SARP is similar to optimizing a supply and demand of LET for a given network. The following section briefs the demand-supply optimization approach.

3.3. DEMAND-SUPPLY OPTIMIZATION

The SARP algorithm is realized using a demand-supply optimization approach. During the route discovery phase of the protocol, a LET of a potential route is calculated. To determine if this route is reliable or not, the above calculated LET (i.e., supply LET_S) should be measured against a pre-determined value. This predetermined value will be the LET demanded by the network, LET_D. In other words, uninterrupted link time should meet the time required to meet the demand of transmitting the specified amount of data. To successfully implement this algorithm, the demand-supply optimization approach is utilized.

Consider a network of 3 nodes with 2 links. Let node 1 be the source moving at a velocity 'V_1' initially at a distance 'd_1' from node 2; node 2 be the intermediate node at velocity 'V_2' at a distance 'd_2' from node 3 and node 3 be the sink at velocity 'V_3'. The nodes move away from each other causing the link to break after the distance reaches the range of transmission for the nodes, d_0.

That is, $d1 \rightarrow d0$ at time t1 and $d2 \rightarrow d0$ at time t2.

Then the supply time, the uninterrupted link, would be the minimum of both the link times LET_1 and LET_2.

$$St = min [LET_1, LET_2].$$

Both LET_1 and LET_2 are dependent on the individual velocities of the nodes.

The LET_D for the required network depends on the application supported. It can be calculated as:

$$LET_D = \text{Demand Data size in bytes / Data rate supplied by the network.}$$

To optimize the demand-supply of the network, that is to have a stable route to transmit the demand data,

$$\text{Supply time} \geq \text{Demand time,}$$

$$\text{i.e., } LET_S \geq LET_D.$$

3.4. SECTION SUMMARY

The rapid unpredictable movement of intermediate nodes and mobile objects in a MANET environment dynamically changes the network topology thereby causing a disruption in the established communication links. These frequent disruptions force the underlying protocol to reconfigure the network resulting in high control overhead. SARP

proposes to limit these link disruptions by ceasing the formation of the unreliable links. The following section elaborates the methodology implemented to inculcate speed-awareness in a well-established MANET routing protocol.

4. DESIGN AND IMPLEMENTATION OF SARP

As discussed in the preceding section, node mobility reduces the length of active connectivity within the nominal range thus increasing the potential for link disconnections. The proposed algorithm to reduce the occurrence of such link disconnections, Speed-Aware Routing Protocol (SARP) is based on excluding the nodes that are too fast from inclusion in the route discovery mechanism. To achieve this functionality the routing protocol drops the packets received from a node that is too fast to maintain an active route.

In (P. Johansson 1999), performance of ad hoc routing protocols AODV, DSDV and DSR was compared against a mobility metric which was designed to reflect the relative speeds of the nodes. This study concluded that the reactive protocols (AODV and DSR) performed significantly better than the proactive protocol DSDV; it also stated that AODV performed better than DSR at higher traffic loads. In addition, the simulations conducted in (J. Broch 1998), (S.R. Das 1998) and (S. R. A. Aziz March 2009) with varying network parameters including mobility levels, multi-path fading and network densities showed that AODV performed better than the other routing protocols in high stress situations of high mobility and fading. Henceforth, this research uses AODV as the underlying routing protocol to implement the Speed-Awareness in the routing algorithm.

4.1. METHODOLOGY

In the SARP routing algorithm, when a node receives a routing request (RREQ) or a routing response (RREP), it calculates the link expiration time (LET) of the node

with respect to the packet sending node. LET is the parameter that predicts the link disconnection time between two nodes; in other words, it is the time two nodes are predicted to have an active route (Song Guo April 2005).

Consider a node must transfer 1 MB of data through the link and the transfer rate is 2 packets per second. Assuming the packet size is 256 KB; the nodes must be connected for a span of around 2 seconds to successfully transfer the data through. The 2 seconds is the LET demanded by the link to sustain successful data transfer without a disconnection or loss of data. If the LET supplied by the link falls below the 2 second mark, the packet-sending node must be excluded from inclusion into the link route; therefore, the packet-receiving node drops such packets.

Implementation of SARP is similar to a demand-supply optimization approach. The demand LET, LET_D, of a link is determined for a given size of data and transmission rate of the link; it is a limiting factor to identify ineffective routes. When a node receives a routing packet (RREP/RREQ), the supplied LET, LET_S is determined for the sending and receiving nodes. Ideally, when the value of the LET_S is lower than that of the LET_D, the link is predicted to be ineffective for the required amount of time; therefore, the packet is dropped, and the sending node is excluded from further routing activity.

This scenario assumes that the source and destination nodes of the packet are at one-hop distance. It does not consider the delays caused by intermediate nodes. When an intermediate node receives a routing packet, it processes the packet, sets up a forward path and updates its routing table. Depending on the availability of a fresh reverse route in its routing table, it then either floods the network with more routing packets or replies to the source node with a reverse route. This processing at each intermediate node adds to

high end-to-end delay in the network. In order to compensate for this delay, a time-lenience factor 'ΔT' is introduced. Therefore, a node must exclude a packet-sending node from route inclusion unless the condition specified by equation (4.1) is satisfied.

$$\text{LET}_S \leq (\text{LET}_D + \Delta T). \tag{4.1}$$

The value of ΔT is influenced by the grid-size of the network. Consider the scenario depicted in figure 4.1 with 5 nodes in a network of grid-size 500mx500m.
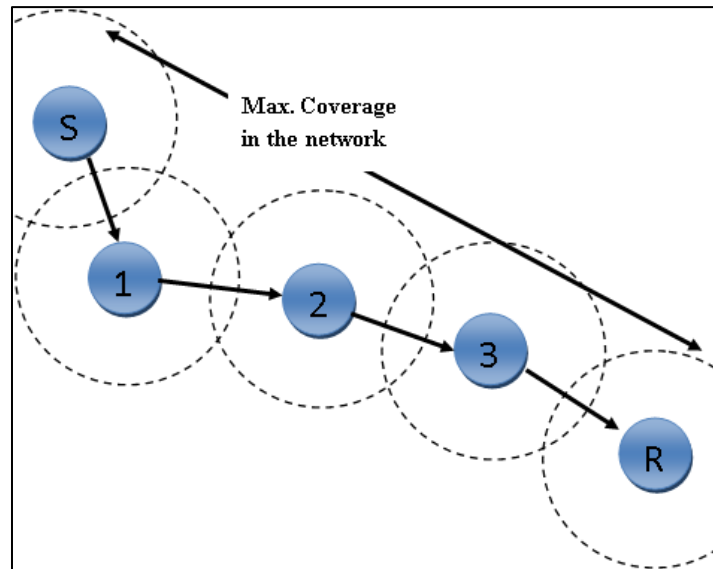
Figure 4.1. Determination of Time-lenience factor, ΔT

Let $\Delta_i t$ be the delay introduced by the node '*i*'. When sender node 'S' forms a route through intermediate nodes 1, 2, and 3 to send packets to the receiver node 'R', the time lenience factor ΔT is calculated as the summation of the delays introduced by the three intermediate nodes.

$$\Delta T = \sum_{i=0}^{3} \Delta_i \ t$$

Assume that the network is heterogeneous and each node inserts the same delay 'Δt' into the route:

$$\Delta_1 t = \Delta_2 t = \Delta_3 t$$

$$\Rightarrow \Delta T = 3x(\Delta t)$$

$$\Rightarrow \Delta T = (\text{No. of intermediate nodes in the route}) \ x$$

$$(\text{Delay introduced by each node})$$

$$\Rightarrow \Delta T \propto \text{No. of intermediate nodes in the route}$$

The possible number of intermediate nodes in a route could be determined as follows:

$$\text{Possible no. of intermediate nodes in a route} = \frac{Max.CoverageinNetwork}{TransmissionRangeofaNode}.$$

In the scenario given by figure 4.1, the maximum coverage in the network is given by the length of the diagonal of the grid which is equal to 500 x $\sqrt{2}$ = 707m (approx.) and the average transmission range of a wireless node with an Omni-directional antenna is 250 m. This gives us the possible no. of intermediate nodes within any route in the network as 707/250 = 2.828 $\approx$ 3. Since delay introduced by a single node Δt is a negligible value, the cumulative delay introduced by the intermediate nodes i.e., ($3x\Delta t$) is determined to be quite a small and negligible number. However, with growing network sizes and reduced transmission range of nodes due to attenuation (caused by fading) the value of ΔT could be significant but is expected to be smaller than one second. Hence, this study uses a fixed maximum value of one second for ΔT to compensate for the delays introduced by possible intermediate nodes in a route.

The SARP algorithm comprises of the below steps:

1. The determination of node coordinates and velocities,

2. The calculation of LET and,

3. The identification and exclusion of unstable links from the routing procedure.

Each of these procedures is discussed in detail in the following sections.

4.2. DETERMINATION OF NODE COORDINATES AND VELOCITIES

When a MANET node receives a routing packet (RREP/RREQ), the packet is transferred from lower network layers to higher node layers. At the medium access layer (MAC) of the packet-receiving node, GPS information of is noted; this includes the spatial coordinates and node spatial velocities of both the sender and receiver nodes.

At a given simulation time 't', the node coordinates and velocities are noted along the three spatial axes, as listed in table 4.1. Figure 4.2 shows these parameters diagrammatically.

Table 4.1. Determination of Node Coordinates and Velocities

	Receiver Node	Sender Node
Node Coordinates	X_r, Y_r, Z_r	X_s, Y_s, Z_s
Node Velocities	V_{Xr}, V_{Yr}, V_{Zr}	V_{Xs}, V_{Ys}, V_{Zs}
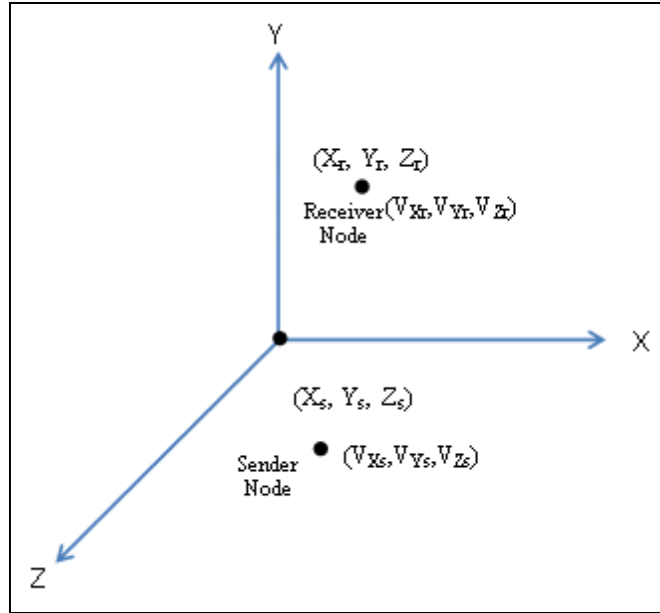
Figure 4.2. Receiver and Sender Node Coordinates

4.3. CALCULATION OF LINK EXPIRATION TIME

Once the coordinates are determined, the LET of the receiver node is calculated with respect to the sender node. This section presents the formulae used to calculate LET.

The LET of the receiver node with respect to the sender node is determined through each axis. At time 't', the velocities of the sender node along X-axis, Y-axis, and Z-axis are represented by V_{Xs}, $V_{Ys,}$ and V_{Zs} m/s respectively, whereas the velocities of the receiver node along the axes are represented by V_{Xr}, $V_{Yr,}$ and V_{Zr} m/s.

Since the simulations are performed on grid-frames in ns-2.33, the parameters along the Z-axis are assumed to be zero:

$$Zs = Zr = 0. \tag{4.2}$$

Similarly the velocities along the Z-axis are zero:

$$V_{Zs} = V_{Zr} = 0. \tag{4.3}$$

Equations (3.2), (3.3), (3.4) and (3.55) were substituted values from equations (4.2) and (4.3). The resulting formulae are exemplified in equations (4.4), (4.5), (4.6) and (4.7) respectively.

$$a = V_r \, Cos\theta - V_s \, Cos\theta_j = V_{Yr} - V_{Ys}, \tag{4.4}$$

$$b = X_r - X_s, \tag{4.5}$$

$$c = Vr \, Sin\theta - Vs \, Sin\theta = V_{Yr} - V_{Ys}, \text{ and} \tag{4.6}$$

$$d = Y_r - Y_s. \tag{4.7}$$

where θ_r and θ_s are the directions of motion of the receiver and sender nodes respectively.

The amount of time the nodes are predicted to be in active communication, LET, is calculated using the formula given by equation (4.8). This equation is the same as equation (3.1).

$$LET = \frac{-(ab+cd) + \sqrt{(a^2+c^2)r^2 - (ad-bc)^2}}{a^2+c^2} \tag{4.8}$$

The above determined LET value is the value calculated per route and will be considered as the supplied LET, LET_S in the SARP implementation. This value is calculated per every potential link and compared to the demand LET_D, elaborated in section 4.5.1. LET_D is the required LET value that a link must possess in order to sustain active communication till the transfer of the data is completed. When the supply LET_S is less than the demand LET_D, the link is predicted to be unstable.

4.4. IDENTIFICATION AND EXCLUSION OF FAST-MOVING NODES

The LET_S of the receiver and sender nodes is used to identify the fast moving nodes. This algorithm uses a predetermined value for the demand LET, LET_D, as a limiting factor. Section 4.5.1 explains the significance of this factor and how it is

determined. A node is considered to be fast or travelling in a direction not feasible for effective communication when the LET$_S$ is short of the demand LET$_D$.

4.4.1. Demand Link Expiration Time (LET$_D$). Consider two nodes i and j are within communication range of each other. Let there be a demand to transfer 'x' KB of data from node i to node j with a packet size of y KB and a rate of z packets per second, as illustrated in figure 4.3.
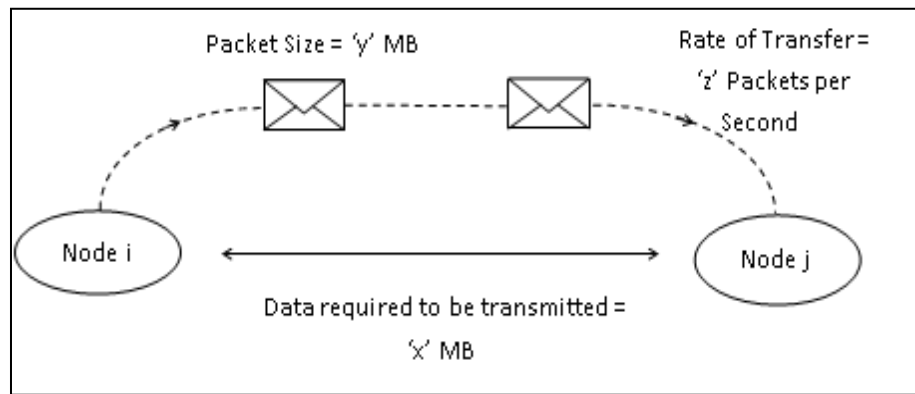
Figure 4.3. Demand Link Expiration Time (LET$_D$)

Hence, actual size of data transferred between the nodes per second is calculated to be yz Kbps.

For successful data transmission without any link breakage between the nodes, the length of time during which both nodes must have an active link to transfer the 'x' KB through the link is calculated to be:

$$\text{LET}_D \ = \ \frac{Size of Data to be Tranmitted\,(KB)}{Size of Data\,Transmitted per Second\,(Kbps)} \text{seconds.} \quad (4.9)$$

Hence,

$$\text{LET}_\text{D} = \frac{x}{yz} + \Delta\text{T seconds.} \tag{4.10}$$

where ΔT seconds is the time-lenience factor.

The LET_D thus calculated will be the expectant LET a link must last to be included in further routing procedures by the packet-receiving node.

4.4.2. Identification of Unstable Links. Once a node determines its LET_S with respect to the packet-sending node, it can determine whether the packet-sending node is too fast to form a stable route with. As discussed in section 4.5.1, the acceptable LET_S must be greater than or equal to the LET_D. When the LET_S of the receiver node with respect to the sender node is less when compared to the network LET_D, the receiver node considers the sender node too fast for effective communication and hence, dismisses it from further routing processes.

The two parameters 'a' and 'c' used in the calculation of LET are the relative velocities of the receiver node with respect to sender node along the x and y axes respectively. Since LET is the decision parameter for these experiments, validation of the discussion relies on the relative velocity and direction of the nodes; and is considered the key factor driving the decision behind SARP algorithm. Relative velocity is the velocity with which a node approaches or recedes from another node. The three scenarios described below represent the exhaustive set of outcomes considering relative velocity.

4.4.2.1 Zero relative velocity. When two nodes are at rest or are moving in the same direction at equal speed, the relative velocity of the nodes is zero. This is the best scenario for mobile wireless communication since both the nodes are relatively stationary. In such a scenario, parameters a and c will be zero.

$$a = V_{Xr} - V_{Xs} = 0$$

$$c = V_{Yr} - V_{Ys} = 0$$

By simplifying equation (4.8) with respect to the above conditions, LET_S is calculated as follows:

$$LET_S = \frac{-(0) + \sqrt{0 - (0 - bc)^2}}{0} = \infty$$

The LET_S value of infinity signifies that the two nodes will be connected for a very long time unless changes its direction of motion or velocity. Hence, this scenario promises the most optimal link between two mobile nodes.

4.4.2.2 Two nodes moving in the same direction but at different speeds.

When two nodes are moving in the same direction, the communication is effective only when the difference in their speeds is not large. For example, consider a packet-receiving node n_r moving with a velocity 'V_r' and it receives a routing packet from another node n_s moving with a velocity 'V_s'. Since both the nodes are moving in the same direction, both V_r and V_s will be positive. Under these circumstances, two possible scenarios are possible.

4.4.2.2.1 <u>Receiver node velocity is higher than sender node velocity</u>. When the receiver node velocity is higher than the sender node velocity, that is when V_r greater than V_s, the relative velocity of the receiver node with respect to the sender node will be positive. If V_r is much greater than V_s, the relative velocity is very high, and the receiver node is too fast to form an effective link.

When V_r is much greater than V_s, both a and c are large positive values. As a result, LET of the nodes is negative, and the packet-sending node will be excluded from the routing activity.

4.4.2.2.2 <u>Sender node velocity higher than the receiver node velocity.</u> When Vs is greater than Vr, the relative velocity of the receiver node with respect to the sender node will be negative; that is, both a and c are negative. If nodes can connect until the successful transmission of the required data size, the nodes are considered able to form a stable route, whatever their direction of travel. However, if V_r is much larger than V_s, the relative velocities (a and b) will be a very large negative numbers. This scenario usually generates a low positive value of LET. To exclude the node from this scenario, a cap on the acceptable positive range of LET is necessary.

4.4.2.3 Two nodes travelling in opposite directions. An **active communication** channel between two nodes moving in opposite directions creates a challenge for MANET routing and may involve significant packet loss if not handled prudently. Nodes moving in opposite directions may be outside communication range for too long to sustain dialogue; that is, they may have a low LET. Since the receiver node nr is treated as the reference node, Vr will be positive; in this case however, Vs will be negative; therefore, the relative velocity of receiver node with respect to the sender node will always be positive.

$$a = V_{Xr} - (-V_{Xs}) = V_{Xr} + V_{Xs}$$

and

$$c = V_{Yr} - (-V_{Ys}) = V_{Yr} + V_{Ys.}$$

4.5. VALIDATION OF THE METHODOLOGY

Using an ns2.33 all-in-one package (The ns Manual, 2009), the MAC layer of the AODV protocol was modified to include the speed awareness of SARP within AODV.

The functions getLoc() and getVelo() are used to determine a nodes' spatial coordinates and velocities. SARP calculates LET_S based on the formula given in equation (4.8). When it is less than the required LET_D, the node drops the control packets to ensure that the packet-sending node remains available to participate in further routing activities with the current node. Once the SARP algorithm was implemented, a scenario was simulated to validate the functioning of the SARP. Figure 4.4 illustrates this scenario.

Figure 4.4. Scenario to validate of SARP

A set of four nodes has initial spatial coordinates as follows: node 0 (20, 200), node 1 (200, 200), node 2 (220, 200), and node 3 (400, 200). Nodes 0, 1, and 3 travel in one direction at speeds of 5 m/s, 20 m/s, and 5 m/s respectively; however, node 2 travels the opposite direction at 20 m/s. Thus, the nodes at the farthest ends (node 0 and 3) are outside communication range and cannot form a direct route. The nodes between them, nodes 1 and 2, act as intermediate nodes for communication between nodes 0 and 3. At time 1.0 seconds, node 0 tries to connect to node 3, sending out a RREQ. These RREQs

are received by intermediate nodes 1 and 2. On receiving the RREQ, nodes 0 and 1 calculate their respective LETs.

When node 1 receives the RREQ from node 0, it calculates the LET_S using equation (4.8). The parameters are calculated:

at simulation time '1.0',

$$a = V_{Xr} - V_{Xs} = V_{X1} - V_{X0} = 0 - 0 = 0,$$

$$b = X_r - X_s = X_1 - X_0 = 200 - 20 = 180,$$

$$c = V_{Yr} - V_{Ys} = V_{Y1} - V_{Y0} = 20 - 5 = 15, \text{ and}$$

$$d = Y_r - Y_s = Y_1 - Y_0 = 0 - 0 = 0.$$

The supply LET is then calculated as

$$LET_S(0\text{-}1) = \frac{-(0+0) + \sqrt{(15^2 \, x 250^2) - (0 - 180*15)^2}}{(0^2 + 15^2)}$$

$$= 11.57 \text{ seconds.}$$

Similarly, the LET_S of the link 0-2 is calculated to be approximately $LET_S(0\text{-}2) = 6$ seconds.

Figure 4.5 is a graph that shows how LET_S is affected by the relative velocity between nodes. It indicates that when the relative velocity is too high or too low, the LET drops to a low value. The LET_D is depending on network requirements or on the amount of data to be transferred. Thus, the range of acceptable relative velocities between the two nodes is limited. For example, in this scenario, assuming a need to transfer 20 MB of data with a packet size of 0.5 MB at a rate of 5 packets per second, using equation (4.6), LET_D is calculated as

$$LET_D = \frac{20}{5*0.5} + 1 \text{ second} = 9 \text{ seconds.}$$
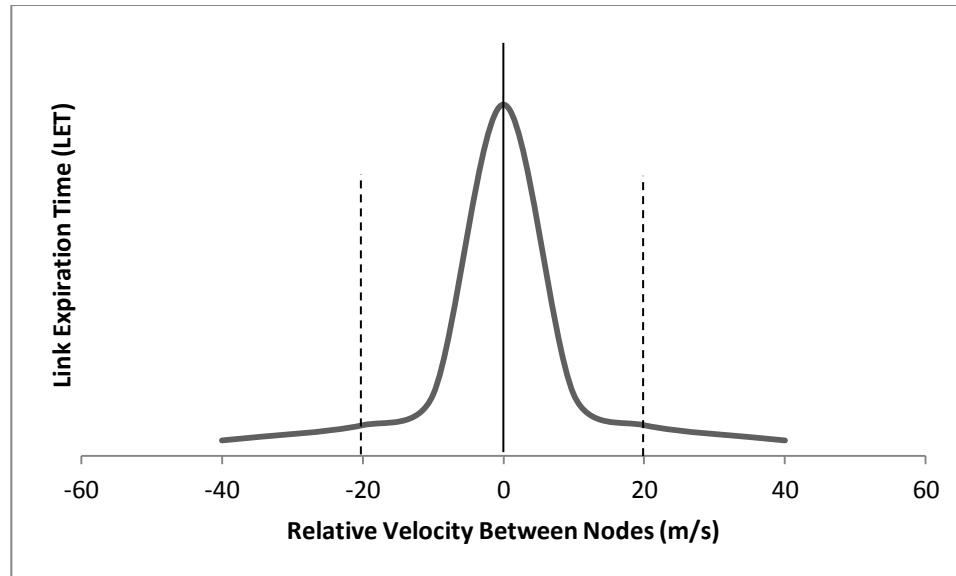
Figure 4.5. Relative velocity between the nodes vs. Link expiration time

Thus, to transfer 20 MB for of data through this network without link breakages, two nodes at one-hop distance are expected to be connected for at least 9 seconds. From the plot in figure 4.5, at an LET_S of 9 seconds, the relative velocity is 19.28 m/s. Therefore, to transfer the 20 MB of data with no link disconnections, two nodes must have a relative velocity within the range (-19.28 m/s, +19.28 m/s). The relationship between the relative velocity and LET was thus verified, and this scenario with LET_D of 9 seconds was simulated; and the results are discussed below. Figure 4.6 shows the cumulative sum of control bytes generated by SARP and AODV in this scenario. SARP generated low control overhead (536 bytes); compared to that generated by AODV (638 bytes).

The simulations demonstrated that there was no major variation in other end-to-end performance metrics.
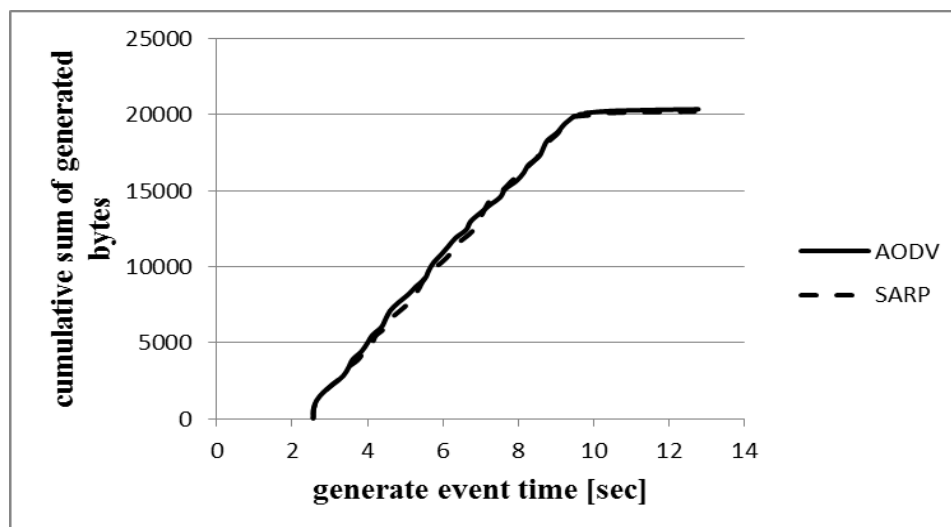
Figure 4.6. Scenario: Control traffic generated vs. Generate event time

SARP proved successful in creating speed awareness in the underlying AODV protocol. Figure 4.7 plots the variation in throughput of received data bytes against simulation time. Although the average throughput received was almost the same for both protocols, the time at which the peak of throughput occurred showed the difference between the performances of the protocols more clearly.

Node 2 went out of range of node 0 (sender) and node 3 (receiver) at 3.6 seconds. Initially, AODV created route 0-2-3 and began transmitting data at 3.1 seconds, causing an early throughput peak in AODV at 4.6 seconds. When this link broke at 3.6 seconds causing the peak, there was a drop in the throughput until the 4.6s point. Node 0 then began formed a new route, 0-1-3, and throughput stabilized from 6.6 seconds to 9.2 seconds. At 9.2 seconds, the links 0-1 and 1-3 broke and did not generate throughput.

SARP handled this scenario efficiently. While forming an initial route, SARP recognized node 2 as an unstable link with LET above the acceptable limit. Therefore, it

formed route 0-1-3, thus maintaining more stable throughput throughout the simulation until the links broke at 9.2 seconds.
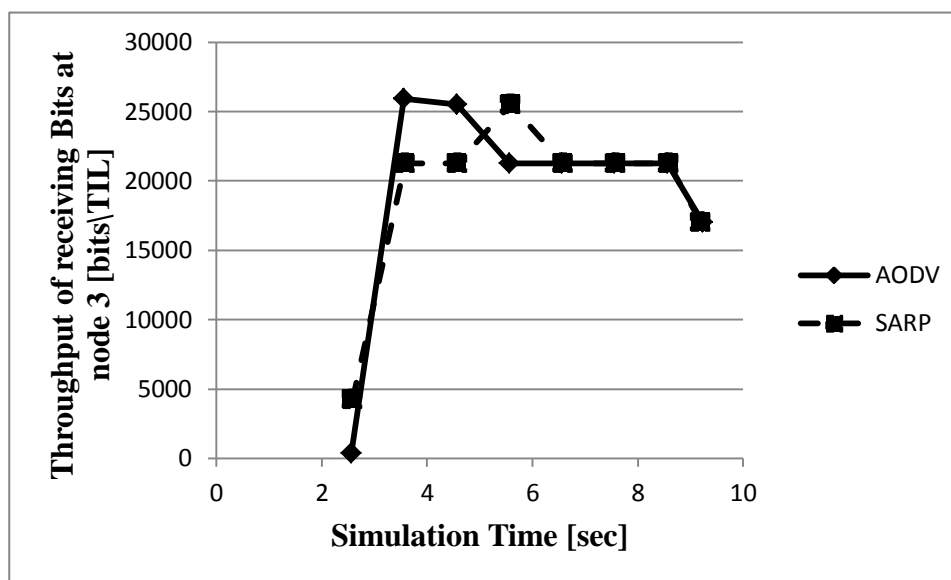
Figure 4.7. Throughput of received data bytes vs. simulation time

This experiment shows that SARP fulfills its expectations of reducing the control overhead while improving or maintaining the other QOS metrics of the underlying routing protocol. However, SARP implementation suffers a few limitations; these limitations are discussed in the below section.

4.6. LIMITATIONS OF SARP ROUTING ALGORITHM

SARP implementation requires the determination of node velocities. A node determines its velocity by pinging itself twice at two different instances of time. This

activity reserves the node for the interval in order to update its own velocity before sending or forwarding a RREP or RREQ. This interval introduces a delay in forming and maintaining routes. This delay contributes to the overall end-to-end delay for packet transmission and thus, poses a risk of possible swell in the networks' average end-to-end delay. Since this is an inherent foible of SARP algorithm, the implementation of SARP should be vigilant to ensure that this QOS metric is minimally affected.

SARP eliminates unreliable links on the basis of its LET value which might result in the elimination potential links. When the value of LET applied is high, SARP eliminates higher number of nodes from routing, thus, eliminating more potential routes. This elimination of nodes might result in complete system failure in specific scenarios such as communication between node clusters. If the potential routes were dismissed from creating routes between the clusters, it might result in partitioning of the network leading to a system failure. On the other hand, a low value of LET would result in ineffective realization of SARP where unreliable links are included for communication. This makes it crucial to determine the optimal value of LET for a scenario. One significant approach to handle this sensitivity could be the development of a routing protocol which calculates includes the proportional delay before forwarding a packet; this value of delay could be used to determine the most optimal route. This routing protocol would promise a better throughput than SARP since it would not eliminate any potential routes. However, unlike SARP, this protocol might not precisely mitigate the effect of mobility since delay would be the key decision criteria.

Another approach to mitigate the sensitivity of SARP towards the value of LET would be designing a smart implementation of the algorithm which dynamically

calculates the value of LET_D. This method of determination of LET also satisfies the varying data demands of the network. However, apart from the knowledge of the size of data, this approach requires an elaborate study of the impact of varying LET values on different network scenarios including different network densities, different mobility levels, and different link capabilities which will determine the optimal value of LET that could be used in a given scenario.

Another concern with the implementation of SARP is the trade-off between the reduction in the number of control packets generated as promised by SARP and the control bytes added for the inclusion of node velocity and spatial coordinates in the routing packet. When SARP is deployed, each node adds the parameters, velocity and spatial coordinates, to the routing packet and transmits it to its one hop neighbors. This addition of control information increases the packet size of the routing packets within the network, thereby, increasing the control overhead generated by the network. On the contrary, SARP proposes to reduce the excess control overhead generated by on-demand protocols by eliminating unreliable routes. This trade-off complicates the implementation of SARP. To ensure that this infirmity is tested for, the metric average control overhead generated was measured in bytes instead of the number of control packets generated. The effectiveness of SARP in handling this tradeoff will be discussed as part of the results under section 6.1.

4.7. SECTION SUMMARY

The SARP algorithm assimilated speed awareness in a MANET routing protocol using LET. LET takes into consideration node speed and direction to determine how long

a link could sustain active transmission without disconnections. This section elaborated the relationship between the LET_S and LET_D and demonstrated its significance. It validated the new routing methodology experimentally and also listed its limitations. Section 5 describes the elaborate simulations designed to compare the performance of SARP and AODV. It annotates the environmental variables used and presents the end-to-end performance metrics used for the comparative study.

5. SIMULATION DESIGN

Network simulation has been important for analyzing the results obtained from comparative study. NS-2, OPNET, QualNet, and GloMoSim (D. Xiaojiang 2006) are among the more popular tools used to simulate MANETs and wireless sensor networks. Simulators provide the flexibility to reproduce experiments with different network types, network parameters, routing protocols, mobility models, and traffic models. However, to ensure accurate performance measure, simulator objects and network parameters must be fine-tuned so that simulation scenario depicts the real network scenario, more accurately.

A new routing algorithm like SARP requires thorough testing using a simulator to verify and validate the new methodology before deploying it to the real-world. This experimental phase helps in early detection of errors and thereby, promises constant improvement of the methodology leading to the development of a robust algorithm. This process of experimental validation also eliminates the high cost and increased resources incurred in fixing the shortcomings of SARP algorithm in a real world deployment without prior validation. Hence, a very popular network simulator tool, network simulator 2, otherwise referred to as ns2, had been chosen to validate SARP. Since ns-2 is an open-source tool, it provided a convenient platform to alter current implementation of the pre-existing components within ns2 to implement SARP algorithm. The flexibility of generating a variety of randomized test environments also provides the SARP designer with an exhaustive set of possible scenarios to verify the algorithm. Though ns2 helps in preliminary testing and designing a robust methodology, it is only a simulator model of real-world system and is necessarily a simplification of the real-world system itself. The limitations of ns2 including 802.11 approximations and assumption of heterogeneous

networks, increase the risk of system failure if implemented in the real world. Hence, it is prudent that prior to its deployment in real world, SARP must be validated by generating a true MANET configuration using real wireless devices.

This research used ns-2.33 to analyze the impact of node mobility on the end-to-end performance of SARP and AODV as the network scales up in size. AODV implementation package come with ns2.33-all-in-one package (M. Lacage October 2006) (The ns Manual 2009). The simulation used simple network topologies and in some ways similar to those used in past comparative studies such as in (J. Mullen October 10– 13, 2005), (S. R. A. Aziz March 2009), (Nikkei Electronics Asia 2009) and (Varshney U. 2000). This research, however, had greater validity because it used realistic simulation parameters, including the node speed, data traffic model, and network density. Thus, this study provides useful insights into performance of SARP as compared with AODV. It demonstrates how the speed awareness of the protocol enhances the performance of a MANET on-demand routing protocol with increasing traffic and network density.

Details of the simulation and performance metrics used in this research are provided in the following sections.

5.1. DETAIL DESIGN OF THE EXPERIMENTS

This section provides details of the simulations, along with the physical channel specifications, mobility models, and network traffic. The network performance measures are also defined here. All simulations were performed using ns-2.33.

5.1.1. Propagation Channel Specification. All the simulations were performed using the technological specifications of IEEE 802.11b wireless channel for

communication and essential network operations. A simple modification to the ns-2 package in the MAC package of the specification to implement SARP, as discussed in section 4. Appendix B describes this modification.

Orinoco IEEE 802.11b wireless card specification (Xiuchao 2004) was used in the wireless nodes forming the simulated network. This wireless device has an expected nominal range of 172m, operational frequency of 2.472 GHz, and transmission power of 0.031622777 W. NS-2 uses carrier sense threshold and receive power threshold to determine whether a frame has been detected and correctly received by the receiver node. The sensing and receiving thresholds were set to $5.012x10^{-12}$ W and $1.15x10^{-10}$ W, respectively. The parameters for Orinoco 802.11b channel with CCK11 (11 Mbps) were written in NS-2 using OTcl code, as indicated in table 5.1. The wireless channel was simulated using a two ray ground propagation model included in the ns-2.33 distribution package.

Table 5.1. Orinoco 802.11b channel specifications

Phy/WirelessPhy set L_ 1.0	;# System Loss Factor
Phy/WirelessPhy set freq_ 2.472e9	;# Channel-13. 2.472GHz
Phy/WirelessPhy set bandwidth_ 11Mb	;# Data Rate
Phy/WirelessPhy set Pt_ 0.031622777	;# Transmit Power
Phy/WirelessPhy set CPThresh_ 10.0	;# Collision Threshold
Phy/WirelessPhy set CSThresh_ 5.011872e-12	;# Carrier Sense Power
Phy/WirelessPhy set RXThresh_ 1.15126e-10	;# Receive Power Threshold
Phy/WirelessPhy set val(netif)	;# Network Interference Type

5.1.2. Achieved Levels of Network Density. The comparative study demonstrat-
-es the combined effects of node velocity on the routing protocol performance under
sparse, normal, and high network densities and varying traffic densities. A simple flat
grid topology measuring 500m X 500m and 700m X 700m was chosen for the
simulations. Simulations were performed with 25 and 50 mobile nodes in each topology.
By varying the number of nodes per unit area, three different density levels were
achieved; they are tabulated in table 5.2.

Table 5.2. Achieved Network Density Levels

Grid Dimension (m2)	Number of Nodes	Average Area per Node	Density Level
500 X 500	25	100	Moderate
500 X 500	50	70.7	Dense
700 X 700	25	140	Sparse
700 X 700	50	98.9	Moderate

5.1.3. Mobility Model. Mobility was generated using a random waypoint mobilit-
-y model (RWMM) (Bettstetter 2006) (F. Bai 2007). CMU "setdest" command was used
to generate the communication scenario with random initial placement of nodes within a
defined environment. The nodes were set to continuous motion with pause time of 0

seconds. The mobility status of a node is described in terms of its speed and angle of direction. Instead of allocating uniformly distributed velocities between specified minimum and maximum values, nodes were moved at two different velocity types, low and high, as shown in table 5.3.

Table 5.3. Achieved Degrees of Mobility

Mobility Type	Node Velocity
Low	80 % nodes @ velocity range 0.1 m/s - 3 m/s
	20 % nodes @ velocity range 18 m/s - 21 m/s
Medium	50 % nodes @ velocity range 0.1 m/s - 3 m/s
	50 % nodes @ velocity range 18 m/s - 21 m/s
High	20 % nodes @ velocity range 0.1 m/s - 3 m/s
	80 % nodes @ velocity range 18 m/s - 21 m/s

Mobility is thus representative of a real environment in which people in a high speed vehicle are trying to access a network. Three different levels of mobility were simulated by varying the percentage of total nodes moving at low velocity (0.1m/s-3m/s) and high velocity (18m/s-21 m/s). A low positive value for minimum velocity was set to avoid any stationary nodes and to ensure uniform velocity distribution throughout the simulation time (X. Hong January 2007).

5.1.4. Traffic Model. The traffic pattern was generated using cbrgen routine incl-

-uded in the ns-2.33 following a randomized distribution. Then the number of active

routes, that is, the number of active transmitter-receiver (Tx/Rx) pairs, was set to 10 for

the 25 nodes scenario and to 20 for the scenario with 50 nodes, initiating communication

at different points of time during the simulation.

The source node transmitted 512 bytes of constant bit rate (CBR) packets per

second, resulting in a data rate of 256 kbps. This value corresponds to an average of the

data rate specified for a high speed vehicle and travel on foot, and it is in accordance with

the standard specified by ITU for multimedia/voice transmission (R.Samarajiva 2001). A

user datagram protocol (UDP) was implemented at the transport layer, allowing a

message to be sent without prior communications to set up a transmission path. It uses a

simple transmission model and assumes that error checking and correction is either

unnecessary or performed at other layers. A UDP is often used with time-sensitive

applications, where, dropping packets is preferred to delayed packets. A transmission

control protocol (TCP) can be used alternatively if a reliable stream delivery of packets is

desired. This study used UDP to ensure timely delivery of data packets with low network

overhead.

5.1.5. Link Expiration Time (LET). LET is the decision-making parameter for

the implementation of SARP; it accounts for the relative velocity between sender and

receiver nodes. The selection of LET is crucial for the analysis of SARP. However, for

the simulations performed here, three values of LET_D were selected for each network

depending on the amount of data to be transferred. SARP was analyzed for end-to-end

performance using these three LET values. Table 5.4 gives the calculated values of the

LET_D used to simulate SARP for various sizes of data in bytes. Equation (4.8) calculates LET_D for a network.

Table 5.4. Simulated values of demand link expiration times

Amount of data to be transferred (MB)	Calculated LET_D (seconds)
1	1.5
5	3.5
10	6.0

Simulations were executed with SARP implementation for three values of LET, 1.5, 3.5, and 6.0 seconds. Simulation time was set to 200 seconds. Each simulation was repeated 10 times with varying traffic routes, traffic sources and traffic receivers, creating a different set of routes for each simulation run. Appendix B provides a sample OTcl script. Figure 5.1 shows the overall simulation design.

5.1.6. Performance Comparison Metrics. Tracegraph 2.04 (Malek n.d.) was used to extract data from the trace files generated by the simulations. The performance analysis conducted uses four average end-to-end performance metrics: normalized routing load (NRL), packet delivery ratio (PDR), average end-to-end Delay (E2E), and average throughput of the data received. Among these four metrics, NRL was the most significant parameter for measuring the performance of SARP because it focuses on the control overhead generated for each scenario.
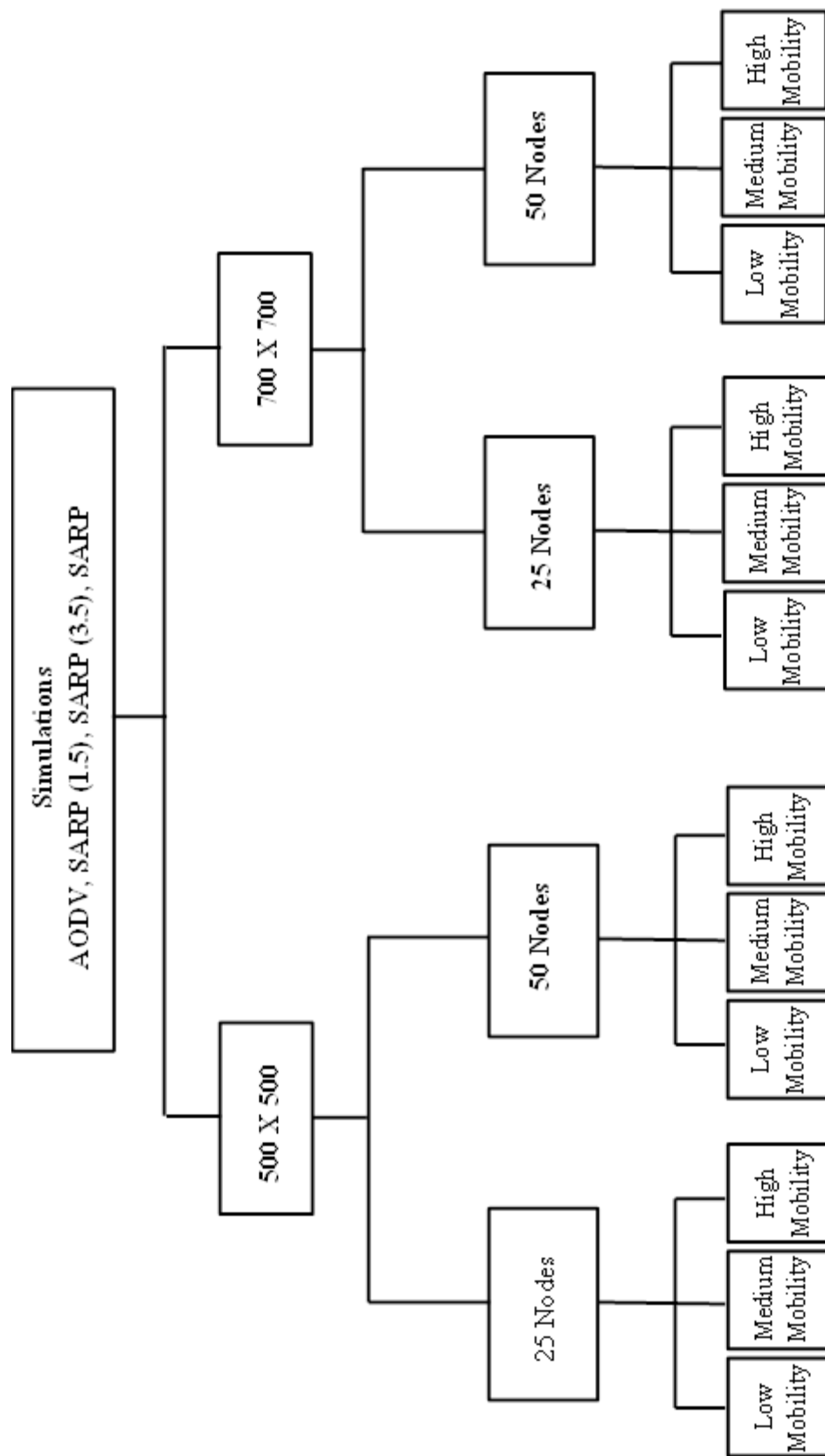
Figure 5.1. Simulation Design

5.1.6.1 Normalized routing load (NRL). The scenarios used for comparison ge-
-nerated a range of control overhead values; depending on a variety of factors including network and traffic densities. Thus, direct comparison of control overhead values would have been inappropriate. This introduced the normalization of the control overhead by measuring only the useful control overhead generated using an end-to-end performance metric called Normalized Routing Load (NRL). NRL is defined as the ratio of the amount of control overhead generated to the total number of data bytes successfully transmitted:

$$\text{NRL} = \frac{TotalNumberofControlBytesGenerated}{TotalNumberofDataBytes\,\text{Re}\,ceived}\,.\tag{5.1}$$

In other words, it denotes the useful traffic generated in the network during simulations. This ratio indicates how much traffic was involved in the successful transmission of data. Hence, it is a good measure of the control overhead generated in a network.

5.1.6.2 Packet delivery ratio (PDR). PDR is a significant measure of the rate of successful data transmission within a network. It can be defined as the ratio of the amount of data received by an application in the network to the amount of data sent out by the application:

$$\text{PDR} = \frac{TotalNumberofDataBytesreceived}{TotalNumberofDataBytesSent}\,.\tag{5.2}$$

The PDR is also a good metric to compare the utilization of network resources because it provides an insight into the amount of data lost during the simulation.

5.1.6.3 Average end-to-end delay (E2E). End-to-end delay can be defined as the delay that a packet suffers from the time it leaves the sender application to the time it arrives at the receiver application. The average end-to-end delay is the average of such delays suffered by all data packets successfully received within a network; it does not consider dropped packets. This parameter ensures that the determination of node velocity and the calculation of LET during simulations do not significantly increase the end-to-end delay of the network.

5.1.6.4 Average Throughput of Received Data Packets. Average throughput can be defined as the average of the data rates delivered to all terminals in a network. The maximum throughput is the minimum load in bit/s that causes delivery time (i.e., latency) to become unstable and increase towards infinity. It accurately measures the network performance and confirms that the throughput was not compromised with the implementation of SARP.

5.2. SECTION SUMMARY

This section has described the simulation environment created to compare SARP and AODV. It has discussed the mobility model, traffic model, and Orinoco 802.11 channel and its specifications. It has described the performance metrics used for the following section which analyzes the results to compare the performance of SARP and AODV.

6. RESULTS AND DISCUSSION

This section discusses the outcome of the trace-based simulations described in Section 5. A comprehensive analysis permitted visualization of a wide range of phenomena occurring in the mobile ad hoc communication network, and the results are presented here in terms of graphs and tables. All results discussed here represent an average of the 10 simulation runs for each scenario. Sections 6.2 and 6.3 evaluate the impact of mobility on the generated control overhead and the NRL, respectively. For brevity, this discussion addresses only the impact of mobility on packet delivery ratio, delay, and throughput. Appendix C lists the average of the 10 simulation runs.

6.1. NORMALIZED ROUTING LOAD (NRL)

The underlying routing protocol, AODV, floods a network with control packets during route discovery and route maintenance phases. Due to frequent link disconnections, the protocol tends to generate a high number of control packets to maintain a route. SARP attempts to limit this increased amount of control packets generated during route maintenance by predicting and curbing link disconnections due to high node mobility. NRL provides a measure of control overhead generated due to the unique routing mechanisms of the protocol. Control overhead provides significant information on link stability and route longevity, which are important means to gauge the effectiveness of a reactive protocol. This work studied the impact of mobility on the performance of reactive protocols in terms of NRL. It should be noted that the following discussion refers to SARP at a LET value of 'a' as SARP(a).

6.1.1. The Networks with 25 Nodes. Figures 6.1a and 6.1b compare the control overhead generated by the protocols against various degrees of mobility in 500mX500m and 700mX700m grids, respectively.
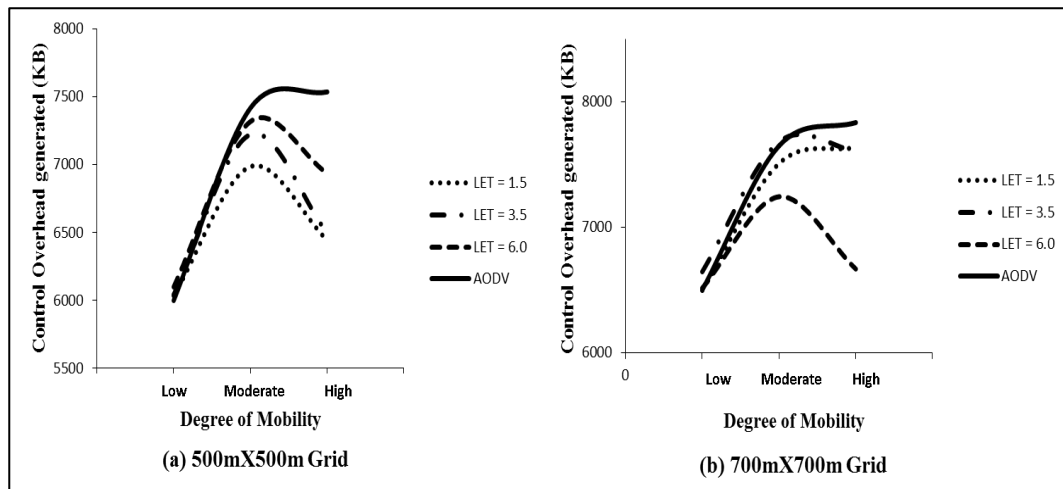
Figure 6.1. Control overhead generated vs. mobility in networks with 25 nodes

The trend followed by the protocols in both the networks for generating control overhead is similar. In both networks, AODV and SARP generated similar control overhead at low-moderate mobility but gradual variation was observed with an increase in mobility. This behavior confirms the initial prediction that SARP would be more effective at moderate-high mobility and would not hinder the functionality of the underlying protocol at low mobility. SARP generated significantly reduced control overhead at high-moderate mobility as compared to AODV. This reduction in the generated control traffic of SARP is a result of the reduced number of fast-moving

intermediate nodes. At moderate mobility, SARP generated low control overhead than that of AODV in both the networks. At moderate-high mobility, the protocols show a significant increase in control traffic, however, SARP still generated low control overhead as compared to that generated by AODV.

The significant increase in the amount of control traffic generated at moderate mobility as compared to low mobility scenario is a consequence of the on-demand nature of underlying protocol, AODV. At moderate mobility level, the protocols witnessed more link breakages than at lower mobility level. These link breakages resulted in generation higher amount of control traffic at moderate mobility. At high mobility, the MANET experienced higher number of link breakages than at moderate mobility. However, at high mobility nodes tend to move out of each other's transmission range and hence, form lower number of routes than at moderate mobility level. The low number of routes resulted in low number of link breakages and hence, generated lower control traffic than in moderate mobility.

The sparse network (i.e., in figure 6.1d) shows a similar amount of control overhead generated by SARP(1.5), SARP(3.5) and AODV. This behavior is due to the intended ineffectiveness of SARP in sparse networks.

In the denser network, all three values of LET used in simulating SARP generated a lower control overhead generation as compared to AODV, with increasing mobility. However, there was a slight increase in the control overhead generated with increasing values of LET. This limited increase may be attributable to an increase in control traffic during route discovery phase since the elimination of fast nodes required a longer route discovery. The higher the LET value, the greater is the restriction on the acceptable

relative velocity of the nodes, and the greater the restriction, the greater is the possibility of dropped routes. As the number of dropped routes increase, the control overhead generated during route maintenance also increased significantly. This behavior of high value of LET may cause an advert effect on routing by eliminating even useful routes; hence, it suggests that the selection of LET is crucial to ensure that the network is not negatively influenced by incorporating SARP.

The sparser network (i.e., in figure 6.1b) also showed an increase in the generation of control traffic by SARP with increasing mobility; the only exception was an LET of 6.0 seconds. A node cluster may have formed, which might complicate the routing activity by making two nodes not accessible by cutting off any intermediate nodes. This phenomenon has been listed as a limitation of SARP and further accents the significance of selection of LET to effectively realize SARP.

In general, control overhead increased with increasing mobility and the variation was affected most by the values of LET. Nonetheless, SARP performed better than AODV in generating low control traffic at moderate-high mobility and similar control traffic as AODV at low mobility confirming that SARP algorithm is minimally effective in low mobility scenarios.

Figures 6.2a and 6.2b compare the NRL caused by the protocols against various degrees of mobility in 500mX500m and 700mX700m grids, respectively.

As a measure of control overhead, the NRL follows the same trend as the control overhead generated. However, the NRL generated by the protocols in the smaller yet denser network of 500mX500m grid with 25 nodes, is slightly lower than that of the sparsely-populated network of 700mX700m grid with 25 nodes. In denser networks, the

number of forwarding intermediate nodes is higher thus, forming more number of routes. Hence, lower NRL in the denser network is attributed to higher amount of data packets transmitted by the smaller network as compared to the sparser network.
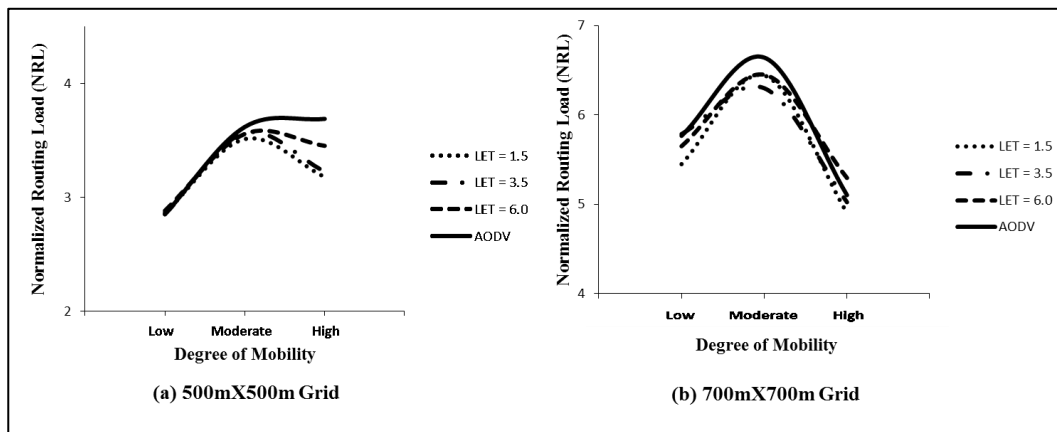
Figure 6.2. NRL vs. mobility in networks with 25 nodes.

The trend of data packets successfully transmitted by each of the protocols is observed to be the similar. In the dense network, there was a gradual increase in NRL with increasing mobility. SARP caused lower NRL than that of AODV, however, with the growing value of LET, NRL increased. This trend can be attributed to the similar trend in control overhead generated. However, all the protocols caused similar NRL in sparse networks; this again confirms that SARP is ineffective in sparse networks.

In the networks with 25 nodes, SARP limits the amount of average control overhead generated with smart selection of LET. At high values of LET, SARP generates

higher control traffic. With increasing mobility and network density, SARP becomes more efficient in reducing the control traffic generated by eliminating unreliable links.

6.1.2. The Networks with 50 Nodes. Figures 6.3a and 6.3b plot the amount of control traffic generated vs. various degrees of mobility in 500mX500m and 700mX700m, respectively.
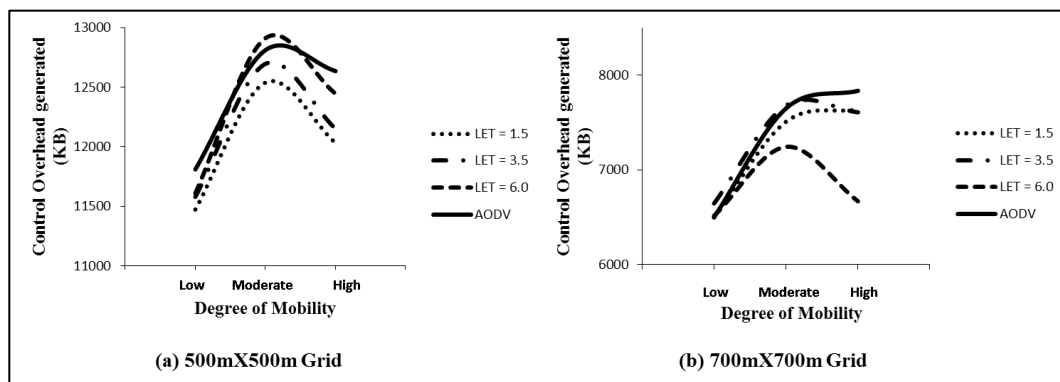
Figure 6.3. Control overhead generated vs. mobility in networks with 50 nodes

In 500mX500m network with 50 nodes, both the protocols generated control overhead approximately 3 – 4 MB higher than in the scenario of 25 nodes. This increase can be attributed to greater congestion and intermodal interference in a dense network, since this is the densest network in these simulations. The moderately dense network of 700mX700m grid with 50 nodes showed a trend very similar to the 500mX500m grid with 25 nodes. This could be a result of their similar network densities.

Although both protocols showed high control traffic at medium mobility, control traffic dropped significantly when the mobility was high. In high-mobility scenarios, the

communicating nodes can be out of range for most of the time during a simulation run. The sender, however, resends routing packets until it reaches the allocated retry limit, which is a MAC layer parameter. If no routes can be established within the maximum retry limit, the sender assumes a permanent link failure and therefore stops sending routing packets.

In general, the amount of control traffic generated increased from low to moderate mobility levels and decreases from moderate-high mobility. The higher the value of LET employed, higher the control traffic generated; the only exception is the SARP(6.0) in the moderately dense network of 700mX700m grid. This trend is the same as observed in the similar density network, 700mX700m grid with 25 nodes and is explained to be a consequence of sparseness of the network.

In both the networks, control traffic generated by the protocols is similar at low-moderate mobility; however, in the dense network, SARP(1.5) and SARP(3.5) generated slightly lower control overhead than that of AODV. In addition, SARP(1.5) and SARP(3.5) generated significantly less control overhead than AODV at moderate-high mobility level in this network.

At moderate mobility, SARP(6.0) generated higher control traffic than AODV in both the networks. This is likely a consequence of high value of LET that restricted the number of potential intermediate nodes. However, at high mobility SARP(6.0) generated less control traffic than AODV by reducing frequent link disconnections.

At high mobility, the trend remains the same as in the scenario with 25 nodes. AODV generated the highest control overhead and SARP(1.5) generated the least. As expected, with increasing LET the control overhead generated increased in the dense

network. However, in the sparser network, all the protocols except SARP (6.0) generated similar amounts of control overhead, further confirming the ineffectiveness of SARP in sparse networks.

Figures 6.4a and 6.4b plot the NRL vs. various degrees of mobility in 500mX500m and 700mX700m, respectively; both the networks have 50 nodes.
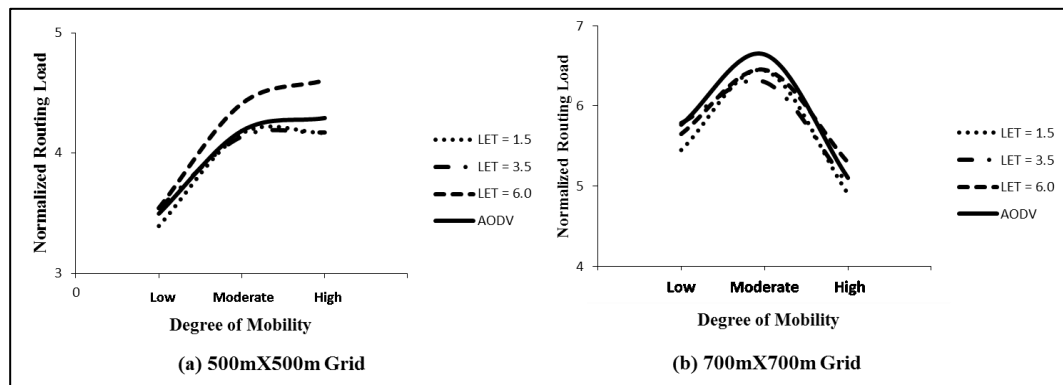
Figure 6.4. NRL vs. mobility in networks with 50 nodes.

In the dense network, all the protocols showed a gradual increase in NRL as mobility increased. However, the performance of protocols was identical. However, SARP(6.0) recorded highest NRL through varied levels of mobility indicating that this value of LET is too high to effectively implement SARP and hence, a lower value should be appropriate in this scenario.

In the sparser network, the general trend of AODV causing the highest NRL and SARP(1.5) reporting the least, was reiterated as noted in the networks with 25 nodes.

The amount of control overhead generated increased with increasing values of LET. At moderate-high mobility, all the protocols showed a decrease in NRL, similar to the trend in the 700mX700m grid with 25 nodes. However, at high mobility, AODV generated higher NRL than the other two and SARP(6.0) generated high NRL throughout the simulation despite low control traffic generation at both low and high mobility. This high NRL could be the result of the reduced number of data packets received by SARP(6.0) due to the formation of low number of routes.

In general, at low-moderate mobility, SARP and AODV performed almost identical in terms of both NRL and control traffic generation. At moderate-high mobility, SARP generated significantly lower control overhead and hence lower NRL than AODV, given an appropriate selection of LET. At high values of LET, the control overhead generated by SARP was higher than that generated by AODV.

The routing loads discussed in this section were larger than that observed in the network topologies described in Section 6.2.1. This increased routing load can be attributed to high interference and congestion in the scaled-up network. AODV showed insignificant increase in the control overhead and high NRL compared to SARP. Furthermore, NRL increased more under high mobility conditions than in low mobility conditions. The increase in routing load due to mobility can be explained by frequent link updates and by updates to ensure local connectivity through hello packets. The behavior of SARP with respect to control overhead remains similar to that observed in previous scenarios. As expected, SARP again outperformed AODV in generating optimal control traffic.

6.1.3. Conclusion. These scenarios provide significant information on the effecti-

-veness of the protocols in various operating environments. The trends observed here

indicate that routing overhead increases with an increase in mobility. However, this

research does not permit precise estimates of degree of increase. The performance of all

three protocols degraded with increase in mobility.

In terms of NRL with respect to mobility, SARP(1.5) and SARP(3.5) reduced the

control traffic generated than AODV. The SARP(6.0) outperformed AODV in dense,

high traffic networks, it degraded the performance of the underlying protocol sparser

networks with less traffic. This further demonstrates that careful selection of optimal LET

is crucial for effective performance of SARP.

6.2. PERFORMANCE ANALYSIS USING OTHER END-TO-END METRICS

Further study compared the performance of SARP and AODV using other end-to-

end performance metrics such as packet delivery ratio (PDR), average throughput and

end-to-end delay. These parameters were analyzed to ensure that SARP algorithm does

not degrade the performance of the underlying protocol. This section summarizes the

most important findings of this analysis.

6.2.1. Packet Delivery Ratio. Figure 6.5 shows graphs for PDR versus mobility

under various traffic and movement scenarios. PDR decreased from low to moderate

mobility levels because fewer packets were successfully transmitted at moderate mobility

than at low mobility resulting in low data packets received. From moderate to high

mobility levels, PDR increased as a result of low data packets sent out at moderate

mobility. At high mobility, the MANET formed lesser number of routes resulting in

lesser number of data packets sent and consecutively received, leading to high PDR.
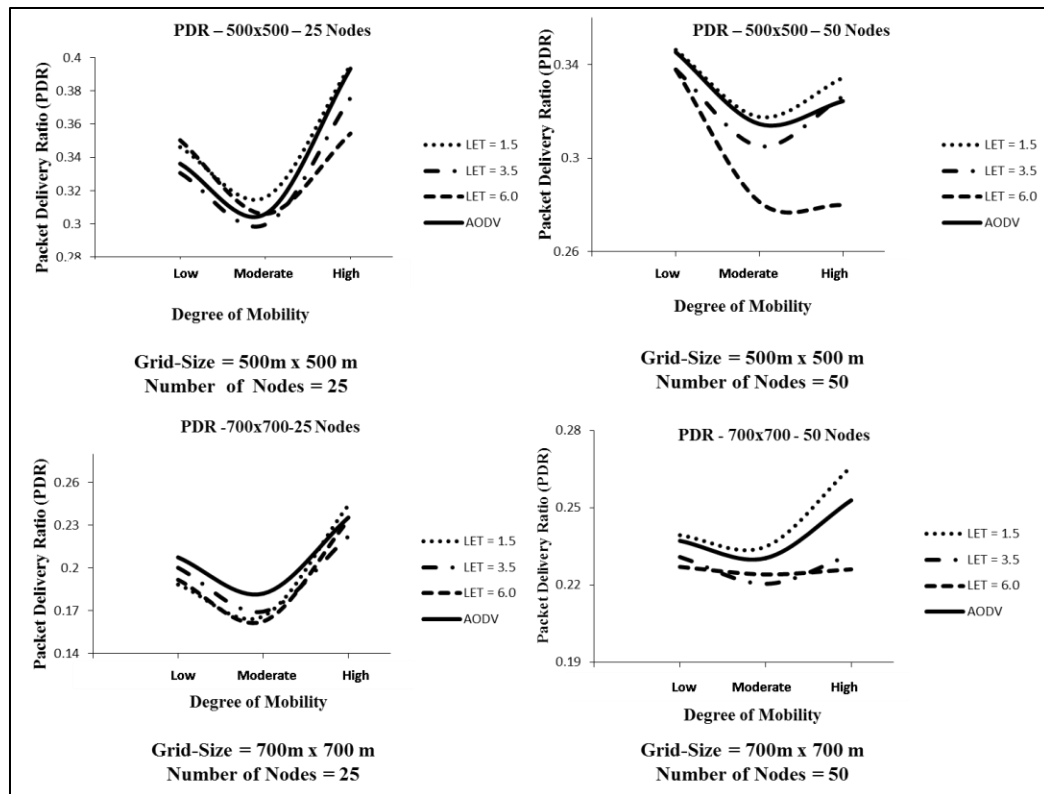
Figure 6.5. Packet delivery ratio vs. mobility

SARP(1.5) outperformed AODV in all the scenarios by generating the highest PDR including the least dense network, (i.e., 700mX700 m grid with 25 nodes). This proves that the implementation of SARP algorithm improved the routing mechanism of AODV by reducing the loss of data packets. SARP(3.5) and SARP(6.0) caused lower PDR than the other two protocols, indicating that the higher the values of LET, the lower the PDR generated. Hence, the choice of LET is crucial role to the effective functioning of SARP.

6.2.2. Average Throughput. Figure 6.6 demonstrates that average throughput decreased with increasing mobility, accounting for the relative stability and reliability of routes at lower mobility. Thus, more data packets were successfully delivered to the receiver at low mobility level than at moderate or high mobility levels. SARP(1.5) recorded higher average receiving throughput than AODV, except in the case of a sparse network of 700mx700m with 25 nodes, in which AODV outperformed SARP. This again proves the ineffectiveness of SARP in sparse networks. SARP(3.5) and SARP(6.0) once again proved less stable than SARP(1.5) and AODV in generating good throughput.

6.2.3. Average End-To-End Delay. Figure 6.6 indicates that average end-to-end delay increased with an increase in mobility. With increase in mobility, there is an increase in the number of intermediate nodes within a route or formation of lengthier routes; both these scenarios add to higher delay. The abnormality of the graphs for a 700mX700m grid with 50 nodes may be due to higher network congestion and increased MAC retries caused by unreliable routes at moderate mobility. AODV recorded lower average end-to-end delay than SARP. The reason for this behavior was discussed as a limitation for SARP in section 4.6. Both protocols have similar delays at low mobility. In sparse networks, however, AODV had significantly less delay than SARP. Both SARP(3.5) and SARP(6.0) showed a large increase in average end-to-end delay from moderate to high mobility. SARP(1.5) had a slightly greater average end-to-end delay (about 50ms) than AODV. One can safely conclude therefore that SARP(1.5) did not cause high average end-to-end delay in AODV. Further, this work demonstrated that the value of LET plays a crucial role in the successful realization of SARP.
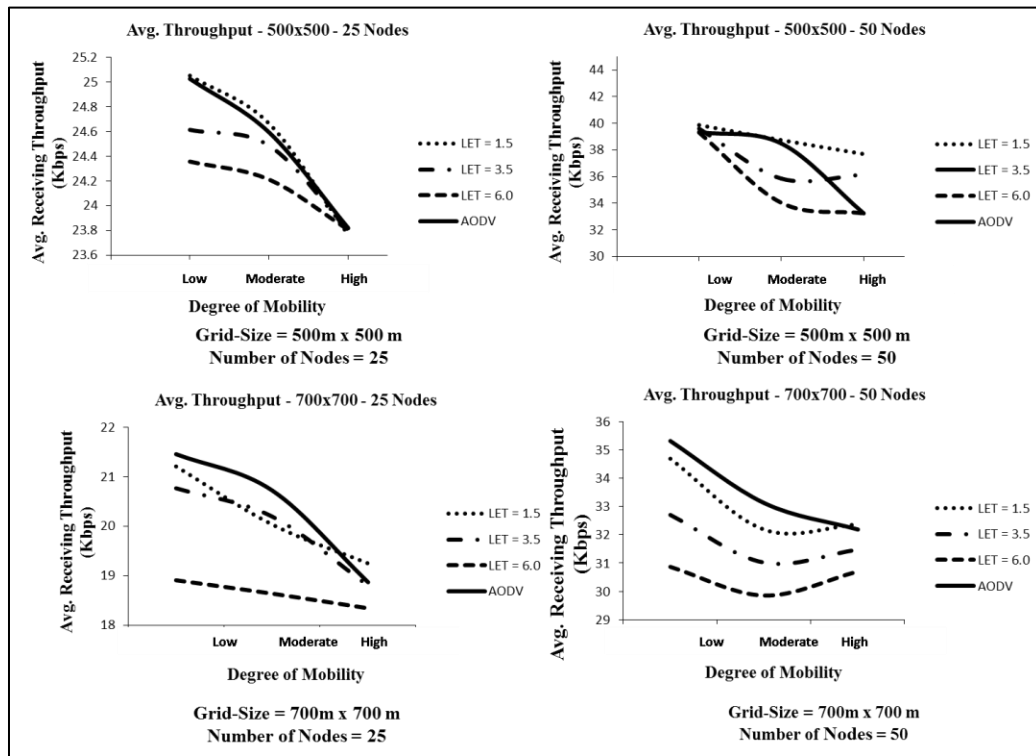
Figure 6.6. Average throughput of receiving data packets vs. mobility

6.3. DISCUSSION

The simulations conducted here proved that control overhead generated by both protocols increased with increasing mobility. The overall increase in control overhead and the decrease in the PDR indicate that protocol performance in general degrades with increasing mobility. In addition, the end-to-end delay increases with increasing mobility, as shown in Figure 6.7. The relationship between the change in NRL and end-to-end delay can be explained in terms of resource utilization. When NRL increases, more network resources and the limited bandwidth are consumed in processing the control

overhead. Consequently, the resources needed to process the data traffic become insufficient, causing large number of delayed and dropped packets, significantly reducing the amount of data received, and increasing end-to-end delay.
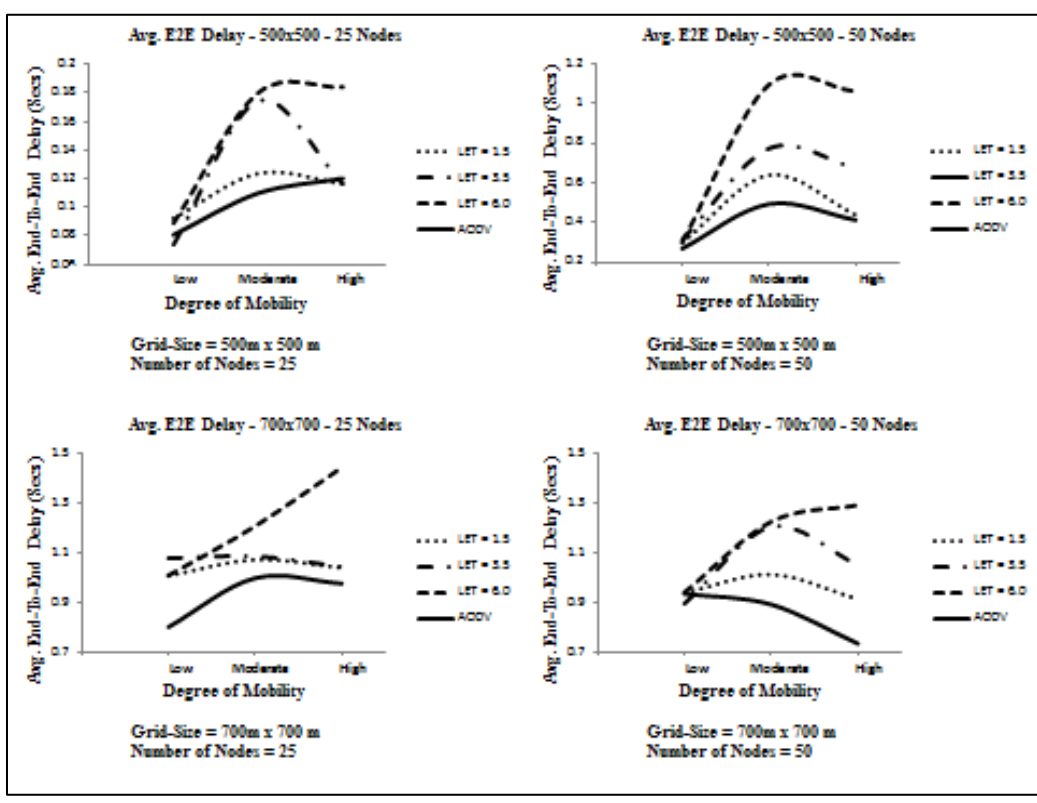
Figure 6.7. Average end-to-end delay vs. mobility

The use of end-to-end performance metrics to compare the performance of SARP and AODV supports several key conclusions:

1. SARP(1.5) and SARP(3.5) generate lower control overhead and lower NRL than AODV.

2. SARP(1.5) improves underlying protocol, AODV by generating higher PDR; which confirms more successful data transmission, except in dense networks.

3. SARP(1.5) outperforms AODV by demonstrating higher average receiving throughput, except in dense networks.

4. SARP(1.5) is stable, resulting in only a marginal increase in average end-to-end delay.

5. SARP(3.5) and SARP(6.0) cannot compete with AODV in terms of PDR, average receiving throughput, and average end-to-end delay.

6. With increasing LET, SARP performance degrades.

7. SARP is effective in dense networks.

The outcome of simulation using AODV with two ray ground propagation agrees with findings of (J. Mullen October 10–13, 2005) and (S. R. A. Aziz March 2009), indicating that control overhead increases with increasing mobility, whereas PDR decreases. However, since (J. Mullen October 10–13, 2005) and (S. R. A. Aziz March 2009) measured mobility in terms of relative velocity and pause time, respectively, rather than in terms of actual speed, no direct comparison is possible. With an appropriate LET, SARP outperforms AODV at moderate-high network density. Comparative study also demonstrated the importance of LET in efficient the SARP routing methodology. Thus, these realistic simulations incorporating numerous variables effectively increase the fidelity of the findings.

6.4. SECTION SUMMARY

This section has compared the performance of SARP with that of AODV. Simulation results confirmed that SARP served its purpose of decreasing control overhead and improving route longevity. Section 7 draws conclusions from this study and proposes future work to enhance SARP.

7. CONCLUSION

Mobile wireless ad hoc networks present significant research challenges extending across many academic disciplines. However, incremental experimentation in support of scientific hypotheses will result ultimately in a MANET that is a reliable, robust communication solution. Although the number of MANET applications continues to grow, the problems they present have remained, spawning numerous scientific endeavors in the academic and industrial communities. Problems of limited bandwidth, constrained power, and complex mobility, and the stochastic effects of fading are inherent in MANETs; thus, experimentation and analysis like that presented in this research are necessary to address the complexity of such systems.

This thesis showed that a speed-aware routing algorithm limits the generation of additional control overhead caused by link breakages due to highly mobile nodes. The control overhead generated by the underlying protocol AODV is greater than necessary, and it does not improve data delivery. The simulations conducted here demonstrate that the SARP, which has minimal control overhead, outperforms AODV, which generates high control overhead. However, the benefits offered by SARP are heavily dependent on selection of the appropriate LET. The work presented here clearly shows that SARP increases link reliability, decreases control traffic, and shows no or minimal deterioration of other performance metrics like the throughput (i.e., number of packets received).

7.1. FUTURE WORK

The research presented in this thesis is preliminary work entrusted to incorporate speed-aware route inclusion methodology to improve the reliability of a MANET routing protocol. A novel mobility-efficient routing protocol can be developed by employing this SARP route inclusion methodology as the basic strategy for forming and maintaining routes within the network. Selective incorporation of the routing algorithm in highly mobile and dense networks also ensures an intelligent realization of SARP. The research could also be extended to validate SARP by incorporating multi-path fading. The limitations introduced by the simulator make it prudent that the new routing algorithm be validated in real world prior to its deployment. Fading when combined with real world data collection increases the fidelity of current simulation packages. In addition, further investigation into the selection of optimal value for link expiration time should be warranted to achieve a highly effective SARP.

APPENDIX A.

MODIFICATION OF NS-2.33 SOURCE CODE

Table B.1. Modification of NS-2.33 Source Code

```
/* Modification was made to the ~/ns-2.33/mac/wireless-phy.cc */


#include <math.h>

#include <iostream.h>

#include <aodv/aodv.h>

#include <aodv/aodv_packet.h>

…


int

WirelessPhy::sendUp(Packet *p)

{


…


if(propagation_) {


 …


/* This is the code inserted for SARP algorithm */

struct hdr_cmn* hdr=HDR_CMN(p);        //Header of the Packet

if(hdr->ptype()==PT_AODV){                //Check if the packet is AODV

struct hdr_aodv* aodv=HDR_AODV(p); //Header of AODV packet


//Determine the Velocities at the Sender and Receiver Nodes

double dXs, dYs, dZs;      //Sender Velocities

double Xs, Ys, Zs;           //Sender Coordinates

double dXr, dYr, dZr;      //Receiver Velocities

double Xr, Yr, Zr;           //Receiver Coordinates

double LET;                   //Link Expiration time & Link Stability
```

```cpp
s.getNode()->getLoc(&Xr, &Yr, &Zr);                    //Coordinates of the receiver

s.getNode()->getVelo(&dXr, &dYr, &dZr);            //Velocities of the receiver

p->txinfo_.getNode()->getLoc(&Xs, &Ys, &Zs);        //Coordinates of the sender

p->txinfo_.getNode()->getVelo(&dXs, &dYs, &dZs); //Velocities of the Sender


//Calculate Link Expiration Time (LET)

double a = dXr-dXs;

double b = Xr-Xs;

double c = dYr-dYs;

double d = Yr-Ys;

double r = 250;

double P = (((a*a)+(c*c))*(r*r))-(((a*d)-(b*c))*((a*d)-(b*c)));

float Q;


if(P>=0)

{

Q = sqrt(P);

}

else

{

Q = sqrt(-(P));

}

if(((a*a)+(c*c)) == 0.0)

{

LET = 1000000;  // Infinity or very high value

}

else

{

LET = (-1*((a*b)+(c*d))+Q)/((a*a)+(c*c));

}
```

```
//If LET is too low, drop the packet
if ((aodv->ah_type == AODVTYPE_RREQ)||(aodv->ah_type == AODVTYPE_RREP))
{
if((LET < 9.0001)&&(LET > -9.0001))
{
pkt_recvd=0; //Resets packet flag;
goto DONE; //Skips all other check
}
}//closes if for checking for RREQ & RREP
}//End of the if AODV
/* End of code Modification */
if (Pr < CSThresh_) {


…
```

APPENDIX B.

SAMPLE OTCL SCRIPT USED FOR SIMULATIONS

```
#===== Basic parameters for the simulation model.=====
puts "DEFINING VARIABLES"
set val(chan) Channel/WirelessChannel ;    # Channel type
set val(prop) Propagation/TwoRayGround ; # Radio propagation model

# Values of the 802.11 b channel
Phy/WirelessPhy set L_ 1.0 ;# System Loss Factor
Phy/WirelessPhy set freq_ 2.472e9 ;# Channel-13. 2.472GHz
Phy/WirelessPhy set bandwidth_ 11Mb ;# Data Rate
Phy/WirelessPhy set Pt_ 0.031622777 ;# Transmit Power
Phy/WirelessPhy set CPThresh_ 10.0 ;# Collision Threshold
Phy/WirelessPhy set CSThresh_ 5.011872e-12 ;# Carrier Sense Power
Phy/WirelessPhy set RXThresh_ 1.15126e-10 ;# Recieve Power threshold
set val(netif) Phy/WirelessPhy ;# Network interference type
set val(mac) Mac/802_11 ;# Mac Layer type
set val(ifq) Queue/DropTail/PriQueue ;# Interface Queue type
set val(ll) LL ;# Link Layer type

Antenna/OmniAntenna set Gt_ 1 ;# Transmit Antenna gain
Antenna/OmniAntenna set Gr_ 1 ;# Reciever Antenna gain

set val(ant) Antenna/OmniAntenna ;# Antenna Model
set val(ifqlen) 50 ;# Max number of packets in ifq
set val(nn) 25 ;# Number of Mobile Nodes
set val(rp) AODV ;# Routing Protocol
set val(x) 500 ;# x dimension of topography
set val(y) 500 ;# y dimension of topography
set val(stop) 200 ;# Time of simulation end

set val(move) "/home/Kirthana/NS2/SARP/500/mov-500-25-l"
set val(traff) "/home/Kirthana/NS2/SARP/traffic/Run8_cbr25"
```

```
set ns_ [new Simulator] ;# Simulator instance
set tracefd [open ra1nc15ms.tr w] ;# Wireless trace
set namtrace [open ra1nc15ms.nam w] ;# Nam trace
$ns_ use-newtrace ;
$ns_ trace-all $tracefd ;# All traces saved
$ns_ namtrace-all-wireless $namtrace $val(x) $val(y);


#=======Set up Topography Model ======
set topo [new Topography]
$topo load_flatgrid $val(x) $val(y)


#====== Set GOD for simulation =======
set god_ [create-god $val(nn)]


#==== Nodes Configuration =====
$ns_ node-config -adhocRouting $val(rp) \
-llType $val(ll) \
-macType $val(mac) \
-ifqType $val(ifq) \
-ifqLen $val(ifqlen) \
-antType $val(ant) \
-propType $val(prop) \
-phyType $val(netif) \
-channelType $val(chan) \
-topoInstance $topo \
-agentTrace ON \
-routerTrace ON \
-macTrace ON \
-movementTrace ON
```

```
#=== Sets the configuration for ALL nodes =======
for {set i 0} {$i < $val(nn)} {incr i} {
set node_($i) [$ns_ node]
$node_($i) random-motion 0
}

#===== Set the movement and traffic model ========
source $val(move)
puts "LOADING THE TRAFFIC SCENARIO.................."
source $val(traff)
#Setting the intial node position for nam
for {set i 0} {$i < $val(nn)} {incr i} {
$ns_ initial_node_pos $node_($i) 30
}
#telling na the nodes when the simulation ends
for {set i 0} {$i < $val(nn)} { incr i} {
$ns_ at $val(stop).0 "$node_($i) reset";
}
$ns_ at 200.01 "stop"
$ns_ at 200.01 "puts \"END OF SIMULATION\" ; $ns_ halt"
proc stop {} {
global ns_ tracefd namtrace
$ns_ flush-trace
close $tracefd
close $namtrace
}
$ns_ run
```

APPENDIX C.

DATA AVERAGED OVER 10 RUNS OF SIMULATION

Table D1. Data Averaged over 10 runs of Simulation (SARP with LET = 1.5 seconds)

Grid Size	No. of Nodes	Degree of Mobility	Control Overhead Generated (B)	NRL	PDR	E2E Delay	Avg. Throughput
500m X 500m	25	Low	6035.234	2.864	0.346	25.052	0.092
		Moderate	6985.719	3.510	0.316	24.664	0.124
		High	6444.04	3.177	0.395	23.763	0.116
	50	Low	11473.59	3.394	0.346	39.867	0.299
		Moderate	12538.73	4.164	0.318	38.737	0.640
		High	12031.5	4.167	0.334	37.693	0.439
700m X 700m	25	Low	6498.405	5.449	0.208	21.210	1.006
		Moderate	7508.859	6.442	0.182	20.036	1.072
		High	7636.392	4.902	0.244	19.248	1.039
	50	Low	15176.76	5.129	0.239	34.695	0.938
		Moderate	15408.49	6.163	0.235	32.186	1.012
		High	14001.43	5.893	0.266	32.370	0.912

Table D2. Data Averaged over 10 runs of Simulation (SARP with LET = 3.5 seconds)

Grid Size	No. of Nodes	Degree of Mobility	Control Overhead Generated (B)	NRL	PDR	E2E Delay	Avg. Throughput
500m X 500m	25	Low	6043.141	2.850	0.331	24.613	0.074
		Moderate	7222.242	3.565	0.300	24.486	0.174
		High	6496.379	3.225	0.376	23.799	0.116
	50	Low	11579.22	3.542	0.338	39.594	0.313
		Moderate	12695.63	4.138	0.305	36.850	0.774
		High	12149.72	4.172	0.326	36.145	0.675
700m X 700m	25	Low	6646.598	5.785	0.200	20.769	1.078
		Moderate	7680.451	6.299	0.169	20.197	1.086
		High	7607.628	5.023	0.222	18.799	1.043
	50	Low	15568.31	5.376	0.231	32.706	0.894
		Moderate	15871.56	6.663	0.220	31.018	1.205
		High	15072.51	6.617	0.232	31.481	1.051

Table D3. Data Averaged over 10 runs of Simulation (SARP with LET = 6 seconds)

Grid Size	No. of Nodes	Degree of Mobility	Control Overhead Generated (B)	NRL	PDR	E2E Delay	Avg. Throughput
500m X 500m	25	Low	6100.132	2.881	0.350	24.356	0.089
		Moderate	7316.891	3.555	0.306	24.212	0.180
		High	6935.219	3.451	0.354	23.805	0.184
	50	Low	11609.75	3.544	0.338	39.304	0.303
		Moderate	12911.08	4.412	0.281	34.030	1.096
		High	12445.06	4.606	0.280	33.242	1.062
700m X 700m	25	Low	6516.718	5.649	0.192	18.907	1.008
		Moderate	7244.256	6.450	0.162	18.638	1.207
		High	6668.623	5.294	0.234	18.341	1.445
	50	Low	15925.43	5.547	0.227	30.868	0.939
		Moderate	16281.53	6.340	0.224	29.853	1.225
		High	16155.76	6.525	0.226	30.705	1.293

Table D4. Data Averaged over 10 runs of Simulation (AODV)

Grid Size	No. of Nodes	Degree of Mobility	Control Overhead Generated (B)	NRL	PDR	E2E Delay	Avg. Throughput
500m X 500m	25	Low	6000.132	2.851	0.336	25.026	0.081
		Moderate	7416.891	3.617	0.306	24.593	0.110
		High	7535.219	3.687	0.393	23.818	0.120
	50	Low	11809.75	3.497	0.345	39.339	0.269
		Moderate	12811.08	4.185	0.315	38.481	0.494
		High	12635.06	4.292	0.324	33.242	0.413
700m X 700m	25	Low	6501.516	5.765	0.188	21.458	0.800
		Moderate	7649.082	6.642	0.166	20.726	0.997
		High	7834.142	5.102	0.235	18.868	0.975
	50	Low	16105.49	5.600	0.237	35.323	0.934
		Moderate	16226.11	6.677	0.230	33.128	0.891
		High	15760.92	6.681	0.253	32.190	0.733

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