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On the effects of small-scale fading and mobility in mobile wireless communication network

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ON THE EFFECTS OF SMALL-SCALE FADING AND MOBILITY IN MOBILE WIRELESS COMMUNICATION NETWORK

by

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ABSTRACT

In this study, a comprehensive analysis of the impact of mobility on end-to-end performance measures of Mobile Ad Hoc Network is performed by using small-scale fading models. Network simulation is performed in order to study a wide range of phenomena occurring during MANET communication. The effectiveness of three reactive routing protocols against different level of mobility is observed under varying network parameter like the network size, number of nodes and network connectivity. The study reveals that the network sparseness or density favors one or the other routing mechanism under varying mobility. Outcome of the simulation also provides a great deal of information about the routing mechanism of the reactive protocols. Based upon the finding of the study, an adaptive speed aware routing protocol is proposed which is expected to increase the effectiveness of the routing protocol by avoiding high velocity nodes in the intermediate route. The proposed protocol is expected to outperform the existing reactive routing protocols at higher mobility and in scaled up network.

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LIST OF ACRONYMS

PDAs	Personal digital assistants
BTS	Base transceiver station
MANET	Mobile ad-hoc network
SARP	Speed aware routing protocol
LOS	Line-of-sight
T	Transmitter
R	Receiver
DSDV	Destination-sequenced distance vector
OLSR	Optimized link state routing
AODV	Ad hoc on demand distance vector
DSR	Dynamic source routing
DYMO	Dynamic MANET on demand
RREQ	Route request
RREP	Route reply
MAC	Medium access control
RWM	Random waypoint mobility
RWMM	Random waypoint mobility model
CBR	Constant bit rate
RxThresh	Receiving threshold
NAM	Network animator

1. INTRODUCTION

1.1. BACKGROUND

In recent years, there has been a tremendous increase in the sale and subscription of mobile wireless devices and communication services [1] [2]. Cellular phones, personal digital assistants (PDAs) and other mobile devices with built in wireless capability have gained enormous popularity. Fixed and wired communication networks have evolved into a wired-wireless network to fulfill the mobile communication need of a mobile workforce. As mobility of users has continued to increase, a truly mobile communication network, i.e. mobile ad hoc network (MANET) has become more popular. In a MANET, wireless communication devices do not rely on the pre-existing infrastructure, but dynamically form a network and perform all required network operations like sending, forwarding and receiving the network traffics by themselves. Thus, the task of effective routing becomes a major issue in a MANET. Significant amount of research has been performed in the design [3] [4] [5] [6] and comparative analysis of MANET routing protocols [7-11]. In these comparative studies, network simulators have been commonly used for performing experiments needed to compare and analyze the performances of protocols under different assumptions.

1.2. RESEARCH OVERVIEW

In this research, comparative analysis of reactive MANET protocols is performed in order to investigate the possibility of a speed aware routing protocol. Network Simulator, ns-2.33-allinone package was used to analyze the impact of increasing node speed on the end-to-end performances of three reactive MANET routing protocols- Ad hoc on demand routing (AODV), Dynamic Source Routing (DSR) and Dynamic MANET on-demand (DYMO). The simulations performed were simple and uses empirical method similar to that used in [8] [9] and [11] to evaluate and compare the performances of the protocols. Yet, the validity of the research is marked high due to a very thorough nature of study. Propagation channel model, mobility model and the network parameters used for the simulation have been chosen such that real communication environment is depicted more accurately.

1.3. RESEARCH OBJECTIVE

Overall objectives of this research are as follows:

1. To study the impact of fading and mobility on the performance of routing protocols.
2. To perform a comparative study of reactive MANET protocols under more realistic assumptions.
3. To address the design considerations of speed aware routing protocol

1.4. THESIS LAYOUT

Section 2 provides an introduction to a MANET. Prevalence of mobile wireless services and true need for a MANET is described. Some of the problems specific to its inherent attributes are pointed out and its applications are mentioned.

Section 3 introduces to the problem statement for the study. Impact of mobility and multi-path fading on the performance of the MANET protocols has been probed into. It discusses the statistical propagation models used in the simulation of fading effects in mobile communication. Initial considerations for the study have been elaborated.

In Section 4, a brief survey of MANET protocol types has been presented. The three reactive protocols used for the study – Ad Hoc on Demand Distance Vector (AODV), Dynamic Source Routing (DSR) and Dynamic MANET (DYMO) have been further elaborated.

In Section 5, simulation environment is described along with the details of network parameters, mobility model, and traffic generation model. All the assumptions about the simulated environment have been stated precisely and performance metrics used for the comparative study have been defined.

Section 6 includes a detail empirical analysis of the outcome of the simulation. Normalized routing load has been used as a primary performance measure for the comparative performance. Other end-to-end performance metrics used are packet deliver ratio (PDR), average end-to-end delay and average throughput. Speed-aware routing protocol (SARP) has been proposed and Future work is discussed in this concluding section.

2. MOBILE AD HOC NETWORK

2.1. WIRELESS TECHNOLOGY AND MOBILITY

Worldwide sales of smart phones, laptops and PDAs have been increasing each year. According to a report by Gartner Inc., in the first quarter of 2009, 12.7% increment in the smart phone sales was observed over one year's period and this business success was attributed to the integration of the phone to applications like music, mobile email and Internet browsing [12]. By providing advanced services like wireless Internet, data services, location based services, advertising and mobile commerce, wireless technology has largely fulfilled on-the-move computational need of its consumers [2] [13]. Furthermore, the fact that the emerging wireless services are necessarily targeted to a highly mobile workforce is highlighted in [13]. Tremendous increase in the number of mobile wireless devices and higher rate of mobile service subscription reveals that mobility is inevitable and information is important. Thus, the development of communication networks and services must be targeted towards supporting the mobility of its users.

Until recently, people largely relied on underlying infrastructures such as wireless access points and base transceiver stations (BTS), for maintaining connectivity among mobile wireless devices. However, increasing demand of mobile services has imposed a serious concern over the expansion of the infrastructure globally. The fact that infrastructure based network takes time and potentially high set up cost has given rise to an alternative way of network connections and information access- the MANET.

2.2. MANET

Mobile ad-hoc Network (MANET) is a network of mobile wireless devices capable of connecting and communicating with each other using limited- bandwidth radio links. Mobile wireless devices within the transmission range connect to each other through automatic configuration, and set up an ad hoc network. Some of the wireless devices forming a MANET are PDA, laptop, mobile phone etc. These devices may be mounted on high-speed vehicles, mobile robots, machines and instruments, thus, making the network topology highly dynamic. The nodes are incorporated with computational power and routing functionality such that they can perform the operations of sender, receiver as well as an intermediate relay node or router.

A MANET has been the focus of many advanced research and development efforts for a long time. In the past, wireless ad-hoc paradigm had been implemented only in military applications and battlefield communication where a decentralized network configuration was an operative advantage or even a necessity [1]. However, advancements in the capability of mobile computing and wireless devices along with support for ubiquitous computing have lead to exponential growth in the application and deployment of mobile ad-hoc networks. Along with the rapid proliferation of wireless technologies such as Bluetooth, Hyperlan, WiMax, and IEEE 802.11 series, MANETs have found myriad applications ranging from disaster relief, battlefield operations, industrial and commercial purposes to information sharing and personal networking. Some important applications of a MANET have been discussed in Section 2.6.

2.3. PROPERTIES OF A MANET

MANETs are infrastructure-less networks since they do not rely on a static infrastructure such as base stations and routers. The network is formed in an on-demand fashion when the nodes come within the transmission range of each other. The nodes are capable of unconstrained mobility and organize themselves arbitrarily, which results in a highly dynamic topology that can change rapidly and unpredictably. A node participating in a MANET operates not only as a host but also as an intermediate relay node, i.e. a router, forwarding packets for other mobile nodes in the network that may not be within direct wireless transmission range of reach other. 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. It is capable of accessing Internet and data services via Internet gateway node. MANET operates under variable capacity links.

After the deployment of a MANET, nodes dynamically self-organize into temporary, multi-hop network topology, allowing people and devices to internetwork seamlessly. Apart from its support to unrestricted mobility, MANET has helped realize network services for mobile users in areas with no pre-existing communication infrastructure [1]. All the activities of the nodes concerned with network configuration, route discovery, communication establishment, and local route maintenance is governed by the underlying protocol. Thus, a dynamic and an adaptive protocol is very important for operating a MANET successfully.

2.4. ADVANTAGES AND DESIGN CHALLENGES OF A MANET

MANET has played an important role in fulfilling reliable communication needs in various areas. It has helped in realizing connectivity and network services in area with no pre-existing infrastructure, at a reduced cost and by utilizing limited network resources. It is remarkable for its flexibility and availability which are the features that mobility enabled. MANET has been considered a robust wireless communication network, and its robustness has been attributed to its ease of deployment and configurability. Advantages of a MANET have made it an attractive choice for military and commercial applications [9]. With additional features like higher reliability and higher Quality of Service (QoS), MANET can be accepted as a sound alternative to future generations of wireless network.

However, the freedom and flexibility of MANET doesn’t come without complication and challenges. The lack of pre-existing infrastructure, dynamically changing topology, multi-hop nature, bandwidth constraints, energy constrained operations and network scalability adds to the complexities of traditional wireless networks, creating additional issues and design challenges specific to mobile ad hoc nature of a MANET [1]. In this research we address above mentioned challenges and design constraints in context to performance comparison of routing protocols due to mobility of the wireless nodes.

2.5. AD HOC ROUTING AND MOBILITY

Unlike conventional wireless protocols, MANET protocol is responsible for maintaining more complex network functionalities and logical operations in determining reliable routes in a highly dynamic environment. MANET performance largely depends on multi-hop routing governed by its routing protocols. It is responsible for performing all the operations required for route acquisition and local route maintenance. Several factors affect the performance of a routing protocol, among which the mobility is a significant one [7] [14]. The terms speed and mobility have been used interchangeably throughout this thesis.

Mobility has been a major hindrance to a smooth operation of a MANET protocol [14]. Higher mobility causes increased link disruption and consequently, higher network activities, exerting pressure on the performance of the protocol. Increased network operation forces protocols to generate more control packets thereby increasing the overall control overhead. Furthermore, in a real scenario, mobility of the wireless node is closely tied to multi-path fading effects [15], which further worsen the network performance. 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 solution is needed, in which the protocol keeps information about the speed of the intermediate nodes and utilizes this information to determine a more stable routing path with the addition of minimal overhead.

2.6. APPLICATION

Several industrial and commercial applications of a MANET have been proposed [16]. Some important areas of applications are mentioned below. Some of the applications of a MANET that has been discussed in [1] are summarized in Appendix A.

1. Wireless sensor network is one of the most significant application areas of a MANET which has been widely used for domestic and environmental applications. Significant environmental applications include data tracking and remote sensing for weather forecasting.
2. MANET provides flexible method for establishing communications [16] for disaster relief efforts and rescue operations in areas where pre-existing network infrastructures do not exist or have been damaged.
3. Rapid deployment and self configuration ability of a MANET make it a suitable network for relaying information for situational awareness in military network [1].

~~4.~~ Business colleagues, conference participants and students have started to use a MANET for networking among themselves for sharing documents, presentation materials and so on.

2.7. SECTION SUMMARY

MANET has a potential of becoming extremely useful in providing reliable communication services across areas with no pre-existing infrastructure. It ensures flexibility and convenience by supporting unconstrained mobility. It has the desirable features of future generation networks. However, it does suffer from some of the limitations imposed by its inherent characteristics. Lack of a fixed infrastructure and a dynamic topology has resulted into some serious protocol design challenges. Mobility and fading have further imposed a serious concern over the reliability of the communication link thereby reducing the overall network performance. Section 3 addresses some of the practical issues about the network emphasizing on the impact of mobility and multi path fading on overall performance of the network.

3. PROBLEM STATEMENT

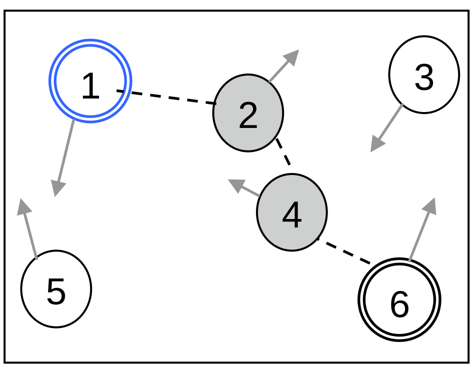
3.1. INTRODUCTION

Dynamic environment in which MANETs are deployed poses protocol design challenges at different layers of network architecture from a physical layer to the network layer. Several factors affect the performance of a protocol operating in the network. Mobility may cause link failure, thereby, affecting the routing and overall network performance [12]. Similarly, network size, control overhead and traffic density will have considerable impact on the performance of a protocol. Also, it has been proven that different protocols operate in a different manner in terms of route discovery, link establishment, route updates and other essential network activities [3] [4] [5] [6]. This causes a significant difference on the performance of two or more protocols operating in a same environment. In this research a comparative study is performed in order to gauge how different reactive protocols respond to a highly mobile scenario under different propagation model and varying network parameters. Mobility has a major impact on the link and route lifetime in an ad hoc network and therefore on the protocol and application performance [17]. This study culminates into a design consideration of a scalable, speed aware routing protocol (SARP) that would rely on the route stability and link reliability. Later sections provide a detail study about the impact of mobility on the network performance, route stability and reliability of communication links.

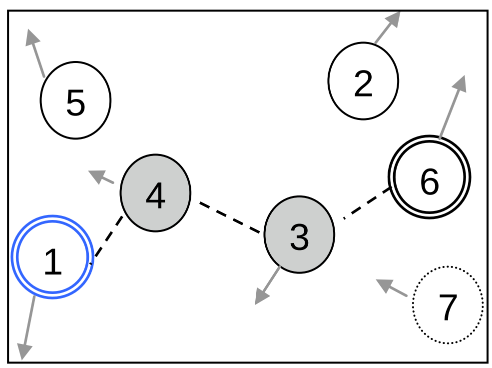
3.2. MOBILITY AND NETWORK TOPOLOGY

Many factors affect the performance of ad-hoc wireless networks, among which the impact of individual node mobility plays a significant role [14] [17].The effect of mobility on the performance of practical ad-hoc wireless network has been proven deleterious [10]. 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. As the links break, a large amount of data packets that were being transmitted through those links, are dropped. The network then forces the underlying protocol to repair the broken links or initiate search for new routing paths resulting into a continuous reconfiguration of the network [18].

Increased network activity results into a frequent exchange of routing information over the bandwidth constrained communication channel thereby, causing an increase in overall routing overhead of the network. The dynamic change of topology under node movement and multi-hop nature of a MANET has been illustrated in Figure 3.1. Figure 3.1a and Figure 3.1b represents the network topology at time t and t+1, respectively. Here, node 6 and node 1 are sender and receiver respectively. The dotted line represents the active link and the arrow represents the velocity of the nodes. At time t, 6-4-2-1 is the active route with nodes 4 and 2 as intermediate routing nodes. However, nodes 4 and 6 tend to move in different direction such that they are no longer within each other's transmission range. At the same time node 3 while moving towards node 6 and node 4 appears within the transmission range of sender and receiver nodes. At t+1, the weaker links break and newer links are created. Thus, a new active route 6-3-4-1 is established with node 4 and node 3 as intermediate nodes. These events cause a large number of network activities that has to be performed by the underlying protocol.



a. Network state at time t



b. Network state at time t+1

Figure 3.1. Dynamically Changing Network Topology

3.3. EFFECT OF MOBILITY AND LINK STABILITY

Discussions in Section 3.2 lead to a fact that independent node mobility causes link disruption in a MANET. Mobility directly impacts the number of links created, number of links disrupted and the duration of links [17] in a mobile ad hoc network. As a result, the amount of information that can be transmitted over the wireless link is also decreased. Mobility of the individual node causes a dynamic change of the network topology, thereby prompting the protocol to perform network reconfiguration continuously. It further impacts end-to-end performance measures such as throughput, amount of control overhead, in-order delivery, delay and allocation of resources [10]. Higher node mobility renders communication route unstable by causing more link breakages within the communication route.

In addition, links might also fail due to diverse source of signal interference and packet collision. It has been found that the mobility of the node and interference/collision have completely different impact on the lifetime of link routes [17]. Mobility is more likely the main cause of link failure in case of longer activation time. When the link activation time is short, or small data size is being transmitted, multi-path fading and other environmental interferences become more significant [18]. In the following section, the relationship of mobility and small-scale fading is discussed.

3.4. MOBILITY AND FADING

Small-scale fading is caused by the movement of transmitter, receiver or the objects in the environment [20] [21]. As the node moves over a small distance, the instantaneous received signal strength may vary giving rise to a small-scale fading. Relative motion of the communicating nodes causes a Doppler shift on the propagated signal. One of the important effects of fading is that random frequency modulation occurs in multi-wave signal due to varying Doppler shift. Thus, mobility and fading are closely tied to each other. Since a MANET is marked with a high degree of random node mobility, it becomes very important to consider the effects of mobility as well as fading as far as accurate analysis of the MANET protocol performance is concerned.

3.5. MOBILE RADIO PROPAGATION

In a MANET, transmission path between the transmitter and receiver can vary from a direct line-of-sight (e.g. path in a sensor network) to the one that is heavily obstructed by towers, buildings and mountains. More obstruction along the propagation path causes more reflection, diffraction and scattering of the signal being transmitted which deteriorates the network performance. Also, due to mobility, propagation characteristics of a MANET vary from place to place, and from time to time. The diverse nature of radio channel causes a fundamental limitation on the performance of the network. While methods exist to closely model exact nature of propagation phenomenon, these methods require a large amount of detailed information specific to its terrain, time and operating environment specific data[15] [20], limiting general applications of the model to certain types. An alternative, statistical propagation models are more commonly in use for the evaluation of mobile radio channels. Radio wave propagation is largely attributed to reflection, diffraction and scattering. The transceiver antennas of mobile devices are small and provide a low clearance. As a result, direct line-of-sight (LOS) path is usually absent causing the propagated wave to suffer from a diffraction loss. Due to multiple reflections, the received signal becomes the superimposition of direct signal as well as reflected, scattered and diffracted signal characterizing multipath reception[20] [22] also called as multipath propagation. The signals received are called as the multipath waves or multipath signal. The strength of the wave decreases as the distance between the transmitter (T) and receiver (R) increases.

Typical signal propagation and multipath reception in an urban environment is shown in Figure 3.2.

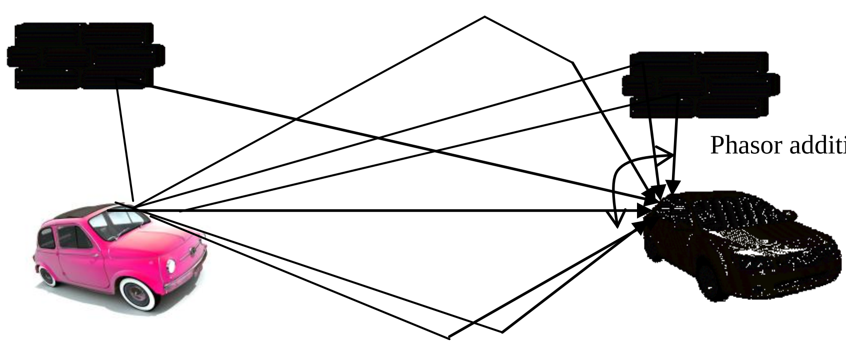


Figure 3.2. Multipath Signal Reception

3.6. STATISTICAL PROPAGATION MODELS

Statistical propagation models treat instantaneous received power $P_r(d)$ as a stochastic random variable that varies with the transmission-receiver (T-R) distance. Statistical interpretation of the three mutually independent propagation phenomena observed in mobile communication environment - large-scale path loss, shadowing and multipath fading [22] have been discussed briefly in subsequent sections. Narrowband channels have been assumed in the discussion that follows. The idea presented in subsequent sections in this section is largely based on the discussions in [15] and [20] unless otherwise stated.

3.6.1. Large-Scale Path Loss. Path loss is a large scale effect. Due to a large-scale the received field strength varies gradually with the transmitter-receiver (T-R) distance due to signal attenuation determined by the geometry of the path profile along the propagation channel. The large-scale effects determine a power level averaged over an area of tens or hundreds of meters which ensures that the rapid fluctuations of the instantaneous received power due to multipath effects are largely removed. Path loss is often expressed as a received power $P_r(d)$ as a function of the distance (d) between the transmitter and receiver as illustrated by equation 3.1.

$$P_r(d)\,\alpha\,\frac{\lambda^2}{4\pi \mathrm{d}^2}P_t \tag{3.1}$$

where, λ is the wavelength and P_t is the power transmitted.

3.6.2. Shadowing. In shadowing, the received signal power fluctuates due to large objects obstructing the propagation path between transmitter and receiver. This phenomenon causes a substantial deviation of the received signal from its mean. That is when an obstacle lies on the path of the signal or if the receiver happens to enter the shadow zone of the obstacle, deep fades appear in the signal [23]. Thus, shadowing is also large scale due to large losses in the signal power as it is propagated over a large distance and time. Furthermore, these fluctuations are experienced on a local-mean power, which implies that the fluctuation due to multipath effect is largely removed.

3.6.3. Small-Scale Fading. Multipath propagation leads to a rapid fluctuation of the amplitude and phase of a radio signal even when the mobile node moves over a very small distance. Fading is caused by the interference of two or more multi-path signals arriving at the receiver at slightly different times. On a narrowband signal, variation of up to ±30 dB has been noted in the resultant received signal [15] in urban centers. This phenomenon is considered a small-scale phenomenon in the sense that the level of attenuation of the signal changes substantially even if the position of the transmitter or receiver changed by about a wavelength. Small-scale fading heavily contributes to the fragility and non-reliability of the wireless link [23]. Small-scale fading is also known as multi-path fading or simply fading. A fading in which the reflected signal components reaching the receiver are of almost equal strength is called a Rayleigh fading and the one in which there is one principal LOS component that has higher contribution towards signal reception is called Ricean fading. A third type of fading model exists which is used to describe the interference accumulated from the multiple independent Rayleigh-fading sources-the Nakagami fading.

3.7. SMALL-SCALE FADING MODELS

The goal of this research is to identify common interaction of MANET protocols due to signal variation brought by the mobility of the communicating nodes. In this context it is very important to incorporate small-scale fading effects when simulating the signal behavior and consequently the network performance within a MANET [10] [24]. Although fading is a complex phenomenon, powerful stochastic models have been developed that can accurately predict the fading effect thereby increasing the fidelity of

MANET simulation. Ricean model and Rayleigh model have been successfully implemented in [10] [18] [23] to simulate fading effects in MANET simulation. A third type of model exists which has been used to describe the interference accumulated from the multiple independent Rayleigh-fading sources- the Nakagami model.

Narrow band Rayleigh and Ricean models are based on the probability distribution of multi path signals arrival times that are based on appropriate assumptions [20]. The three small-scale fading models are described in the following subsections.

3.7.1. Ricean Fading. Ricean fading is a specialized stochastic model for a multi-path fading in which there is a principal LOS component that has higher contribution towards signal reception. This means, there is at least one dominant signal component in the mix of the multi-path waves reaching the intended receiver. As mentioned in Section 3.5, wave interference leads to fast fluctuation of the field strength when the antenna position is varied. In the narrowband channels, time interval of the reflected waves is small and thus, the resultant signal is assumed to be a phasor addition of its component signals.

In a typical Ricean fading channel, the received carrier is of the form:

$$v_i(t) = (C_i + \zeta_i) cos\omega_i t + \xi_i sin\omega_i t \tag{3.2}$$

where the constant Ci represents the direct component and the random variable ξi and ζi represent the in-phase and quadrature component of the sum of reflections. These variables are function of time when the antenna is in a motion. Ricean fading occurs if the number of reflection is large and none of the reflections substantially dominates the joint reflected power. In this case ξi and ζi are independently Gaussian distributed random variable with identical pdfs, of the form N $(0, \bar{q}_{si})$, with zero mean and variance equal to the local-mean reflected power $\bar{q}_{si}$. Hence, the received carrier $v_i\,(t)$ can be expressed in terms of amplitude ρ_i and the phase θ i as equation 3.3.

$$v_i t = \rho_i \cos(\omega_i t + \theta_i) \tag{3.3}$$

with,

$$\rho_i = \sqrt{(C_i + \zeta_i)^2 + \xi_i^2}$$

$$\theta_i = \arctan\left(\frac{\mathrm{C_i} + \zeta_\mathrm{i}}{\xi_\mathrm{i}}\right)$$

The instantaneous amplitude ρ_i has been shown to have the Ricean pdf as in equation 3.4.

$$f_{\rho_i}(\rho_i|\bar{q}_{si}, C_i) = \frac{\rho_i}{\bar{q}_{si}} exp\left(-\frac{\rho_i^2 + C_i^2}{2\bar{q}_{si}}\right) I_0\left(\frac{\rho_i C_i}{\bar{q}_{si}}\right) \tag{3.4}$$

where, the local- mean power $\bar{p}_i$ is the sum of power $\bar{q}_{di}$ in the dominant component ($\bar{q}_{di}$ being equal to ½C_i^2 and the average power $\bar{q}_{si}$ in the scattered component, i.e.

$$\bar{p}_i = \bar{q}_{di} + \bar{q}_{si} \,.$$

The Ricean *K*-factor is defined as the ratio of signal power in dominant component over the (local-mean) scattered power. With further substitution, the pdf of the signal amplitude in terms of local-mean power $\bar{p}_i$ and the Ricean K factor equation becomes,

$$f_{\rho_i}(\rho_i|\bar{p}_i, K) = (1 + K)e^{-K} \frac{\rho_i}{\bar{p}_i} exp\left(-\frac{1 + K}{2\bar{p}_i}\rho_i^2\right) I_0\left(\sqrt{\frac{2K(1 + K)}{\bar{p}_i}}\rho_i\right) \tag{3.5}$$

The instantaneous power p_i($p_i = \frac{1}{2}\rho_i^2$) has the noncentral chi-square pdf as shown in equation 3.6.

$$f_{p_i}(p_i|\bar{p}_i, K) = f_{\rho_i}(\rho_i|\bar{p}_i, K)\left|\frac{d\rho_i}{dp_i}\right| = \frac{(1 + K)e^{-K}}{\bar{p}_i} exp\left(-\frac{1 + K}{\bar{p}_i}p_i\right) I_0\left(\sqrt{4K(1 + K)\frac{p_i}{\bar{p}_i}}\right) \tag{3.6}$$

Ricean factor of K=5 has been proved to adequately describe the most microcellular channels although its value can range from K=4 to 1000 [8]. Rayleigh fading is recovered for *K* = 0.

3.7.2. Rayleigh Fading. In an urban environment setting with often obstructed propagation paths, the power of the direct LOS is small compared to the reflected signal power which produces a special case of Rayleigh fading. In this case *Ci* ->0, K->0, variance of ξi and ζi is equal to the local mean power p_i, the phase θ_i is uniformly distributed over [0,2 π], and the instantaneous amplitude ρ_i has the Rayleigh pdf given by equation 3.7.

$$f_{\rho_i}(\rho_i|\bar{p}_i, K = 0) = \frac{\rho_i}{\bar{p}_i} exp\left(-\frac{\rho_i^2}{2\bar{p}_i}\right) \tag{3.7}$$

With substitutions, the total instantaneous power *Pi* received from the *i*th mobile terminal is exponentially distributed about the mean power which is illustrated by equation 3.8.

$$f_{p_i}(p_i|\bar{p}_i, K = 0) = f_{\rho_i}(\rho_i|\bar{p}_i, K = 0)\left|\frac{d\rho_i}{dp_i}\right| = \frac{1}{\bar{p}_i} exp\left(-\frac{p_i}{\bar{p}_i}\right) \tag{3.8}$$

3.7.3. Nakagami Fading. Nakagami is much refined model suggested for the communication with multipath scattering with relatively large delay-time spreads, with different clusters of reflected waves [20]. Within any one cluster, the phases of individual reflected waves are random but the delay times are approximately equal for all waves. As a result the envelope of each cumulated signal is Rayleigh distributed. The average time delay is assumed to differ significantly between clusters. If the delay times also significantly exceed the bit time of a digital link, then the interference among different clusters produces approximately the case of co-channel interference with multiple incoherent Rayleigh fading signals.

The pdf of the amplitude ρ_i of a mobile signal was described by Nakagami m-distribution which is shown by equation 3.9.

$$f_{\rho_i}(\rho_i|\bar{p}_i = m\bar{p}) = \frac{\rho_i^{2m-1}}{\Gamma(m)2^{m-1}\bar{p}^m} exp\left(-\frac{\rho_i^2}{2\bar{p}}\right) \tag{3.9}$$

where, $\Gamma(m)$ is the gamma function, with $\Gamma(m+1)=m!$ Local mean power is $\overline{p}_i = m\overline{p}$. The corresponding instantaneous power $\overline{p}$ is gamma-distributed, with pdf as shown in equation 3.10.

$$f_{p_i}(p_i|\bar{p}_i = m\bar{p}) = \frac{1}{\bar{p}\Gamma(m)}\left(\frac{p_i}{\bar{p}}\right)^{m-1} exp\left(-\frac{p_i}{\bar{p}}\right) \tag{3.10}$$

In the above expression, m is called the shape factor of Nakagami. With the value of m being 1, Rayleigh fading is recovered with exponentially distributed instantaneous power in equation 3.8 and with higher values of m the fluctuation of the signal is reduced as compared to equation 3.6.

3.8. IMPACT OF FADING IN MANET

Fading and its impact in network performance has been the topic of research performed in radio communication applications like robot communications [25], wireless sensor networks and MANETs [12] [13] [18]. Impact of fading is higher in MANET than in conventional mobile communication scenario because of highly mobile short range mobile antennas of the nodes as opposed to powerful routers and base stations of mobile networks. Furthermore, MANET protocols are responsible for identifying, establishing and maintaining multi-hop routes between a sender and a receiver and facilitating communication when the nodes can no more communicate through a direct one-hop link. Thus, how well the protocols perform in the given scenario depends on how well they can identify between a good link and bad link during active communication. Fading causes alternating constructive and destructive signal interference at the receiving node. Thus, it often results into misleading information about the received radio signal strength and nominal communication range [18], thereby, affecting the performance of the protocol in two ways. First, fading protocol makes a false assumption that the link is no longer usable when it is still usable. This incident forces the routing protocol to start a new route search resulting into increased consumption of network resources, bandwidth and the battery power of the processing nodes. Second case is that the protocol assumes a bad link to be a good one and includes it in its route. Thus, during the data transmission, the link fails causing increased network activities and increased overhead through route recovery or additional route discoveries. Multipath fading reduces the reliability of the wireless links. Packets can be lost even on a good link, at a shorter distance and received on a weak link outside the range leading to a risk that a weak link will be identified as good and may be included in the routing updates. Thus, the design of MANET and its protocols must be preceded with enough attention towards minimizing the adverse effect of fading.

3.9. OTHER CONSIDERATIONS

From the above discussion, it is clear that the fading effect is necessarily tied to mobility and that its effect cannot be neglected when protocol performance is evaluated under mobility. Furthermore, the effect of fading increases with the speed of mobile nodes [15]. Thus, it becomes very important to incorporate a small-scale fading effect when simulating the signal behavior and consequently the network performance within a MANET [10] [18].

In this study, basic models for the Ricean fading, Nakagami fading and TwoRayGround models have been implemented for the comparative performance of MANET protocols due to signal variation brought about by the mobility of the communicating nodes. Here onwards TwoRayGround model is also termed as no-fading model. The motive behind the comparative study is to identify a protocol that can perform better even under the influence of high speed nodes and fading without significantly increasing the routing overhead. Some of the desirable characteristics of a MANET protocol have been identified in various literatures as - minimal control overhead, minimal processing, loop prevention, efficient topology formation, stable routes, scalability, security and reliability. Real-time protocols generate relatively low control overhead and help in increasing effective network utilization. Hence, reactive protocols are chosen over proactive ones for the comparative study. Some important aspects of these routing protocols are covered in more details in Section 4.

3.10. SECTION SUMMARY

Mobility has been the real strength of MANET. However, some of its inherent characteristics pose major obstacles in the performance of reactive MANET protocols. Multi-path fading adds to this complication by rendering the communication link unreliable. This study addresses a need for a more accurate performance evaluation of reactive protocols across different levels of mobility and by incorporating the effects of fading. A thorough simulation of a wireless communication under all considerations of a MANET provides significant insight into critical factors that need to be addressed in achieving an effective design of a robust speed-aware routing protocol. It becomes important to investigate into the existing reactive protocols to understand the routing mechanism that can handle the effects of mobility and fading in a better way. The next section provides insight into the basic mechanism of the three reactive routing protocols considered for the study.

4. MANET ROUTING PROTOCOLS

4.1. INTRODUCTION

The routing protocols enable the multi-hop communication in a MANET thereby assuring that the information sent from a sender reaches the intended receiver reliably. Several routing protocols have been proposed and their performances have been compared [7-11] [26]. Ad hoc routing protocols are classified based on the approach they use for updating their routing table during route discovery and route maintenance. Three classes of routing protocols have been explored so far – proactive routing protocols, reactive protocols and hybrid protocols. Hybrid protocols are the recent addition to the existing groups of protocols which have been developed by incorporating the advantages of both reactive and proactive protocols. In a hybrid protocol, node uses the principle of proactive routing within the zone and reactive algorithms outside it. Zone Routing Protocol is an example of a hybrid protocol. Although the effectiveness of hybrid routing protocols like the ZRP have been tested on specific applications, major part of work on the performance evaluation across wider domain still remains.

4.2. PROACTIVE (TABLE DRIVEN) ROUTING PROTOCOL

In this approach, the routing protocol attempts to maintain a routing table for each node with routes to all other nodes in the network. That is, routes are maintained to all potential destinations at all the time, whether or not all routes are actually used [7] [9]. Any changes in the network topology are propagated by means of updates throughout the entire network to ensure that all the nodes are aware about current network topology. An advantage of this approach is that the routes between arbitrary source-destination pairs are readily available at all times. The disadvantage being that there is a lot of control overhead due to frequent route updates performed even in those links that are not active or may never be used. Frequent network activity also leads to higher consumption of limited battery resource, available bandwidth and storage space. Destination-Sequenced Distance vector (DSDV) and Optimized Link State Routing (OLSR) routing have been two proactive protocols that have been largely explored and implemented in the past.

4.3. REACTIVE (ON-DEMAND) ROUTING PROTOCOL

In these routing protocols, routes are acquired via route discovery process as the communication demand arises. The advantage of this approach is that unnecessary exchange of routing information and updates are avoided. As a result less control overhead is generated and fewer resources consumed. However, it takes more time compared to proactive protocols due to the on demand fashion of route creation. Representative reactive routing protocols that are time tested and more commonly used include Ad Hoc on Demand Distance Vector (AODV) and Dynamic Source Routing (DSR). Dynamic on MANET Protocol (DYMO) have been recently developed reactive protocol which is based on AODV and the DSR protocol.

4.4. COMPARISON OF PROACTIVE Vs. REACTIVE PROTOCOL

In general, on demand reactive protocols have been shown to be more efficient than proactive for implementation in a MANET [1] [7]. Due to the frequent movement of the nodes, more updates are required resulting into more consumption of the limited network resources. Proactive protocols have been shown to be less scalable as compared to reactive protocols [7] [9]. However, they provide better quality of service and significant end-to-end delay reduction than the reactive protocols [26]. It has been argued that existing proactive protocols are suitable for a small-scale static network where time is a critical factor whereas, the reactive protocols are suitable to work with medium sized network with moderate mobility [1] where efficient utilization of limited resources is of prime concern. Furthermore, through the performance comparison of AODV, DSR and DSDV [7] it has been shown that the proactive protocols cannot adapt to increased node mobility. This study is based on the response of routing protocols to mobility in a wireless mobile ad hoc communication.

4.5. SURVEY OF REACTIVE PROTOCOLS

A brief survey on the operation and performance of the AODV, DSR and DYMO is performed in this section.

4.5.1. AODV. AODV is a distance vector routing in which the routing table contains next hop information, to reach the destination with one entry per destination [27]. When a source node desires to send a message to some destination node, it broadcasts a route request (RREQ) packet to its neighboring nodes, which is further forwarded until the destination or an intermediate node with recent route information about the destination is located. AODV utilizes destination sequence numbers to ensure loop freedom and freshness of the routes. Each node maintains its own sequence number, as well as a broadcast ID. The broadcast ID is incremented for every RREQ the source node initiates. The intermediate nodes which have a valid route to the intended destination can also reply to the RREQ with the information about the destination.

When the source node moves, it is able to reinitiate the route discovery protocol to find new updates to the destination. However, if a router node moves, its upstream neighbor notices the move and propagates a link failure notification (RERR) to more nodes in its neighborhood to inform them of the loss of previous route information. [3] This error message is propagated further until the source node is located. The source node may initiate a route rediscover if the route is still needed. AODV also broadcasts periodic hello packets to ensure local connectivity among the nodes.

4.5.2. DSR. Source routing is the main essence of a DSR protocol. In DSR, the sender creates a source route in the packet header which includes the address of all the intermediate routes along the path to the destination. When a host node wants to establish a communication, it checks its cache for the information of the destination node. If no information is found it broadcasts the RERR. It has a potentially larger control overhead and memory requirements than AODV. This is essentially because the DSR packet carries full routing information of the destination node. Also, the nodes maintain alternative routes to a destination in their cache. This feature becomes very useful in the case of link failure [27]. However, in a network with a large number of nodes, its performance decreases due to large number of node information that has to be carried in the control packet header.

4.5.3. DYMO. DYMO is a relatively new reactive protocol which builds upon the experience of AODV. As in AODV its basic operations include route discovery and route maintenance. It also uses sequence number to ensure loop freedom and to prevent stale routes. In the route discovery, the sender disseminates route request (RREQ) throughout the network to locate the target. During this hop-by-hop dissemination process, each intermediate node remembers a route to the sender node. On receiving the RREQ, the receiver responds with a route reply (RREP), which is sent back to the originator along the multi-hop route. Route between the sender and the receiver will have been established when the originator receives the RREP. However, when a broken link occurs or the intended receiver is not located, the source packet is notified through the route error message (RERR) after which it deletes the stored route. The DYMO routing protocol is designed to handle a wide variety of mobility patterns and variety of traffic by dynamically determining routes on-demand [4]. In larger networks with larger number of nodes DYMO is best suited for sparse traffic scenarios. The significant difference between DYMO and AODV is due to the fact that , AODV generates route table entries for the destination node and the next hop only, while DYMO stores routes for each intermediate hop along the route. NS-2 implementation of DYMO, the DYMOUM was implemented for the simulation. DYMOUM and DYMO have been used interchangeably throughout this thesis.

4.6. SECTION SUMMARY

Reactive protocols have been shown to be more meaningful in a dynamic situation, as opposed to proactive which possesses an operative advantage in a more static environment. In this study reactive protocols have been simulated under different levels of mobility and varying network parameters. This study can be extended to include proactive and the hybrid protocols without adding significant complexity. The simulation design under which the protocols’ performances were evaluated and compared is discussed in Section 5.

5. NETWORK SIMULATION

5.1. INTRODUCTION

In the past years, a large amount of research has been performed for comparing the responses of MANET protocols to dynamically changing network topology. In most cases, effectiveness of one protocol type over the other has been discussed based on end-to-end performance metrics obtained by varying one or more network parameters such as grid size, node numbers, mobility model, traffic density and energy consumption. Modifying well established protocols for optimizing some specific performance metrics to ensure better performance in a more specific scenario for a more specific application has also been a very common trend. Network simulation has been very instrumental for performing experiments needed to compare and analyze the result obtained from comparative study. NS-2, OPNET, QualNet, GloMoSim [28] are some of the more popular tools used these days for simulating MANET and wireless sensor networks.

Simulators provide the flexibility of reproducing the experiment with different network type, network parameters, routing protocols, mobility models and traffic models. However, to ensure a more accurate performance measure, simulator objects as well as the network parameters has to be fine tuned such that simulation scenario depicts the real network scenario, more accurately. In this research Network Simulator, ns-2.33 was used to analyze the impact of increasing node speed on the end-to-end performance of three reactive MANET routing protocols- AODV, DSR and DYMO as the network is scaled up in size. AODV and DSR implementation packages come along with NS-2 [30]. DYMOUM, a separate implementation of DYMO was implemented in NS-2. In the simulation, network topologies used are simple and in some ways similar to the comparative studies performed in the past [7-10]. Yet, the validity of the research is marked higher due to the incorporation of fading effect which is imminent in the MANET propagation channel, along with the selection of realistic simulation parameters like the node speed, data traffic model and the network density. Thus, in addition to providing useful insight into the response of reactive protocols to the node speed, this research also helps us understand the tolerance of those protocols to the effects of fading along with increasing traffic and network density. Details about the simulation and performance metrics are provided in sections below.

5.2. SIMULATION OVERVIEW

Detailed information on the simulation along with the physical channel specification, propagation models, mobility models, network traffic and network performance measures are presented in this section. All the discussions included in this section are on based on the network simulation performed in NS-2.33.

5.2.1. Propagation Channel Specification. All the simulations are performed using the technological specifications of IEEE 802.11 b wireless channel for communication and essential network operations. A simple modification has been made in NS-2 package in the Medium Access Control (MAC) package of the specification to assure communication under dynamic infrastructure environment, a property inherent to MANET. The modification is illustrated in Appendix B. Orinoco IEEE 802.11b wireless card specification [29] 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 is detected and received correctly by the receiver node. The sensing and receiving thresholds were set to $5.012x10^{-12}$ W and $1.15x10^{-10}$ W, respectively. The parameters used to specify Orinoco 802.11b channel with CCK11 (11 Mbps) was written in NS-2 using OTcl code and is illustrated in Table 5.1.

The wireless channel was simulated under three different propagation channels:

1. TwoRayGround propagation model, that is included in the distribution package of NS-2 (all versions)
2. CMU Ricean propagation model documented in [21] and
3. Nakagami fading model, included in the NS-2.33 base distribution package.

As described earlier, small-scale fading is eminent in mobile communication environment. Thus, using fading models in the propagation channels becomes necessary to ensure higher simulation fidelity.

Table 5.1. Orinoco 802.11 b Channel Specification

```
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
```

5.2.2. Achieved Levels of Network Density. Comparison under three different propagation types not only provides insight on the consequences of including and not including effects of fading but also helps to envision the combined effects of node velocity and fading in the performance of a particular protocol under sparse, normal and dense network density and varying traffic density. A simple flat grid topology was chosen for the simulations with the grid dimension of 500m X 500m and 700m X 700m. Simulations were performed with 25 and 50 mobile nodes in each of the topology. By varying the number of nodes per unit area, three different density levels were achieved and are tabulated in Table 5.2.

Table 5.2. Achieved Network Density Levels

Grid Dimension (m^2)	Number of Nodes	Average Area per Node	Density Level
500 X 500	25	100	proper
500 X 500	50	70.7	dense
700 X 700	25	140	sparse
700 X 700	50	98.9 $\approx$ 100	proper

5.2.3. Mobility Model. In this research, mobility has been generated using Random waypoint mobility model (RWMM). For each node the speed of the node CMU 'setdest' command was used to generate the communication scenario with random initial placement of nodes within defined environment. The nodes are set to continuous motion with pause time set to 0. Mobility is defined according to modified random waypoint mobility (RWM). Mobility status of a node is described in terms of its speed and its direction angle. Instead of allocating uniformly distributed velocities between specified minimum and maximum values, nodes were moved with 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 the real environment where people on a high speed vehicle are trying to access a same network. Three different levels of mobility are simulated by varying the percentage of total nodes moving at a low velocity range(0.1m/s-3m/s) and high velocity range (18m/s to 21 m/s). A minimum velocity has been set to a small positive number to be able to avoid any stationary nodes. Also, by setting the minimum velocity to a small positive number more uniform velocity distribution is achieved throughout the simulation time [32].

5.2.4. Traffic Model. The traffic pattern was generated by cbrgen routine included in the NS-2 package that follows a randomized distribution. Number of active routes, i.e. number of active transmitter-receiver (Tx/Rx) pairs was set to 10 and 20 for scenario with 25 nodes and 50 nodes respectively, initiating communication at different point of time during the simulation. The source node transmitted 62.5, 512 bytes constant bit rate (CBR) packets per second resulting into 256 kbps data rate. This value corresponds to an average of the data rate specified for a high speed vehicle and while walking, and is according to the standard specified by ITU for multimedia/voice transmission [33]**.** A User Datagram Protocol (UDP) was implemented at the transport layer. With UDP, message can be sent without requiring prior communications to set up a transmission path. It uses a simple transmission model and assumes that error checking and correction is either not necessary or performed at other layers. UDP is often used with time-sensitive applications, where, dropping packets is preferred to delayed packets. Transmission Control Protocol (TCP) can be used alternatively if a reliable, stream delivery of packets is desired. UDP is implemented in the study to ensure timely delivery of data packets with lower network overhead.

Formulated simulations were executed with three reactive protocols AODV, DSR and DYMOUM to achieve the objectives of this research. Simulation time was set to 200 seconds. The total simulations were repeated 10 times by varying the traffic route. The traffic source and receiver were changed thus, achieving 10 different sets of routes in 10 simulation runs. A sample OTcl script is illustrated in Appendix C. Overall simulation design is depicted in Figure 5.1. Each of the simulations are performed in all three propagation models specified in Section 5.2.1.

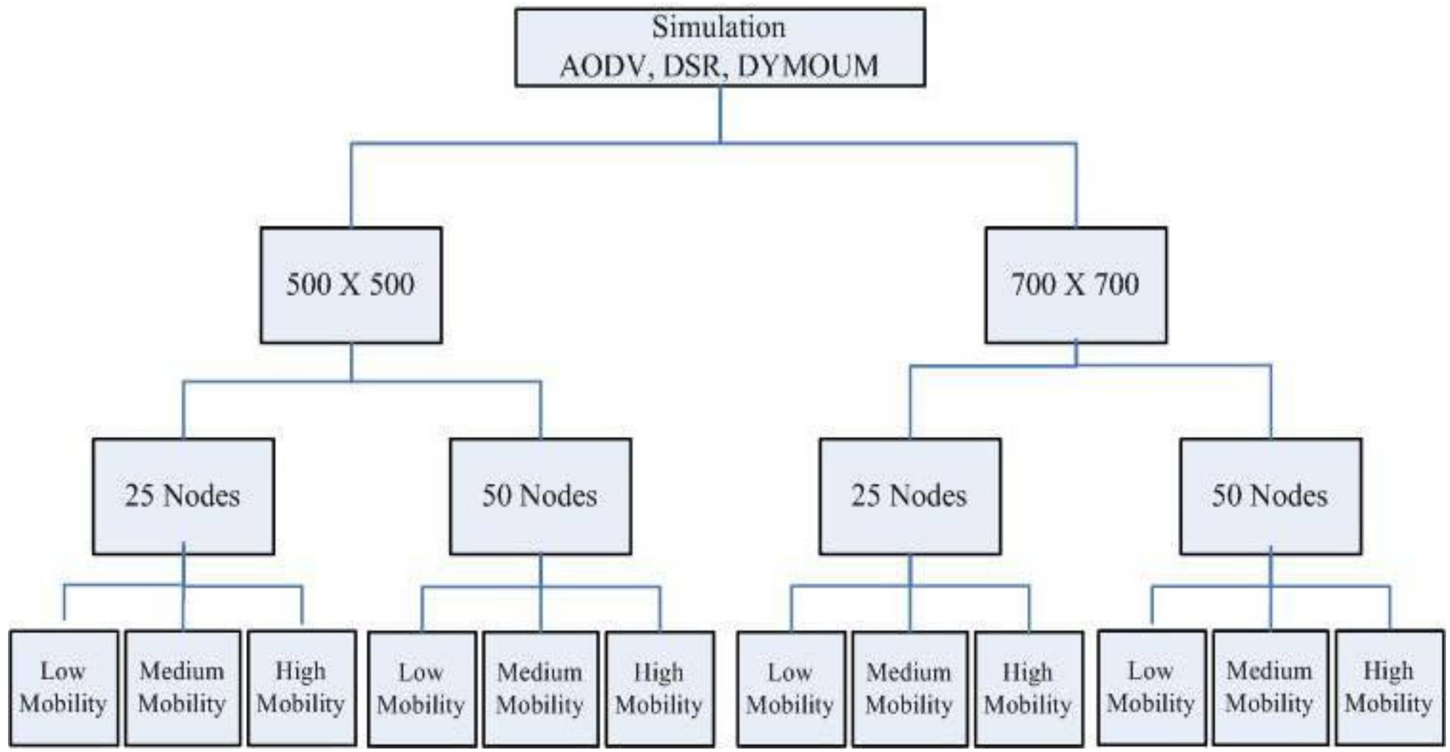


Figure 5.1. Simulation Design

5.2.5. Performance Comparison Metrics. Tracegraph [31] was used for obtaining data from the trace files that were generated by NS-2 [30]. The performances of the protocols were evaluated on the basis of four average end-to-end performance measures. Normalized routing load was the most significant parameter across which the performance analysis was performed.

5.2.6. Normalized Routing Load. Normalized Routing Load is the ratio of total amount of control packets generated during the simulation to the total number of received data packets. It is a measure of the amount of useful traffic generated in the network.

5.2.7. Packet Delivery Ratio. Packet delivery ratio is a significant metric to measure the utilization of network resources under a specific protocol. It is the ratio of amount of packets successfully received by an application to the amount of packets sent out by the corresponding peer application at the sender.

5.2.8. Average End-to-End Delay. It is the delay a packet suffers from leaving the sender application to arriving at the receiver application. Dropped packets are not considered in the calculation of delay.

5.2.9. Average Throughput. Average throughput is the measure of total amount of data received per node per second.

5.3. SECTION SUMMARY

Detail about the simulation performed during this study has been explained in this section along with the explanation of the mobility model, traffic model and the implementation details of the adopted propagation types used for the study. Performance of the three reactive routing protocols, AODV, DSR and DYMOUM was evaluated using the performance metrics defined in Section 5.2. A comprehensive analysis of the obtained result has been discussed in Section 6.

6. RESULTS AND DISCUSSION

6.1. INTRODUCTION

Outcome of a trace-based simulation described in Section 5 has been discussed in this section. A comprehensive analysis was performed to be able to visualize a wide range of phenomena occurring in the mobile ad hoc communication network and results have been presented in terms of graphs and tables. It is important to note that all the results discussed are based on the average result of the 10 runs of simulation under. A comprehensive observation of the impact of mobility on the normalized routing load (NRL) is presented in Section 6.2. However, for brevity only a brief section is included with important observations of the impact of mobility on packet delivery ratio, delay and throughput. The data set for the average of the 10 simulation is included in Appendix D.

6.2. NORMALIZED ROUTING LOAD

MANET protocols have been designed with the objective of limiting the amount of bandwidth consumed in routing and route maintenance. Different protocols consist of different information in their control header depending on which the amount of control packets generated varies. NRL gives a measure of control overhead, which is generated due to the unique routing mechanisms of the implemented protocol. Control overhead provides significant information on link stability and route longevity which are important qualitative factors to gauge the effectiveness of a reactive protocol. The impact of mobility on the performance of reactive protocols was observed and analyzed in terms of Normalized Routing Load.

6.2.1. 500m X 500m Grid Size and 25 Nodes. The analysis of the comparative performance under this scenario has been illustrated in Figure 6.1.

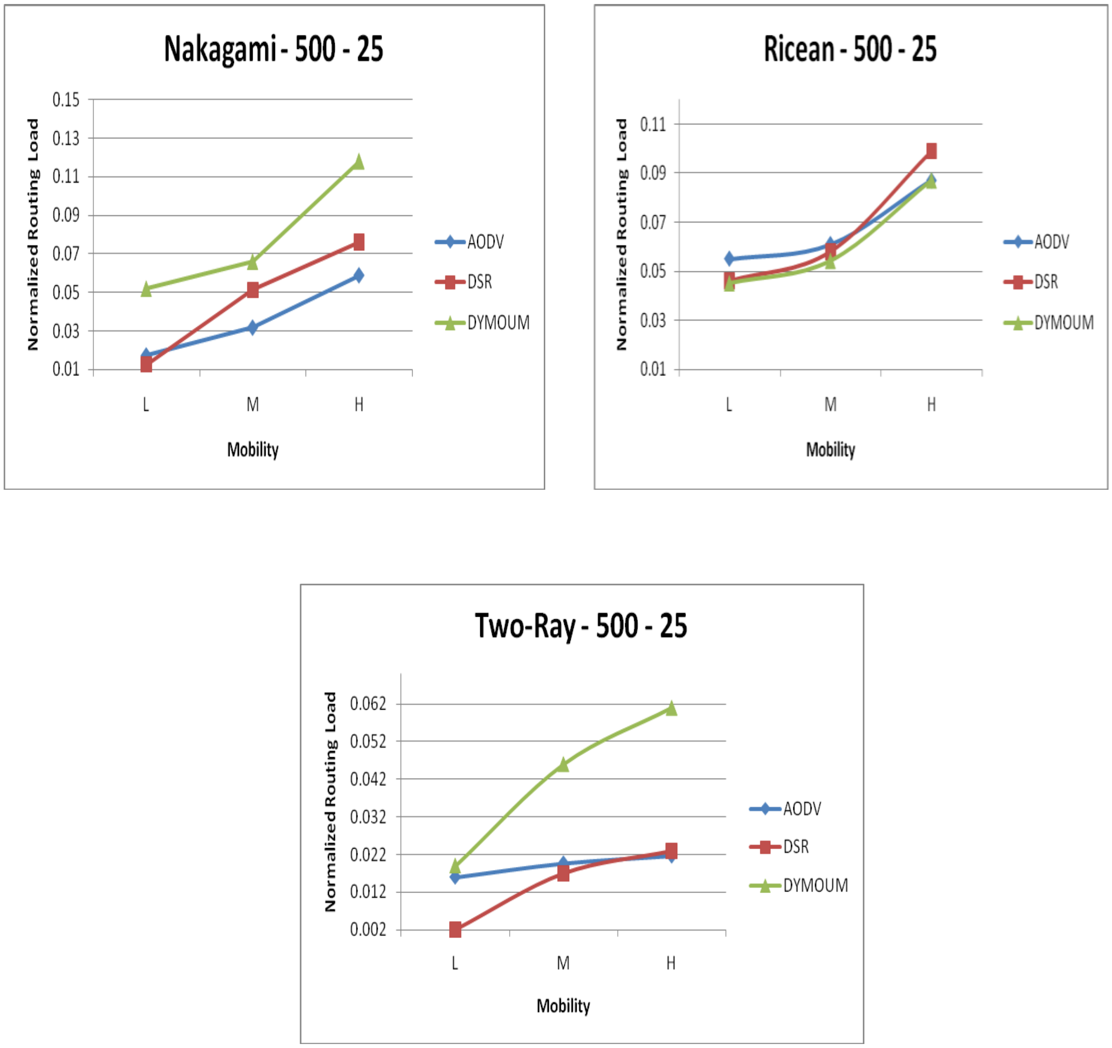


Figure 6.1. NRLVs. Mobility in 500mX500m Grid and 25 Nodes

It is observed that, with no fading, all the protocols exhibit a very low normalized routing load, here onwards referred to as NRL. AODV and DYMO exhibit almost equal routing load at a lower mobility. However, DSR shows a least overhead at lower mobility and this can be attributed to the fact that routing operation of the intermediate node is not required in DSR protocol. As the mobility increases, AODV and DSR show a very small increment, whereas, DYMO shows a drastic increase in the amount of NRL. This can be explained in terms of path accumulation feature of DYMO. Due to path accumulation, a lot of routing information stored by the potential routing nodes becomes obsolete due to fast link creation and link breaks under higher mobility. Thus, with increasing mobility, a lot of control traffic is generated in frequent updating of alternative routes, thereby resulting into a very high control overhead.

However, when modeled under a Ricean fading, all three protocols show an approximately similar behavior at different levels of mobility. In Nakagami fading, DSR and AODV has almost the equal amount of overhead. At medium mobility, DSR shows a slightly higher routing load than AODV. DYMO has a very high overload during lower mobility which further increases as the mobility increases. This observation provides a clue to the fact that AODV can be relatively more resistant to the effect of fading even under a high mobility.

In general, every case of 500m X 500m topology size with 25 nodes and under all propagation channels has shown an increase in the normalized routing load as the mobility increased. AODV and DSR show a comparable performance increasing almost proportionally with increasing mobility. However, DYMO exhibited a large increase in NRL during higher mobility. Amount of variation is significantly impacted by the effects of fading.

6.2.2. 500m X 500m Grid Size and 50 Nodes. Performance under a 50 node scenario can be analyzed by careful observation in Figure 6.2.

All the protocols caused a higher normalized routing load in case of 50 nodes as compared to the 25 nodes. This can be attributed to higher congestion and high internodal interference. The variation of normalized routing load in a non fading propagation was, however, uniform across all three protocols. While control overhead due to DYMO was very high under all degrees of mobility, AODV and DSR showed approximately equal performances. A sharp increase was observed in the routing load as the mobility varied from medium to high and this is essentially due to frequent link breaks. In case of Ricean fading, DYMO performed worst with normalized routing load as high as 20% desirable.

NRL increases as the mobility increases and this is evident in fading as well as non fading channels. All three protocols show almost equal performance in terms of NRL at lower mobility. At higher mobility and under the effects of fading, AODV outperforms DSR and DYMO. Under the chosen operating environment, higher node density further increases NRL at every level of mobility.

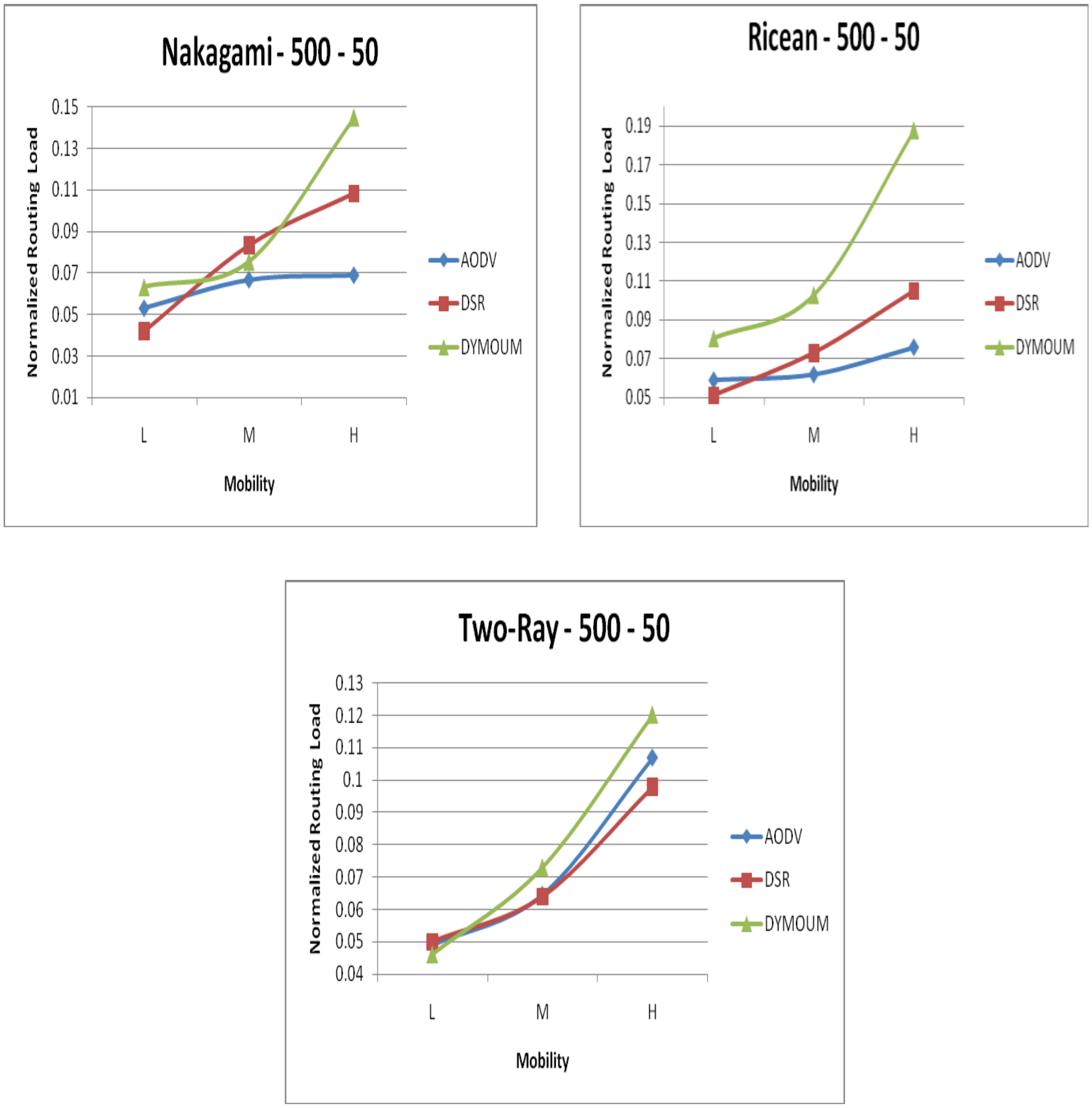


Figure 6.2. NRL Vs. Mobility in 500mX500m Grid and 50 Nodes

6.2.3. 700m X 700m Grid Size and 25 Nodes. The effect of mobility on normalized routing load in 700m X 700m grid size with the 25nodes can be understood by careful observation of Figure 6.3. Higher NRL can be observed even at a low mobility, as compared to the smaller and denser networks. In general NRL increased with increasing mobility. This can be explained based on the network sparseness.

The nodes are at a range of 140 m at an average which is still within the nominal range but much sparser than in case of the two operating scenarios discussed in Sections 6.2.1 and 6.2.2. .Furthermore, in case of fading, due to multi-path the signal perceived by the receiving node is less than the Receiving Threshold (RxThresh). Thus, multiple retries over the weak link causes increased control packet generation thereby increasing the normalized routing load.

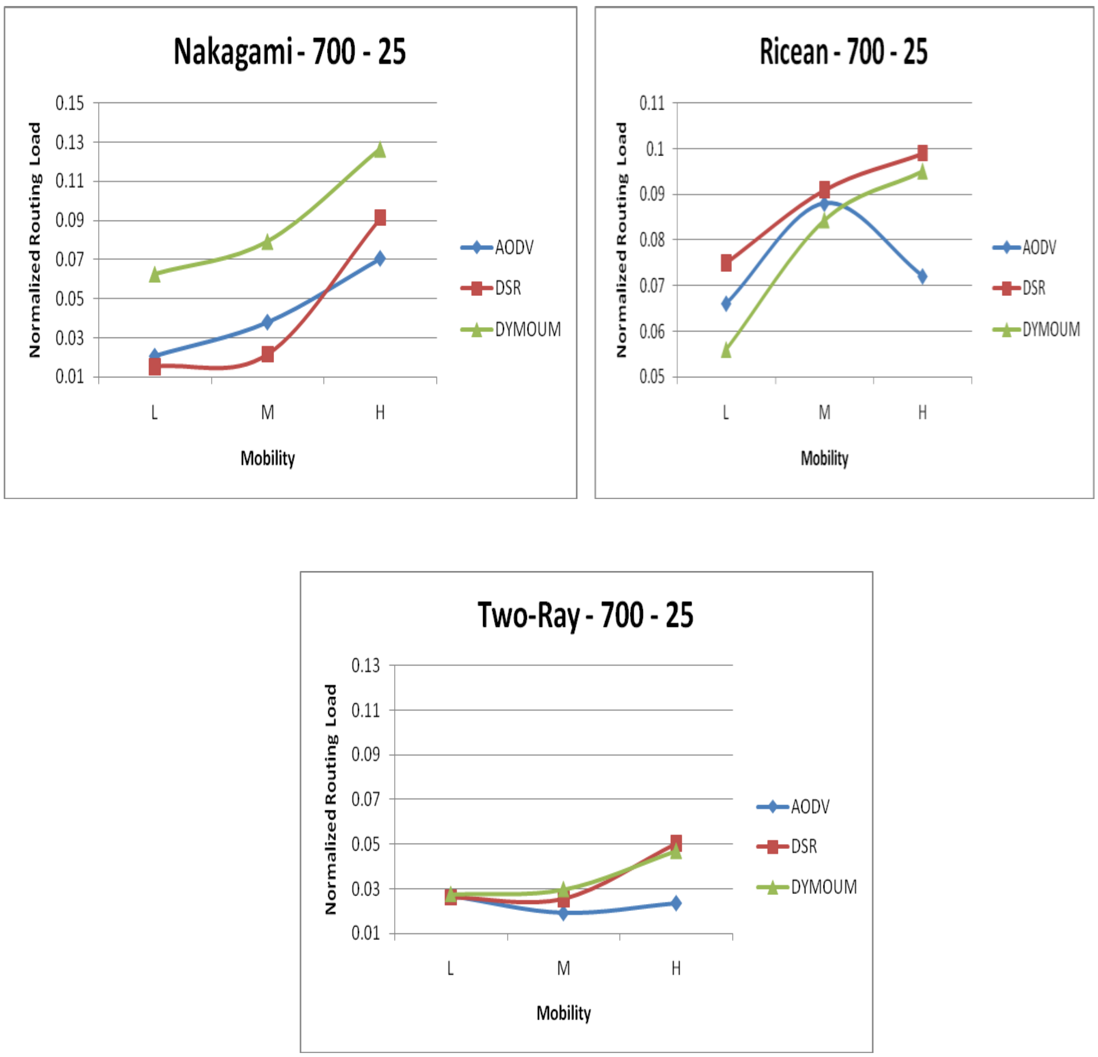


Figure 6.3. NRL Vs. Mobility in 700mX700m Grid and 25 Nodes

Under all three propagation DYMO shows a higher increase in the NRL with increasing mobility which can be attributed to ineffective usage of the accumulated routing information. A lot of obsolete accumulated routing path is updated each time the topology changes. However, due to lesser traffic this routing information are not utilized effectively. Thus, higher control packets are generated for the updates but due to lesser connectivity amount of received packets in low. Another significant observation can be made by observing the NRL of AODV due to Ricean fading. The NRL increases as the mobility increase from low to medium mobility. However, under higher mobility the NRL is significantly lower than under a medium mobility case. This can be attributed to the constructive interference phenomena due to multi path signal propagation. It is also possible that node cluster could form which can render the task the of protocol complex. Thus, this phenomenon could better be described by considering other mechanisms which might not be within the scope of the study. As in previous sections, increasing normal routing load was observed across increasing mobility in most cases. Also, the variation was largely affected by the fading effects.

6.2.4. 700m X 700m Grid Size and 50 Nodes. The outcome of the simulation with 50 nodes in 700m X 700m grid size is illustrated in Figure 6.4. While all three protocols have shown a higher routing load at medium mobility, a significant drop has been observed when the mobility is very high. Due to a very high mobility, the communicating nodes can be out of range for most of the time. Sender, however, resends routing packets up to the allocated retry limit. Retry limit is a mac layer parameter. If no routes could be established within the maximum retry limit, the sender assumes a permanent link failure and therefore, it stops sending more control packets.

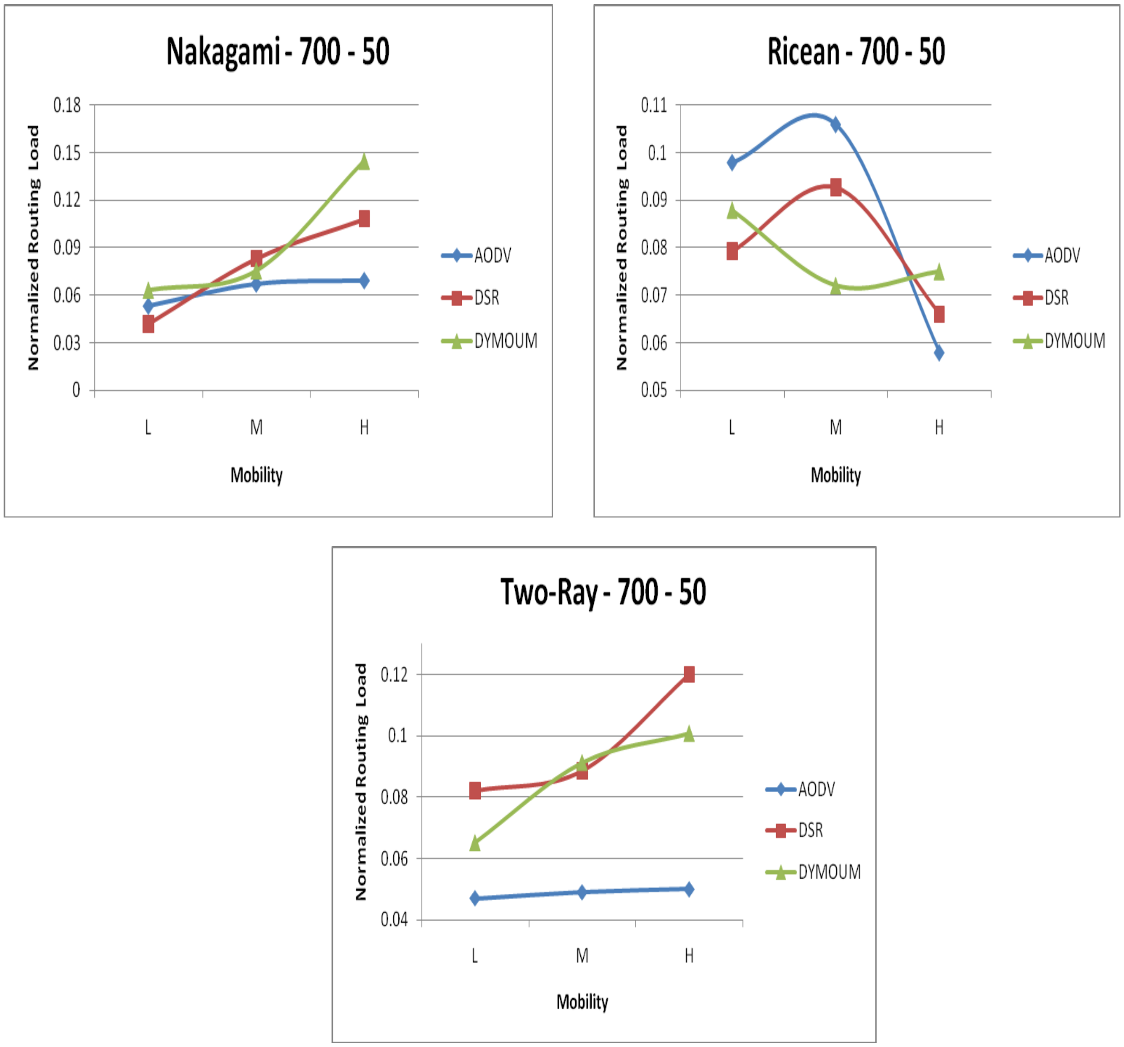


Figure 6.4. NRL Vs. Mobility in 700mX700m Grid and 50 Nodes

In the absence of any large amount of dropped communication the normalized routing load also reduces. Furthermore, a larger routing load is observed as compared to the network topology of Section 6.2.3 which can be attributed to high interference and congestion on the scaled up network. Under a no fading condition, AODV shows insignificant increase in the routing load. Furthermore, much increase is observed under higher mobility as compared to low mobility condition. Increase in the routing load due to mobility can be explained with respect to frequent link updates and updates to ensure local connectivity through hello packets DYMOUM shows a more expected result, control overhead increasing with the degree of mobility.

An expected trend of increasing NRL with increasing mobility was observed. DYMO exhibited a reduced NRL as compared to its performance under 500m X 500m scenario. However, unlike in less denser networks, DSR exhibited a significantly high NRL. Although this had been expected for a non fading environment from the findings of [7], it has also been shown valid under the effects of fading. With this, it can be conclude that more control overhead is generated by DSR when implemented in a highly mobile scenario under the effects of fading.

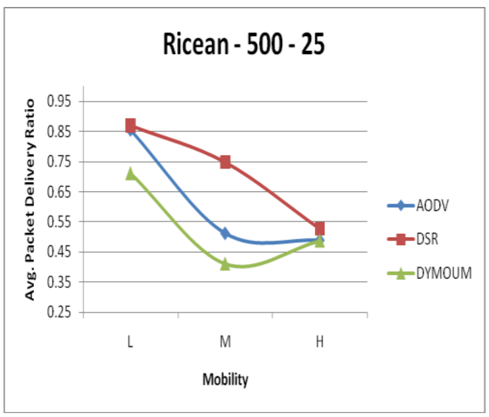
6.2.5. Conclusion. Several significant insights can be drawn pertaining to the effectiveness of the protocols under various operating environment types. Based on the observed trend, it can be concluded that the routing overhead increases as the mobility increases. However, no exact proportion of the increment can be suggested within the scope of the study. All three protocols showed performance degradation across mobility with few exceptions in case of extreme density and Ricean fading. This is due to random nature of simulation and limited time for which the simulation was run.

Based on the performance of the protocol in terms of NRL with respect to mobility, it can also be concluded that each of the protocols perform well under specific operating condition. All the protocols had almost similar NRL at lower speed. However, in higher mobility, AODV was marked for its consistence and comparatively minimal routing load. DSR outperformed the other two in most cases of lower mobility and at a lower network density. By comparing the operation of DYMO in 500X500 and 700X700 scenario, it can be argued that under higher mobility, DYMO is more effective in a sparse network than in dense. Another important conclusion that can be drawn from the analysis is about the effects of fading. Performance of the protocols showed significant variation when operating with fading or without fading. The abnormal simulation results in a denser network and higher mobility can be expected to be the impact of fading; however, it cannot be stated within the scope of this research.

6.3. IMPACT OF SPEED ON OVERALL END-TO-END MEASURES

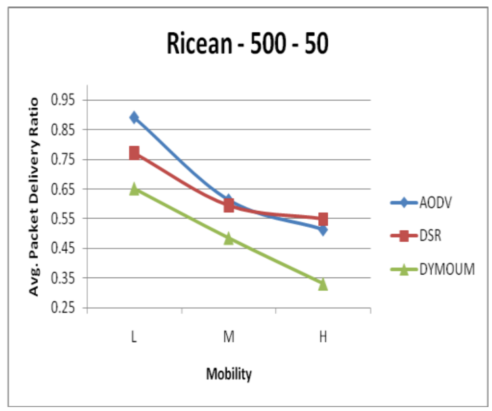
Some important findings from the analysis of the end-to-end performance of the protocols are discussed in this section. Only the graphs representing the outcome in the case of Ricean propagation are included in the subsections to provide more illustration. More detailed information can be obtained from Appendix E.

6.3.1. Packet Delivery Ratio. It can be seen from Figure 6.5 that the packet delivery ratio decreases with the increasing mobility.



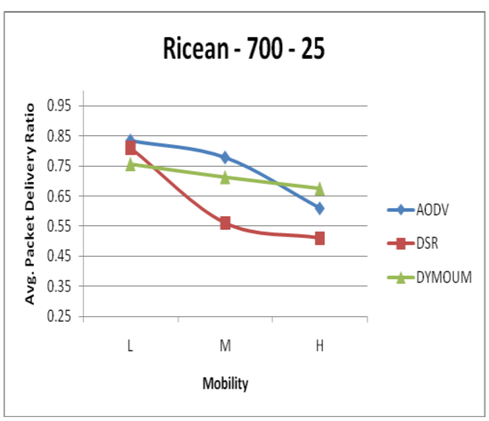
Grid size= 500mX 500m

Number of Nodes=25



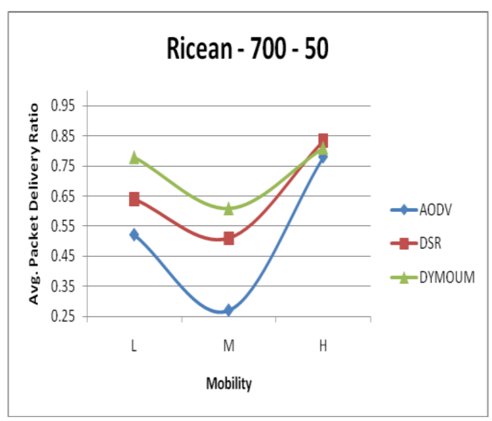
Grid size= 500mX 500m

Number of Nodes=50



Grid size= 700mX 700m

Number of Nodes=25



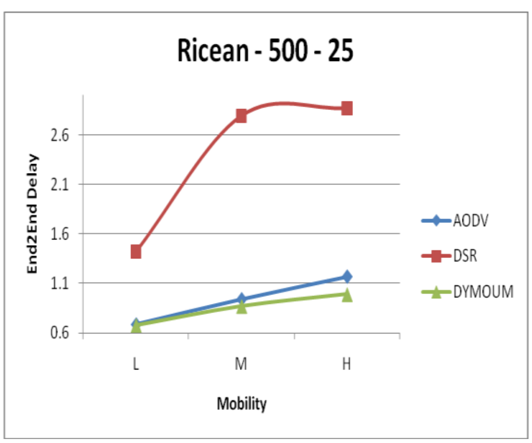
Grid size= 700mX 700m

Number of Nodes=50

Figure 6.5. Packet Delivery Ratio Vs. Mobility

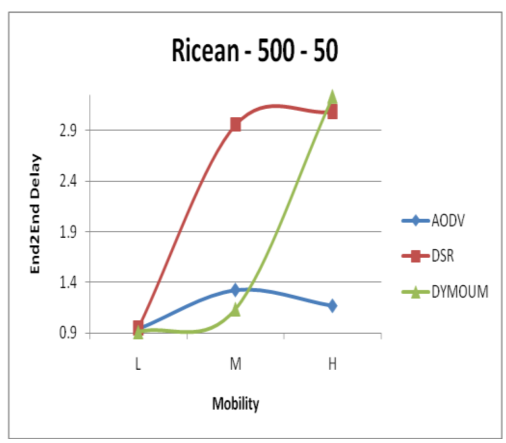
While DSR outperforms AODV and DYMO in 500mX500m at lower mobility, DSR shows a reduced performance at larger networks with more number of traffic. This is due to the fact that a lot of packets are dropped due to higher congestion, higher congestion being the outcome of larger data packets carrying the information of all intermediate nodes in its header. Comparatively, DYMO seems more prone to the performance degradation due to increasing mobility, but it shows a better performance in higher sparseness.

6.3.2. End-to-End Delay. In Figure 6.6, it can be seen that DYMO and AODV exhibit low and almost equal delay under low mobility. DSR has a very high delay even at a low mobility which increases with the mobility. In DSR a large number of routes are cached and updated frequently; however, routes become obsolete before they could be used effectively. A lot of time is spent in caching and cache update. The abnormality of graphs in 700m X 700m grid with 50 nodes may be due to due to higher congestion and increased mac retries caused by unreliable routes. In large number of cases in TwoRayGround propagation, delay increases with increasing mobility. However, this cannot be declared in case of Ricean and Nakagami propagation where high variation in end-to-end delay has been observed particularly in case of large denser network.



Grid size= 500mX 500m

Number of Nodes=25



Grid size= 500mX 500m

Number of Nodes=50

Figure 6.6. End-to-End Delay Vs. Mobility

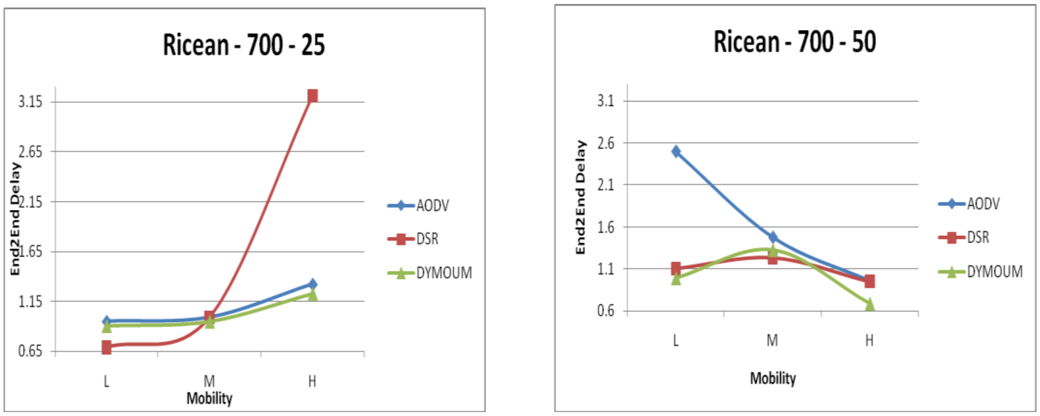


Figure 6.6. End-to-End Delay Vs. Mobility (cont.)

6.3.3. Average Throughput. It can be observed from Figure 6.7 that average throughput decreased with increasing mobility. This implies that the links are relatively stable and more reliable at lower mobility. Thus, more data is successfully delivered to a receiver. Route cashing seems a better choice in a smaller network even with fading effects. At the same time, more routing operation at the intermediate node, which occurs in DYMO routing, seems to reduce the average throughput.

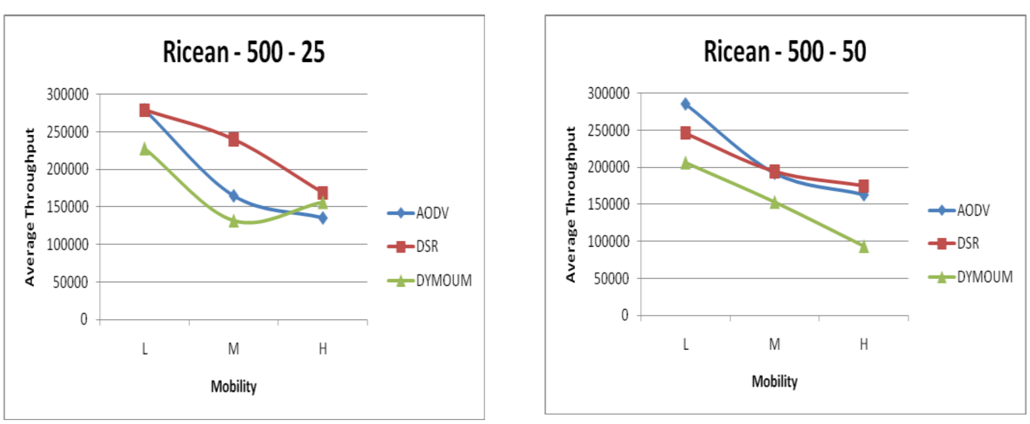
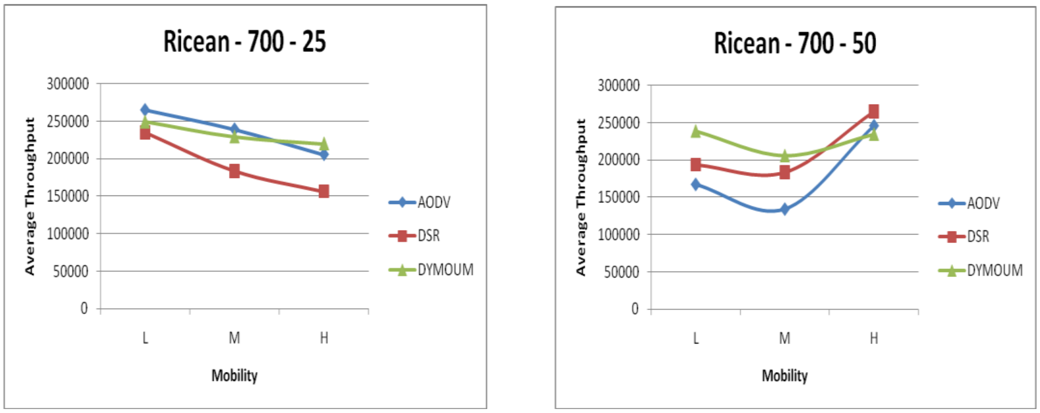


Figure 6.7. Average Receiving Throughput Vs. Mobility



Grid size= 700mX 700m Number of Nodes=25

Grid size= 700mX 700m Number of Nodes=50

Figure 6.7. Average Receiving Throughput Vs. Mobility (Cont.)

6.3.4. Discussion. It has been proved through the simulations that control overhead increases with increasing mobility. Overall increase in the control overhead and decrease in the PDR gives an important insight that the performances of the protocols in general are degraded with increasing mobility. In addition, the end-to-end delay increases with increasing mobility as shown in Figure 6.6. The relation 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. This significantly reduces the number of received data and increases end-to-end delay.

The other significant conclusion can be derived on the basis of difference in performance of a protocol due to fading effect. Although the variation of PDR is almost linear across TwoRayGround model, highly inconsistent variation is observed in case of Ricean and Nakagami Models. This suggests that the average PDR is significantly affected by small-scale fading under high mobility. As the amount of mobility increases, there is an increase in the number of dropped and lost packets due to frequent link-route breaks. This results into a smaller amount of successful data delivery to the intended receiver. All three reactive protocols exhibited a significantly decrease of PDR along increasing mobility. This provides an important clue to the fact that the implemented protocols are less adaptive to rapidly changing topology.

The outcomes of the simulation with TwoRayGround propagation comply with the findings of performance comparison in [7] [8], where, control overhead has been found to be increasing with increasing mobility where as PDR has been found to be decreasing. However, the fact that mobility has been measured in terms of relative velocity and pause time respectively in those studies as opposed to actual speed in this study doesn't allow direct comparison. Similarly, the performances of AODV, DSR and DYMO at different degree of network density can be validated with the findings of [11]. All the comparative study performed in the past on a similar domain has made simplifying assumptions about the propagation channel and mobility. Thus, by providing the result of a highly realistic simulation performed across a large number of variables, this research makes an important contribution to this research area.

6.4. SECTION SUMMARY

By performing simple simulations on a highly realistic simulated environment, a more accurate response of a MANET due to varying mobility, node density and traffic has been observed across the three reactive routing protocols. Although DSR and DYMO have shown to outperform the other protocols under a specific operating conditions, AODV exhibited a more stable response across wider range of operating condition. However, it was observed that all three protocols suffered from performance degradation as the mobility increased and this was more conspicuous with added effects of fading. Thus, it becomes very important to address the fact that further enhancement to the existing routing protocol is needed to incorporate adaptability towards mobility and fading. This fact leads to a new direction towards protocol design and consideration-the realization of mobility aware reactive routing protocols.

No generalized conclusion can be made on the effectiveness of a protocol from this study. However, based on the response of the protocol towards increasing mobility and a scaled up network, it is highly suggested that AODV be taken into further consideration for incorporating speed awareness in its routing strategy.

7. FUTURE DIRECTIONS

Although the existing reactive MANET protocols have shown a fair performance under small sized network with less traffic and moderate mobility, their capabilities might not be sufficient to achieve the performance demand imposed by high-priority safety critical applications, where, high mobility is crucial. These applications include mobile medical facilities and tactical warfare where reliability of a communication link is of a very high prominence. Thus, a routing protocol which is robust and can effectively operate under fading, without significantly compromising the network performance needs to be developed. The proposed routing strategy considers incorporating speed awareness into an existing reactive protocol such that less stable and unreliable links due higher mobility can be avoided. While there can be many alternative ways to achieve the proposed goal, one possible way in which the proposed goal can be achieved without incurring higher overhead is briefly explained in this section.

It is proposed that speed be included as one of the parameters in control packet headers. As in any reactive protocols, a host node sends a RREQ in order to establish a new route. RREP from all the potential intermediate nodes is sent back to the host along with the information about intended receiver. The reply which also includes speed as one of the routing information is then processed at the lower layer to analyze if the speed of the node is within acceptable range for creating a stable route. Any node in the intermediate route with higher velocity is subject to immediate exclusion from the list of potential intermediate nodes. GPS information is suggested for selective routing through only those nodes with lower speed. This routing strategy ensures that all the intermediate nodes have relatively lower velocity and consequently, all the links formed are relatively stable. However, it is important to realize that generating higher control overhead to achieve this goal would violate the whole essence of effective routing for a MANET. There are several issues that have to be taken into consideration before proceeding with the design of proposed routing strategy.

The routing mechanism could be effective only if the algorithm could be implemented at a physical layer of a mac layer. This saves time and resources that can be consumed for processing speed-included control packet header. The mechanism should ensure no degradation along a significant performance measures depending on the application type. Also, it is important to validate if the proposed strategy complies with the routing operations at the higher layer. While the idea is expected to be an effective approach to counter the challenge of creating multi-hop routing in high mobility environment, nothing can be said about its usefulness without a comprehensive study.

Although some of the design consideration towards achieving a SARP is addressed in this section, a comprehensive study is needed for the validation of the proposed idea. Protocol design and implementation more comprehensive research and is left for a future work.

APPENDIX A.
MANET APPLICATIONS

Table A.1. MANET Applications

Applications	Description/services
Tactical Networks	• Military communication, operations • Automated Battlefields
Sensor Networks	• Home Applications: smart sensor nodes and actuators can be buried in Appliances to allow end users to manage home devices locally and remotely • Environmental applications include tracking the movement of animals (e.g. birds and insects), chemical /biological detection, precise agriculture etc. • Tracking data highly correlated in time and space e.g. remote sensors for weather , earth activities
Emergency Services	• Search and rescue operations, as well as disaster discovery; e.g. early retrieval and transmission of patient data (record, status, diagnosis) from/to hospital • Replacement of a fixed infrastructure in case of earthquakes, hurricanes, fire etc.

Commercial Environments	• E-Commerce e.g., Electronic payments from anywhere (i.e. taxi)
	• Business :
	    • dynamic access to customer files stored in a central location on the fly
	    • provide consistent databases for all agents
	    • mobile office
	• Vehicular Services:
	    • Transmission of news, road condition, weather, music
	    • Local ad hoc network with nearby vehicles for road/accident guidance

Home and Enterprise Networking	• Home/Office Wireless Networking (WLAN) e.g., shared white board application; use PDA to print anywhere, trade shows • Personal Area Network(PAN)
Educational Applications	• Virtual classrooms or conference rooms • Ad hoc communications during conferences , meetings or lectures
Entertainment	• Multi-user games • Robotic pets • Outdoor internet access

Location Aware Services	• Follow-on services e.g., automatic call forwarding, transmission of the actual workspace to the current location
	• Information Services:
	    • Push, e.g., advertise location specific service like gas stations
	    • Pull, e.g., location dependent travel guide; services(printer, fax, phone, server, gas stations) availability information

APPENDIX B.

MODIFICATION OF MAC-802_11.CC

Table B.1. Modification of MAC-802_11.cc

Current Code Snippet

```
if (*rcount == 3 && handoff == 0)* {
        //start handoff process
        printf("Client %d: Handoff Attempted\n",index_);
        associated = 0;
        authenticated = 0;
        handoff = 1;
        ScanType_ = ACTIVE;
        sendPROBEREQ(MAC_BROADCAST);
        return;
    }
```

Even in case of ad hoc scenarios where there is no Access Points, a node attempts for Handoff, viz., it configures a Probe Request and goes to start the Backoff timer.

The correction is trivial as shown below. We have to just include the condition for the existence of infra structure mode.

Modification Suggested

```
if (*infra_mode_ *&& *rcount == 3 && handoff == 0) {
        //start handoff process
        printf("Client %d: Handoff Attempted\n",index_);
        associated = 0;
        authenticated = 0;
        handoff = 1;
        ScanType_ = ACTIVE;
        sendPROBEREQ(MAC_BROADCAST);
        return;
    }
```

APPENDIX C.

OTCL SCRIPT USED FOR THE SIMULATION

```
#===== Basic parameters for the simulation model.=====
puts "DEFINING VARIABLES"
set val(chan)     Channel/WirelessChannel   ;# Channel type
set val(prop)     Propagation/Ricean       ;# 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/bandana/Desktop/NS/500/mov-500-25-l"
set val(traff) "/home/bandana/Desktop/NS/traffic/Run8_cbr25"
set val(RiceanK)        0                  ;# Ricean K factor
set val(RiceanMaxVel)   0.0          ;# Ricean  Propagation  MaxVelocity
# Ricean  Propagation: Maximum ID of nodes
set val(RiceMaxNodeID)  [expr {$val(nn)-1}]        ;
```

```
# Ricean Propagation Data File
set val(RiceDataFile)   "/ home/bandana/Desktop/NS/ rice_table.txt "
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
# Set propagation settings
if { $val(prop) == "Propagation/Ricean"} {
   set prop_inst [$ns_ set propInstance_]
```

```
   $prop_inst MaxVelocity  $val(RiceanMaxVel);
   $prop_inst RiceanK      $val(RiceanK);
   $prop_inst LoadRiceFile  $val(RiceDataFile);
   $prop_inst RiceMaxNodeID $val(RiceMaxNodeID);
 }
#=== Sets the configuration for ALL nodes =======
for {set i 0} {$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 D.

DATA AVERAGED OVER 10 RUNS OF SIMULATION

Table D.1. Data Averaged Over 10 runs of Simulation (AODV)

Grid Size	No. of Nodes	Propagation Model	Level of Mobility	NRL	PDR	E2E Delay	Avg. Throughput
500m^2	25	Nakagami	Low	0.784	0.909	0.017	286780
			Medium	0.850	0.725	0.032	239610
			High	1.476	0.580	0.059	184578
500m^2	50	Nakagami	Low	0.560	0.931	0.053	296559
			Medium	0.930	0.872	0.067	275612
			High	1.590	0.681	0.069	210944
700m^2	25	Nakagami	Low	0.650	0.881	0.021	245102
			Medium	0.700	0.732	0.038	189762
			High	1.340	0.410	0.071	155686
700m^2	50	Nakagami	Low	0.450	0.910	0.034	287612
			Medium	0.830	0.854	0.061	253356
			High	1.850	0.657	0.066	192401
500m^2	25	Ricean	Low	0.685	0.856	0.055	279750
			Medium	0.940	0.512	0.061	164615
			High	1.169	0.489	0.087	135007
500m^2	50	Ricean	Low	0.940	0.891	0.059	285389
			Medium	1.324	0.613	0.062	192127
			High	1.169	0.514	0.076	163064
700m^2	25	Ricean	Low	0.950	0.835	0.066	264850
			Medium	0.990	0.779	0.088	238954
			High	1.323	0.610	0.072	205471
700m^2	50	Ricean	Low	2.500	0.521	0.098	167433
			Medium	1.480	0.270	0.106	134564
			High	0.960	0.780	0.058	245673
500m^2	25	Two-Ray	Low	0.670	0.946	0.016	302720
			Medium	0.925	0.920	0.020	294400
			High	1.439	0.864	0.022	276480
500m^2	50	Two-Ray	Low	0.970	0.912	0.049	294126
			Medium	1.240	0.847	0.065	277903
			High	1.390	0.779	0.107	223455
700m^2	25	Two-Ray	Low	0.730	0.891	0.027	245102
			Medium	1.020	0.622	0.019	189762
			High	1.142	0.410	0.024	155686
700m^2	50	Two-Ray	Low	0.540	0.910	0.047	276589
			Medium	0.750	0.740	0.049	197534
			High	0.970	0.660	0.050	186812

Table D.2. Data Averaged Over 10 runs of Simulation (DSR)

Grid Size	No.of Nodes	Propagation Model	Level of Mobility	NRL	PDR	E2E Delay	Avg. Throughput
$500m^2$	25	Nakagami	Low	1.120	0.923	0.013	298860
			Medium	1.490	0.826	0.051	267895
			High	2.138	0.684	0.076	210953
$500m^2$	50	Nakagami	Low	1.352	0.926	0.042	292869
			Medium	2.850	0.723	0.083	239541
			High	3.174	0.539	0.108	174890
$700m^2$	25	Nakagami	Low	1.043	0.877	0.015	203481
			Medium	1.052	0.829	0.021	198751
			High	3.120	0.578	0.091	170862
$700m^2$	50	Nakagami	Low	1.790	0.643	0.091	192345
			Medium	2.500	0.521	0.098	167433
			High	1.480	0.270	0.106	134564
$500m^2$	25	Ricean	Low	1.420	0.871	0.046	278720
			Medium	2.790	0.749	0.058	239680
			High	2.868	0.527	0.099	168640
$500m^2$	50	Ricean	Low	0.950	0.771	0.051	246210
			Medium	2.960	0.594	0.073	194237
			High	3.090	0.549	0.105	174521
$700m^2$	25	Ricean	Low	0.690	0.810	0.075	234590
			Medium	0.990	0.560	0.091	183610
			High	3.212	0.510	0.099	156304
$700m^2$	50	Ricean	Low	1.104	0.640	0.079	193754
			Medium	1.230	0.510	0.093	183645
			High	0.950	0.835	0.066	264850
$500m^2$	25	Two-Ray	Low	0.960	0.978	0.002	312960
			Medium	1.003	0.817	0.017	261440
			High	4.100	0.635	0.023	203200
$500m^2$	50	Two-Ray	Low	2.156	0.941	0.050	301780
			Medium	2.780	0.826	0.064	213890
			High	3.113	0.576	0.098	184523
$700m^2$	25	Two-Ray	Low	2.043	0.870	0.026	203481
			Medium	2.890	0.829	0.021	198751
			High	3.610	0.578	0.020	170862
$700m^2$	50	Two-Ray	Low	2.280	0.750	0.082	210976
			Medium	2.994	0.684	0.089	179643
			High	3.539	0.540	0.120	153870

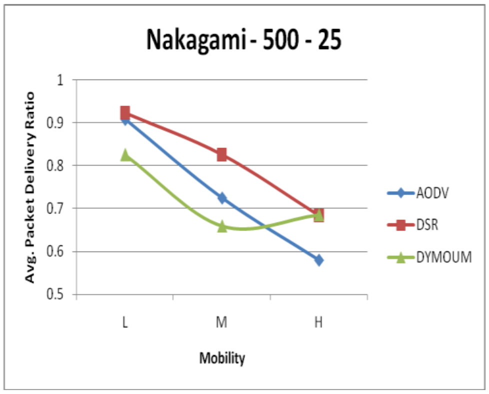
Table D.3. Data Averaged Over 10 runs of Simulation (DYMO)

Grid Size	No.of Nodes	Propagation Model	Level of Mobility	NRL	PDR	E2E Delay	Avg. Throughput
$500m^2$	25	Nakagami	Low	0.833	0.826	0.052	257094
			Medium	0.970	0.659	0.066	167839
			High	1.162	0.685	0.118	98875
$500m^2$	50	Nakagami	Low	0.590	0.515	0.063	164069
			Medium	0.923	0.453	0.076	142739
			High	1.245	0.390	0.145	128654
$700m^2$	25	Nakagami	Low	0.560	0.913	0.062	268912
			Medium	0.990	0.891	0.079	223454
			High	0.990	0.670	0.127	163456
$700m^2$	50	Nakagami	Low	0.960	0.780	0.058	245673
			Medium	1.104	0.640	0.079	193754
			High	1.230	0.510	0.093	183645
$500m^2$	25	Ricean	Low	0.678	0.713	0.045	228160
			Medium	0.870	0.412	0.054	131840
			High	0.990	0.489	0.087	156480
$500m^2$	50	Ricean	Low	0.910	0.653	0.081	205914
			Medium	1.137	0.485	0.103	152986
			High	3.240	0.330	0.188	93786
$700m^2$	25	Ricean	Low	0.906	0.756	0.056	248971
			Medium	0.950	0.713	0.084	229187
			High	1.230	0.676	0.095	219745
$700m^2$	50	Ricean	Low	0.990	0.779	0.088	238954
			Medium	1.323	0.610	0.072	205471
			High	0.690	0.810	0.075	234590
$500m^2$	25	Two-Ray	Low	0.460	0.881	0.019	281920
			Medium	0.670	0.710	0.046	227200
			High	1.450	0.560	0.061	179200
$500m^2$	50	Two-Ray	Low	0.978	0.521	0.046	162390
			Medium	1.194	0.390	0.073	124056
			High	2.000	0.372	0.120	119578
$700m^2$	25	Two-Ray	Low	0.650	0.929	0.028	268912
			Medium	0.680	0.791	0.023	223454
			High	0.740	0.560	0.127	163456
$700m^2$	50	Two-Ray	Low	0.850	0.755	0.065	205739
			Medium	0.770	0.633	0.091	183471
			High	1.146	0.513	0.101	165837

APPENDIX E.

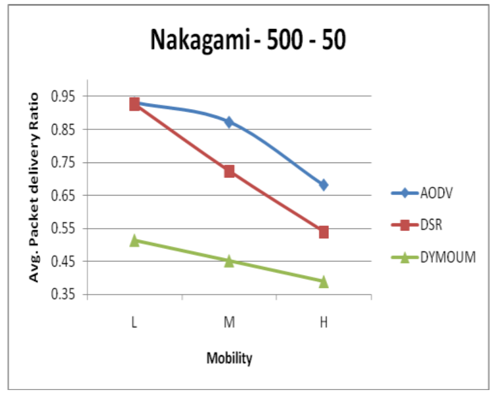
PERFORMANCE COMPARISION OF THE PROTOCOLS

I. Packet Delivery Ratio



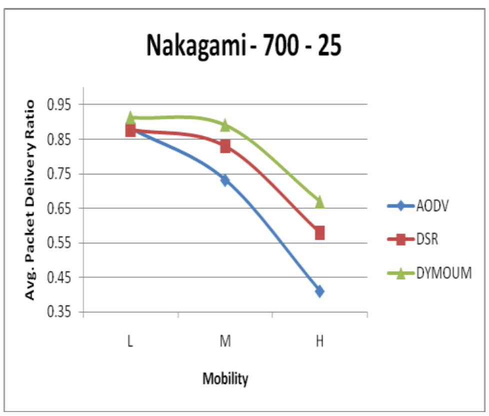
Grid size= 500mX 500m

Number of Nodes=25



Grid size= 500mX 500m

Number of Nodes=50



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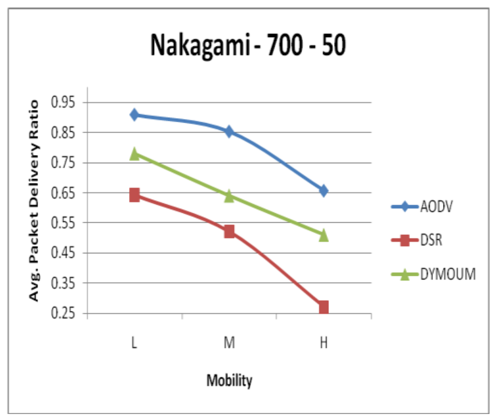
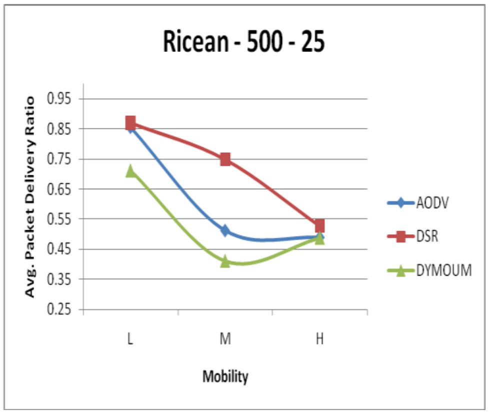


Grid size= 700mX 700m

Number of Nodes=50

Figure E.1. Packet Delivery Ratio Vs. Mobility Under Nakagami Fading



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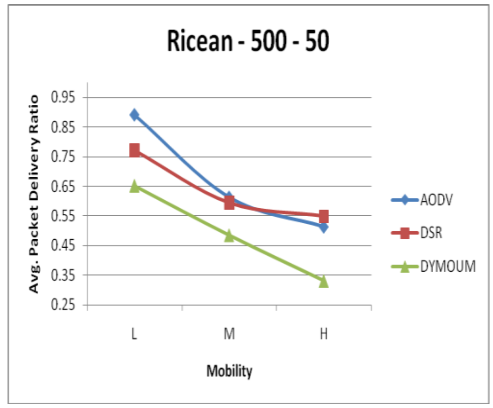
Number of Nodes=25



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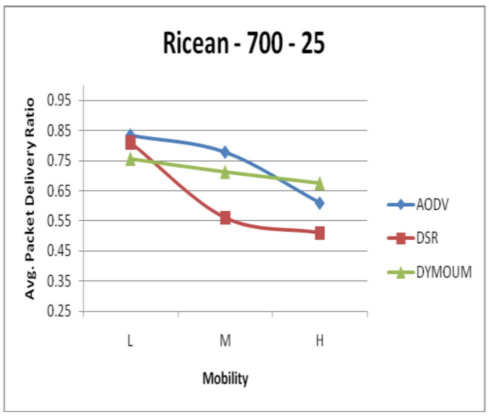
Number of Nodes=50



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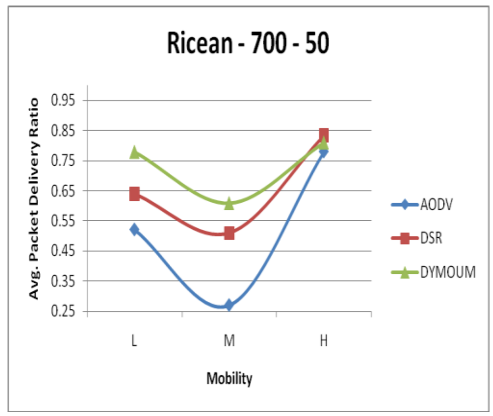

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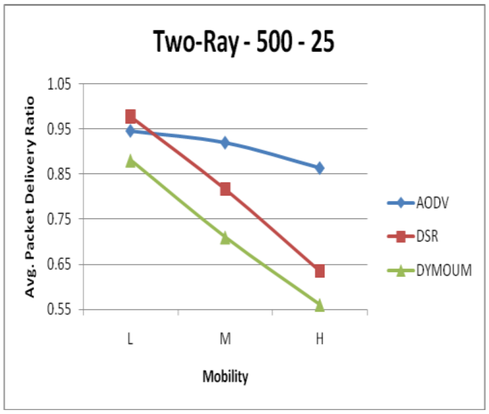
Figure E.2. Packet Delivery Ratio Vs. Mobility Under Ricean Fading



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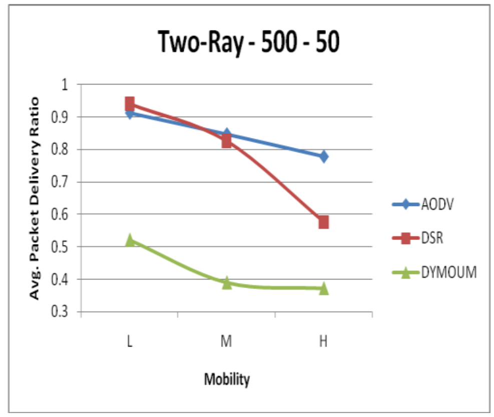

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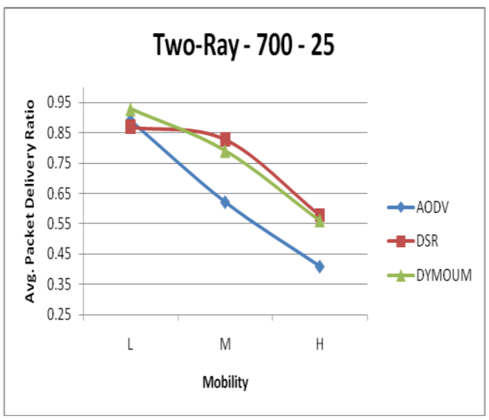

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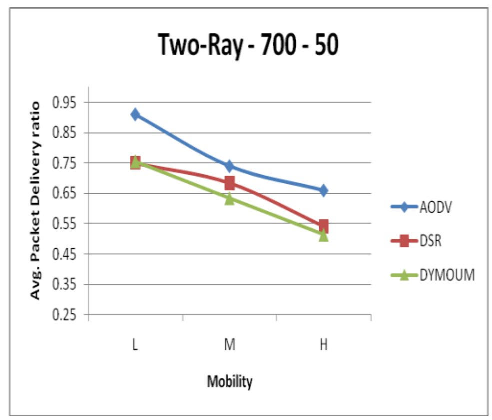

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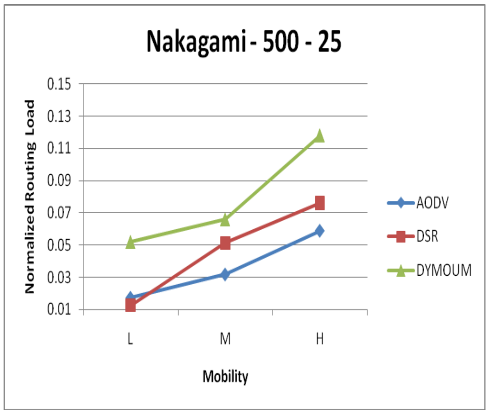
Number of Nodes=50

Figure E.3. Packet Delivery Ratio Vs. Mobility Under TwoRayGround Propagation

II. Normalized Routing Load



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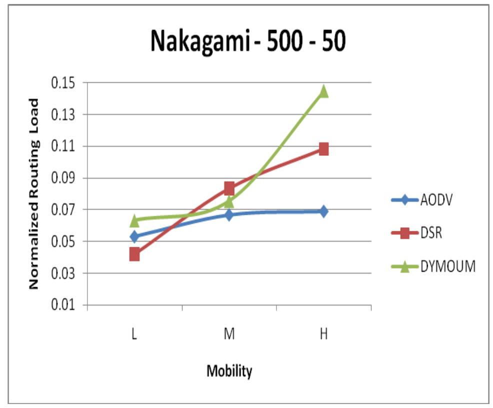
Number of Nodes=25



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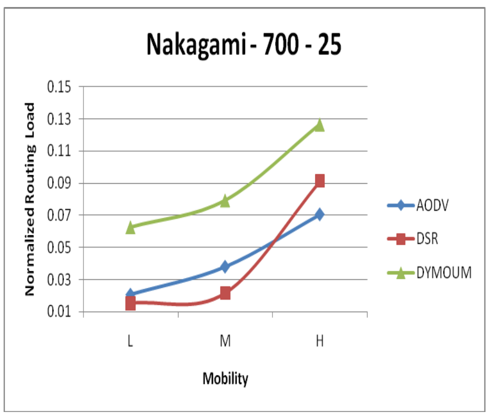

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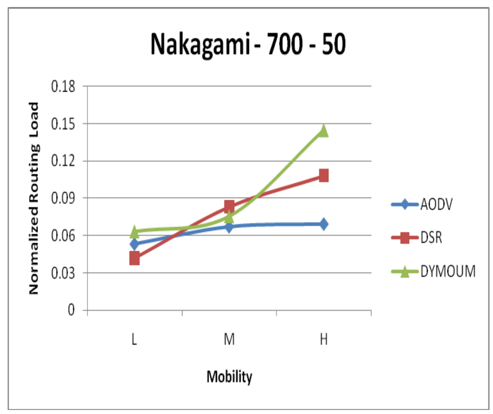

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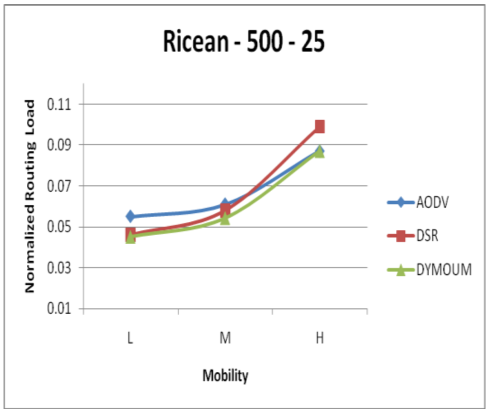
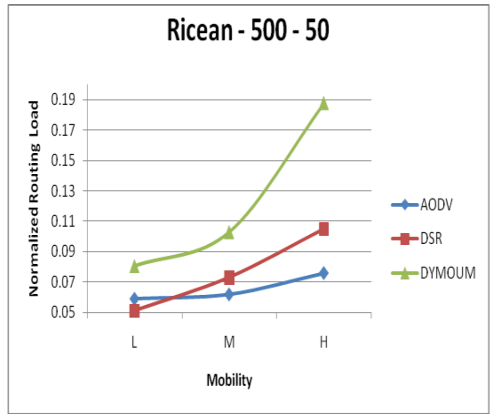
Number of Nodes=50

Figure E.4. Normalized Routing Load Vs. Mobility Under Nakagami fading



Grid size= 500mX 500m

Number of Nodes=25



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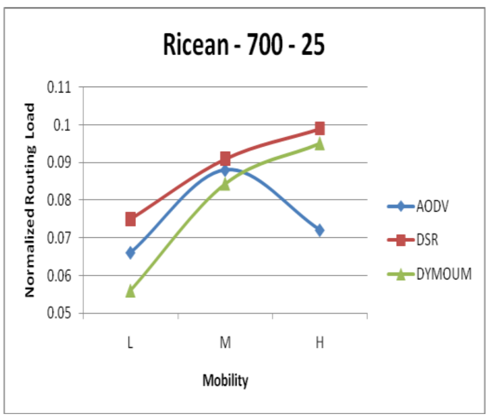

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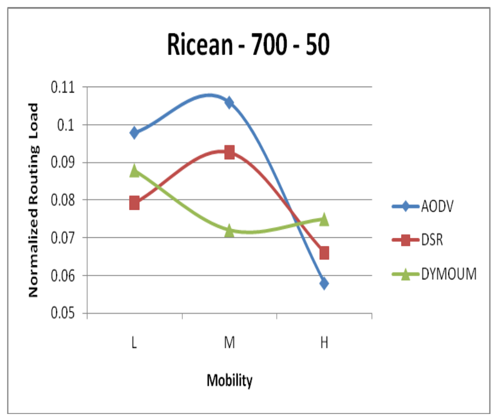
Number of Nodes=25



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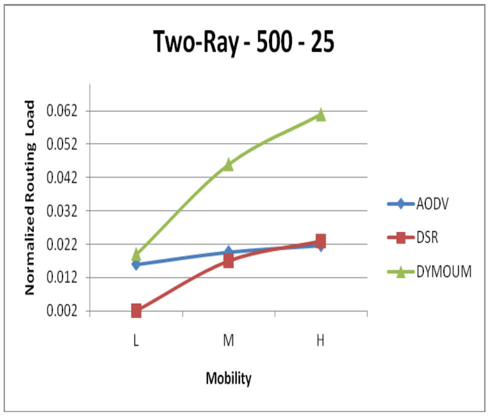
Number of Nodes=50

Figure E.5. Normalized Routing Load Vs. Mobility Under Ricean Fading



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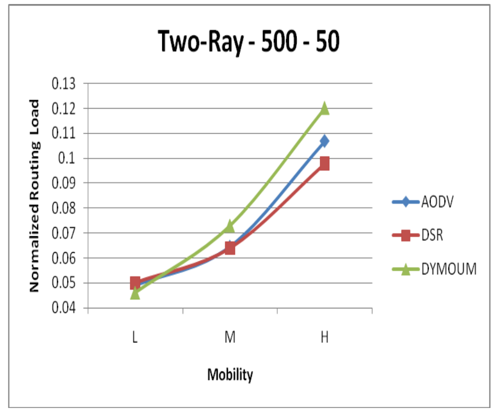
Number of Nodes=25



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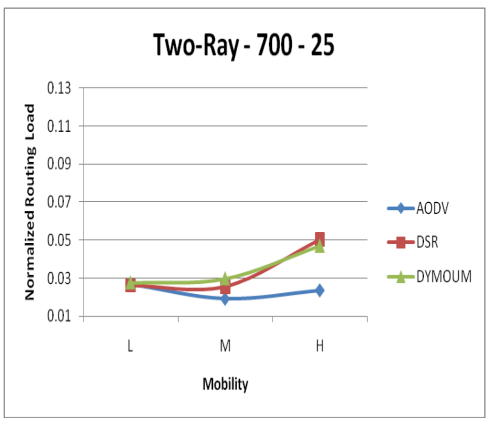

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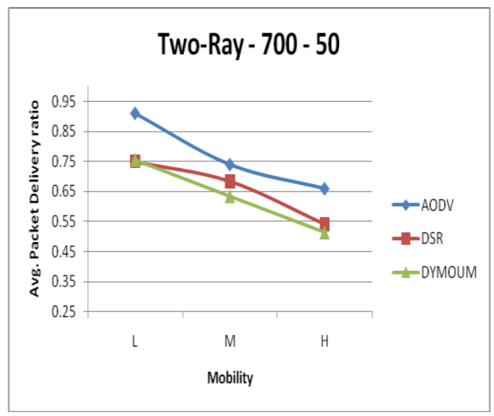

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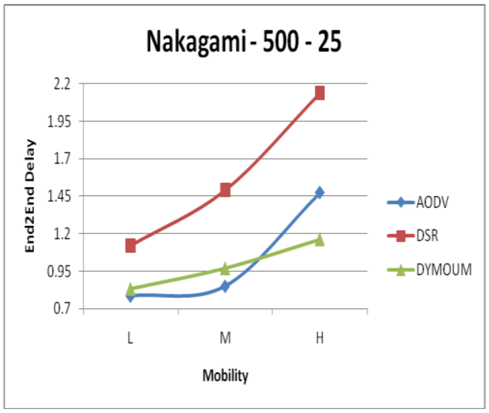
Number of Nodes=50

Figure E.6. Normalized Routing Load Vs. Mobility Under TwoRayGround Propagation

III Average End-to-End Delay



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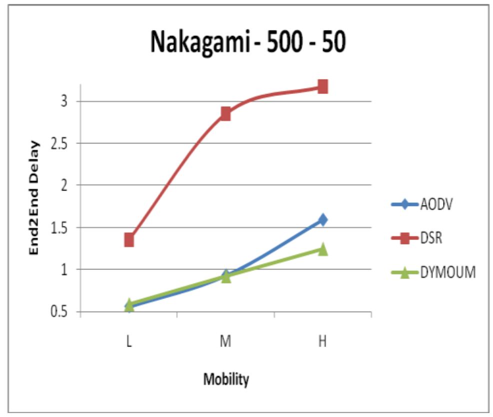
Number of Nodes=25



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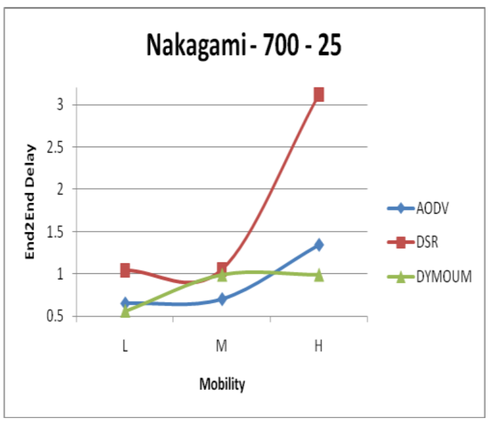

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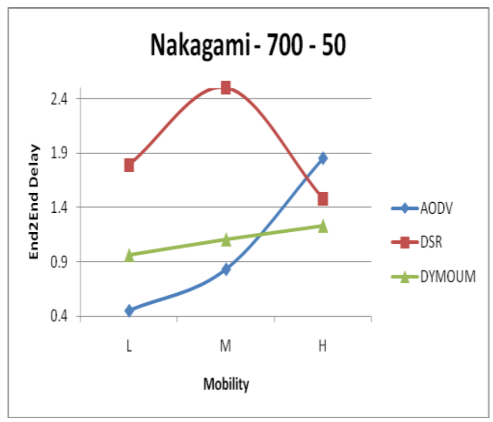

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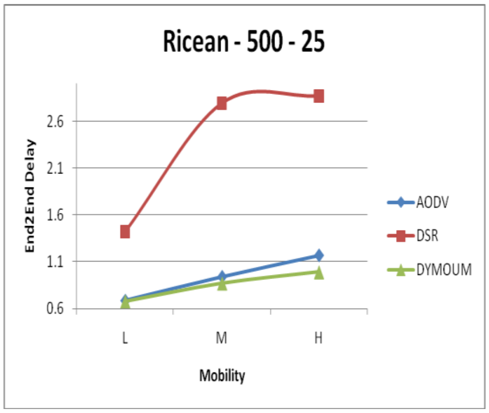
Number of Nodes=50

Figure E.7. Average End-to-End Delay Vs. Mobility Under Nakagami Fading



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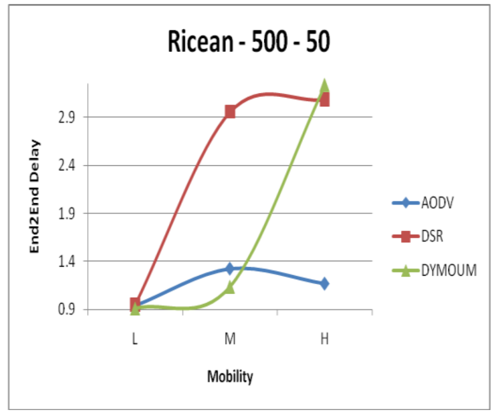

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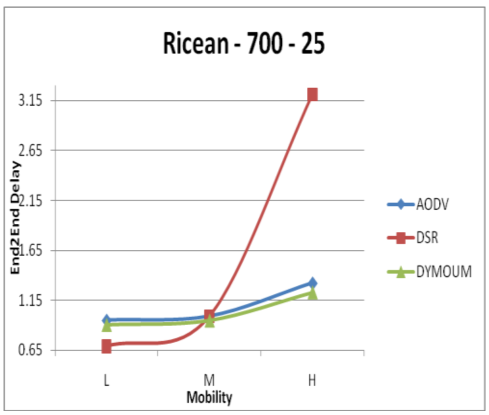

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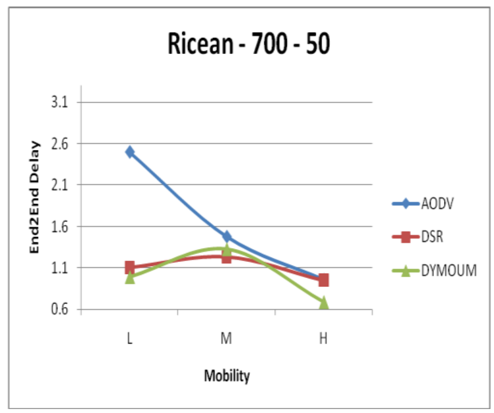
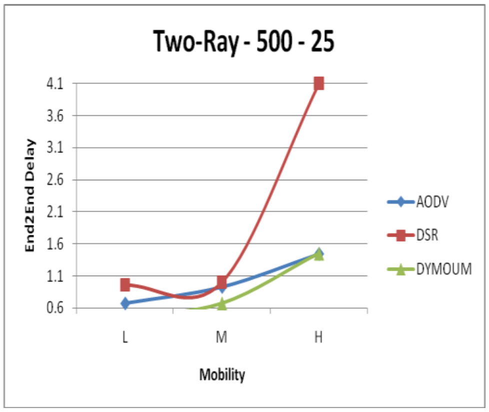
Number of Nodes=25



Grid size= 700mX 700m

Number of Nodes=50

Figure E.7. Average End-to-End Delay Vs. Mobility Under Ricean Fading



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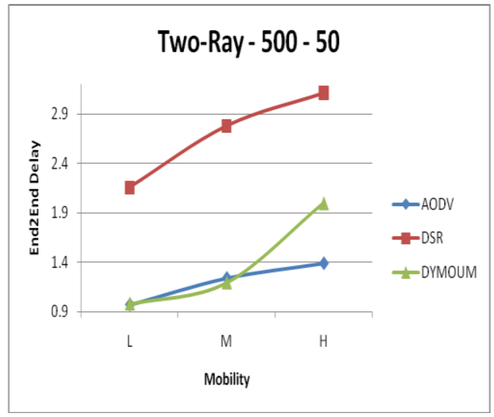

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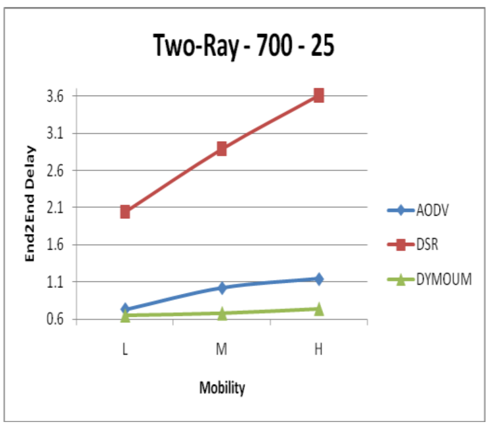

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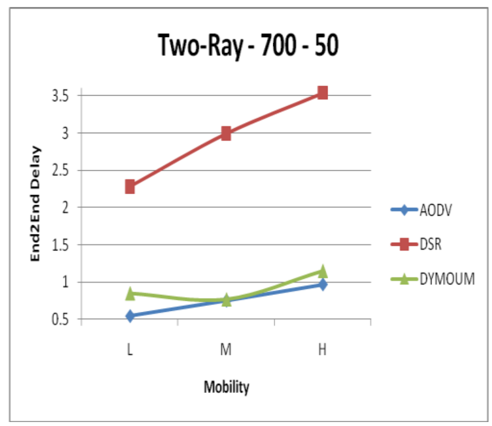
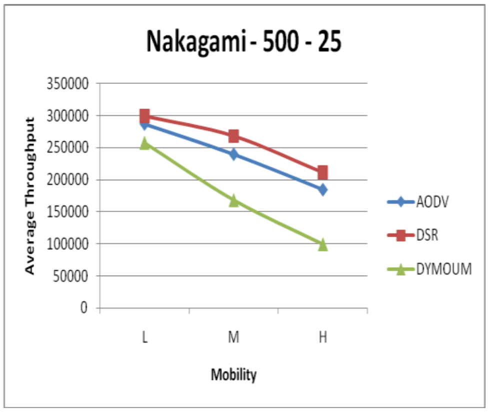


Grid size= 700mX 700m

Number of Nodes=50

Figure E.8. Average End-to-End Delay Vs. Mobility Under TwoRayGround Propagation

IV. Average Receiving Throughput



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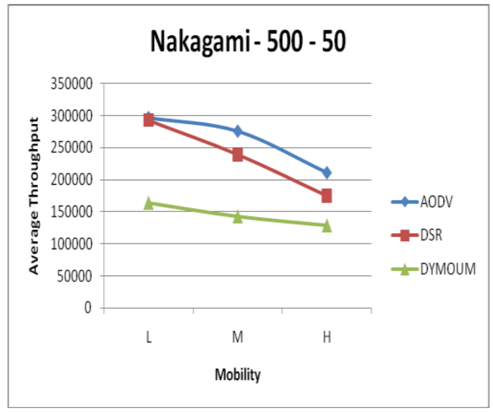
Number of Nodes=25



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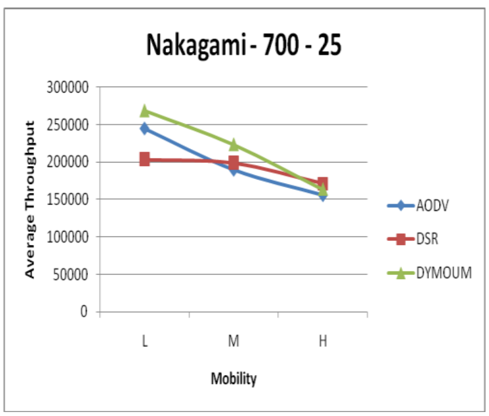
Number of Nodes=50



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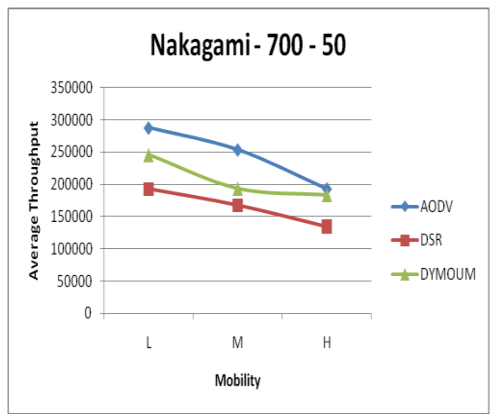

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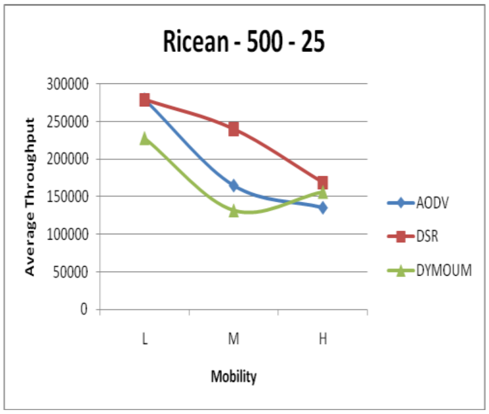
Number of Nodes=50

Figure E.9. Average Receiving Throughput Vs. Mobility Under Nakagami Fading



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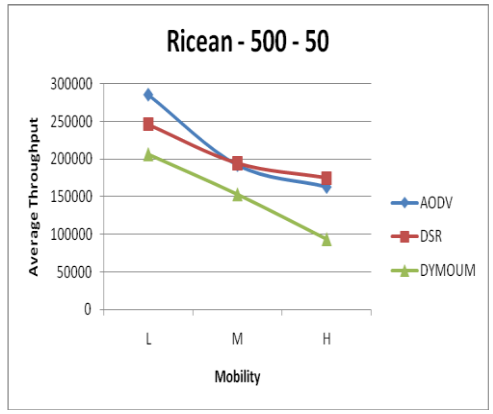

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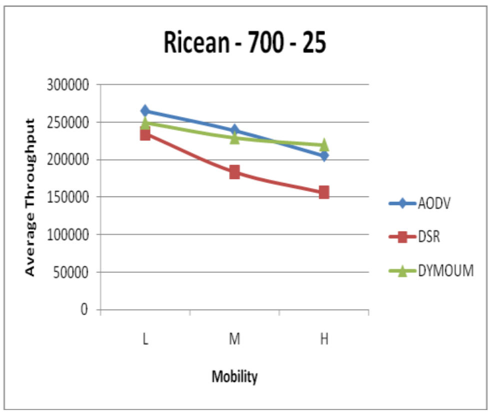
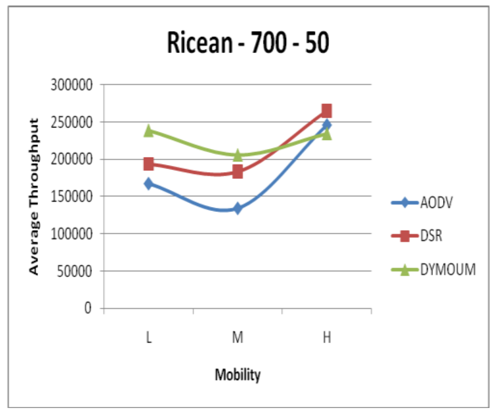


Grid size= 700mX 700m

Number of Nodes=25



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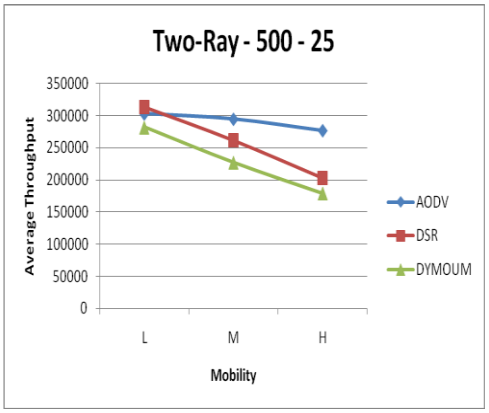
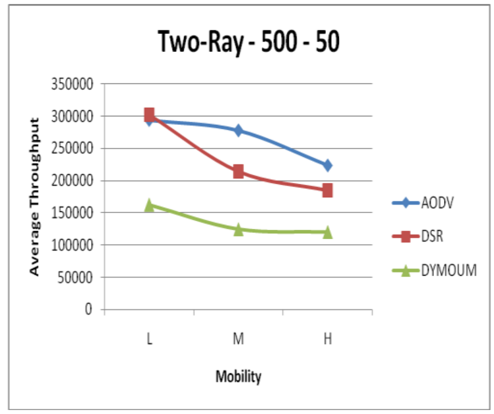
Number of Nodes=50

Figure E.10. Average Receiving Throughput Vs. Mobility Under Ricean Fading



Grid size= 500mX 500m

Number of Nodes=25



Grid size= 500mX 500m

Number of Nodes=50

Grid size= 700mX 700m

Number of Nodes=25

Grid size= 700mX 700m

Number of Nodes=50

Figure E.11. Average Receiving Throughput Vs. Mobility Under TwoRayGround Propagation

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