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Performance Evaluation of Mobile Ad Hoc Networks in Realistic Mobility and Fading Environments

by

Preetha Prabhakaran

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Electrical Engineering
Department of Electrical Engineering
College of Engineering
University of South Florida

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Keywords: ns-2, rayleigh fading, mobility models, packet delivery ratio, control overhead

Dedication

To my Parents and Sister for their everlasting love.

Acknowledgments

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Performance Evaluation of Mobile Ad Hoc Networks in Realistic Mobility and Fading Environments

Preetha Prabhakaran

ABSTRACT

Mobile Ad hoc Networks (MANETs) are wireless networks, which consist of a collection of mobile nodes with no fixed infrastructure, where each node acts as a router that participates in forwarding data packets. They are a new paradigm of wireless communications for mobile hosts that are resource-constrained with only limited energy, computing power and memory.

Previous studies on MANETs concentrated more on energy conservation in an idealistic environment without taking into consideration, the effects of realistic mobility, interference and fading. The definition of realistic mobility models is one of the most critical and, at the same time, difficult aspects of the simulations of networks designed for real mobile ad hoc environments. The reason for this is that most scenarios for which ad hoc networks are used have features such as dynamicity and extreme uncertainties. Thus use of real life measurements is currently almost impossible and most certainly expensive. Hence the commonly used alternative is to simulate the movement patterns and hence the reproduction of movement traces quite similar to human mobility behavior is extremely important.

The synthetic models used for movement pattern generation should reflect the movement of the real mobile devices, which are usually carried by humans, so the movement of such devices is necessarily based on human decisions. ‘Regularity’ is an important characteristic of human movement patterns. All simulated movement models are suspect

because there is no means of accessing to what extent they map reality. However it is not difficult to see that random mobility models such as Random Walk, Random Waypoint (default model used in almost all network simulations), etc., generate movements that are most non-humanlike. Hence we need to focus on more realistic mobility models such as Gauss Markov, Manhattan Grid, Reference Point Group Mobility Model (RPGM), Column, Pursue and other Hybrid mobility models. These models capture certain mobility characteristics that emulate the realistic MANETs movement, such as temporal dependency, spatial dependency and geographic restriction. Also a Rayleigh/Ricean fading channel is introduced to obtain a realistic fading environment.

The energy consumed by the data, MAC, ARP and RTR packets using IEEE 802.11 MAC protocol with the various mobility models in fading and non-fading channel conditions are obtained using *ns-2* simulations and AWK programs. The realistic movement patterns are generated using three different mobility generators – BonnMotion Mobility Generator, Toilers Code and Scengen Mobility Generator. This thesis work performs an in-depth study on the effects of realistic mobility and fading on energy consumption, packet delivery ratio and control overhead of MANETs.

Chapter One

Introduction

1.1 Wireless LANs

Wireless networking is an exciting technology that enables two or more computers to communicate using standard network protocols, but without network cabling. WLAN (Wireless Local-Area Network) is a category of local-area network that uses high-frequency radio waves rather than wires to communicate between nodes such as computers, Internet devices or other appliances. It is a flexible data communication system implemented as an extension to or as an alternative for, a wired LAN within a building or campus. Wi-Fi networks use radio technologies called IEEE 802.11b or 802.11a to provide secure, reliable, fast wireless connectivity. A Wi-Fi network can be used to connect computers to each other, to the Internet, and to wired networks (which use IEEE 802.3 or Ethernet) [1]. Wi-Fi networks operate in the unlicensed 2.4 and 5 GHz radio bands, with an 11 Mbps (IEEE 802.11b) or 54 Mbps (IEEE 802.11a) data rate or with products that contain both bands (dual band), so they can provide real-world performance similar to the basic 10BaseT wired Ethernet networks used in many work places, IEEE 802.11 being the IEEE standard for WLANs. WLANs are becoming more important due to increased interest in connection of mobile and portable computers mutually, or to the wired LANs.

1.1.1 Working of WLANs

Wireless LANs use electromagnetic waves to communicate information from one point to another without relying on any physical connection. WLANs combine data connectivity with user mobility and enables movable LANs through simplified configurations. Radio waves are often referred to as radio carriers because they simply perform the function of delivering information to a remote receiver. Data is modulated onto a radio carrier and then transmitted. At the radio receiver the data is extracted from the modulated signal by demodulation [2].

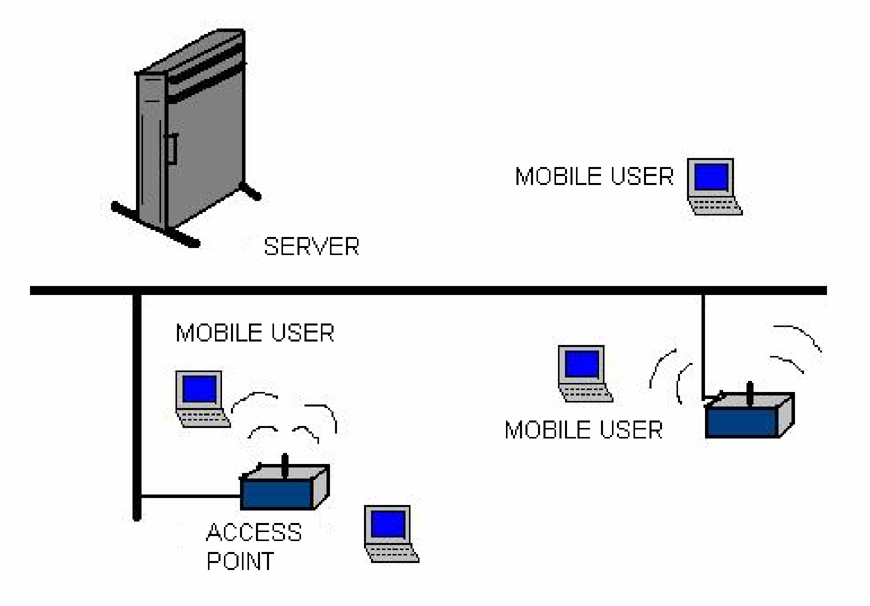

Figure 1.1. Typical WLAN Configuration

In a WLAN configuration, as shown in Figure 1.1, an *access point* (AP), which is a transceiver device, connects to a wired network using a standard Ethernet cable. A single AP can function within a certain range and can support a small group of users. The AP receives, buffers, and transmits data between the WLAN and the wired network infrastructure. End users access the WLAN through wireless LAN adapters, which are implemented as PC cards in notebook computers or use fully integrated devices within handheld computers [2].

1.1.2 Wireless LAN Technology Options

There are various WLAN technology options. Each has its own advantages and disadvantages [3]. They are:

Direct-Sequence Spread Spectrum Technology: Figure 1.2 represents a Direct – Sequence Spread Spectrum (DSSS) which generates a redundant bit pattern for each bit to be transmitted. This bit pattern a chip or chipping code. The longer the chip, the greater the probability that the original data can be recovered. Even if one or more bits in a chip are damaged during transmission, statistical techniques embedded in the radio can recover the original data without the need for retransmission. To an unintended receiver, DSSS appears as low-power wideband noise and is rejected by most narrowband receivers.

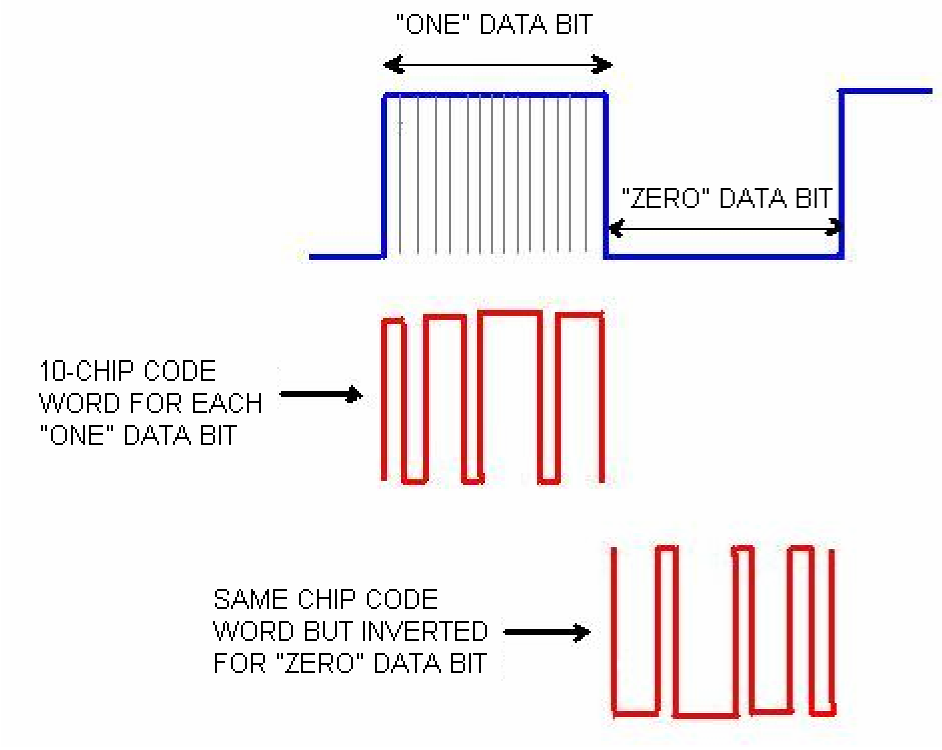

Figure 1.2. Direct-Sequence Spread Spectrum

Frequency - Hopping Spread Spectrum Technology: Figure 1.3 represents a Frequency - Hopping Spread Spectrum (FHSS) which uses a narrowband carrier that changes frequency in a pattern known to both transmitter and receiver. To an unintended receiver, FHSS appears to be short – duration impulse noise.

Narrowband Technology: A narrowband radio system transmits and receives user information on a specific radio frequency. Narrowband radio keeps the radio signal frequency as narrow as possible just to pass the information. Undesirable crosstalk between communications channels is avoided by carefully coordinating different users on different channel frequencies.

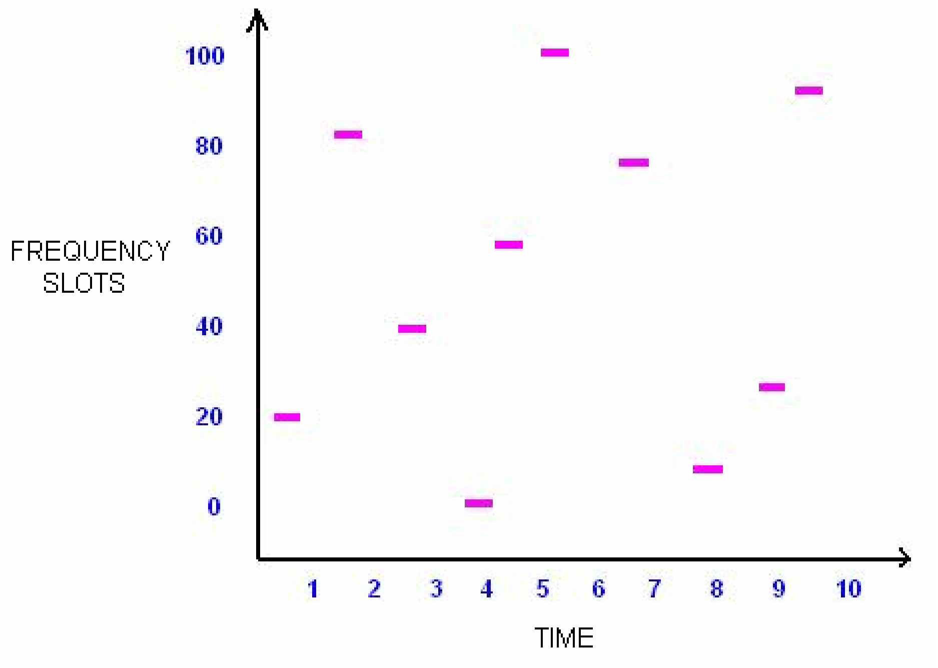

Figure 1.3. Frequency - Hopping Spread Spectrum

In a radio system, privacy and non-interference are accomplished by the use of separate radio frequencies. The radio receiver filters out all the radio signals except the ones on its designated frequency.

1.1.3 Classification of WLANs

Infrastructure Network: In an infrastructure network, as shown in Figure 1.4, the wireless devices communicate with a central node that in turn can communicate with wired nodes on that LAN. They are comprised of WLANs connected to wired LANs and contain access points to channel network traffic.

Ad hoc Network: Ad hoc network is comprised of wireless devices that communicate with each other in a peer-to-peer mode. Ad-hoc mode is useful for establishing a network where wireless infrastructure does not exist. Figure 1.5 depicts a single hop and multi-hop ad hoc network configurations. In single hop ad hoc mode, there is no routing operation and hence only one-to-one communication, while in a multi-hop ad-hoc mode the network nodes communicate via other nodes.

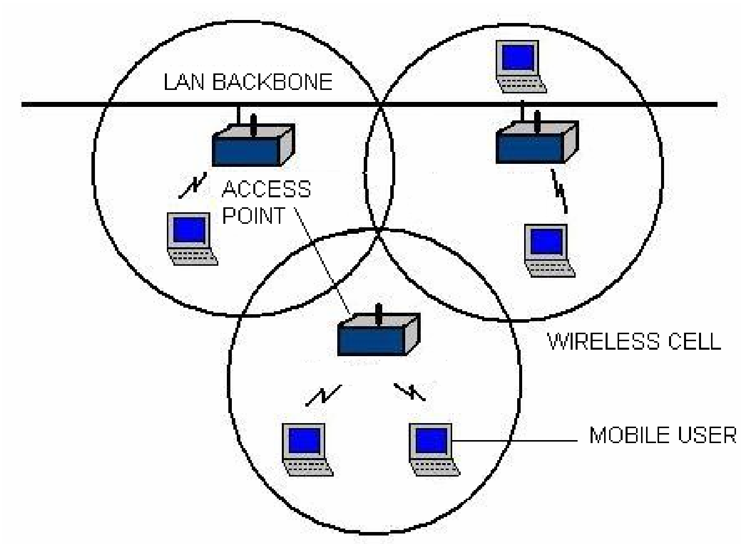

Figure 1.4. Schematic of a WLAN Infrastructure Network

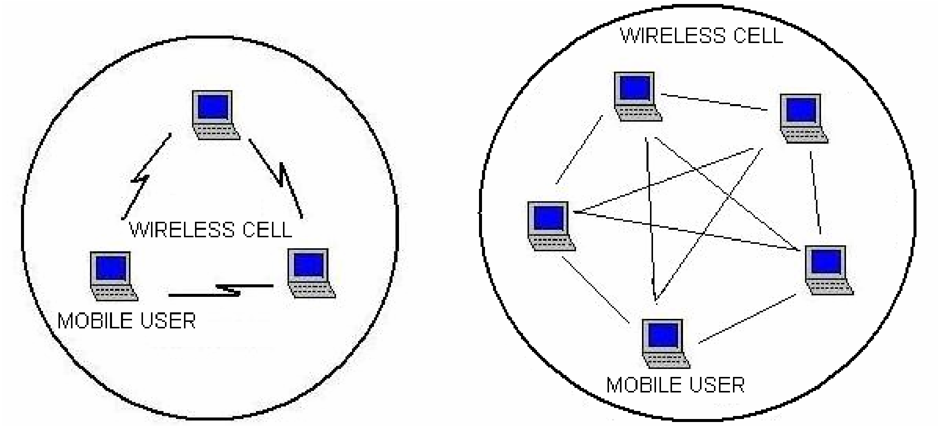

Figure 1.5. Schematic of a WLAN Ad hoc Network – Single hop and Multi-hop Configurations

1.2 Mobile Ad hoc Networks (MANET)

Mobile and wireless technology is growing at a rapid rate. Ad hoc networks are a consequence of the ceaseless research efforts in mobile and wireless networks. They are a new paradigm of wireless communications for mobile hosts. Each MANET is a set of wireless mobile hosts forming a temporary, dynamic autonomous network without the aid of any established infrastructure or centralized administration, such as base stations or mobile switching centers [4][5].

Wireless technologies such as General Packet Radio Service, Wi-Fi, Home-RF, and Bluetooth make it possible to access the Web from mobile phones, print documents from PDAs, and synchronize data among various office devices. However, such applications rely at some point on mobility support routers or base stations, and it is often necessary to establish communication when the wired infrastructure is inaccessible, overloaded, damaged, or destroyed [6].

However, MANETs do not rely on any fixed infrastructure but communicate in a self-organized way. Nodes communicate with each other without the intervention of centralized access points or base stations. All nodes share the responsibility of network formation and management. Also they all behave as routers and take part in the discovery and maintenance of routes to other nodes in the network.

In areas in which there is little or no communication infrastructure, or the existing infrastructure is expensive or inconvenient to use, wireless mobile users may still be able to communicate through the formation of an ad hoc networks. Their main advantages are the lower costs, inherent scalability, portability, mobility, ease of installation and their suitability to free unlicensed spectrum [5]. Ad hoc networks have received growing research attention during the last decade. This is partly due to significant developments in local area wireless technologies that are now starting to enable low cost wireless network build-out for local area communications. Such networks are emerging first of all in corporate environments especially through WLAN technologies, and similarly WLAN is also taking more and more footprint in residential solutions. They are applied most commonly in situations such as military tactical operations, emergency cases, target tracking, law enforcement, rescue missions during disaster, virtual classrooms, and conferences [7].

The strength of ad hoc networks resides in the diversity of computer networking and the growth of wireless over IP that patches the Internet together. Ad hoc networks are seen as the potential market for embedded network devices in multiple environments such as vehicles, mobile telephones and personal appliances. They are considered the infrastructure-less that will allow the users to create their Personal Area Networks (PANs) [8].

Wireless Personal Area Networks (WPANs) are short-range wireless networks that permit communication between wireless devices at a distance of around 10 meters. Bluetooth is a WPAN standard used for short distance transmission of digital voice and data that supports both, point-to-point and multipoint applications between mobile phones, computers, personal digital assistants (PDAs) etc,. It transmits in the unlicensed 2.4 GHz band and uses the frequency hopping spread spectrum technique. IEEE 802.15 is the working group of IEEE that develops standard protocols and interfaces for WPANs.

1.3 Research Challenges of MANETs

1.3.1 Throughput

One of the fundamental challenges in MANETs research is how to increase the overall network throughput while maintaining low energy consumption for packet processing and communications. The low throughput is attributed to the harsh characteristics of the radio channel combined with the contention-based nature of medium access control (MAC) protocols commonly used in MANETs. The notorious near-far problem undermines the throughput performance in MANETs [9]. Further, concurrent wireless transmissions in an ad-hoc network limit its throughput capacity, because they create mutual interference [10].

When two mutually out of range hosts compete over a common host, undetectable receiver side collisions result. When two mutually out of range hosts compete over a common host, undetectable receiver side collisions result. In other words, due to the limited transmission range of mobile stations, multiple transmitters within range of the same receiver may not know one another's transmissions, and hence are in effect "hidden" from one another. When these transmitters transmit to the same receiver at around the same time, they do not realize that their transmissions collide at the receiver. This so-called "hidden terminal" problem degrades the throughput significantly. The near-far SNR problem has a significant effect on the performance of an ad-hoc network. It causes collisions which results in loss of efficiency (reduction of throughput). One solution might be to use RTS/CTS signaling, but it may not help much in a multi-hop ad hoc network due to the difference between the transmission range and sensing/interference range and also due to the fact that it increases control signal overhead [4].

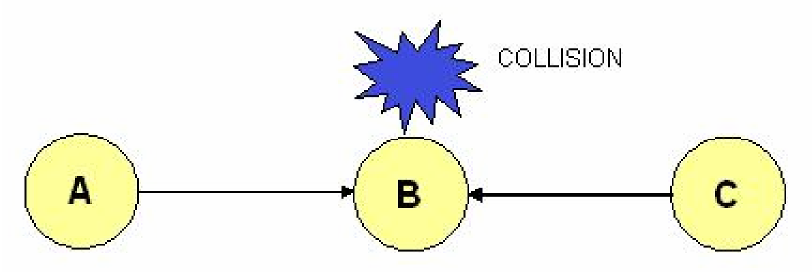

Figure 1.6. Hidden Terminal Scenario

Figure 1.6 represents the hidden terminal problem [13] where:

- A talks to B
- C senses the channel
- C does not hear A's transmission (out of range)
- C talks to B
- Signal from A and B collide
- Causes wastage of resources, mainly throughput

Another problem related to segment overlapping in ad hoc networks is the exposed-terminal problem [4]. In this case the problem arises when the sensing mechanism prevents parallel transmission, from two or more terminals, toward receivers that would not observe collision as the receivers are located far apart [11]. In exposed terminal scenario the free channel is not used, resulting in loss of efficiency. Hence hidden terminal problem and exposed node problem are conflicting [12].

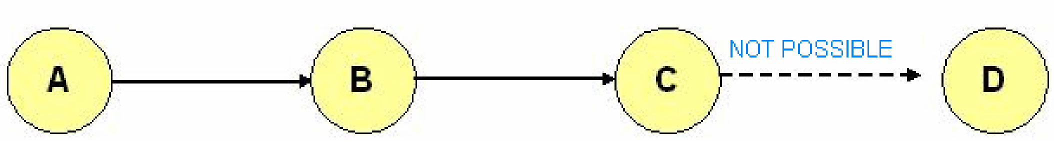

Figure 1.7. Exposed Terminal Scenario

Figure 1.7 illustrates the exposed terminal problem [13] where:

- B talks to A
- C wants to talk to D
- C senses channel and finds it to be busy
- C stays quite (when it could have ideally transmitted)
- Lower effective throughput due to underutilization of channel

1.3.2 Multi-path Fading

This is caused by multipath propagation of radio frequency (RF) signals between a transmitter and a receiver. Multipath propagation can lead to fluctuations in the amplitude, phase, and angle of the signal received at a receiver. If there is a strong LOS (Line Of Sight) between the transmitter and the receiver, diffraction and scattering are not the dominant factors in the propagation of the radio waves. However, in the absence of a LOS between the transmitter and the receiver, diffraction and scattering become the dominant factors in the propagation. Typically, the received signal is a sum of the components arising from the above three phenomena. The strength of the received signal fluctuates rapidly with respect to time and the displacement of the transmitter and the receiver [14].

A fundamental characteristic of mobile wireless networks is the time variation of the channel strength of the underlying communication links. Such time variation occurs at multiple time scales and can be due to multipath fading, path loss via distance attenuation, shadowing by obstacles, and interference from other users. The impact of such time variation on the design of wireless networks parameters throughout the layers, ranging from coding and power control at the physical layer to cellular handoff and coverage planning at the networking layer [15].

1.3.3 Energy Utilization

MANETs face power problems because of a lot of reasons [16] such as,

- Battery power is limited
- Recharging or replacing batteries may be difficult.
- Large relay traffic in multi-hop routing might cause faster depletion of the node power source.
- Increased battery size increases the size and weight of the node, while decreased battery size results in less capacity.
- Consumption of battery charge increases with an increase in the transmission power.

Power control in MANETs has recently received a lot of attention for two main reasons. First, power control has been shown to increase spatial channel reuse, hence increasing the overall (aggregate) channel utilization. This issue is particularly critical given the ever-increasing demand for channel bandwidth in wireless environments. Second, power control improves the overall energy consumption in a MANET, consequently prolonging the lifetime of the network [17]. Portable devices are often powered by batteries with limited weight and lifetime, and energy saving is a crucial factor that impacts the survivability of such devices.

Energy efficiency is one of the most important aspects in mobile networks. Power is arguably the scarcest resource for mobile devices, and power saving has always been a major design issue for the developers of mobile devices, wireless communication protocols and mobile computing systems. It is not practically possible to recharge or change batteries every other hour, or to carry a heavy battery pack, power puts many limitations on operations of a mobile device [18]. Computing ability is sacrificed because high performance processor needs more power. Also transmission range and bandwidth are restricted due to the fact that long range high bandwidth transceivers consume much energy.

1.3.4 Mobility

An ad hoc network consists of nodes that communicate with each other without the help of pre-existing infrastructure. The links between the nodes may change and the network adapts rapidly to the new situation. The freedom of movement makes wireless communication very attractive. But at the same time mobility brings challenges owing to bandwidth and power constraints, limited or no infrastructure and mobility of users. When a link between two nodes that is in use disconnects, the routing protocol needs to adapt to the new situation. This creates a cost both in the amount of control traffic and in the message delay i.e., frequent route changes due to mobility of the nodes would increase the signaling overhead and end-to-end delay which is required to establish a route [19]. When signaling overhead increases the energy consumed by the network will in turn increase which leads to a reduced network lifetime. Also because of the quick topology changes due to mobility of the nodes, ordinary routing protocol fails to give good performance. Since nodes are mobile most of the time a lot of undesirable effects such as disconnection, bit errors, reduction in throughput, etc. take place In order to evaluate the impact of mobility while simulating a MANET routing protocol, it is crucial that the underlying mobility model accurately emulates real-world node mobility or at least the essential characteristics.

1.3.5 Scalability

Over the last decade, many mobile ad hoc routing protocols have continually been designed and refined. However, most of the designs have been for small to mid size networks, especially those with low node density. As a result, most mobile ad hoc routing protocols suffer large performance degradations when used in large-scale networks. Performing *route discovery* in a large or high-density network using reactive protocols, for instance, can be expensive due to network-wide broadcast floods. Using a proactive protocol in a highly mobile network, on the other hand, also causes significant performance degradations due to large amount of resource spent on updating the routing tables. While many proposed optimizations have been done to mitigate the shortcomings of ad hoc routing protocols in large-scale networks, most of the proposals were designed to address problems related to specific routing protocols in specific environments [20].

Wireless communication systems for military and commercial infrastructures have been significantly scaled up in their sizes as well as complexities. Such systems are analytically intractable and simulation is a common alternative to explore the behavior of large-scale, complex wireless network systems. However, existing popular simulation tools such as OPNET [21] or *ns-2* [22], which have contributed to the wireless communication community in the design and evaluation of new protocols, are not capable of simulating large-scale network models as the execution times of those simulation tools can be unreasonably long. Moreover, the memory requirement to simulate such systems physically limits the maximum number of network nodes with the existing simulation tools [15].

1.4 Motivation

A majority of the previous studies on MANETs concentrated on energy utilization, throughput, scalability and packet drop rate in an idealistic environment without giving much importance to the effects of realistic mobility and fading. A lot of interesting details about routing energy overheads of various ad hoc routing protocols were obtained from [23]. The mobility models were classified into entity and group mobility models [24]. Reference [25] studied the effect of RPGM on various performance metrics such as throughput and control overhead. In [26] the effect of *random waypoint* model, RPGM model and *Manhattan grid* model on the overall energy consumption was compared. But energy-goodput, network lifetime, packet drop rate, throughput performance, scalability, etc were not analyzed in detail in the presence of fading with realistic mobility models. There have been many schemes to extend the use of mobile ad hoc routing protocols to environments much larger than the traditionally small and low-density ad hoc networks. Such large-scale mobile ad hoc networks are characterized by high node density and high mobility [20].

The commonly used free space model is computationally efficient but ignores many losses that are common in wireless signal propagation. Accurate simulation of wireless networks requires realistic models of the channel propagation medium. An in-depth analysis of the effects of high mobility of MANETs on the performance three prominent ad hoc routing protocols; DSR, AODV (reactive protocols) and DSDV (proactive protocol) under realistic mobility and multi-path fading environments was not performed before. Earlier, the effects of realistic mobility characteristics (temporal dependence of velocity, spatial dependence of velocity, and geographic restrictions) on the performance of various ad hoc routing protocols in multi-path fading conditions was not studied in detail.

1.5 Research Objectives

This thesis work performs an in-depth study on the effects of realistic mobility and fading on energy consumption, packet delivery ratio and control overhead of MANETs. It addresses the issues regarding the effect of realistic mobility characteristics on energy efficiency. Network scenarios which mimic realistic environments are used and the effects of various mobility models on protocol performance are to be observed. The simulations are carried out using *ns-2* (Network Simulator).

The energy consumed by the data (CBR – Constant Bit Rate) and control packets using IEEE 802.11 MAC protocol with the various realistic mobility models in multi-path fading channel conditions are obtained. These results are also compared with those obtained for *random waypoint* mobility model [27]. We also generate snapshots of the node movement in the various mobility models so that a lucid understanding of their characteristics is possible. We evaluate the effects of realistic mobility and fading environment on scalability based on protocol performance metrics such as Packet Delivery Ratio (PDR) and Control Overhead.

1.6 Thesis Organization

The rest of the thesis is organized as follows. Next Chapter briefly describes the related literature review and background of the fading channel, IEEE 802.11 MAC, ad hoc routing protocols and realistic mobility models. Chapter 3 investigates the effects of multi-path fading and realistic mobility characteristics – temporal dependency, spatial dependency and geographic restriction on the energy utilization, throughput performance, scalability and packet drop rate of MANETs. Chapter 4 describes our network environment, simulation settings and mobility generators. In Chapter 5 the simulation results are presented and in Chapter 6, we present our conclusions and discuss future work.

1.7 Summary

In this chapter, we briefly studied wireless LANs and mobile ad hoc networks. The main challenges faced by MANETs both in research and real environments were discussed. Next we presented the motivation for the thesis and an overview of how it is organized.

Chapter Two

Literature Review and Background

2.1 Literature Review

Reference [28] investigated the impact of wireless fading channel models on the accuracy and evaluation time of large-scale simulation models. In [29], Bernard Sklar addresses Rayleigh fading, primarily in the UHF band, which affects mobile systems. It also studies the fundamental fading manifestations and the types of degradation. A simple method for modeling small scale Ricean (or Rayleigh) fading is introduced in [30]. It also demonstrates a computationally efficient way to model small-scale fading statistics within a packet level simulator. A set of physical layer factors such as signal reception, path loss, fading, interference, noise computation and preamble length are presented in [31] to evaluate the performance of ad hoc routing protocols such as DSR and AODV.

In [32], Hong Jiang *et al.* analyzed the performance of three routing protocols – AODV, DSR and STAR compared in terms of control overhead, amount of data delivered and average latency in packet delivery. Reference [23] focuses on the energy consumption and studies the ‘range effects’ of DSR, AODV and DSDV and how changes to transmission power and transmission radius affect the overall energy consumed by routing related packets using the *random waypoint* mobility model. But in [33] Juan-Carlos Cano *et al.* measured and compared energy consumption behavior of DSR, AODV, DSDV and TORA by varying pause time, maximum node speed, number of traffic sources, number of nodes, simulation area and sending rate.

Amit Jardosh *et al.*, proposed to create a more realistic movement model through the incorporation of obstacles which are used to restrict both node movement as well as wireless transmissions [34]. In [35], Bor-rong Chen *et al.* performed an energy-based comparison of AODV, DSR, DSDV and TORA using three different mobility models:

RW model, RPGM model and MG model. They showed significant energy conservation performance difference among mobility models. Fan Bai *et al.*, developed a framework called 'IMPORTANT' (**I**mpact of **M**obility on **P**erformance **Of R**ou**T**ing protocols for **A**d hoc **N**e**T**works) [36] to evaluate the impact of different mobility models such as *random waypoint* (RW) model, *reference point group mobility* (RPGM) model, *freeway* model and *Manhattan grid* (MG) model on the performance of popular MANET routing protocols (DSR, AODV and DSDV) and also proposed various protocol independent metrics such as spatial dependence, temporal dependence and geographic restrictions to capture interesting mobility characteristics.

2.2 Fading Channel

Fading is a variation of signal power at receivers caused by the node mobility or environmental changes that create varying propagation conditions from transmitters [37]. There are three main mechanisms that impact radio propagation in wireless channels: Reflection, Diffraction and Scattering as shown in Figure 2.1.

Reflection occurs when an electromagnetic wave impinges on a smooth surface with very large dimensions when compared to the wavelength of the radio wave. It may interfere constructively or destructively at the receiver. *Diffraction* occurs when the path of the electromagnetic wavefront is obstructed and deviated by an impenetrable body of large dimensions as compared to the RF signal wavelength. Diffraction is also called shadowing because the diffracted field can reach the receiver even when shadowed by an impenetrable obstruction. *Scattering* occurs when the radio channel contains objects of dimensions that are on the order (or less) of the electromagnetic wavelength, causing energy from a transmitter to be radiated in many different directions. Scattering results in a disordered or random change in the incident energy distribution [14].

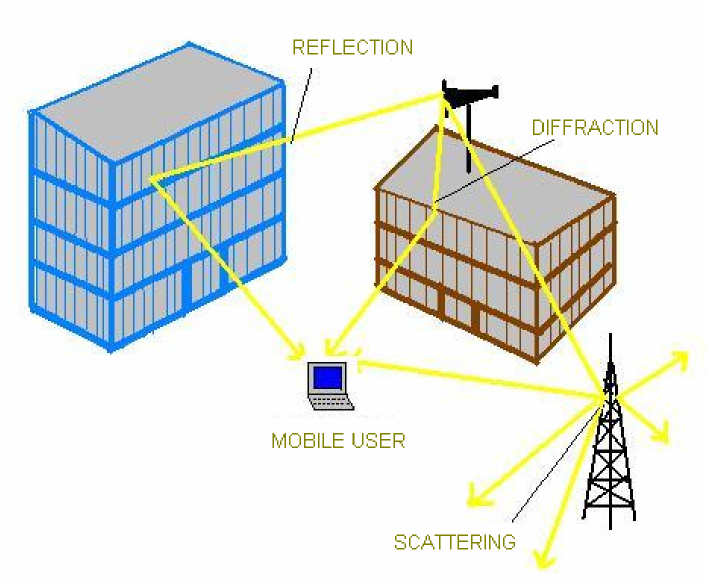

Figure 2.1. Illustration of Fading Mechanisms

There are two major categories of fading: Large Scale Fading, Small Scale Fading. Large Scale Fading is the "loss" that most propagation models try to account for. They are mostly dependant on the distance from the transmitter to the receiver. It is also known as "Large Scale Path Loss", "Log-Normal Fading", or "Shadowing". Small Scale Fading is caused by the superposition or cancellation of multipath propagation signals, the speed of the transmitter or receiver, and the bandwidth of the transmitted signal as illustrated in Figure 2.2. It is also known as "Multipath Fading", "Rayleigh Fading", or simply as "Fading".

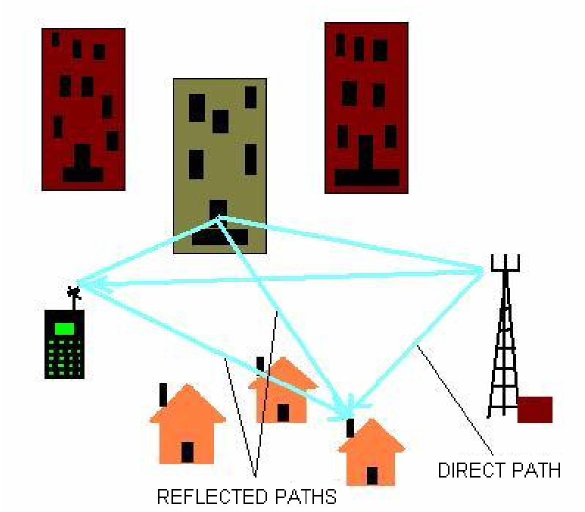

Figure 2.2. Multi-path or Rayleigh Fading

MANET scenarios undergo fading which presents Rayleigh or Ricean distributions, depending on the geometrical conditions [37]. Rayleigh fading is the fading in a channel due to the interference caused between the direct signal and the same signal traveling over different paths, resulting in out-of-phase components incident at the receiver [38]. The fading with the Rayleigh distribution is used for mobiles with no line of sight (NLOS) between the transmitter and the receiver. Rayleigh fading with strong line of sight content is said to be Ricean fading. The signal level from the Ricean path with respect to the power from Rayleigh paths can be controlled by a parameter called Ricean 'K' factor [14]. The additive white Gaussian noise (AWGN) model is used to model an idealistic channel condition where no signal fading occurs.

2.3 IEEE 802.11 Medium Access Control (MAC)

IEEE 802.11 is the most widely adopted protocol standard for wireless local area networks (WLANs). It specifies two different modes: the infrastructure mode and the ad hoc mode. A special device, Access Point (AP), must be presented as the central point of each Basic Service Set (BSS) in the infrastructure mode. Communications inside a BSS happen only between AP and stations, and AP usually connects to the wireline network as the gateway to the Internet. The architecture of infrastructure mode is like a cellular network where a Base Station is the center of each cell. In the ad hoc mode, current standards are built on an environment where stations in a grouup are all within each other's transmission range, and they communicate in a peer-topeer fashion. In other words, the ad hoc mode of 802.11 supports only *single-hop* ad hoc networks, referred to in the specification as *Independent Basic Service Sets* (IBSSs) [18].

IEEE 802.11 Architecture: IEEE 802.11 networks are comprised of Stations, Wireless Medium, AP (Access Points) and a DS (Distribution System), as shown in Figure 2.3.

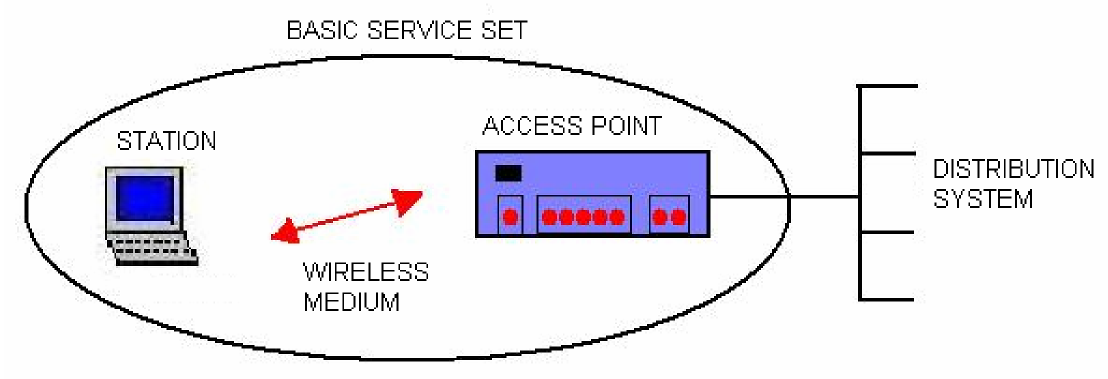

Figure 2.3 Schematic of IEEE 802.11 Network Architecture [41]

Station: It is any device which as a IEEE 802.11 MAC (Medium Access Control) and Physical layer interface to the wireless medium. It maybe a laptop computer or a PDA (Personal Digital Assistant).

Access Point (AP): It is a device found within an IEEE 802.11 network, which provides the point of interconnection between the wireless station and wired network. There are various types of access points and base stations used in both wireless and wired networks. These include bridges, hubs, switches, routers and gateways. The differences between them are not always precise, because certain capabilities associated with one can also be added to another.

Distribution System (DS): A DS is a logical element of IEEE 802.11 network that provides a means of connecting multiple AP's together [39].

IEEE 802.11 MAC mainly relies on two techniques to combat interference: physical carrier sensing and RTS/CTS (request-to-send / clear-to-send) handshake (also known as "virtual carrier sensing"). Ideally, the RTS/CTS handshake can eliminate most interference. However, the effectiveness of RTS/CTS handshake is based on the assumption that hidden nodes are within transmission range of receivers. Resolving hidden terminal problem becomes one of the major design considerations of MAC protocols. IEEE 802.11 DCF (Distributed Control Function) is the most popular MAC protocol used in both wireless LANs and mobile ad hoc networks (MANETs) [40]. This protocol generally follows the CSMA/CA (Carrier Sense Multiple Access / Collision

Avoidance) paradigm, with extensions to allow for the exchange of RTS-CTS (request-to-send/clear-to-send) handshake packets between the transmitter and the receiver. These control packets are needed to reserve a *transmission floor* for the subsequent data packets. Nodes transmit their control and data packets at a common maximum power level, preventing all other potentially interfering nodes from starting their own transmissions. Any node that hears the RTS or the CTS message defers its transmission until the ongoing transmission is over. While such an approach is fundamentally needed to avoid the hidden terminal problem, it negatively impacts the channel utilization by not allowing concurrent transmissions to take place over the reserved floor [17].

2.4 Routing Protocols

Routing protocols are categorized as *proactive and reactive* protocols. Proactive routing protocols DSDV (Destination Sequenced Distance Vector Routing) are table-driven protocols; they always maintain current up-to-date routing information by sending control messages periodically between the hosts which update their routing tables. Reactive or on-demand routing protocols are the ones which create routes when they are needed by the source host and these routes are maintained while they are needed. DSR (Dynamic Source Routing) and AODV (Ad hoc On-demand Distance Vector Routing) are the most popular reactive routing protocols.

2.4.1 Dynamic Source Routing (DSR) Protocol

The Dynamic Source Routing (DSR) [41] is an on-demand routing protocol that is based on the concept of source routing. Mobile nodes are required to maintain route caches that contain the source routes of which the mobile is aware. Entries in the route cache are continually updated as new routes are learned. The protocol consists of two major phases: *a) route discovery, and b) route maintenance*. When a source wishes to communicate with a destination, a source starts with a route discovery by flooding a *route request packet.* The *route request* message contains the address of the destination along with the source node's address and a unique identification number. Each node receiving the packet checks whether it knows of a route to the destination, if not, it adds its own address to the *route record* of the packet along its outgoing links. A node discards the route request, if it finds its own address already recorded in the route.

A *route reply* is generated when either the route request reaches the destination itself, or when it reaches an intermediate node that contains in its cache an unexpired route to the destination. When the destination receives a request packet, it may simply reverse the *recorded route* to reach the source or may use the same route discovery procedure toward the original source. *Route maintenance* is accomplished through the use of *route error packets* and *acknowledgements*. The route error packets are generated at a node when the data link layer encounters a fatal transmission problem. When a route error packet is received, the hop in error is removed from the node's route cache and all the routes containing the hop are truncated at that point. In addition to route error messages, acknowledgements are used to verify the correct operation of the route links.

2.4.2 Ad hoc On-Demand Distance Vector (AODV) Routing Protocol

The Ad hoc On-demand Distance Vector (AODV) routing protocol [42] builds on the *DSDV (Destination Sequenced Distance Vector) algorithm*. It is an improvement on DSDV because it typically minimizes the number of required broadcasts by creating routes on an on-demand basis, as opposed to maintaining a complete list of routes as in the DSDV algorithm. It is classified as a *pure on-demand route acquisition system*. When a source wishes to send a message to some destination and does not already have a valid route to that destination, it initiates a *route discovery* process to locate the other node. It broadcasts a route request (RREQ) packet to its neighbors, which then forward the request to their neighbors, and so on, until either the destination or an intermediate node with a recent route to the destination is located. AODV uses *destination sequence numbers* to ensure that all routes are loop-free and contain the most recent route information. *Route maintenance* is carried out by the use of *link failure notification message (an RREP with an infinite metric)* which is propagated by upstream neighbors (which notice a node's movement) to each of its active upstream neighbors to inform them of the erasure of that part of the route. AODV additionally uses *hello messages* which are periodic local broadcasts made by a node to inform each mobile node of other nodes in its neighborhood. Hello messages can be used to maintain the *local connectivity of a node*.

2.4.3 Destination-Sequenced Distance-Vector (DSDV) Routing Protocol

The Destination-Sequenced Distance-Vector (DSDV) routing protocol is a table-driven protocol requiring every node to periodically propagate routing information updates throughout the network [43]. Each node periodically broadcasts its routing table to all of its neighbor nodes and this route information will be propagated from the source node through the network until it reaches the destination node. *Route maintenance* in DSDV is different from that in DSR and AODV. Whenever significant changes of topology happen, e.g. a MN (Mobile Node) detects a break in the link or it discovers a new neighbor in its proximity, MNs will broadcast its routing table. Each node receiving this information should also broadcast the topology update to its neighbors [44]. In DSDV, each node maintains a *routing table* indexed by sequence numbers, and listing the next hop for every reachable destination. The sequence numbers enable the mobile nodes to distinguish stale routes from new ones. To maintain table consistency each node periodically transmits the routing table over the network.

2.5 Mobility Models

2.5.1 Random Waypoint Model (RW)

It is a ’benchmark’ model to evaluate the MANET routing protocols, because of its simplicity and wide availability. This mobility model includes pause times between changes in direction and/or speed. An MN (Mobile Node) begins by remaining in a particular location for a certain pause time. Once this time expires, the MN chooses a random destination in the network area and a speed that is uniformly distributed between [minspeed, maxspeed] and travels toward the new destination, as shown in Figure 2.4. Upon arrival, the MN pauses for a specified time period before repeating the process again. To generate the node trace of the RW model the ‘*setdest’* tool from the CMU Monarch group is used which is included in ns- 2 [35] [45].

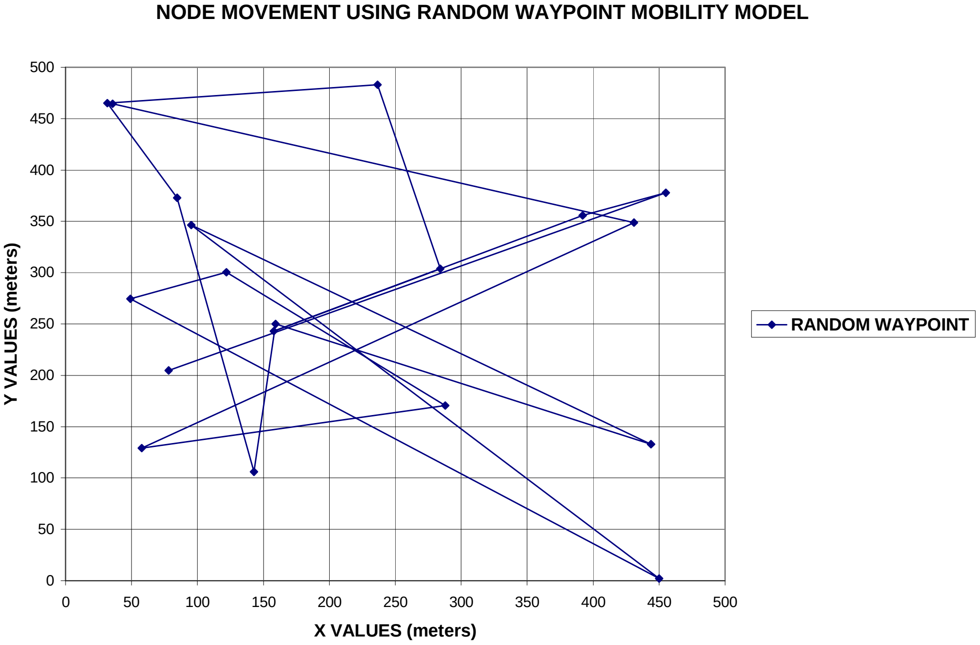

Figure 2.4. Traveling Pattern of a Mobile Node using Random Waypoint Mobility Model

2.5.2 Gauss Markov Model (GM)

In this model, the velocity of mobile node is assumed to be correlated over time and modeled as a Gauss-Markov stochastic process. It is a temporally dependent mobility model where the degree of dependency is determined by the memory level parameter α. By tuning this parameter various scenarios are obtained: (i) $\alpha = 0$ then the model is memoryless, (ii) $\alpha = 1$ then the model has strong memory and (iii) $0 < \alpha < 1$ then the model has some memory [46].

Figure 2.5. illustrates the traveling pattern of an MN using the GM mobility model. This mobility model can eliminate the sudden stops and sharp turns encountered in the *random walk* mobility model by allowing past velocities to influence future velocities (i.e) introducing temporal dependency of velocity.

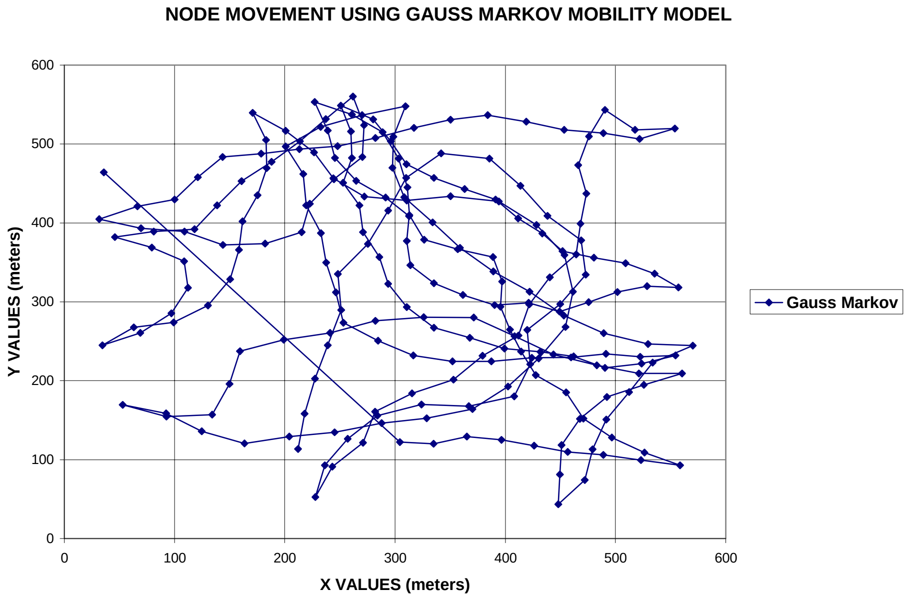

Figure 2.5. Traveling Pattern of a Mobile Node using Gauss Markov Mobility Model

2.5.3 Manhattan Grid Model (MG)

This model emulates the movement pattern of mobile nodes on streets defined by maps. It is useful in modeling movement in an urban area. Maps are used in this model which is composed of a number of horizontal and vertical streets.

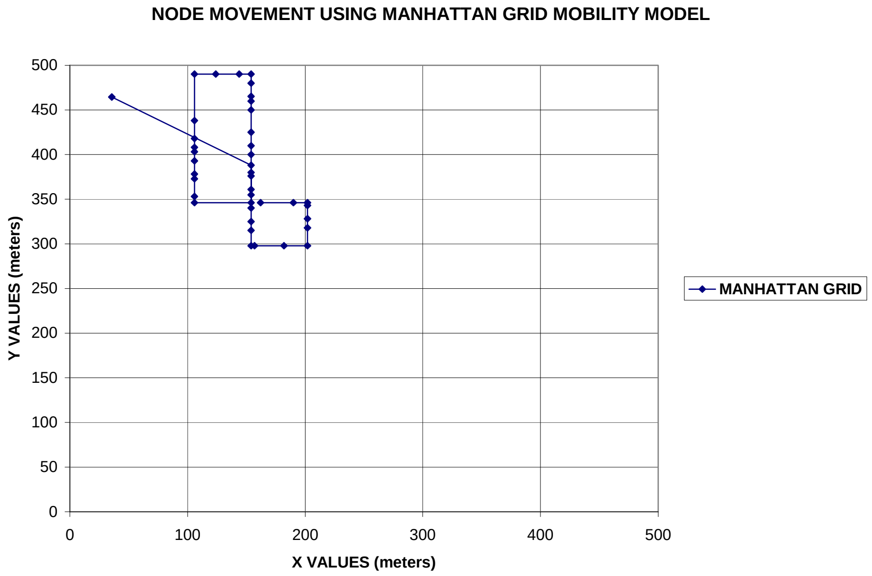

Figure 2.6. Traveling Pattern of a Mobile Node using Manhattan Grid Mobility Model

The mobile node is allowed to move along the grid of horizontal and vertical streets on the map. At an intersection the MN can turn right, left or go straight as depicted in Figure 2.6. This model has high temporal dependency of velocity as well as spatial dependency of velocity. Also it imposes geographic restrictions on the movement of the MN [36] [46].

2.5.4 Reference Point Group Mobility (RPGM) Model

In an ad hoc network there are a lot of scenarios where it is necessary to model the behavior of MNs as they move together. Group mobility can be used in military battlefield communication, rescue operations, tracking etc [45]. Each group has a logical center (group leader) that determines the group's motion behavior. Initially, each member of the group is uniformly distributed in the neighborhood of the group leader. Subsequently, at each instant, every node has a speed and direction that is derived by randomly deviating from that of the group leader. Figure 2.7. illustrates the traveling pattern of three MNs moving together as one group.

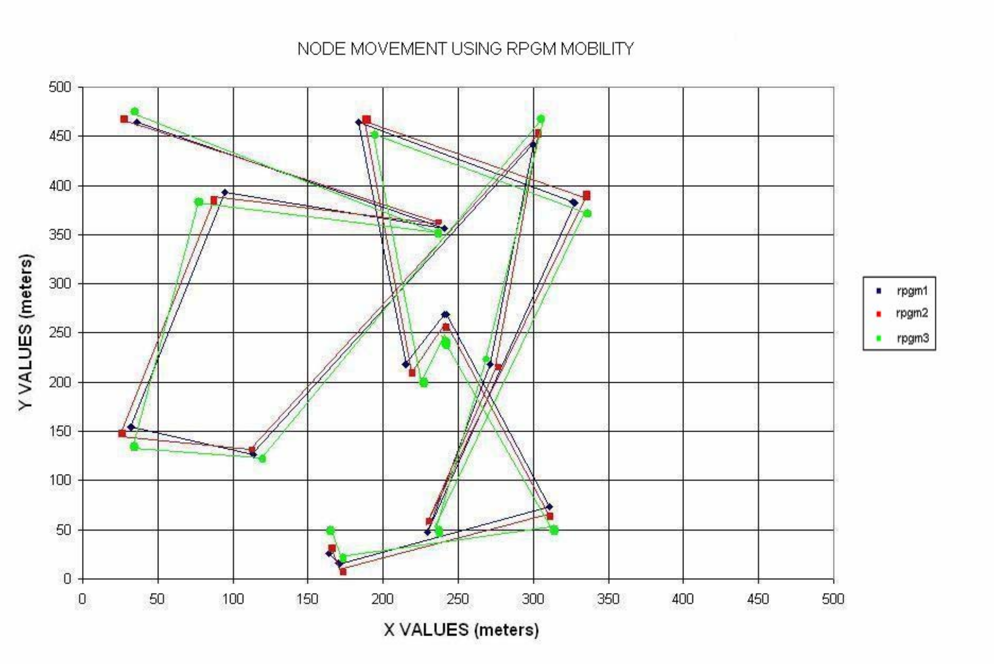

Figure 2.7. Traveling Patterns of Three Mobile Nodes using Reference Point Group Mobility Model

The movement of the logical center for each group, and the random motion of each individual MN within the group, are implemented via the RW Mobility Model. However, the individual MNs do not use pause times while the group is moving.

2.5.5 Pursue Mobility Model (PM)

It emulates scenarios where several nodes attempt to capture a single mobile node ahead. This mobility model could be used in target tracking and law enforcement. The node being pursued moves freely according to the RW model. The current position of an MN, a random vector, and an acceleration function are combined to calculate the next position of the MN. By directing the velocity towards the position of the targeted node, the pursuer nodes try to intercept the target node as seen in Figure 2.8 [45].

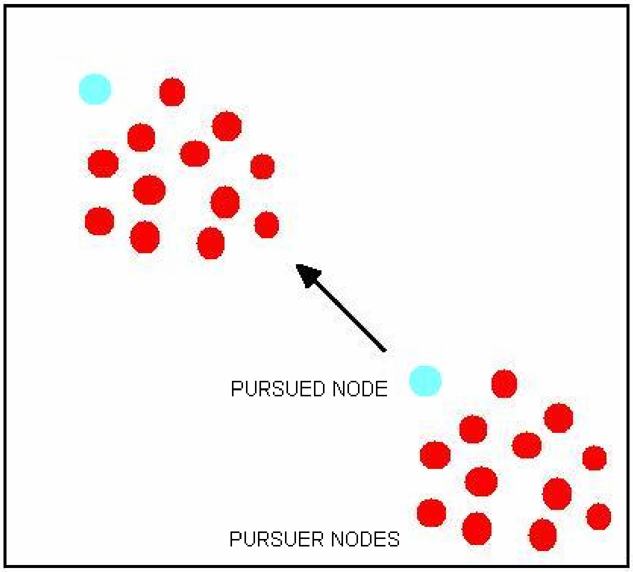

Figure 2.8. Movement of Mobile Nodes using Pursue Mobility Model

2.5.6 Column Mobility Model (CM)

The *column mobility* model represents a set of mobile nodes (e.g., robots) that move in a certain fixed direction. This mobility model can be used in searching and scanning activity, such as destroying mines by military robots [45]. This model represents a set of MNs that move around a given line, which is moving in a forward direction. For the implementation, an initial reference grid is defined as shown in Figure 2.9. Each MN is then placed in relation to its reference point in the reference grid; the MN is then allowed to move randomly around its reference point via an entity mobility model such as RW model or *random walk* model.

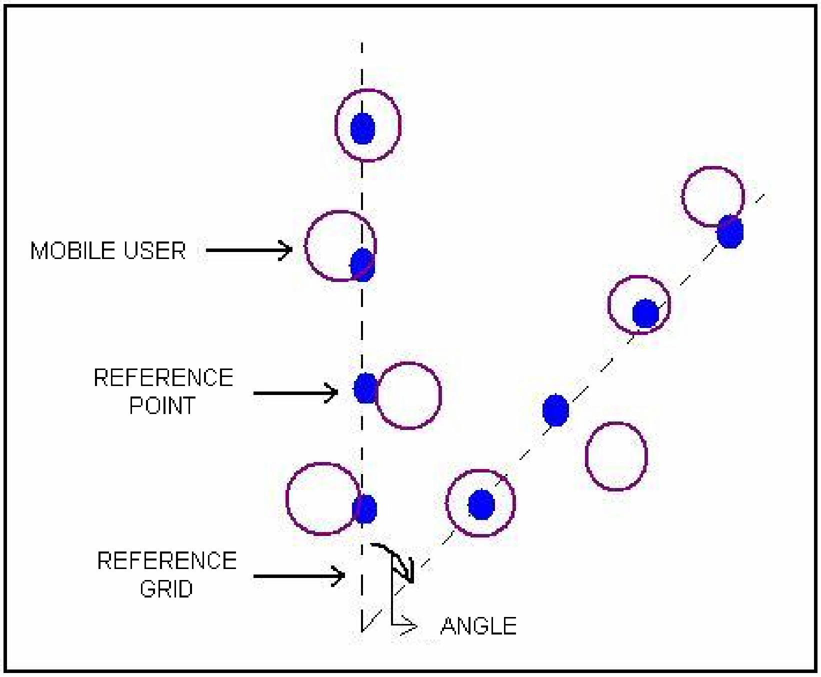

Figure 2.9. Movement of Mobile Nodes using Column Mobility Model

2.6 Summary

In this chapter, we reviewed some of the previous research done in evaluating the effect of multi-fading, energy consumption and mobility on the performance of routing protocols in MANETs. We then briefly described the fading channel, IEEE 802.11 MAC, routing protocols and mobility models that are considered in our network simulations.

Chapter Three

Factors Influencing MANET Performance in Realistic Environments

3.1 Network Simulations in Realistic Environments

Mobile ad hoc network performance can be evaluated through the use of simulation as it provides the capability to analyze the effect of different protocol parameters on different performance metrics in various network scenarios. Previously, most of the simulations of MANETs were done using RW mobility model as a default model. In this entity model, the Mobile Node (MN) moves in a random fashion with a specific pause time. But the scenarios in which ad hoc networks are implemented, the node mobility may not be randomized. Hence it is necessary to evaluate MANET performance with traveling patterns that emulate human movements. Figure 3.1 shows the network simulation settings of a MANET in an unrealistic environment incorporated with RW mobility model, *two ray ground reflection radio* model and CBR traffic.

Two ray ground propagation model considers the direct path and the ground reflection path when calculating the received signal power of each packet. Though it is more accurate than the *free space* model, which assumes the ideal propagation condition that there is only one line-of-sight path between the transmitter and receiver [47], this model does not take into consideration the effect of multi-path fading on the wireless channel.

Figure 3.2 illustrates the network simulation environment created for our MANET performance evaluation. We incorporated mobility models with realistic movement characteristics such as temporal dependence of velocity, spatial dependence of velocity and geographic restrictions. The mobility models are broadly categorized as Entity and Group mobility models [48]. Entity mobility model specifies individual node movement. Group mobility model describes group movement as well as individual node movement inside groups. The entity models considered were GM Model and MG Model. The group mobility presented was RPGM model, CM model and PM model. Table 3.1 tabulates the mobility models used for our simulations and the realistic mobility characteristics they exhibit.

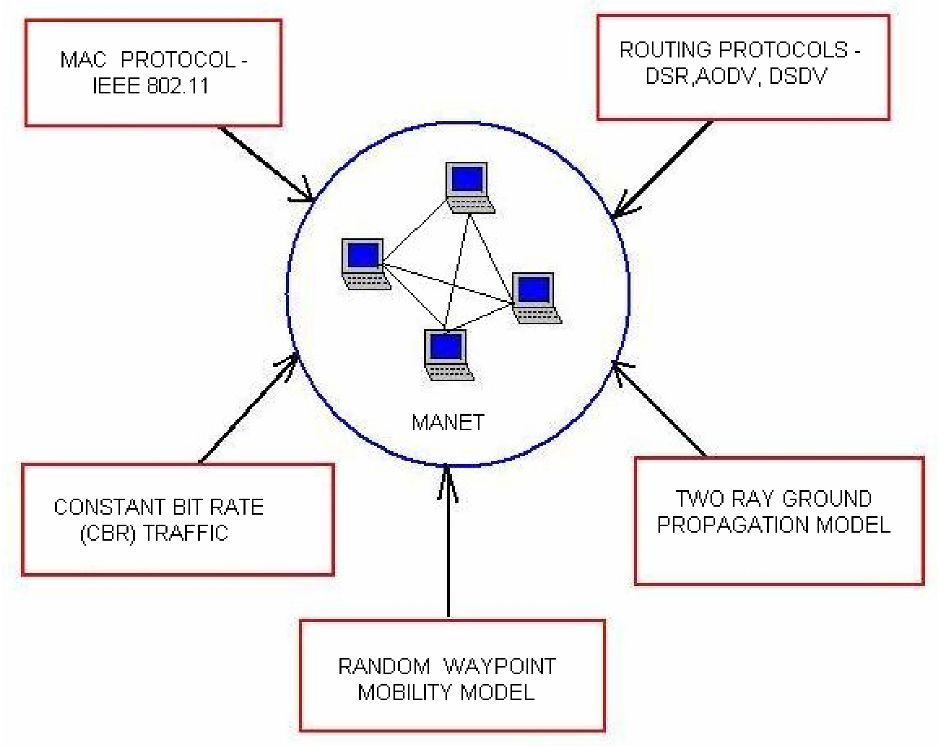

Figure 3.1. Network Simulation in an Unrealistic Environment

3.2 Temporal Dependency of Velocity

Temporal dependence of velocity indicates the similarity in the velocities of a node within a specified time interval [48]. In most real life scenarios, the speed of vehicles and pedestrians will accelerate incrementally. The direction change will also be smooth. Hence the velocity at current time period is dependent on the previous epoch, i.e., the velocities of a node at different time slots are correlated [35] [45]. So the mobility model should have some memory to prevent extreme mobility behavior, such as sudden stop, sudden acceleration and sharp turn, which may frequently occur in the trace generated by the RW model. Hence we use GM model so that the role of temporal dependence of velocity on MANET performance can be understood.

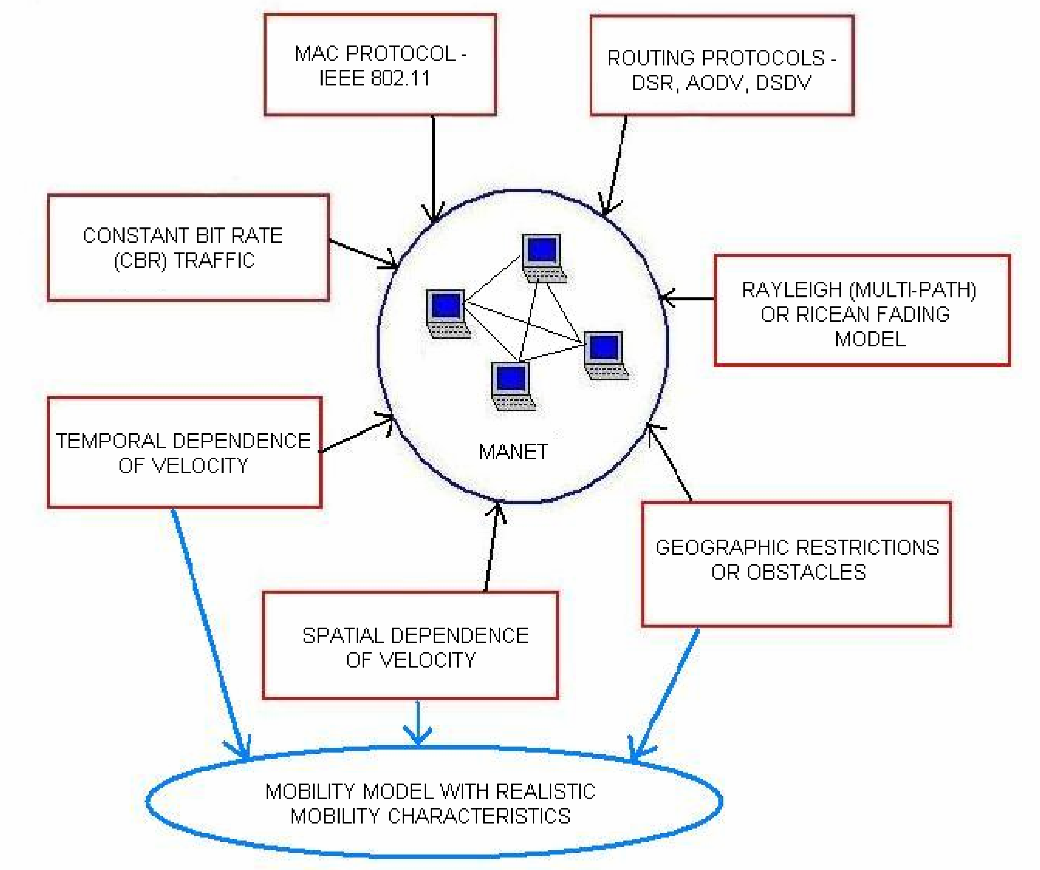

Figure 3.2. Network Simulation in a Realistic Environment

3.3 Spatial Dependency of Velocity

Spatial dependence of velocity indicates the similarity in the velocities of two nodes that are within a specified transmission range from each other, i.e., the velocities of different nodes are correlated in space [48]. In some scenarios such as battlefield communication and museum touring, the movement pattern of a mobile node may be influenced by a certain 'group leader' node in its neighborhood [35] [45]. Hence, the mobility of various nodes is indeed correlated. But the RW model considers a mobile node as an entity that moves independently of other nodes. So we need to consider using group mobility models like RPGM model, CM model and PM model that characterizes inter-dependent movement of nodes.

3.4 Geographic Restriction of Movements

RW and its variants assume that the mobile nodes can move freely within the simulation field without any restrictions. However, in realistic applications in urban area settings, the movement of a mobile node may be bounded by obstacles, buildings, streets or freeways [35] [45]. As the nodes movement is subject to the physical conditions they will move in a pseudo-random fashion on a predefined path. Some realistic mobility models incorporate the predefined paths and obstacles into the mobility models. We use MG mobility model in our simulations which restricts the movement of the mobile node to the pathway in the simulation field.

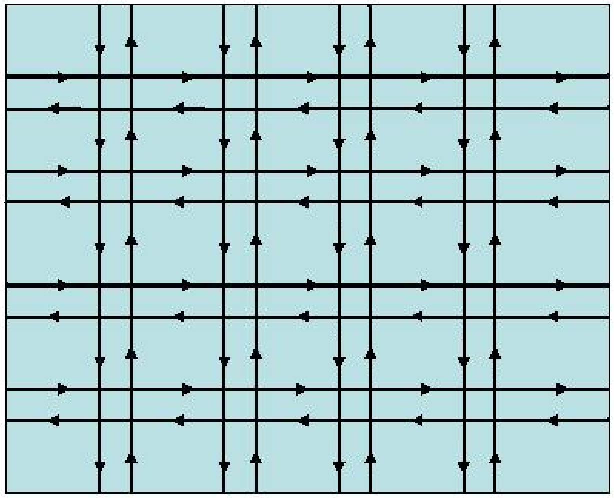

Figure 3.3. Pathway Map of Manhattan Grid Mobility Model

In mobility models with geographic restrictions, the predefined pathways restrict and partly define the movement path of nodes even though there exists a certain level of randomness. Hence the pathway of the simulation field is a key element for characterizing the geographic constraint of a mobility model. The pathway map used for MG mobility model is illustrated in Figure 3.3.

Table 3.1 Mobility Models and their Movement Characteristics

MOBILITY MODELS	TEMPORAL DEPENDENCE OF VELOCITY	SPATIAL DEPENDENCE OF VELOCITY	GEOGRAPHIC RESTRICTIONS/ OBSTACLES
Random Waypoint	No	No	No
Manhattan Grid	Yes	No	Yes
Gauss Markov	Yes	No	No
RPGM	No	Yes	No
Column Motion	No	Yes	No
Pursue Motion	No	Yes	No

3.5 Effect of Multi-path Fading Channel

Figure 3.4 illustrates the effect of Rayleigh fading on a signal's envelope. The time interval corresponding to two adjacent small-scale fades is on the order of a half wavelength (λ / 2).

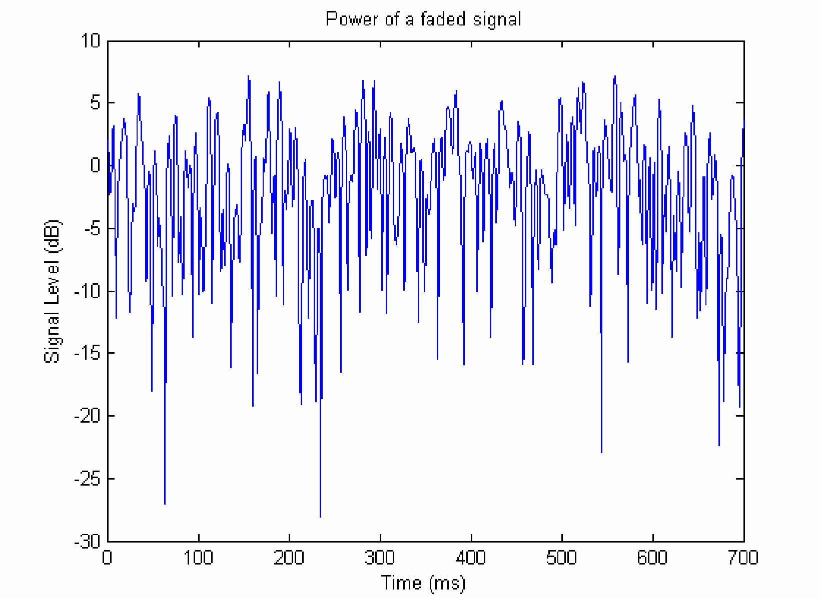

Figure 3.4. Time-Sequenced Rayleigh Fading Envelope

3.6 Scalability of a Network

As wireless ad hoc networks used for security and commercial purposes have significantly magnified in their sizes over the years, it is necessary to explore the behavior of large scale, complex wireless network systems in realistic ad hoc environments. Thus there is a need to use high performance simulation tools to achieve scalability to large networks [28]. But due to the limitations in the network simulator (Ns-2) used for our simulations the number of nodes in our network designed is around 50. Performance metrics such as *packet delivery ratio* (PDR) and *control overhead* are employed to analyze the scalability of the mobile ad hoc network when simulated in a fading environment with realistic mobility models.

3.7 Summary

This chapter reviews the need for realistic ad hoc scenarios in simulations, some of the important realistic movement characteristics and the mobility models that were used in our simulations. It explains the effect of Rayleigh fading on a signal. The scalability of MANETs is also discussed briefly.

Chapter Four

Network Simulation Environment

4.1 *ns-2* (Network Simulator)

4.1.1 Origins

The simulations are carried out using *ns-2* (26th release). *ns-2* is a discrete event, object oriented, simulator developed by the VINT project research group at the University of California at Berkeley targeted at networking research. *ns-2* provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks. *ns-2* began as a variant of the REAL network simulator in 1989 and has evolved substantially over the past few years. In 1995 *ns-2* development was supported by DARPA through the VINT project at LBL, Xerox PARC, UCB, and USC/ISI. Currently Ns development is supported through DARPA with SAMAN and through NSF with CONSER, both in collaboration with other researchers including ACIRI.

ns-2 has always included substantial contributions from other researchers, including wireless code from the UCB Daedelus and CMU (Carnegie Mellon University) Monarch projects and Sun Microsystems. The simulator has been extended by the Monarch research group at CMU to include: nodes mobility, a realistic physical layer that includes a radio propagation model, and the IEEE 802.11 Medium Access Control (MAC) protocol [25].

4.1.2 Functional Description

ns-2 is a simulator, written in C++ with an OTcl (Object Tool Command Language) interpreter as a front-end. C++ is used for detailed protocol implementation which efficiently manipulates bytes, packet headers, and implements algorithms that run over large data sets. On the other hand OTcl is ideal for slightly varying parameters and simulation configurations, or quickly exploring a number of scenarios. One of the main advantages of the split-language implementation of *ns-2* is its object oriented design, which allows for easy replacement of the software modules involved in a simulation - for example a routing protocol, a network application, or a propagation model.

The process of configuring the set of modules required to perform a particular simulation, starting from the physical interface model up to the application layer, is known as *plumbing*, and is usually performed by an OTcl script. When testing a new protocol, or implementing a simulation model, we need to write the code with the correct bindings to the OTcl interface, and afterwards instruct the plumbing script to employ the newly created modules during simulation setup.

MobileNode is the basic *ns*Node object with added functionalities like movement, ability to transmit and receive on a channel that allows it to be used to create mobile, wireless simulation environments. The class MobileNode is derived from the base class Node. MobileNode is a split object. The mobility features including node movement, periodic position updates, maintaining topology boundary etc are implemented in C++ while plumbing of network components within MobileNode itself (like classifiers, dmux , LL, Mac, Channel etc) have been implemented in Otcl [49].

Figure 4.1 illustrates the plumbing for the network stack objects of a MANET node that uses the DSDV routing protocol: an application layer module, the routing protocol, the *address resolution protocol* (ARP) module, a *link layer* (LL) object, an interface queue, the MAC protocol, and the physical interface with the channel’s radio propagation model [50].

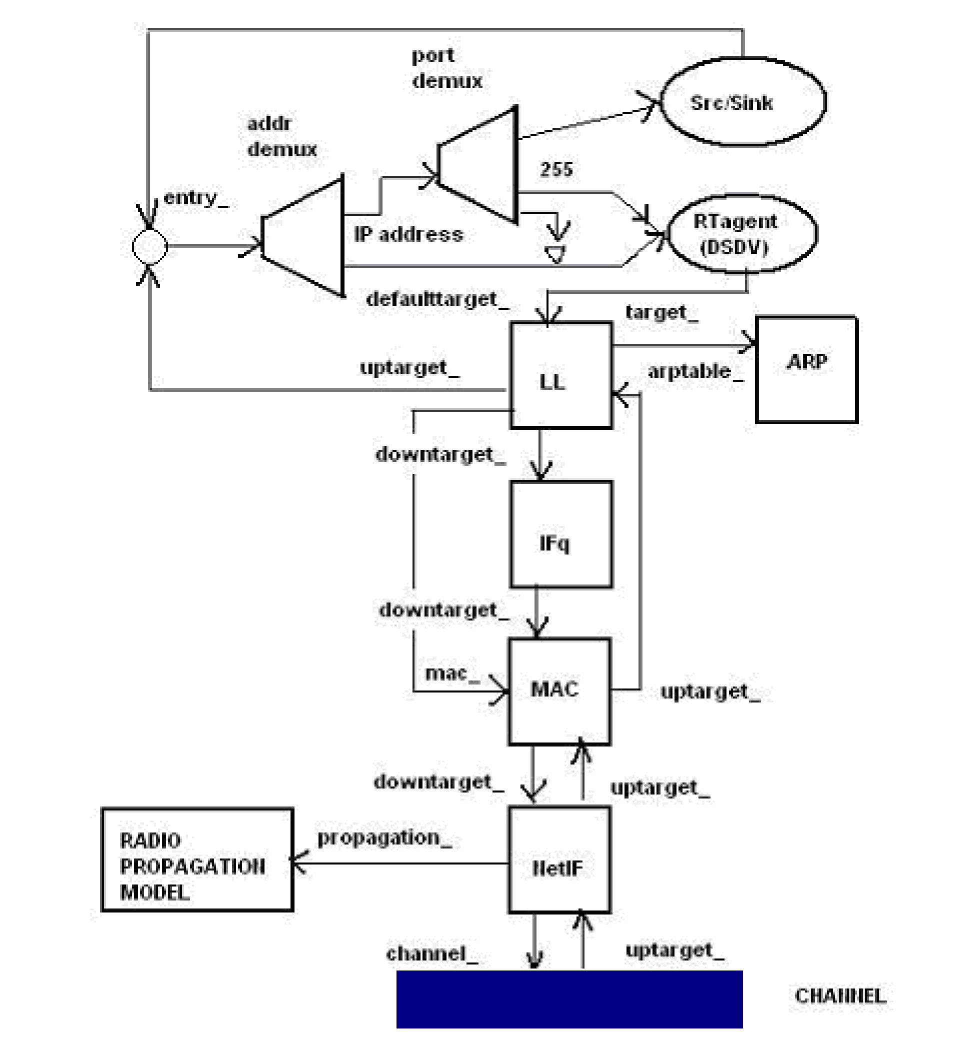

Figure 4.1. Schematic of a MobileNode under the CMU Monarch's Wireless Extensions to *ns-2* [25]

4.1.3 Modifications to *ns-2*

The Ricean (or Rayleigh) propagation model with a Ricean K factor of 0 is included so as to incorporate Rayleigh fading in the channel. A dataset containing the components of a time-sequenced fading envelope is pre-computed. With a few simple mathematical operations during the simulation run, this single lookup table can be used to model a wide range of parameters. The parameters to be adjusted are the time-averaged power, P, the maximum Doppler frequency, fm, and the Ricean K factor. The signal power from the LOS path with respect to the NLOS paths can be controlled by the Ricean K factor. Although the dataset represents a limited length time sequence, long simulations can be performed by using this limited dataset over and over again. The dataset is constructed so that there are no discontinuities when the sequence repeats. It is assumed that the small scale fading envelope is used to modulate the calculations of a large scale propagation model (two-ray ground or some other deterministic model) [30].

The Rayleigh (Multipath) Fading modeled in our simulations has the values as shown in Table 4.1:

Table 4.1. Multipath Fading Model Parameters

PARAMETER	VALUES
Distribution	Ricean - Gaussian components
Fm	20 Hz
N	15584
Fs	1000 Hz
Ricean K Factor	0
MaxVelocity	2.5 / 5.0
LoadRiceFile	rice_table.txt

4.2 Mobility Generators

4.2.1 The *setdest* Mobility Generator

The RW model is most commonly used mobility model in research of MANETs. This model is provided by the *setdest* tool in the standard *ns-2* distribution [51].

Usage: The syntax [52] to run “setdest” with arguments is as shown below:

Syntax: ./setdest [-n num_of_nodes] [-p pausetime] [-s maxspeed] [-t simtime] [-x maxx] [-y maxy] > [outdir/movement-file]

4.2.2 BonnMotion Mobility Generator

BonnMotion is Java-based software which creates and analyses mobility scenarios. It is developed within the Communication Systems group at the Institute of Computer Science IV of the University of Bonn, Germany. It serves as a tool for the investigation of mobile ad hoc network characteristics. The scenarios generated in this mobility generator can be exported for *ns-2* or GloMoSim. The mobility models that are supported are RW model, GM model, MG model and RPGM model [53].

Table 4.2. Parameters used to Generate Manhattan Grid Movement Pattern

PARAMETER	VALUES
Model	Manhattan Grid
Mobility Generator	BonnMotion
Number of Nodes	49
Simulation Time	600
X Dimension	500
Y Dimension	500
Number of Rows	7
Number of Columns	7
Maximum Pause Time	0.1
Pause Probability	0.1
Mean Speed	Varied as speed varies from 5 m/s to 80 m/s

GAUSS MARKOV MOBILITY MODEL:

Usage: All applications described above are started via the "bm" wrapper script [54].

Syntax: ./bm <parameters> <application> <application parameters>

Here, the parameters for simulating the mobility models are those described in the Tables 4.2, 4.3 below and the application can be a mobility model or e.g. the Statistics application used to analyze the scenario characteristics.

We generate MG movement files for five different speeds: 5 m/s, 20 m/s, 40 m/s, 60 m/s and 80 m/s and export them so that it can be used for simulations in *ns-2*. High speeds of around 80 m/s are reasonable whenever a MANET includes highly mobile nodes such as helicopters, police, military and other emergency vehicles.

Table 4.3. Parameters used to Generate Gauss Markov Movement Pattern

PARAMETER	VALUES
Model	Gauss Markov
Mobility Generator	BonnMotion
Number of Nodes	49
Simulation Time	600
X Dimension	500
Y Dimension	500
Random Seed	1
Angle Standard Deviation	0
Maximum Pause Time	0.1
Pause Probability	0.1
Maximum Speed	Varied as speed varies from 5 m/s to 80 m/s

GM movement files for five different speeds: 5 m/s, 20 m/s, 40 m/s, 60 m/s and 80 m/s were generated and then exported them to be used for simulations in *ns-2*. The angle standard deviation can be varied between 0 and 1.

4.2.3 Scenario Generator

It is a tool to generate MANET mobility scenarios for *ns-2*. The mobility models that have been implemented include RW model, PM model, GM model and CM model. Also hybrid models can be constructed so that realistic ad hoc situations such as disaster, conference, etc. can be implemented in simulations [55].

We use this mobility model to generate PM Model for a group of 50 mobile nodes. The movement patterns for five different speeds: 5 m/s, 20 m/s, 40 m/s, 60 m/s and 80 m/s was generated.

Usage: The syntax used is as shown,

Syntax: ./scengen > outdir/movement-file.

The script takes two inputs: "model-spec", which contains the default parameters, and normally does not need to be changed and the other is the scenario specification file "scen-spec", which describes the scenario needed. The “scen-spec” for pursue mobility model was generated and the movement file was obtained. The nodes pursuing the runaway node have a direction that at any instant of time will be in a straight line towards the runaway node.

The parameters which model the PM model used in our simulations is as shown in Table 4.4.

4.2.4 Mobility Generator – Toilers Code

“Toilers” is an ad hoc research group at Colorado School of mines [56]. We use the mobility model codes developed by this group to generate the movement patterns for RPGM and CM models.

Table 4.4. Parameters used to Generate Pursue Movement Pattern

PARAMETER	VALUES
Model	Pursue Motion
Mobility Generator	Scenario Generator
Start time	0 Seconds
Stop time	600 Seconds
Number of Nodes	50 (one node being pursued by the rest)
X Dimension	500
Y Dimension	500
Maximum Speed of Leader (Pursued) Node	Varied as 10 m/s, 25 m/s, 45 m/s, 65 m/s and 85 m/s.
Maximum Speed of other (Pursuer) Node	Varied as 5 m/s, 20 m/s, 40 m/s, 60 m/s and 80 m/s.
Minimum Speed of Leader (Pursued) Node	5 m/s
Minimum Speed of other (Pursuer) Node	0 m/s

Usage (For RPGM): ./rpgm <Number of groups> <Number of nodes group> <Reference point separation> <Max-X> < Max-Y> <End time> <Speed Mean> <Speed Delta> <Pause time> <Pause time delta> <'N' or 'G'>
where, N is *ns-2* file format and G is Gnuplot file format. The values for the different parameters used to generate the RPGM movement pattern is shown in Table 4.5.

We generate five different group scenarios for RPGM model so as to study the effect of inter-group dependency of the mobile nodes on the performance of different routing protocols. The number of groups in RPGM is varied from: 1, 2, 5, 10 and 25 keeping the number of nodes in the network scenario constant at 50. The different scenario movement files generated are as shown in Table 4.6.

Table 4.5. Parameters used to Generate Gauss Markov Movement Pattern

PARAMETER	VALUES
Model	RPGM
Mobility Generator	Toilers Code
Number of Groups	Varied as 1, 2, 5, 10 and 25
Number of Nodes per Group	Varied from: 50, 25, 10, 5 and 2 depending on number of groups to keep the number of nodes in all cases constant.
Simulation Time	600
X Dimension	500
Y Dimension	500
Number of Rows	7
Number of Columns	7
Pause Time	0.1
Pause Delta	0.1
Mean Speed	Varied as speed varies from 5 m/s to 80 m/s

The parameters used for CM model are similar to those described for RPGM.

Usage (For Column-Line): ./col-line <Number of groups> <Number of nodes group> <Reference point separation> <Max-X> < Max-Y> <End time> <Speed Mean> <Speed Delta> <Pause time> <Pause time delta> <'N' or 'G'>
Where, N implies *ns-2* Mobility file format and G is Gnuplot file format.

Table 4.6. Different RPGM Scenarios Simulated

GROUP SCENARIO	NUMBER OF GROUPS	NUMBER OF NODES PER GROUP
RPGM1	1	50
RPGM2	2	25
RPGM3	5	10
RPGM4	10	5
RPGM5	25	2

4.3 Traffic Generation

We generate 12 Constant Bit Rate (CBR) traffic connections with send rate of 4 and packet size of 512 bytes for UDP sources. The source-destination pairs are spread over the network as shown in Figure 4.2.

Random traffic connections of CBR can be setup between mobile nodes using a traffic-scenario generator. This script is available in *ns-2* [52]. It can be used to create CBR and TCP traffics connections between wireless mobile nodes.

Syntax: ns cbrgen.tcl [-type cbr] [-nn nodes] [-seed seed] [-mc connections] [-rate rate]

4.4 Network Scenario

Two different scenarios are considered based on the mobility models used. For the Entity Mobility models like RW model, MG model and GM model we use the Scenario A. For Group Mobility models like RPGM model, PM model and CM model we conduct experiments using the Scenario B.

Scenario A: We generated an ad hoc network with 49 highly mobile nodes. The simulation area is 500 m x 500m and the simulation time was set to 600 seconds.

Figure 4.2 shows the initial position of the nodes and the connections through which the traffic flows.

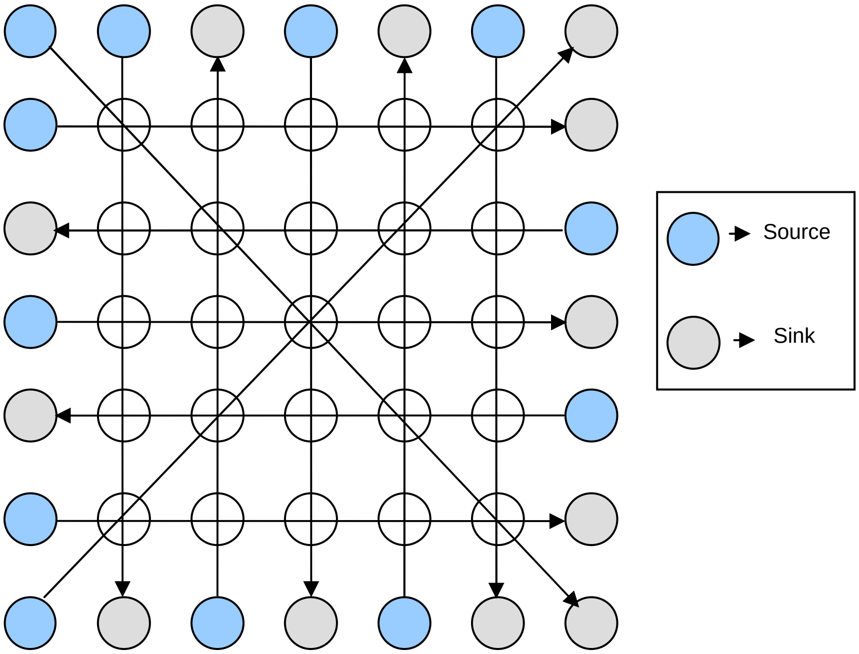

Figure 4.2. Network Schematic Showing Initial Node Positions

Scenario B: This scenario models the mobile nodes in groups. Based on the number of groups generated, we consider five different group scenario cases as shown in Table 4.7. Figure 4.3 illustrates the group scenario 4 where five groups were formed with ten mobile nodes in each group.

Table 4.7. Different Group Scenarios Simulated

SCENARIO	NUMBER OF GROUPS	NUMBER OF NODES PER GROUP
Group Scenario 1	1	50
Group Scenario 2	2	25
Group Scenario 3	5	10
Group Scenario 4	10	5
Group Scenario 5	25	2

The simulation area is set to be 500 m x 500 m. Simulations are run for 600 seconds for 50 nodes. Each data point represents an average of at least five runs with identical traffic models, but different randomly generated mobility scenarios.

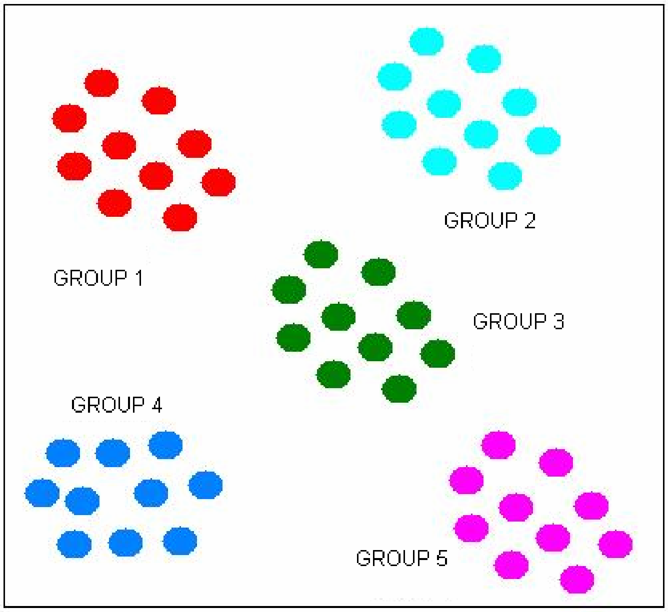

Figure 4.3. Illustration of Group Scenario 3

4.5 Energy Consumption Model

According to the specification of the Network Interface Card (NIC) modeled, the energy consumption varies from 230mA in receiving mode to 330mA in transmitting mode, using 3.3V or 5.0V voltage supply [69]. All nodes are equipped with IEEE 802.11 NICs with data rates of 2 Mbps. The energy expenditure needed to transmit / receive a packet p is: E(p tx / rcv) = i * v* t p Joules, where i is the current value, v the voltage, and t p the time taken to transmit / receive the packet p. Packet transmission time, t p = (packet-size in bits / 2 * 106) sec. In our simulations, the measured values of a Cabletron Roamabout 802.11 DS high rate NIC operating in base station mode is used. Table 4.8 shows the power consumption values of the four modes: Transmit mode, Receive mode, Idle mode and Sleep mode.

Table 4.8. Power Consumption Values

Transmit Mode	1400 mW
Receive Mode	1000 mW
Idle Mode	830 mW
Sleep Mode	130 mW

4.6 Performance Evaluation

The following performance metrics are considered in our simulations:

Energy-Goodput: It is defined as the ratio of the total bits transmitted to the total energy consumed, where the total bits transmitted are calculated for application layer data packets only and the total energy consumed captures the entire energy utilization of the network with all the control overhead included. The unit for energy-goodput is bits/J.

Packet Delivery Ratio (PDR): PDR is the ratio between the number of packets received by the end-point application and the number of packets originated at the source-node application.

Packet Overhead (Control Overhead): Packet Overhead is the number of per-hop non-data packets in the network per originating data packet. In case of CBR applications, this is directly proportional to the number of per-hop routing packets in the network.

4.7 Summary

This chapter focused on the network simulation environment used for our research. It also briefly explained the mobility and traffic generators used to generate movement and traffic patterns. Finally the performance metrics that were used to determine protocol performance was presented.

Chapter Five

Experimental Results

5.1 Scalability in Mobile Ad hoc Networks

Scalability of a protocol can be obtained by measuring the protocol performance in different scalable scenarios. Traditionally ad hoc networks have been used under small and low-density environments. Large-scale mobile ad hoc networks are characterized by high node density, high mobility and large number of nodes. Protocol performances were evaluated based on *Packet Delivery Ratio (PDR) and Control Overhead.*

As mentioned earlier, two sets of analysis are made to evaluate the performance of MANETs with entity mobility models and group mobility models. In [28] scalability analysis for MANETs was performed using DSR and DSDV considering only Random Waypoint Mobility model. Our simulations encompass scalibility analysis for some of the most popular entity and group mobility models cited in Chapter 2.

5.1.1 Scalability Analysis using Entity Mobility Models

The Random Waypoint (RW) model is the default model which does not include any of the realistic mobility characteristics mentioned in Chapter 3. Manhattan Grid model has geographic restrictions incorporated in it through the use of pathway graphs. It was initially expected to have high degree of spatial dependency as the mobility of a node is subjective to the movement of the nodes ahead of it, in the lane. But from [37] we understand that Manhattan Grid (MG) model has negligible spatial dependence of velocity as the positive degree of spatial dependence (due to nodes traveling in same direction) is cancelled out by the negative degree of spatial dependence (due to nodes traveling in opposite direction). Gauss Markov (GM) mobility model has a high degree of temporal dependence as the velocity of the node is correlated over time and modeled as a Gauss Markov stochastic process [35].

The maximum speed is increased from 5 m/s to 80 m/s. We keep the network density constant for all our simulations and hence any changes in protocol performance can be directly attributed to the mobility model used and the variation in speed.

Packet delivery ratio is strongly influenced by the number of packets that are dropped, either at the source nodes or at intermediate nodes. Most packets being dropped are at the intermediate nodes which are mainly due to network congestion or broken links.

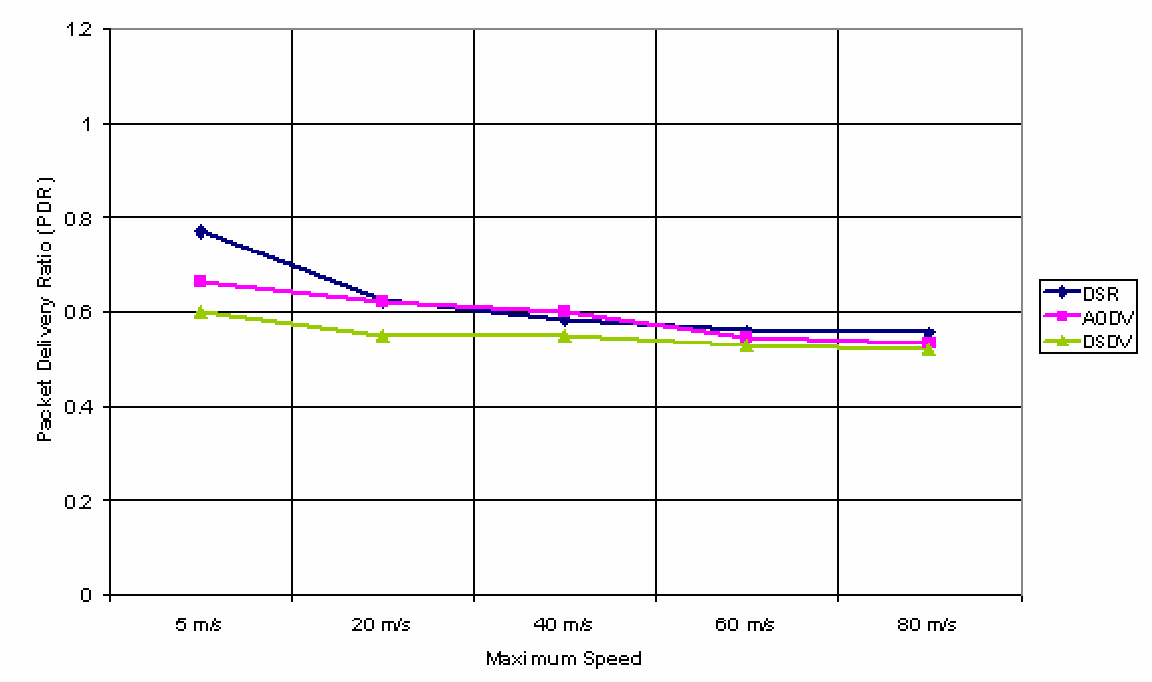

Figure 5.1. PDR Analysis for Various Routing Algorithms using Random Waypoint Mobility Model

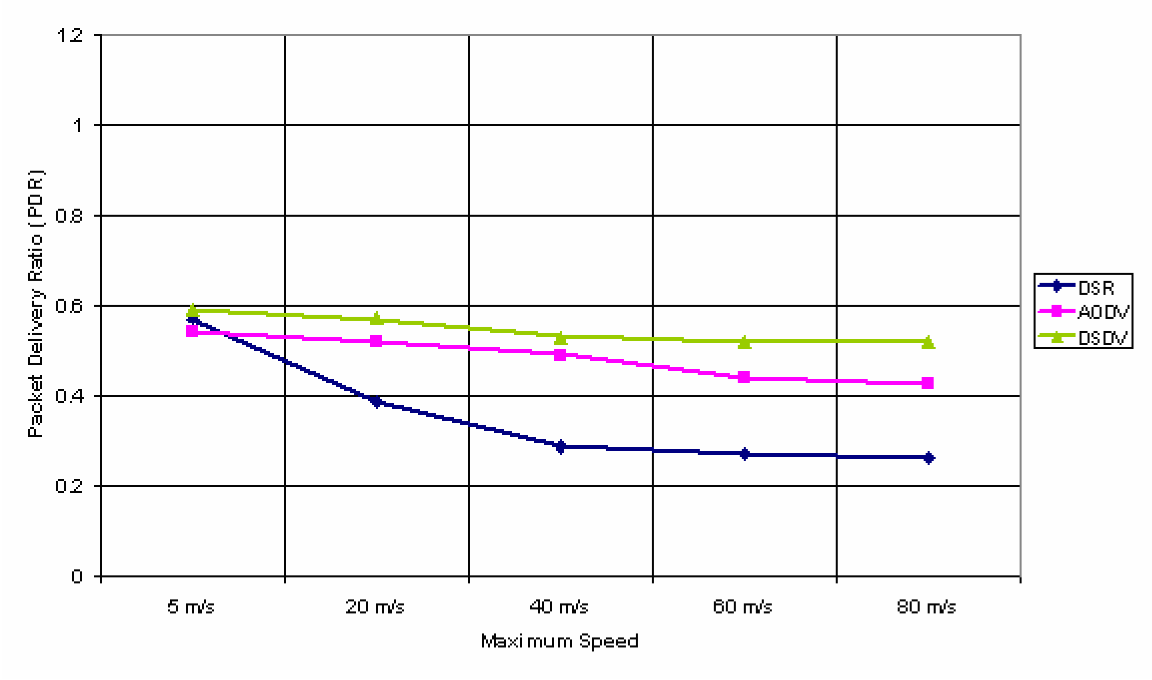

Figure 5.2. PDR Analysis for Various Routing Algorithms using Manhattan Grid Mobility Model

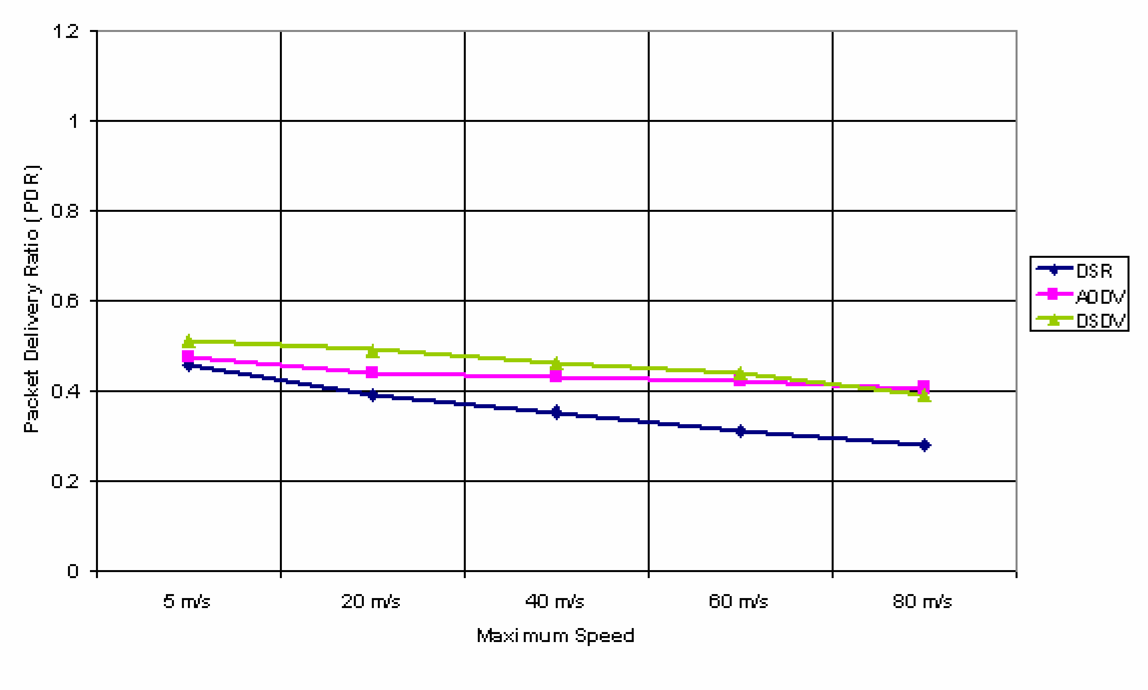

Figure 5.3. PDR Analysis for Various Routing Algorithms using Gauss Markov Mobility Model

From Figures 5.1, 5.2 and 5.3 we observed that DSR has a higher PDR with RW model than AODV and DSDV. But its performance degrades significantly with MG and GM models in comparison with AODV and DSDV. One main reason for this performance drop in DSR can be attributed to the fact that control overhead increases more drastically as speed increases from 5 m/s to 20 m/s, when MG or GM models were used instead of RW model. Higher control overhead is needed to repair the more frequently occurring link breakages. Surprisingly, from Figures 5.4, 5.5 and 5.6 we observe that the control overhead produced by MG model and GM model on AODV and DSDV is lesser when compared to that produced by using RW model.

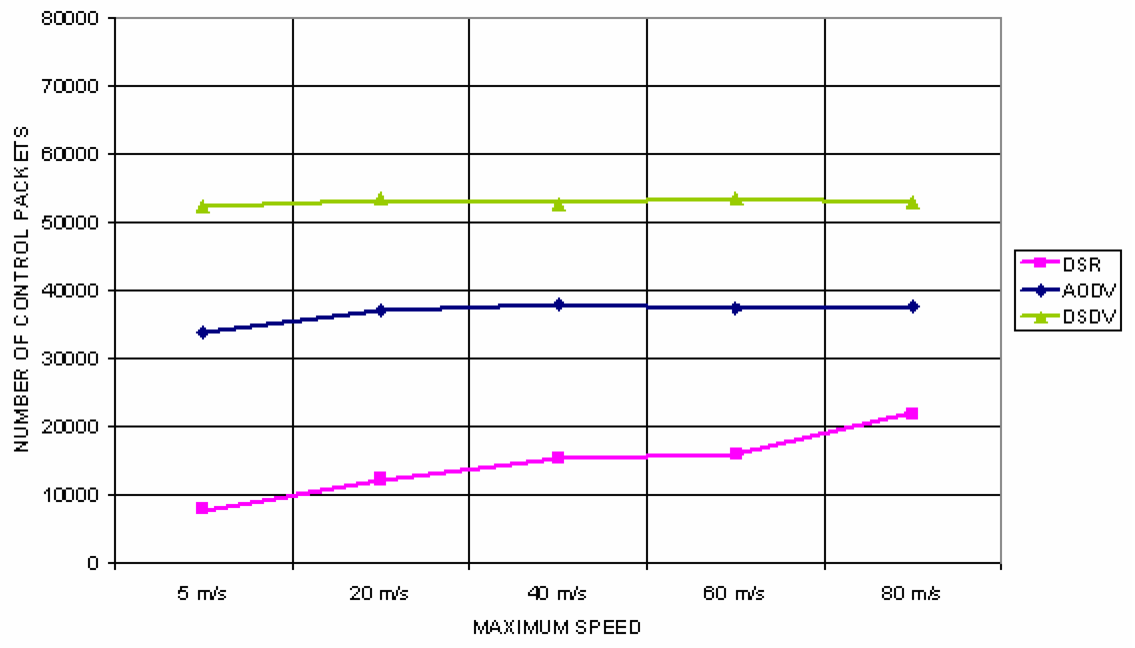

Figure 5.4. Control Overhead Analysis for various routing algorithms using Random Waypoint Mobility Model

Comparing the PDR analysis made for RW and MG mobility models, we can conclude that when there are *geographic restrictions* associated with the movement of a mobile node in a MANET, there are more link breakages and hence there are more packets being dropped by forwarding nodes. When more packets are dropped more retransmissions takes place and there is higher network congestion leading to lower PDR values. As the speed increases the PDR decreases gradually when GM mobility model is used. Here again there are more broken links when compared to RW model.

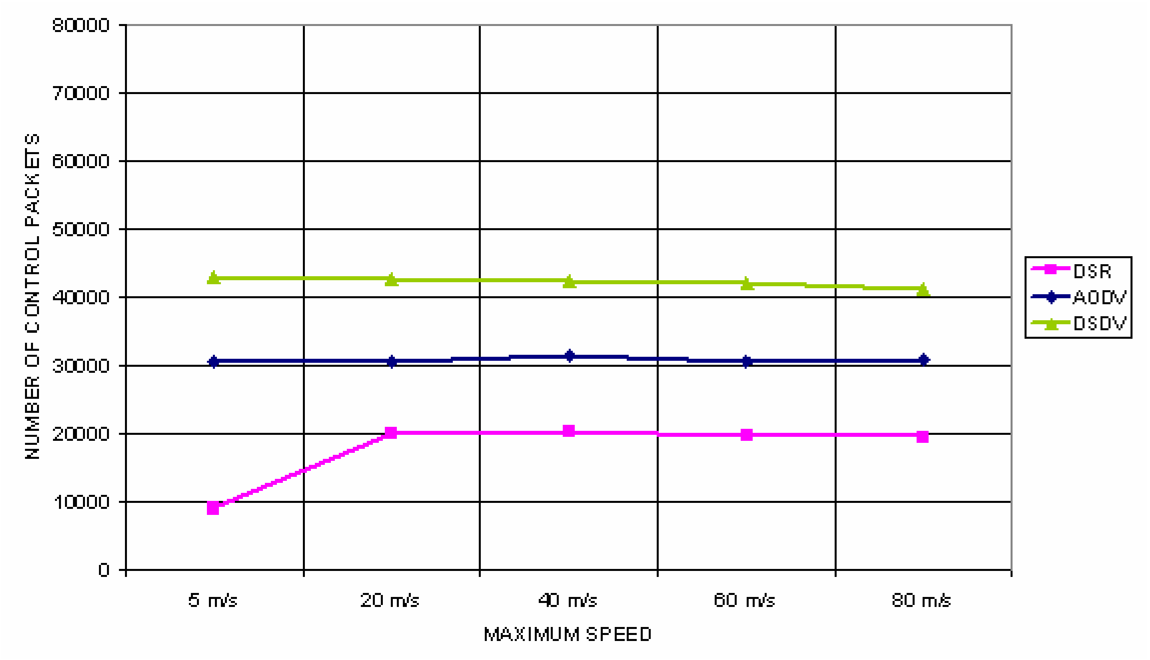

Figure 5.5. Control Overhead Analysis for Various Routing Algorithms using Manhattan Grid Mobility Model

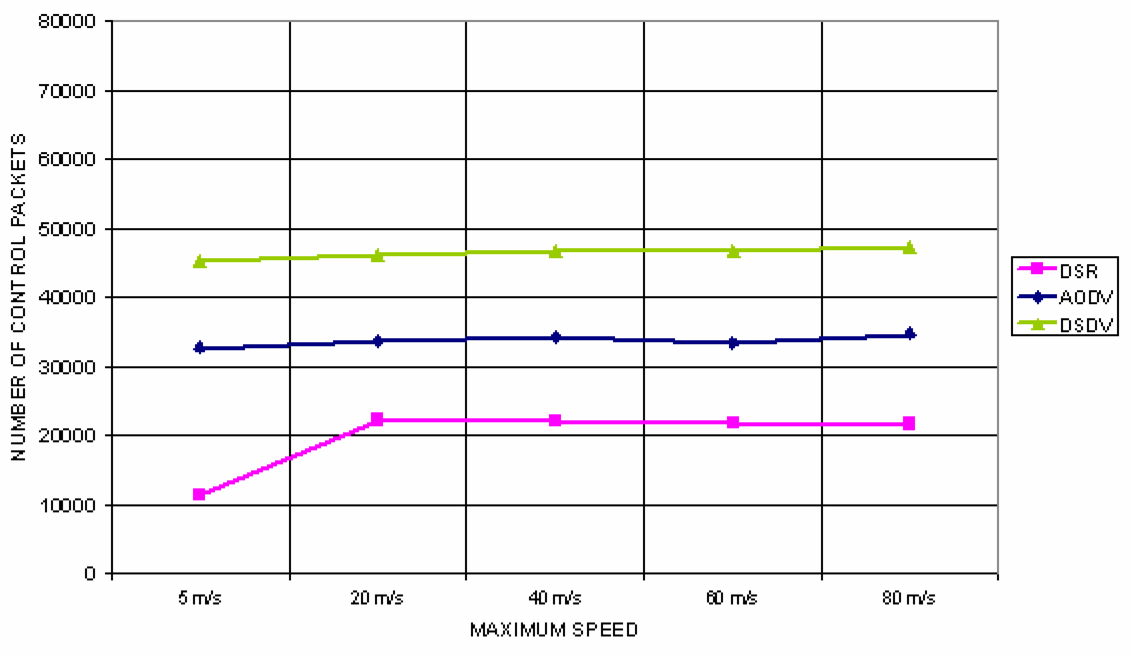

Figure 5.6. Control Overhead Analysis for Various Routing Algorithms using Gauss Markov Mobility Model

5.1.2 Scalability Analysis using Group Mobility Models

The effect of *spatial dependence of velocity* on the protocol performance in MANETs is a major concern when ad hoc networks are utilized in military operations, rescue missions, tracking and law enforcement, where a group of mobile nodes work and move together to achieve a particular goal. The scalability of a MANET using group mobility models is analyzed through simulations carried out in *ns-2* using the Scenario B mentioned in Chapter 4.

It has been proved that the single group mobility has a higher value for degree of spatial dependence than that of multiple group mobility [56]. Hence the degree of spatial dependence of velocity decreases as we go from Group Scenario 1 to Group Scenario 5. These scenarios were explained in detail in Chapter Four. This analysis gives a lucid understanding of the effect of the degree of spatial dependence on the scalability of a protocol when used in a mobile ad hoc network.

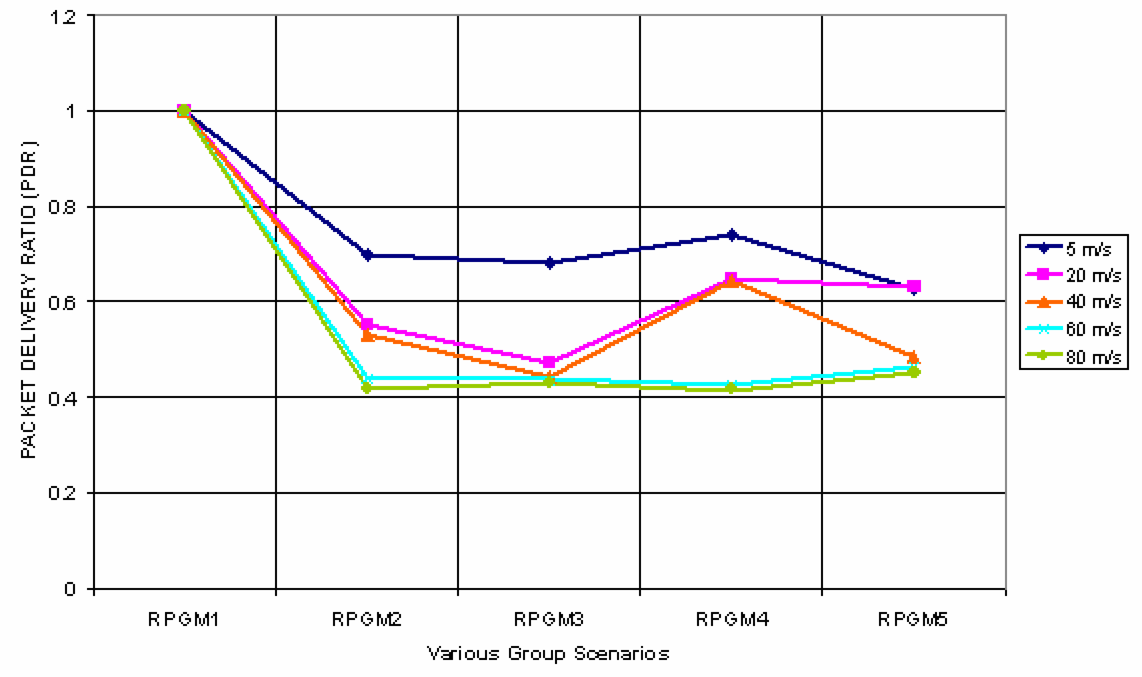

Figure 5.7. PDR Analysis for DSR using RPGM Mobility model for Various Speeds

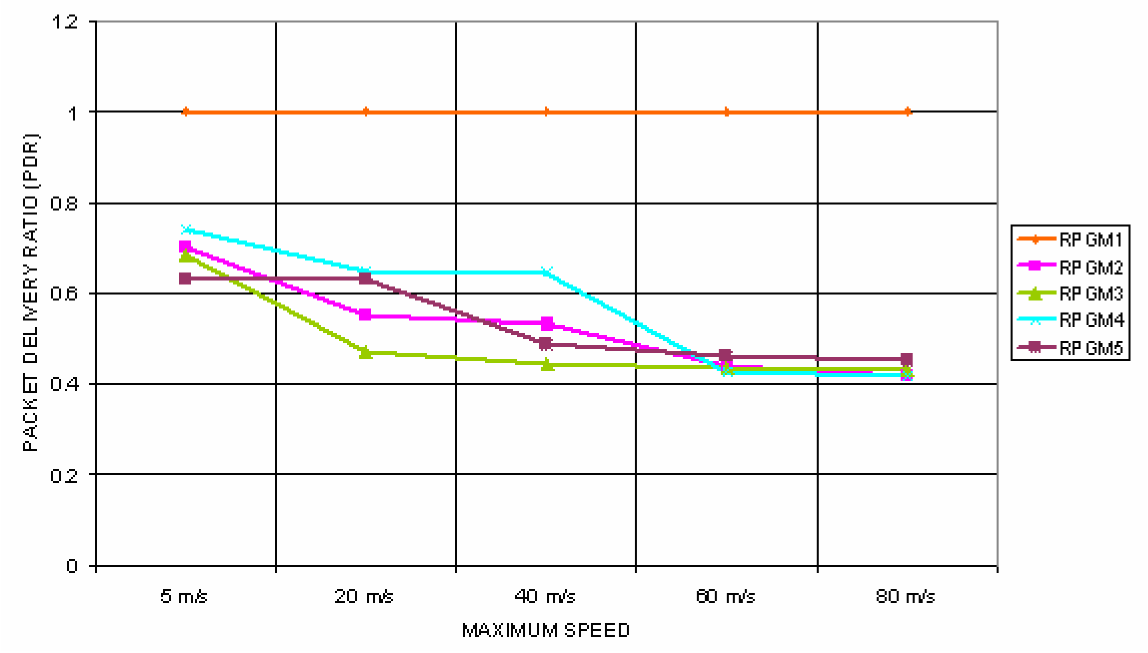

Figure 5.8. PDR Analysis for DSR using RPGM Mobility Model for Various Group Scenarios

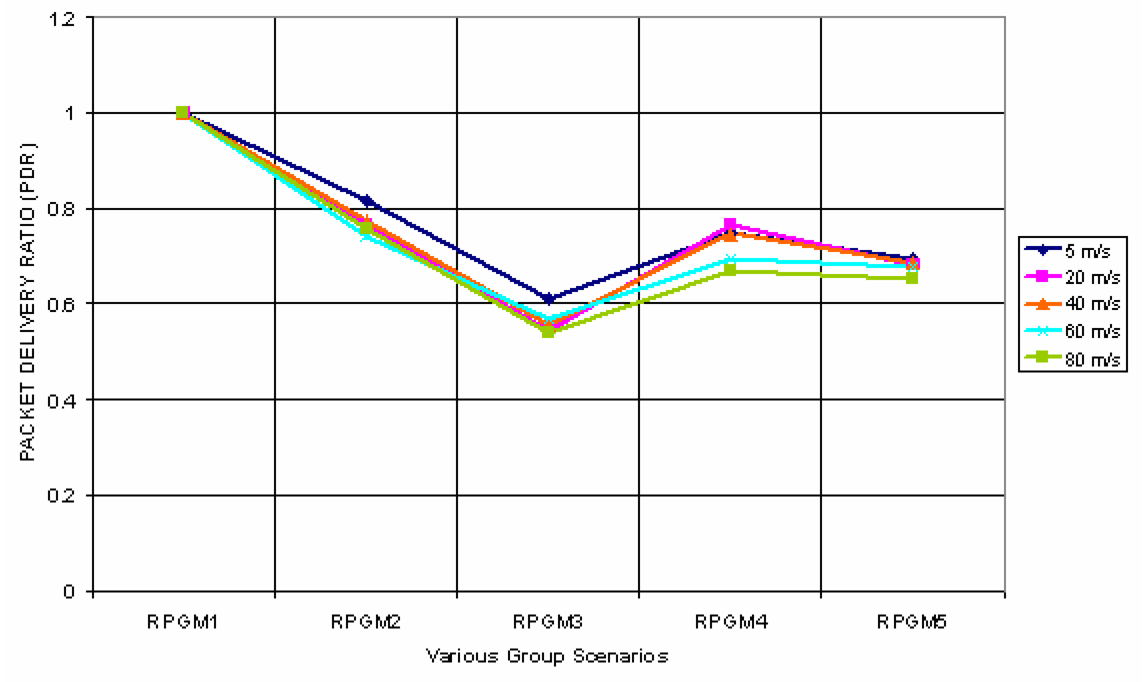

Figure 5.9. PDR Analysis for AODV using RPGM Mobility Model for Various Speeds

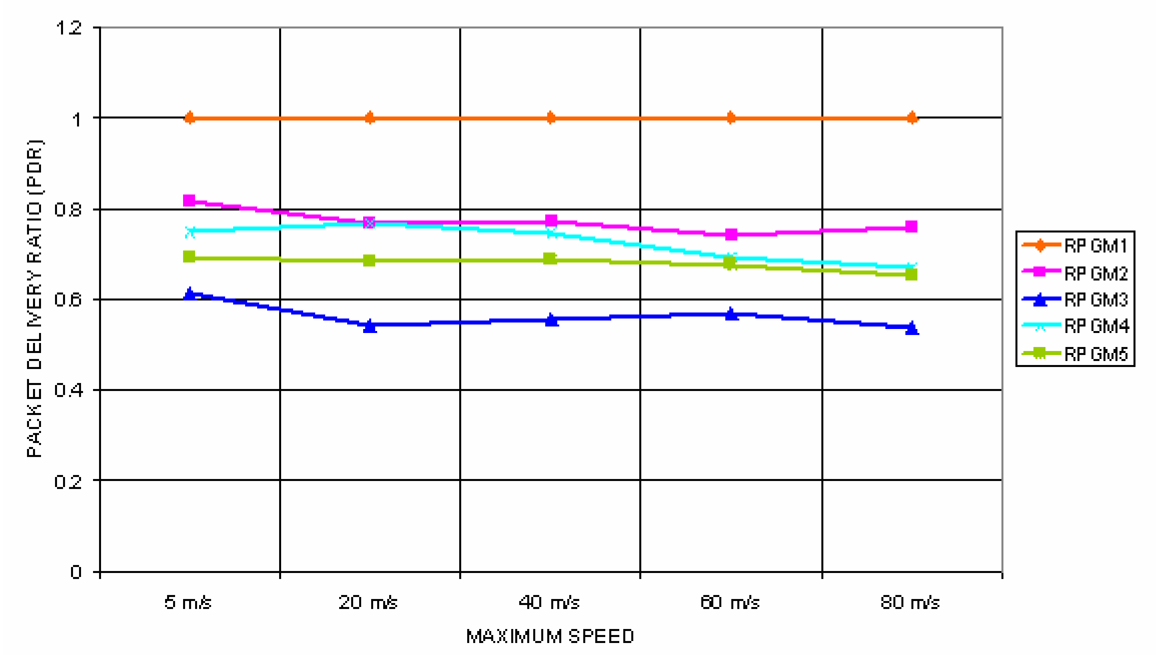

Figure 5.10. PDR Analysis for AODV using RPGM Mobility Model for Various Group Scenarios

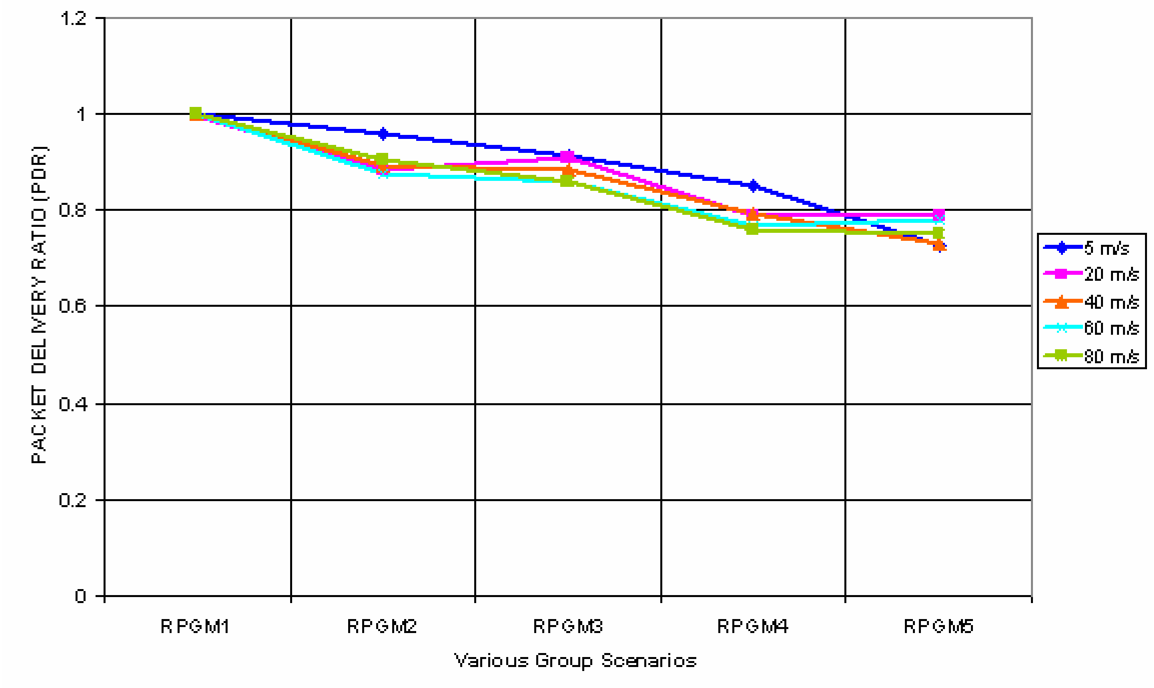

Figure 5.11. PDR Analysis for DSDV using RPGM Mobility Model for Various Speeds

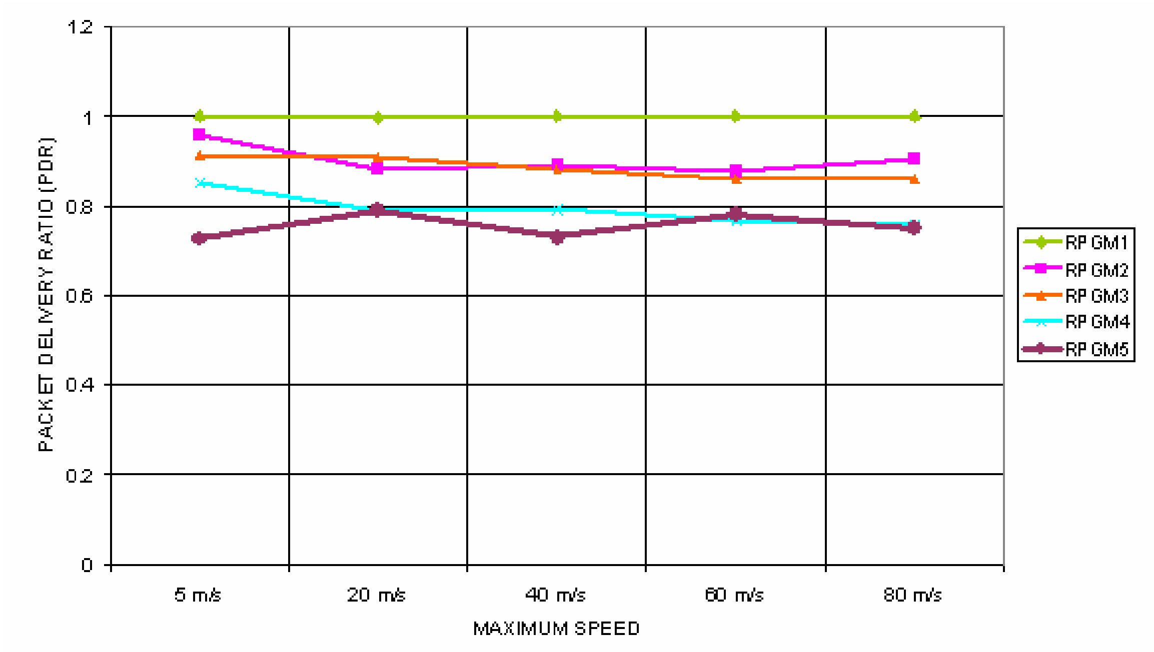

Figure 5.12. PDR Analysis for DSDV using RPGM Mobility Model for Various Group Scenarios

The following conclusions can be made from the PDR analysis made when using RPGM mobility model:

- Considering five different group scenarios, for DSR, as speed increases from 5 m/s to 80 m/s, the PDR decreases from 1.0 to about 0.41. Whereas for AODV the PDR decreases from 1.0 to about 0.54 and for DSDV, the PDR decreases from 1 to 0.726. These results are graphically depicted in Figures 5.7, 5.9 and 5.11.

- In all cases (DSR, AODV, DSDV), the PDR is a maximum at 5 m/s for all group scenarios and a minimum for 80 m/s.

- From Figures 5.8, 5.10 and 5.12 we can infer that as the degree of spatial dependence of velocity decreases from Scenario: RPGM1 to Scenario: RPGM5, PDR decreases in general but DSR shows a more drastic decrease than AODV or DSDV. From the graphs it can be inferred that DSDV shows more consistent values when compared to DSR and AODV.

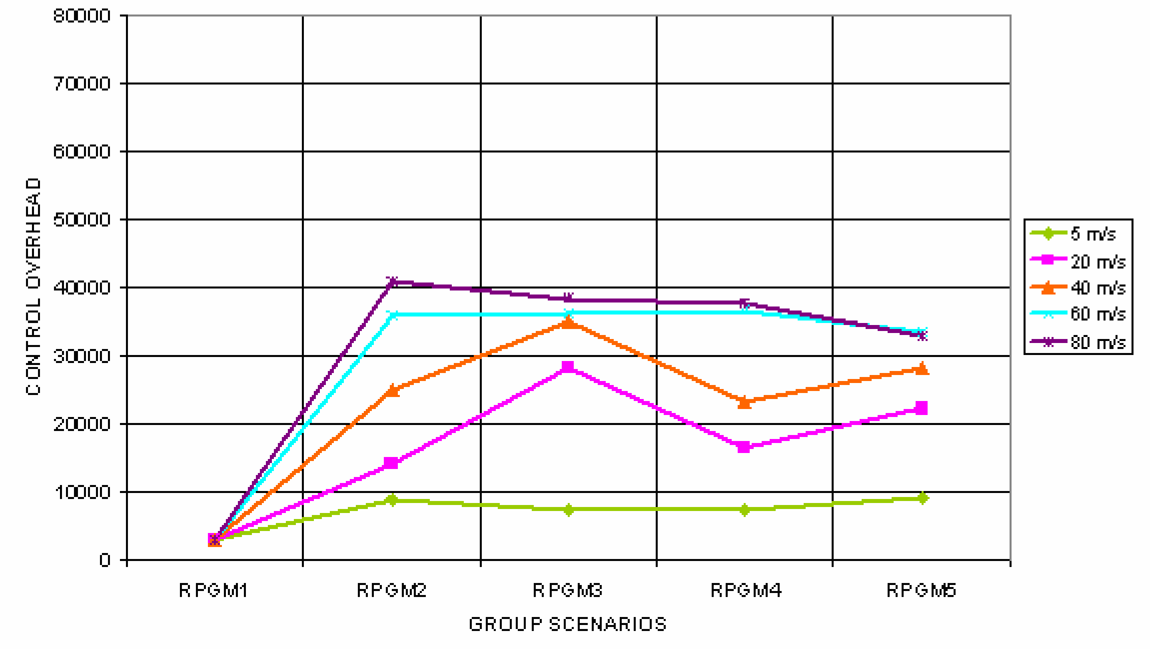

Figure 5.13. Control Overhead Analysis for DSR using RPGM Mobility Model for Various Speeds

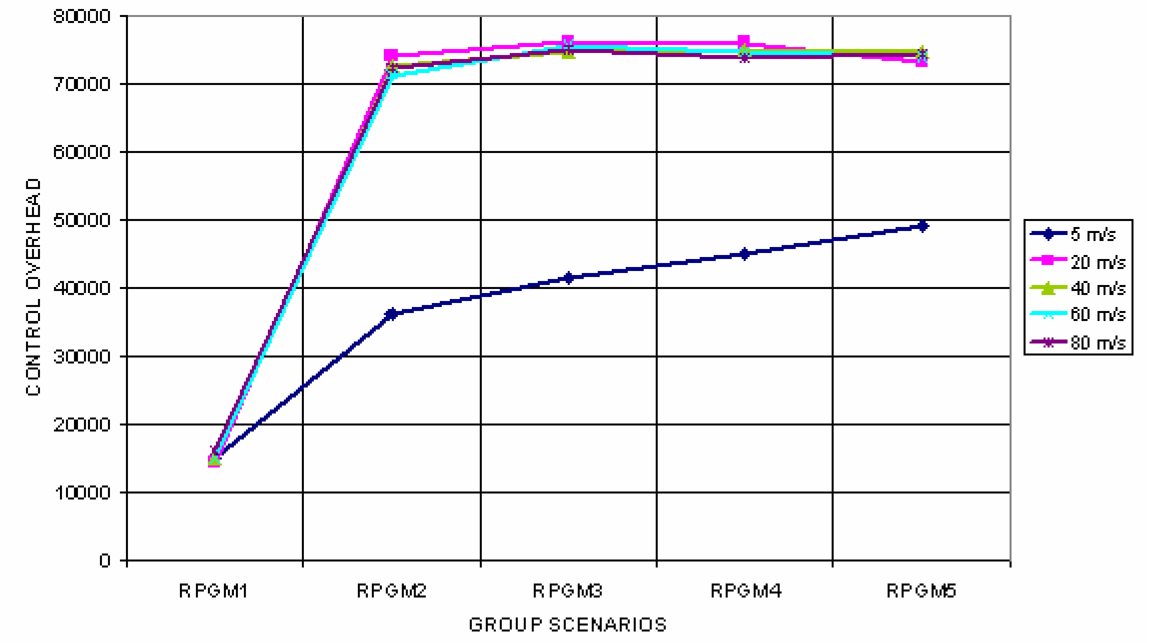

Figure 5.14. Control Overhead Analysis for AODV using RPGM Mobility Model for Various Speeds

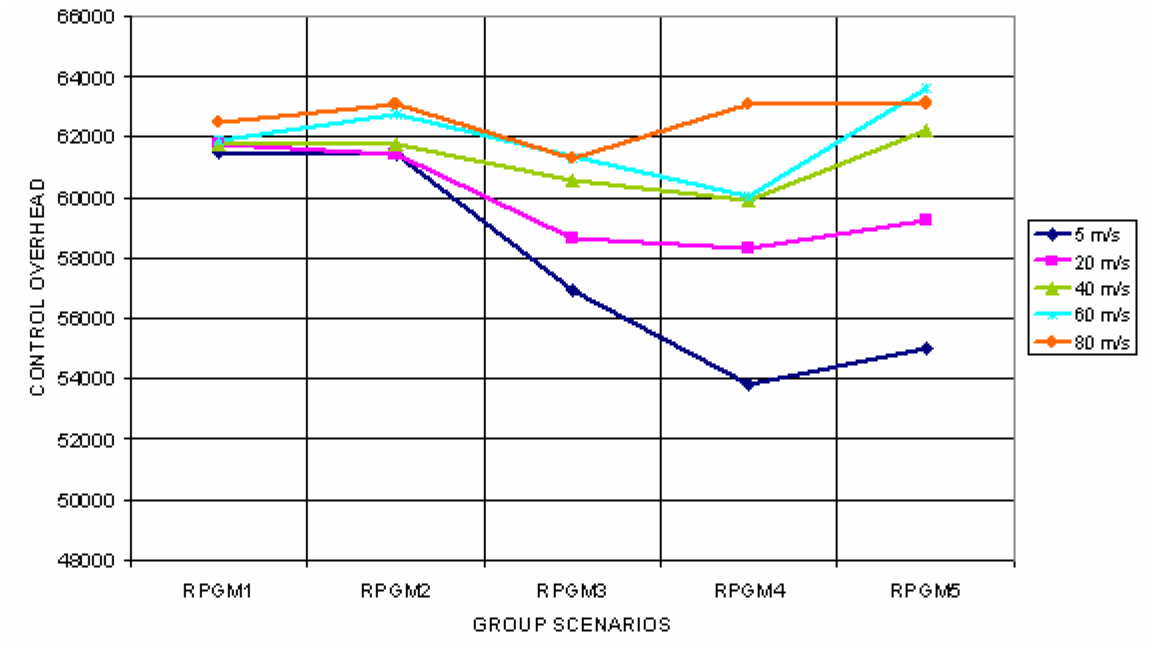

Figure 5.15. Control Overhead Analysis for DSDV using RPGM Mobility Model for Various Speeds

The following conclusions can be made from the control overhead analysis made when using RPGM mobility model:

- From Figures 5.13, 5.14 and 5.15 we infer that the control overhead is maximum for speeds of 80 m/s and minimum for 5 m/s for DSR, AODV and DSDV. These results can be directly related to the PDR results explained earlier.

- Control overhead is very less in DSR (maximum – 43526 control packets) compared to AODV (maximum – 60648 control packets) and DSDV (maximum – 65755).

- The control overhead increases very steeply in AODV as speed increases from 5 m/s to 80 m/s. This is because there is more flooding of route discovery and route request packets as there are more route changes as mobility increases.

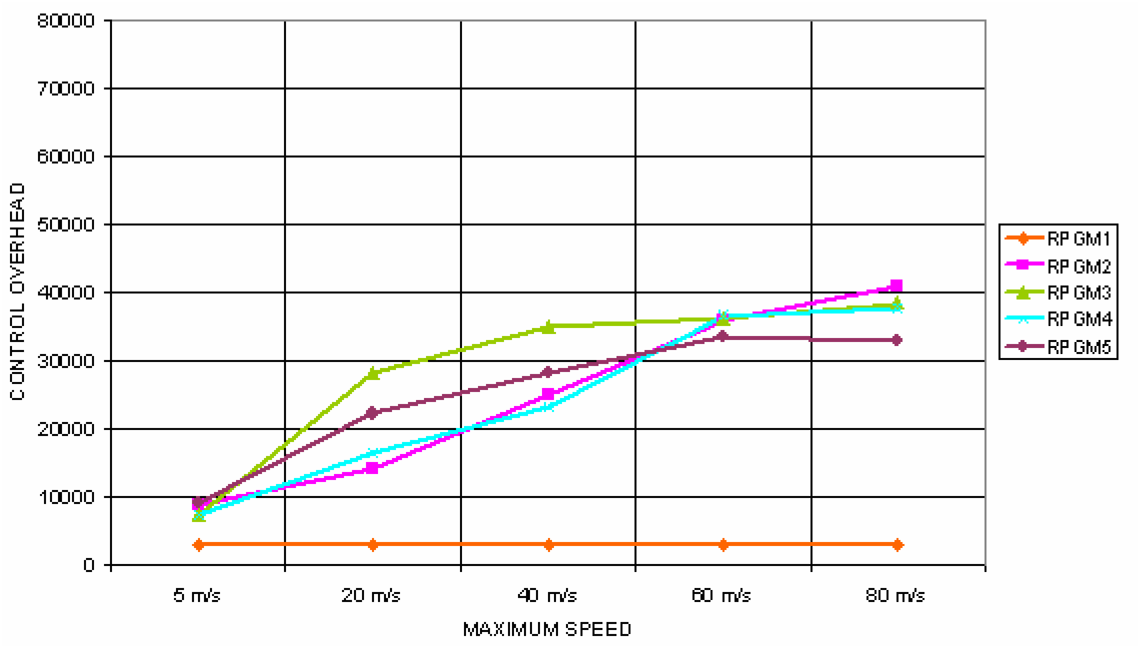

Figure 5.16. Control Overhead Analysis for DSR using RPGM Mobility Model for Various Group Scenarios

- DSDV is least affected by variation in speed. Because DSDV is a distance-vector protocol, it is responsible for periodically announcing its routing table to all one-hop neighbors. Since DSDV routing tables contain a list of next-hop entries for every node in the ad hoc network, the size of this routing update is independent of a node’s transmission range or power level. DSDV can be expected to be less sensitive to higher mobility rates and hence there is not much change (increase) in the number of link breakages as speed is increased from 5 m/s to 80 m/s. Hence we do not find a drastic increase in the control overhead produced, as depicted in Figure 5.18.

- In DSR, there is a considerable increase in the control overhead produced as the scenario transforms from a single group to multiple groups. DSDV shows very slight increase, whereas AODV is the worst affected as the control overhead increases drastically as we move from a single group scenario to a multiple scenario. This behavior is depicted by Table 5.1.

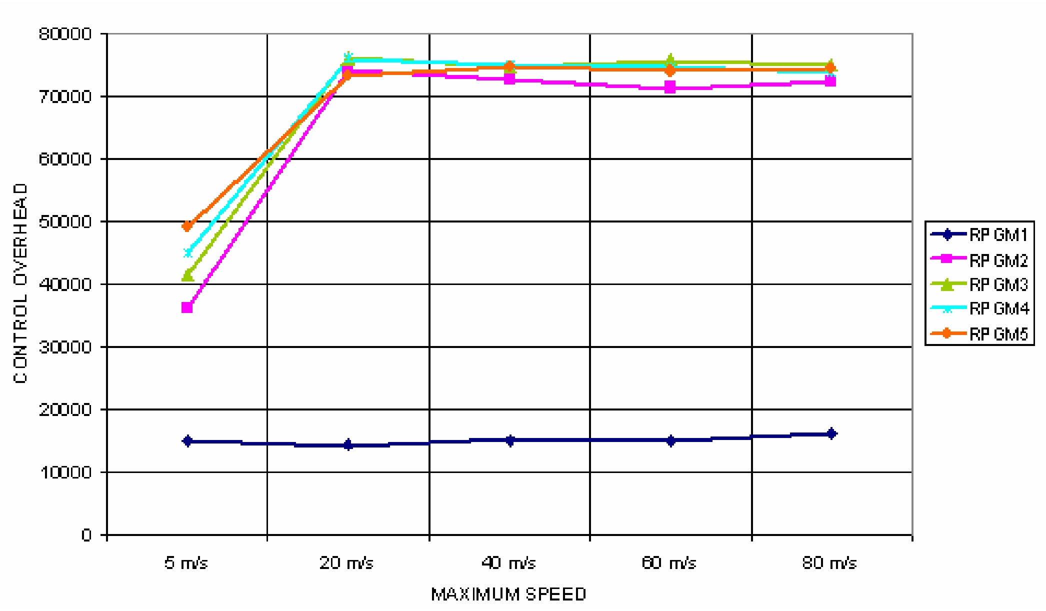

Figure 5.17. Control Overhead Analysis for AODV using RPGM Mobility Model for Various Group Scenarios

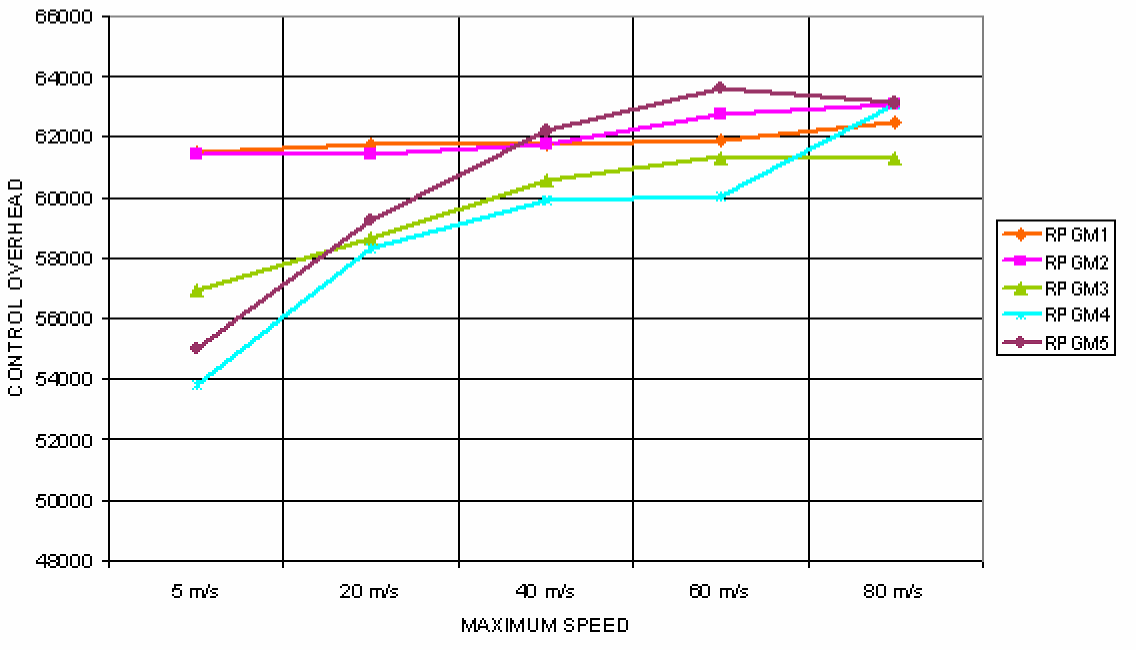

Figure 5.18. Control Overhead Analysis for DSDV using RPGM Mobility Model for Various Group Scenarios

Table 5.1. Maximum Control Overhead Produced for Single and Multiple Group Scenarios when Implementing RPGM Mobility Model

ROUTING PROTOCOL	MAXIMUM CONTROL-OVERHEAD SINGLE GROUP SCENARIO (Control Packets)	MAXIMUM CONTROL-OVERHEAD MULTIPLE GROUP SCENARIO (Control Packets)
DSR	2903	40821
AODV	16238	76100
DSDV	61929	63638

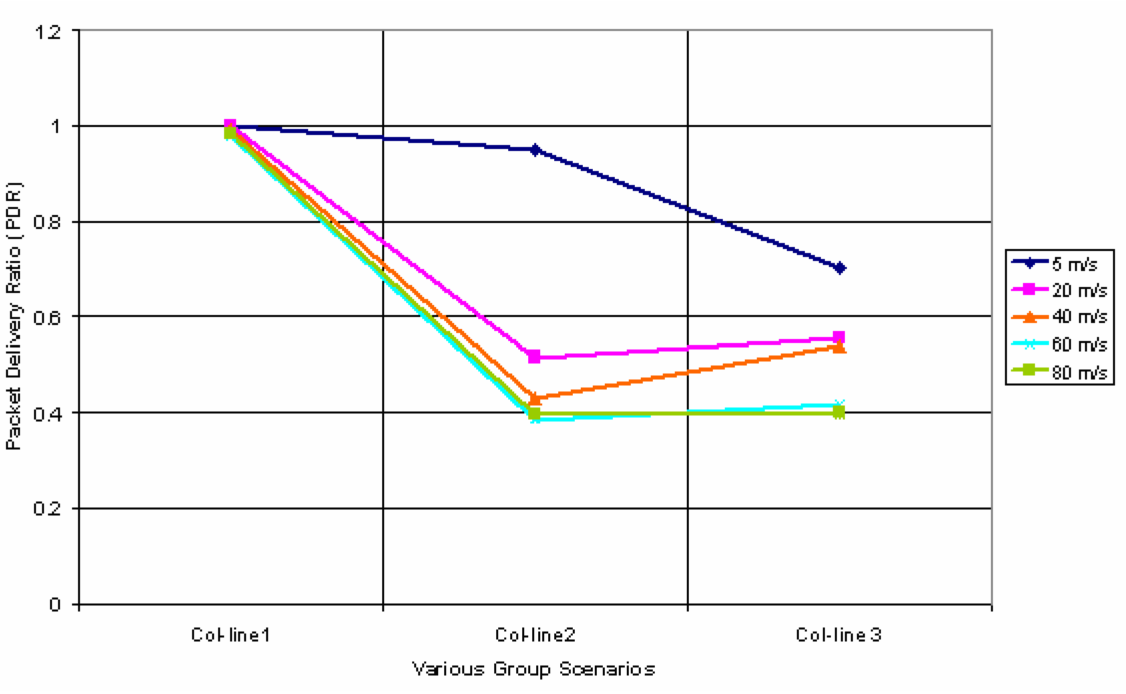

Figure 5.19. PDR Analysis for DSR using Column Mobility Model for Various Speeds

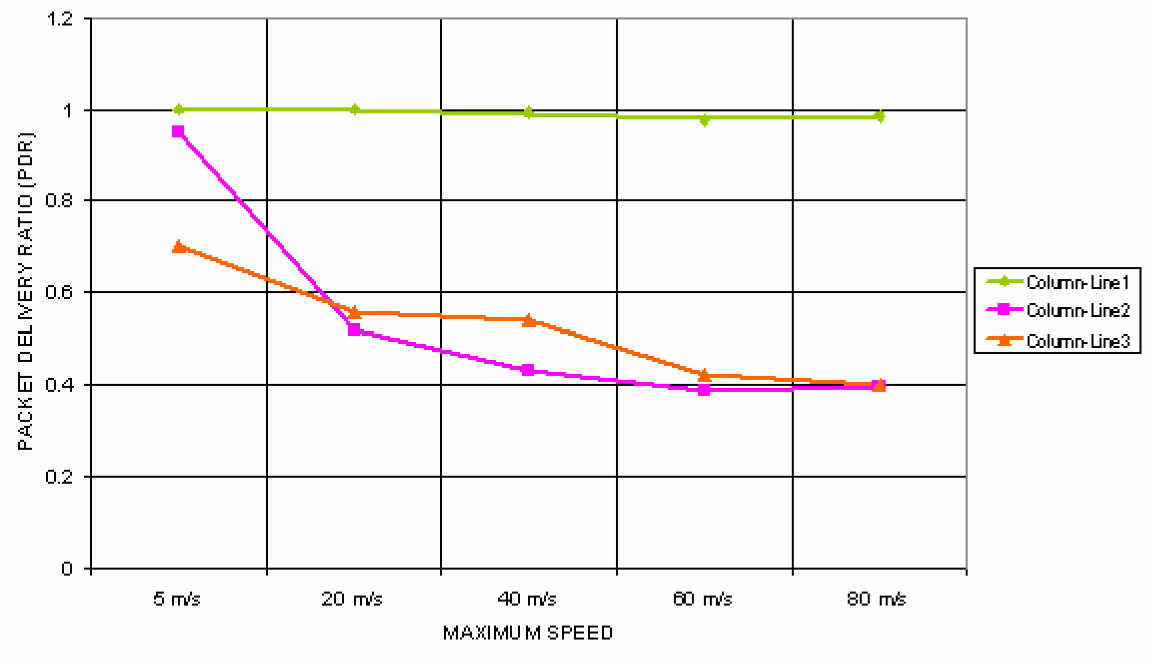

Figure 5.20. PDR Analysis for DSR using Column Mobility Model for Various Group Scenarios

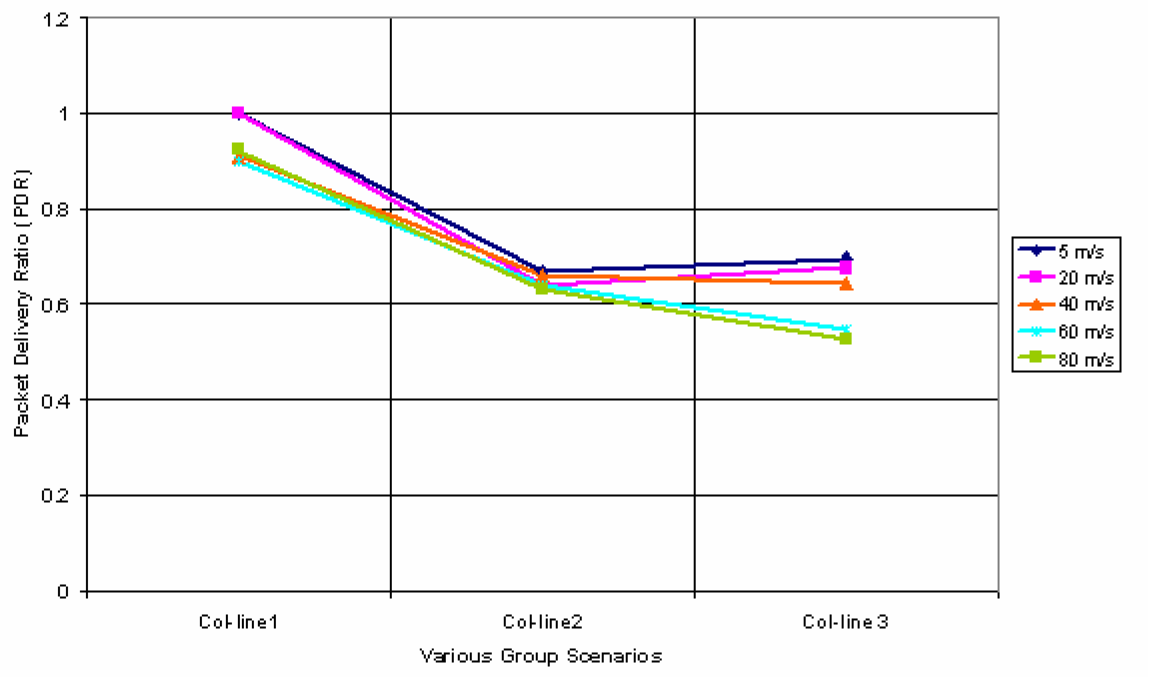

Figure 5.21. PDR Analysis for AODV using Column Mobility Model for Various Speeds

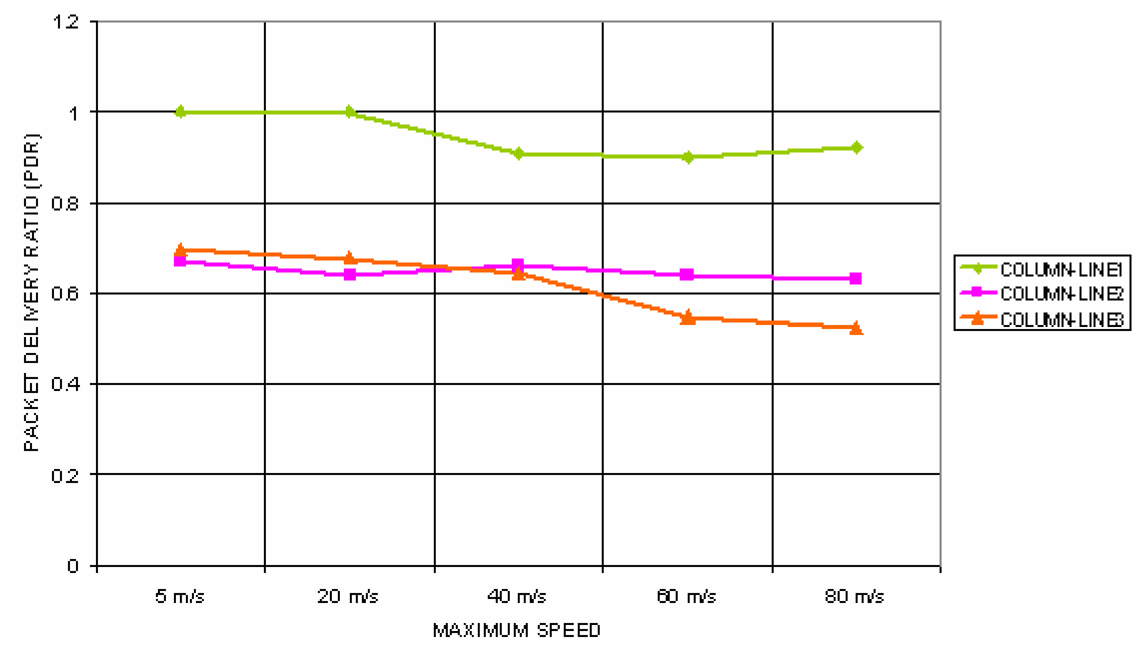

Figure 5.22. PDR Analysis for AODV using Column Mobility Model for Various Group Scenarios

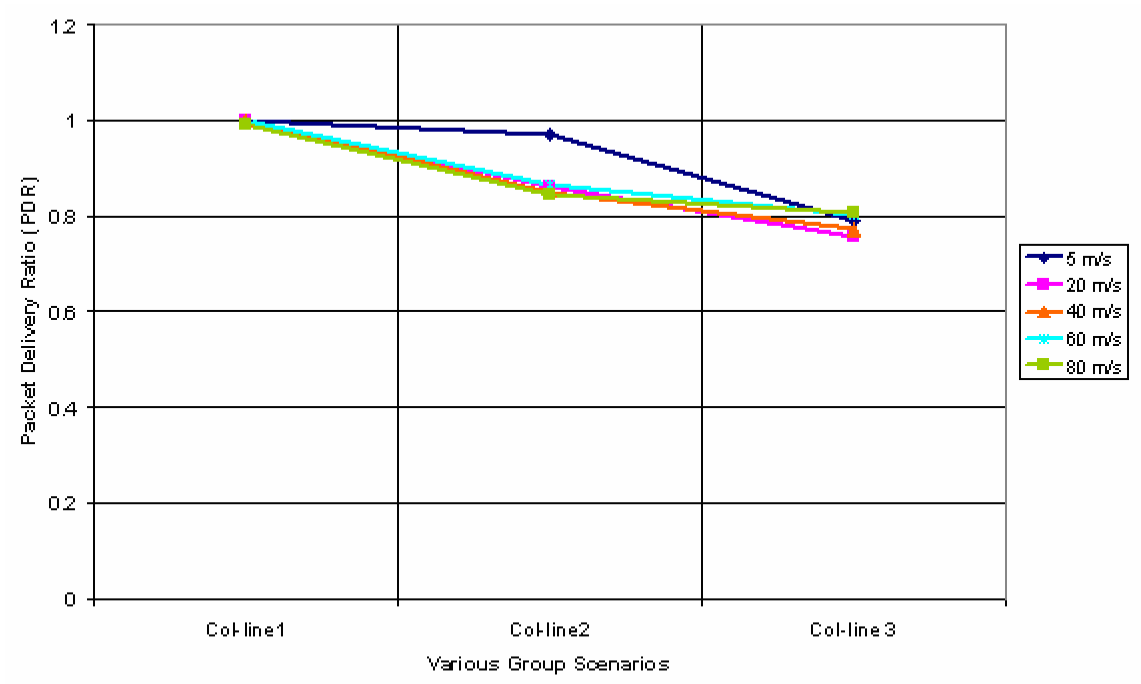

Figure 5.23. PDR Analysis for DSDV using Column Mobility Model for Various Speeds

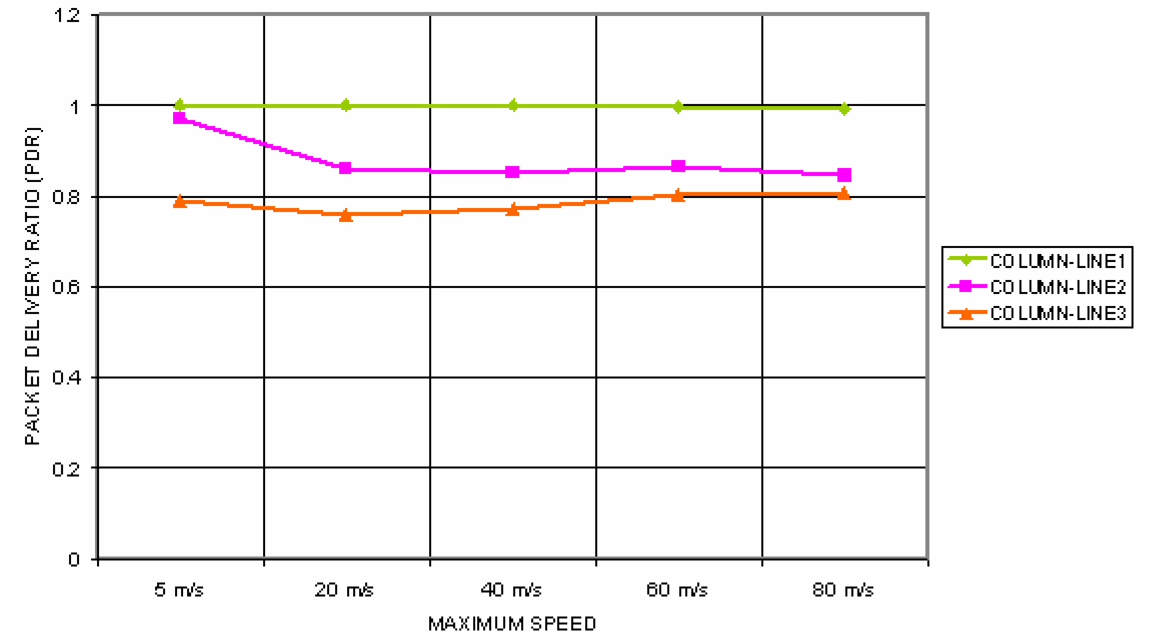

Figure 5.24. PDR Analysis for DSDV using Column Mobility Model for Various Group Scenarios

The following conclusions can be made from the PDR analysis made when using Column mobility model:

- Considering five different group scenarios, for DSR, as speed increases from 5 m/s to 80 m/s, the PDR decreases from 1.0 to about 0.4. Whereas for AODV the PDR decreases from 1.0 to about 0.52 and for DSDV, the PDR decreases from 1 to 0.75. These results are graphically depicted in Figures 5.16, 5.18 and 5.20.

- In all cases (DSR, AODV, DSDV), the PDR is a maximum at 5 m/s for all group scenarios and a minimum for 80 m/s.

- From Figures 5.17, 5.19 and 5.21 we can infer that as the degree of spatial dependence of velocity decreases from Scenario: Column-Line1 to Scenario: Column-Line3, PDR decreases in general but DSR shows a more drastic decrease than AODV or DSDV. From the graphs it can be inferred that DSDV shows more consistent values when compared to DSR and AODV.

These results are compared to those obtained with RPGM performance and it is found that they are similar. Column Mobility model can be derived from the RPGM mobility model implementation and this is the underlying reason for such a comparable performance behavior.

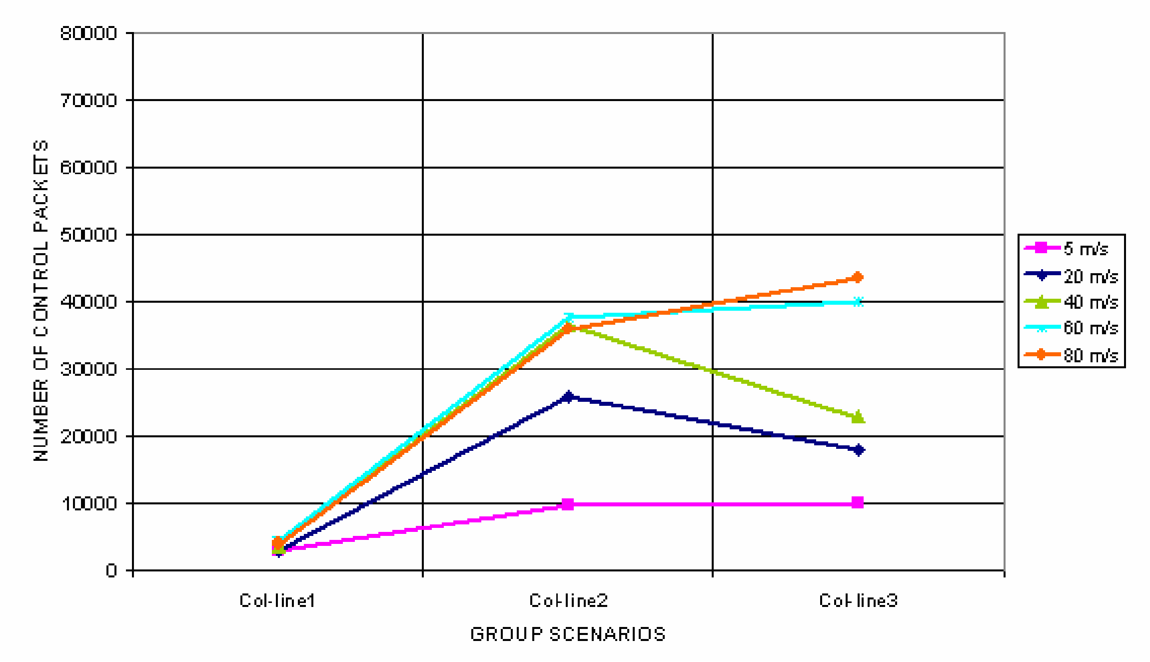

Figure 5.25. Control Overhead Analysis for DSR using Column Mobility Model for Various Speeds

The following conclusions can be made from the control overhead analysis made when using Column mobility model:

- From Figures 5.25, 5.27 and 5.29 we infer that the control overhead is a maximum for speeds of 80 m/s and a minimum for 5 m/s for DSR, AODV and DSDV. These results can be directly related to the PDR results explained earlier.

- Control overhead is very less in DSR (maximum – 43526 control packets) compared to AODV (maximum – 60648 control packets) and DSDV (maximum – 65755).

- The control overhead increases very steeply in AODV as speed increases from 5 m/s to 80 m/s. This is because there is more flooding of route discovery and route request packets as there are more route changes as mobility increases.

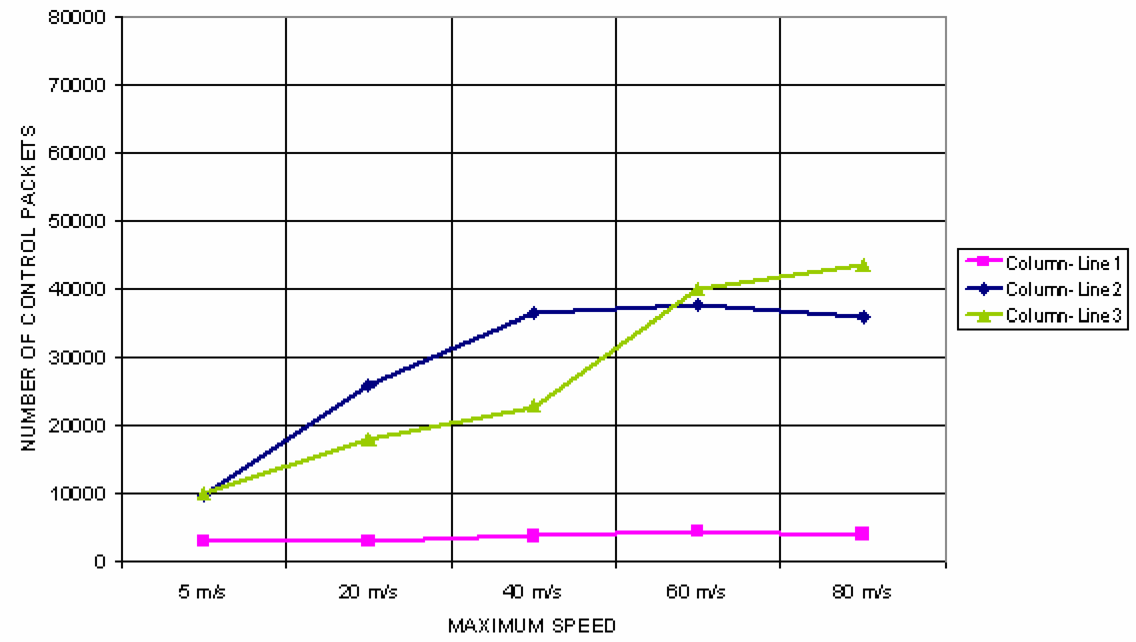

Figure 5.26. Control Overhead Analysis for DSR using Column Mobility Model for Various Group Scenarios

- Although DSDV produces the maximum control overhead with column mobility model, it is least affected when the speed increases from 5 m/s to 80 m/s, as depicted in Figure 5.29.

- Table 5.2 illustrates the maximum variation in control overhead produced as the scenario is transformed from a single group to multiple groups. DSR shows a considerable increase in control overhead and AODV has a drastic increase, whereas DSDV is the least affected protocol.

Table 5.2. Maximum Control Overhead Produced for Single and Multiple Group Scenarios when Implementing Column Mobility Model

ROUTING PROTOCOL	MAXIMUM CONTROL-OVERHEAD SINGLE GROUP SCENARIO (Control Packets)	MAXIMUM CONTROL-OVERHEAD MULTIPLE GROUP SCENARIO (Control Packets)
DSR	4415	43526
AODV	25995	60648
DSDV	65755	64230

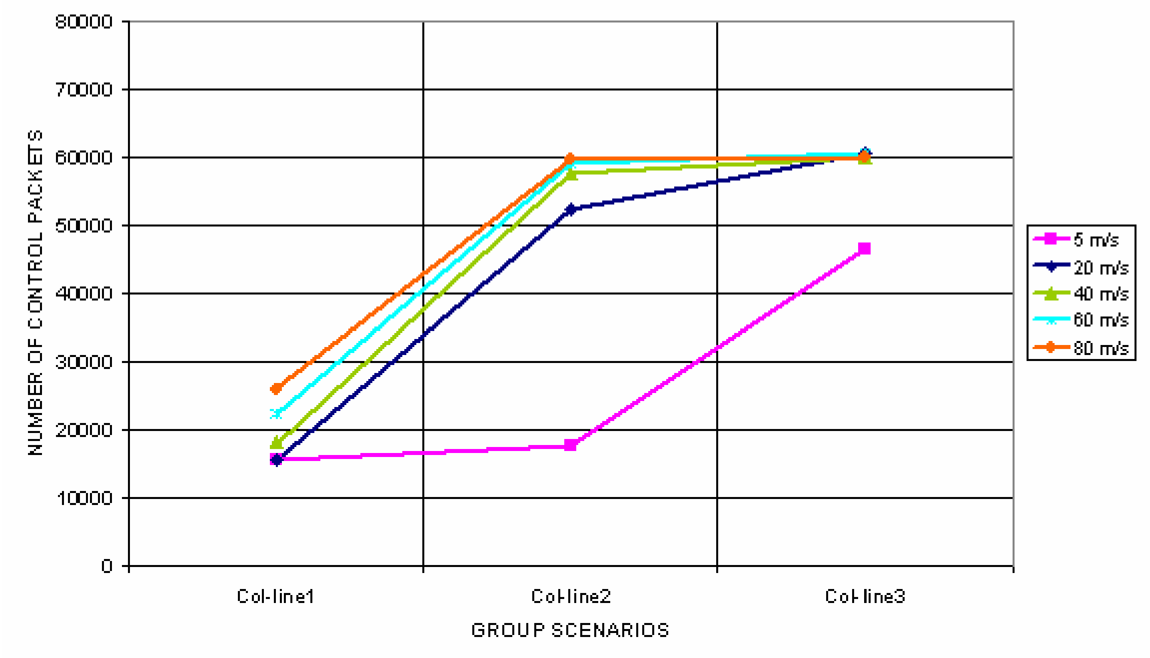

Figure 5.27. Control Overhead Analysis for AODV using Column Mobility Model for Various Speeds

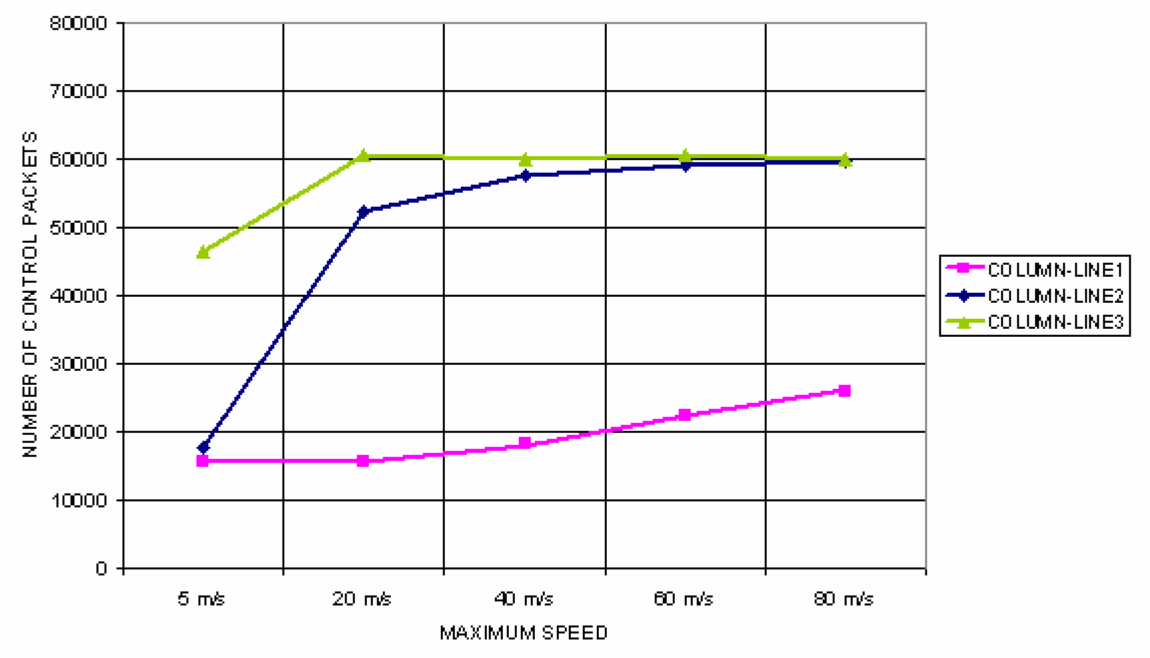

Figure 5.28. Control Overhead Analysis for AODV using Column Mobility Model for Various Group Scenarios

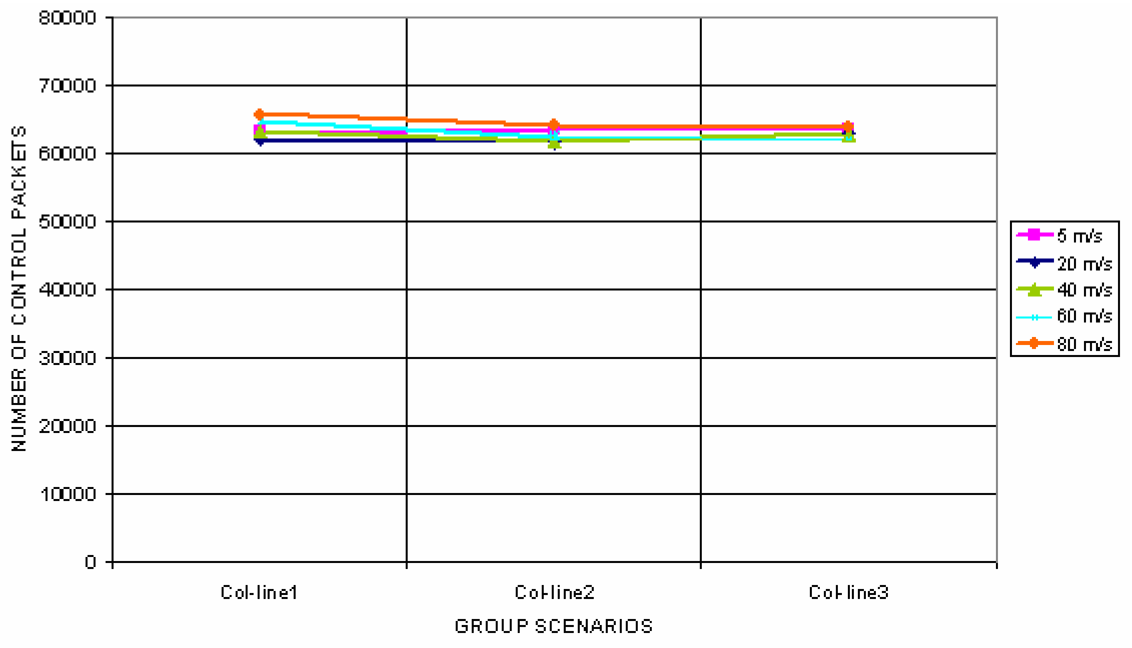

Figure 5.29. Control Overhead Analysis for DSDV using Column Mobility Model for Various Speeds

Pursue mobility model is mostly used in target tracking and law enforcement, where a group of mobile nodes attempt to capture a single node ahead of them. Pursue motion model is also derived from RPGM mobility model.

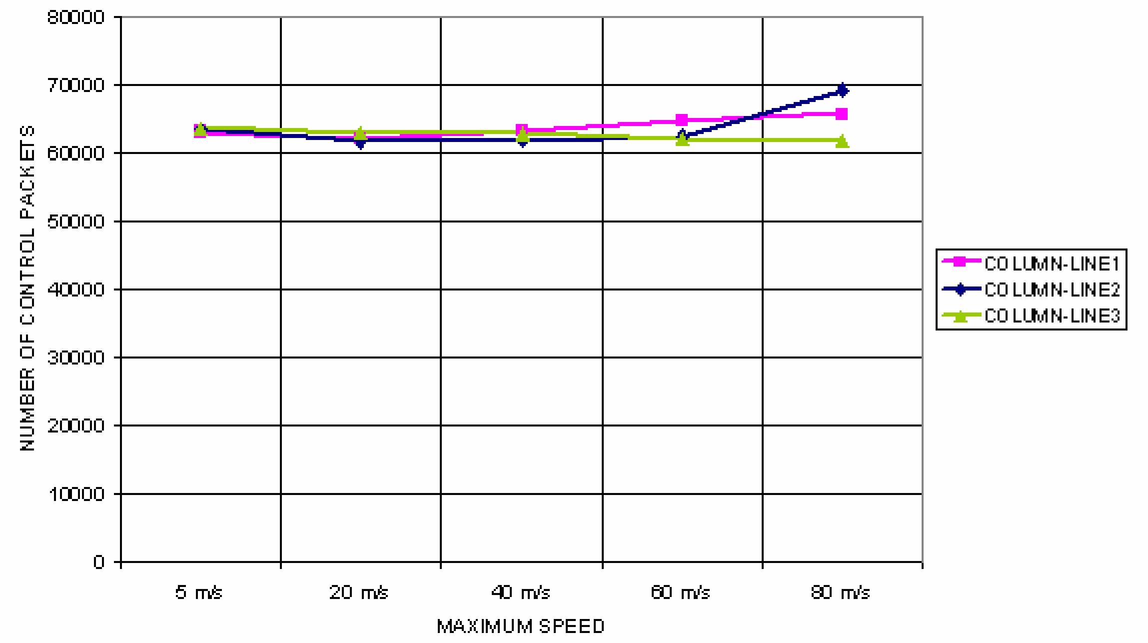

Figure 5.30. Control Overhead Analysis for DSDV using Column Mobility Model for Various Group Scenarios

From Figure 5.31 it was observed that the PDR is almost at a value of 1.0 for all three routing algorithms. Though the control overhead remains almost same for all speeds, for all three routing protocols, the control overhead produced by DSR

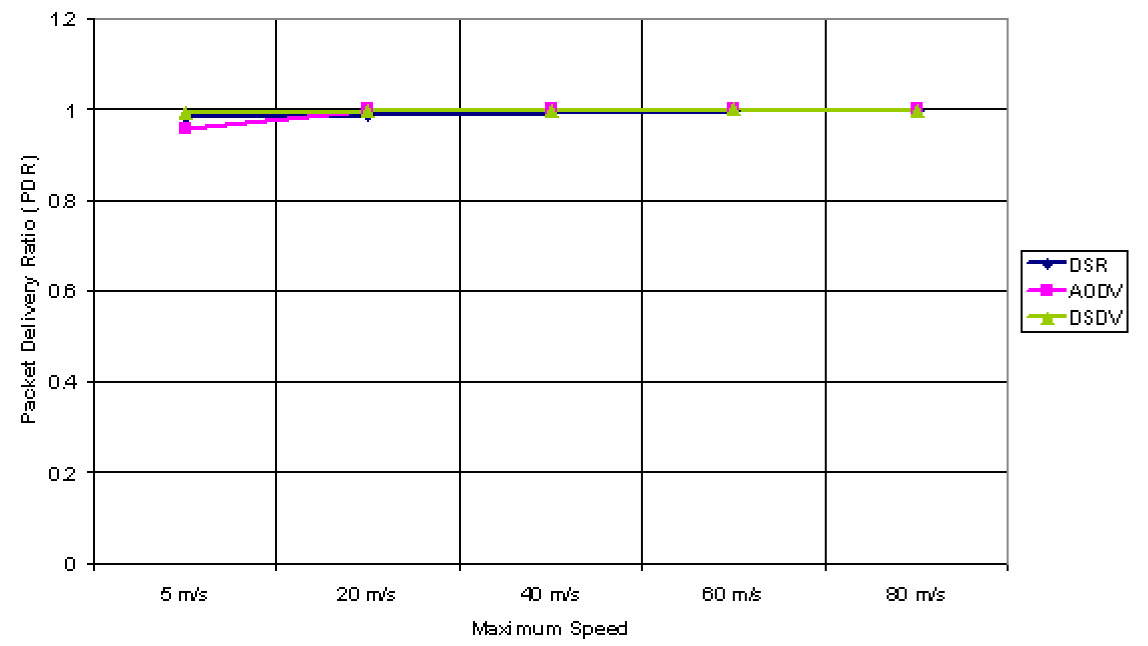

Figure 5.31. PDR Analysis for Various Routing Algorithms using Pursue Mobility Model

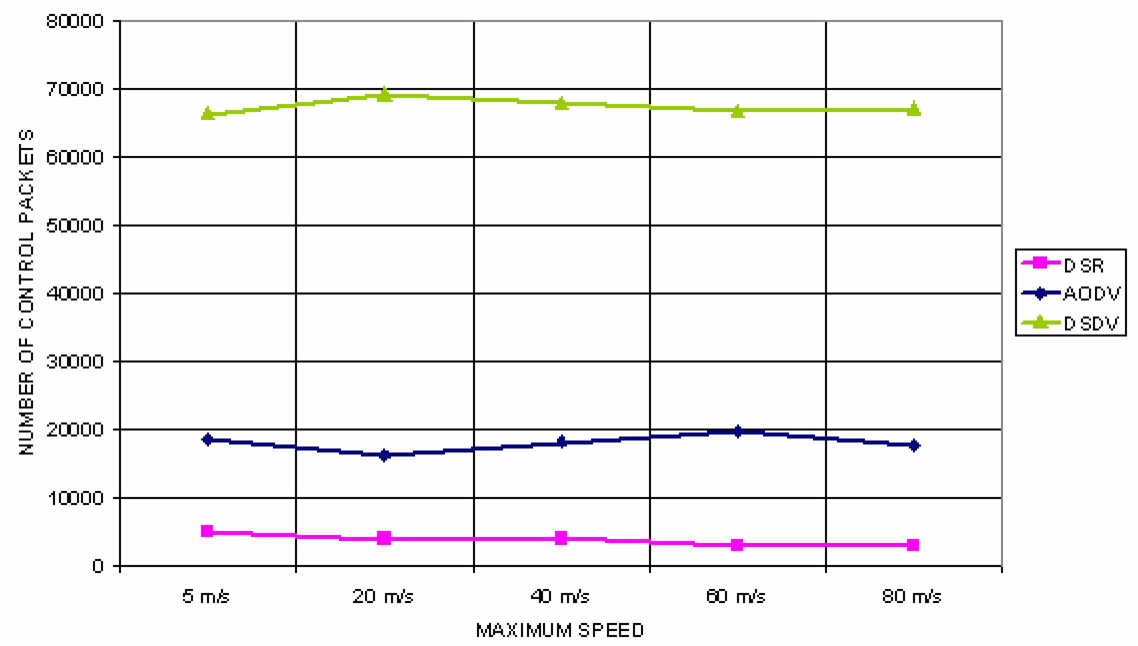

Figure 5.32. Control Overhead Analysis for Various Routing Algorithms using Pursue Mobility Model

is very less (Maximum = 5038 control packets) when compared to AODV (Maximum = 19618 control packets) and DSDV (Maximum = 69227 control packets).

In summary, the following inferences are made from the scalability analysis carried out with group mobility models: RPGM model, Column model and Pursue model.

- In RPGM and Column models, as the network transforms from being a single group scenario to multiple group scenarios, there is lesser homogeneity and therefore there is less route formations between nodes in different groups. This results in longer route formations to transmit data across nodes of different groups.

- In Pursue model, the distribution of nodes is more homogeneous and hence there are shorter route formations between nodes.

- Although DSR has a high PDR and low control overhead at lower speeds, it has to be noted that there is a drastic drop in performance as speed increases and hence we need to consider the consistency of the protocol performance when the mobile ad hoc network is scaled to include more number of nodes and operate in high mobility conditions. As speed increases more route changes take place and hence more routing packets are transmitted which in turn has an effect on the packet delivery of the network.

- DSR performs better with group mobility scenarios which have high degree of spatial dependence than with those which are less homogeneous (multiple groups).

- DSDV seems to be more reliable routing protocol to be used in group mobility scenarios with less homogeneity (multiple groups) as there is no severe effect on protocol performance when speed increases or when the degree of spatial dependency decreases. As speed increases, more route changes take place and hence there is a need for more frequent updates of the routing table which increases routing overhead and hence reduces PDR values.

- In DSDV, when degree of spatial dependency (homogeneity) decreases, all the route formations within a group are usually stable even when mobility increases as the nodes are more closely packed among themselves and hence these routes need not be updated frequently. This helps to maintain the control overhead constant or at the least there is less variation of control overhead. Hence even when the single group transforms to multiple group scenarios, there is very little performance drop.

- AODV performs similar to DSDV when the degree of spatial dependence of velocity (homogeneity) decreases, but there is a more visible drop in protocol performance than DSDV.

5.2 Energy Utilization in Mobile Ad hoc Networks

In this section we study the effect of realistic mobility characteristics such as temporal dependence of velocity, spatial dependence and geographic restrictions on the energy utilization in MANETs. Higher the energy-goodput value better is the energy utilization.

5.2.1 Energy-Goodput Analysis using Entity Mobility Models

Random Waypoint model, Manhattan Grid model and Gauss Markov model are the three entity models used. From the energy-goodput analysis in Figure 5.33 made the following conclusions can be made:

DSR and DSDV perform well in terms of energy with all speeds when Random Waypoint model is used. DSR produces the least number of routing packets and hence consumes less energy. DSDV on the other hand is less sensitive to variation in speeds, as discussed previously and hence the routing packets generated remains almost constant. This contributes to a consistent energy-goodput for all speeds from 5 m/s to 80 m/s.

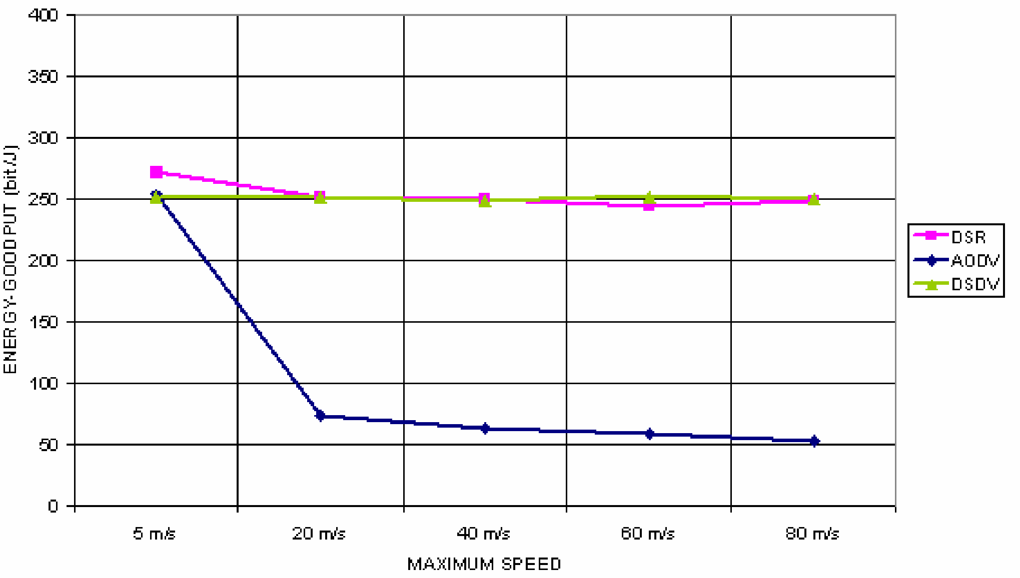

Figure 5.33. Energy-Goodput Analysis of Various Routing Algorithms using Random Waypoint Mobility Model

The energy performance of AODV decreases drastically as speed increases from 5 m/s to 20 m/s. This can be attributed to the fact that as speed increases the topology changes frequently which in turn cause more route changes and hence more routing packets are produced which consumes more power. So the energy-goodput decreases drastically.

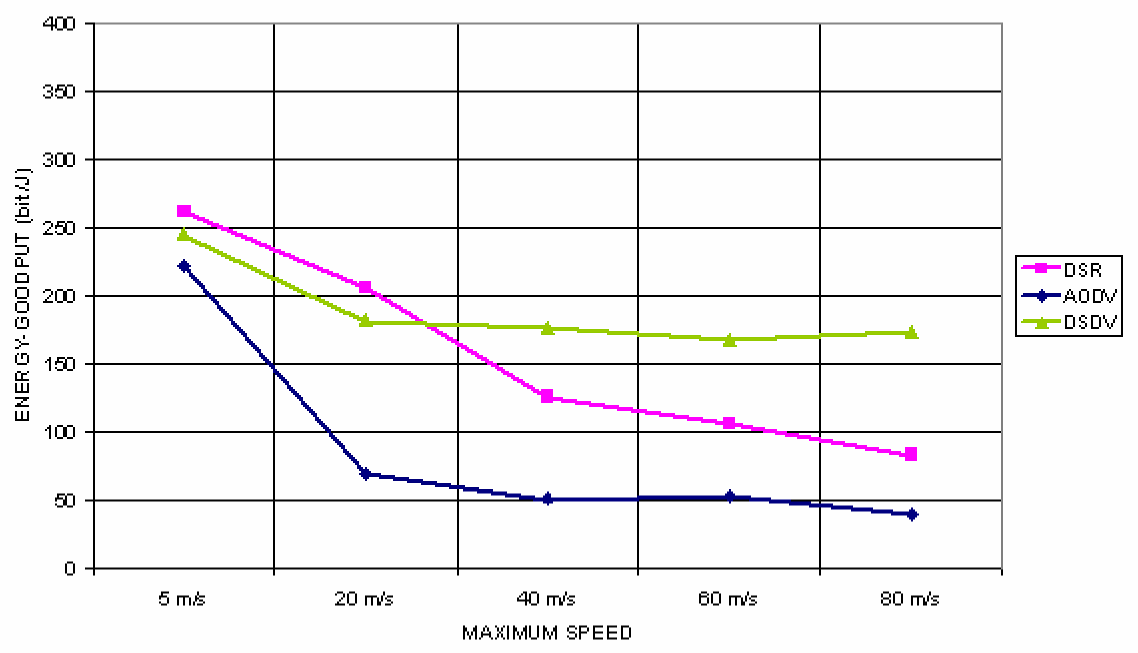

Figure 5.34. Energy-Goodput Analysis of Various Routing Algorithms using Manhattan Grid Mobility Model

Figure 5.34 analyzes the energy performance of DSR, AODV and DSDV using Manhattan Grid mobility model. Comparing this with Figure 5.33 we infer the effect of *geographic restrictions* on the energy utilization of a mobile node in a MANET. The energy-goodput of DSR decreases steadily from 262 bits/J to 83 bits/J as speed varies from 5 m/s to 80 m/s. This steep fall in energy-goodput can be attributed to the geographic restrictions such as predefined pathways which are incorporated into the Manhattan Grid mobility model. In DSDV, energy-goodput reduces from 245 bits/J to173 bits/J but AODV is affected very little by the geographic restrictions present. The energy performance of DSR is better than DSDV and AODV at lower speeds but DSDV performs better as speed increases. AODV shows the worst performance as shown in Figure 5.34. Energy utilized by both DSR and AODV increases as speed increases but energy-goodput value of DSDV almost remains constant after a certain speed. Hence reactive routing protocols are more sensitive to the variation in speed than proactive protocols.

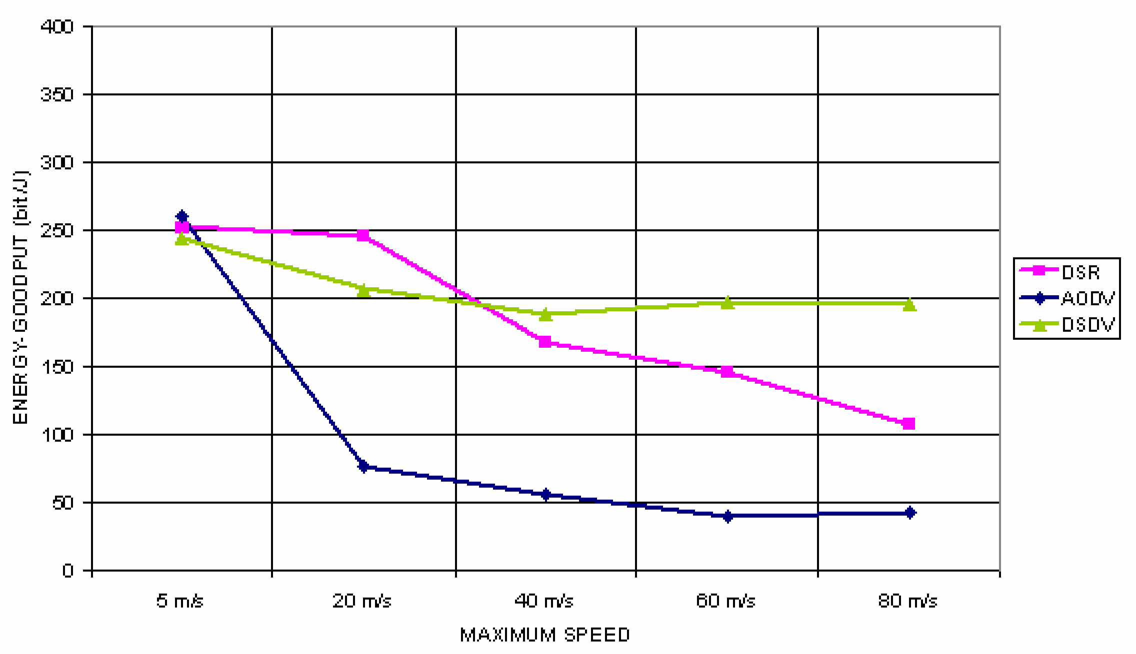

Figure 5.35. Energy-Goodput Analysis of Various Routing Algorithms using Gauss Markov Mobility Model

For increasing speeds, the energy performance of DSR and AODV with Gauss Markov mobility model is slightly worse than its performance with Manhattan Grid model. This may be because reactive protocols are more affected by *temporal dependence of velocity*. DSDV on the other hand performs slightly better with Gauss Markov model than with Manhattan Grid model.

5.2.2 Energy-Goodput Analysis using Group Mobility Models

The effect of spatial dependence of velocity on the energy performance of DSR, AODV and DSDV is analyzed in this section. From Figures 5.39 and 5.40 it can be understood that the energy-goodput of DSR drops from about 340 bits/J to around 250 bits/J as the scenario is transformed from single group to multiple groups (i.e) as the degree of spatial dependence of velocity decreases the energy-goodput also decreases. But the energy-goodput of the various multiple group scenarios is almost of the same level.

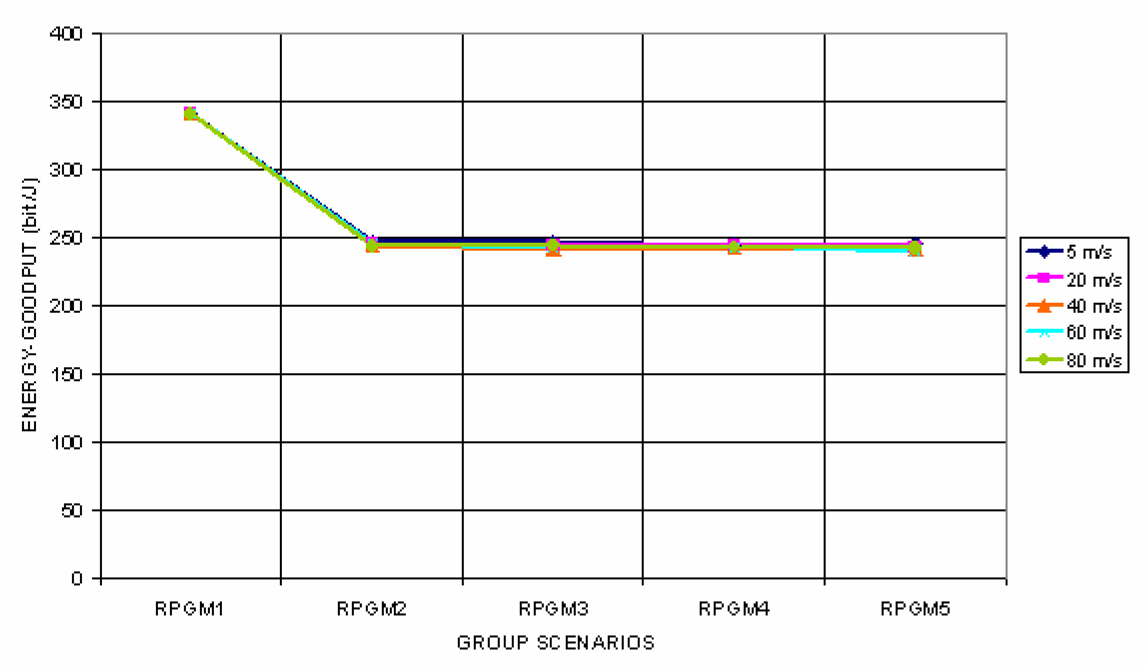

Figure 5.36. Energy-Goodput Analysis of DSR using RPGM Mobility Model for Various Speeds

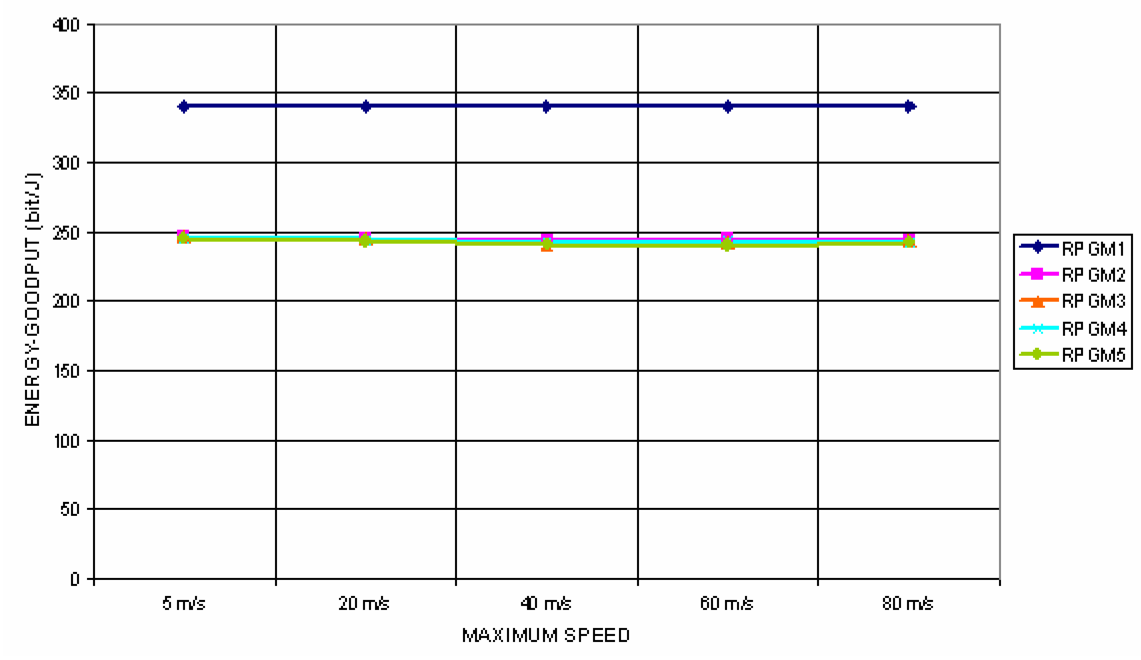

Figure 5.37. Energy-Goodput Analysis of DSR using RPGM Mobility Model for Various Group Scenarios

From Figures 5.41 and 5.42, as speed increases from 5 m/s to 80 m/s the energy-goodput decreases gradually from 336 bits/J to 75 bits/J. Similar to DSR, as the degree of spatial dependency decreases also the energy-goodput decreases gradually. In case of DSDV the energy-goodput decreases minimally when considering DSR and AODV. As speed increases from 5 m/s to 80 m/s the energy-goodput decreases from around 245 bits/J to 206 bits/J.

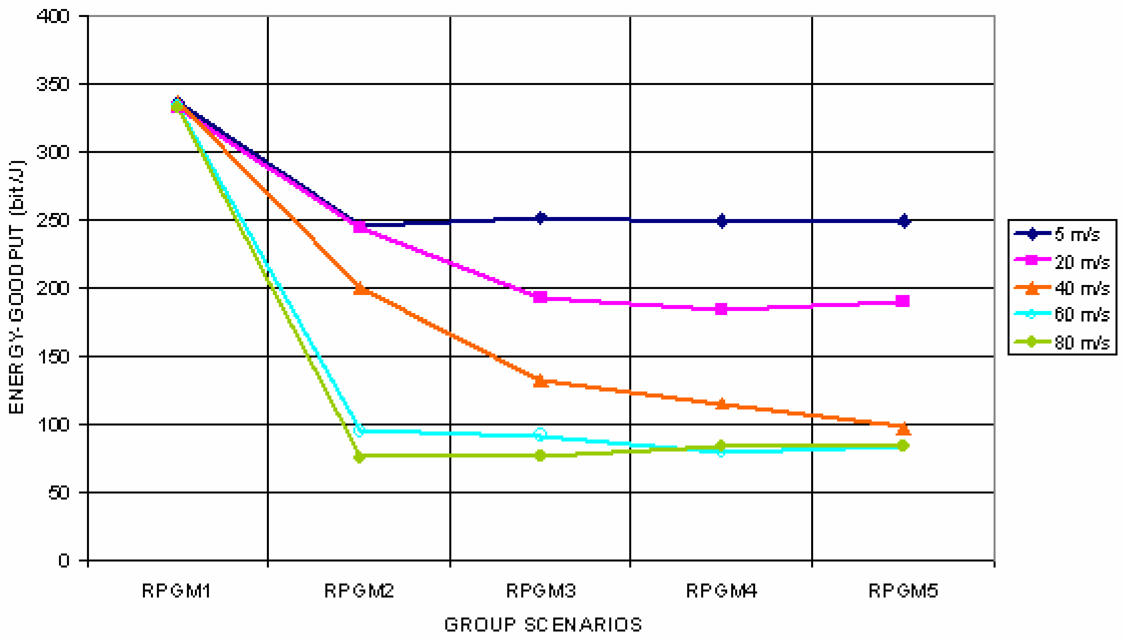

Figure 5.38. Energy-Goodput Analysis of AODV using RPGM Mobility Model for Various Speeds

Again in DSDV as the degree of spatial dependence of velocity in RPGM decreases, the energy-goodput decreases, but this drop is small when compared to the drop obtained using AODV or DSR. Thus we conclude that though DSR and AODV have high energy-goodput at lower speeds, DSDV maintains a moderate energy-goodput for all speeds.

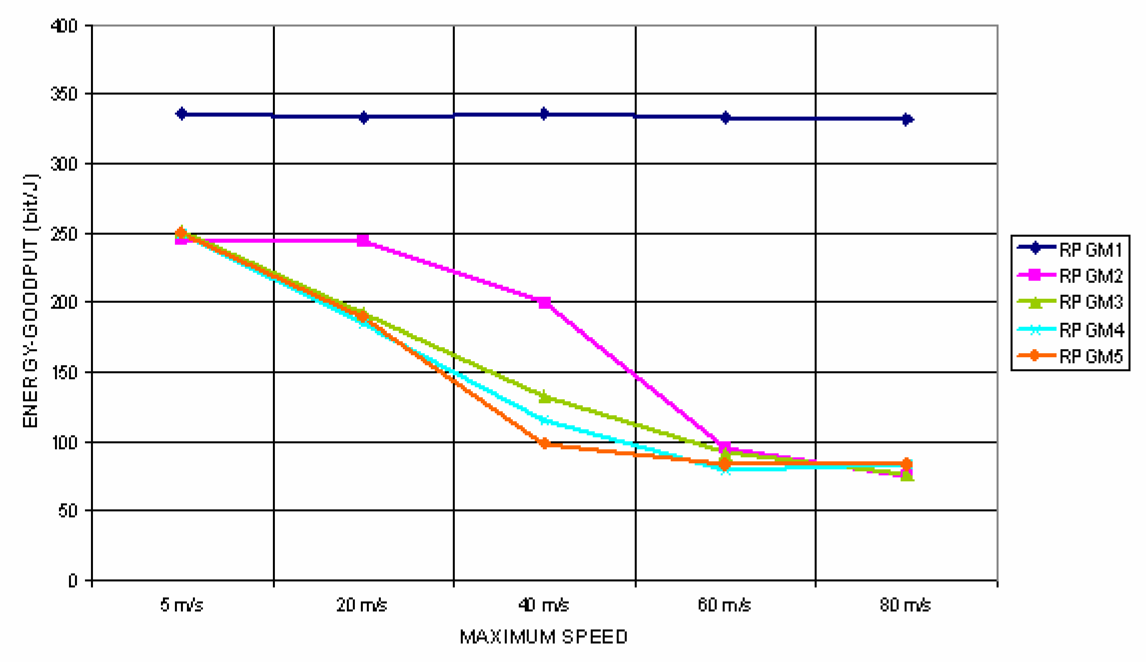

Figure 5.39. Energy-Goodput Analysis of AODV using RPGM Mobility Model for Various Group Scenarios

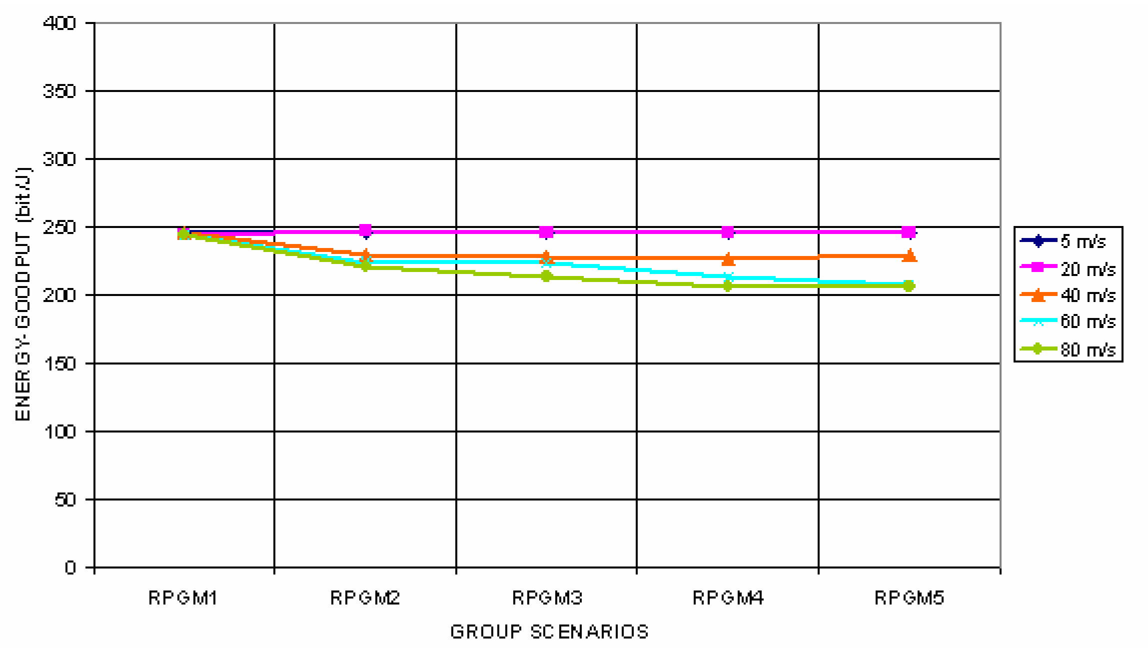

Figure 5.40. Energy-Goodput Analysis of DSDV using RPGM Mobility Model for Various Speeds

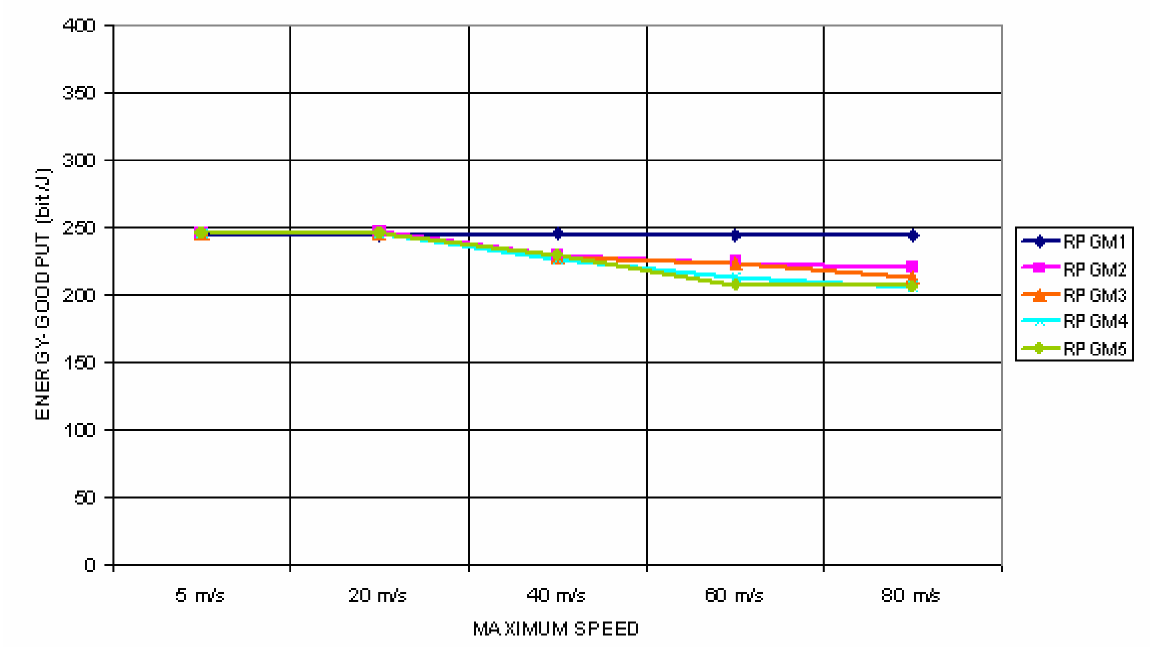

Figure 5.41. Energy-Goodput Analysis of DSDV using RPGM Mobility Model for Various Group Scenarios

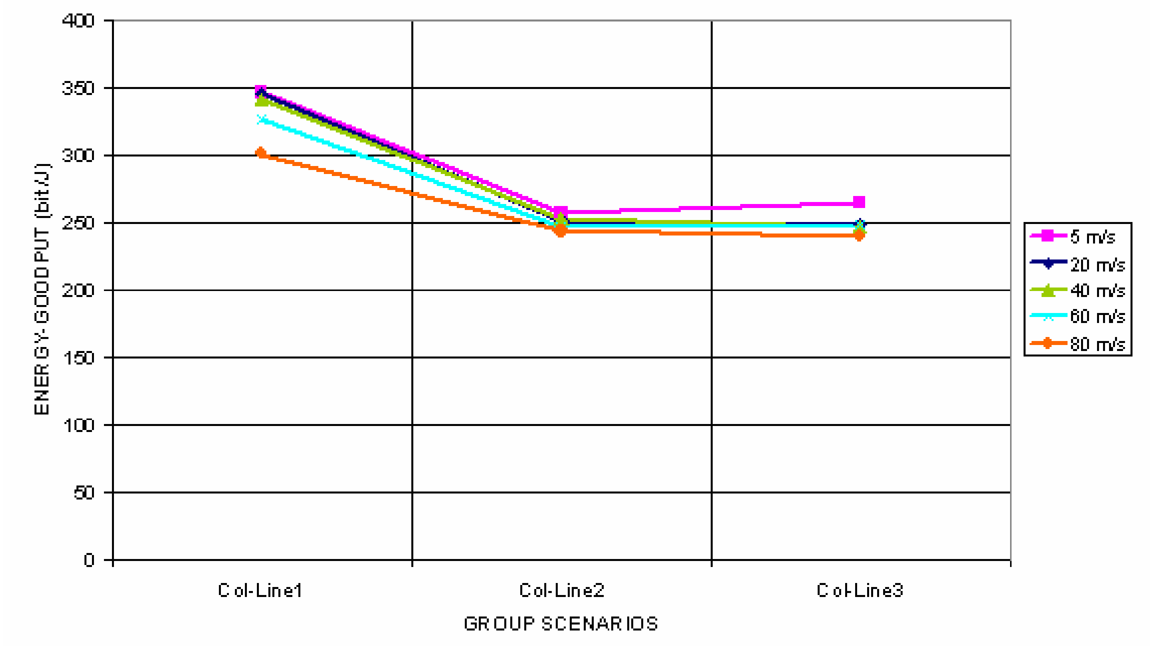

Figure 5.42. Energy-Goodput Analysis of DSR using Column Mobility Model for Various Speeds

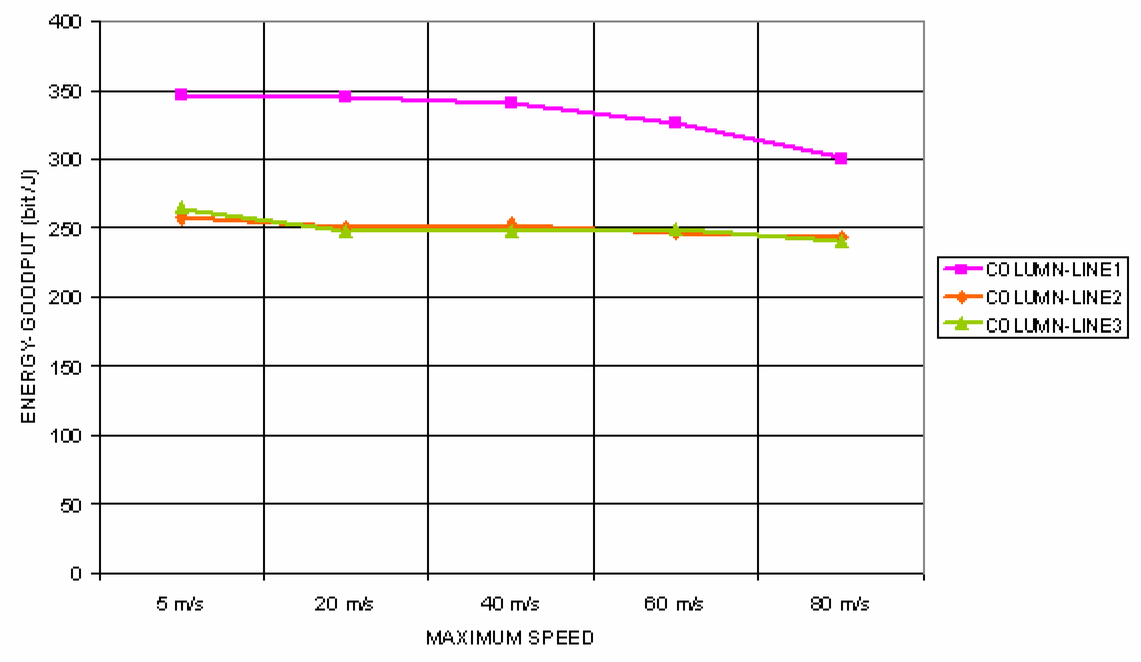

Figure 5.43. Energy-Goodput Analysis of DSR using Column Mobility Model for Various Group Scenarios

The energy-goodput performance of Column mobility model is similar to those displayed by RPGM. This can be easily comprehended from Figures 5.45, 5.46, 5.47, 5.48, 5.49 and 5.50.

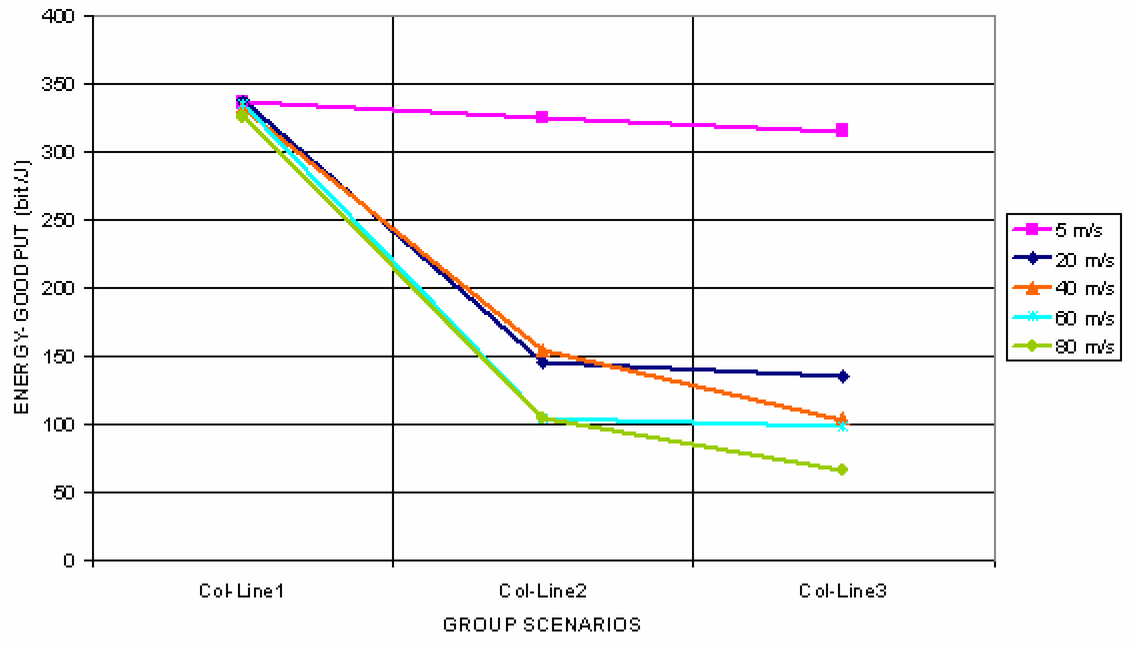

Figure 5.44. Energy-Goodput Analysis of AODV using Column Mobility Model for Various Speeds

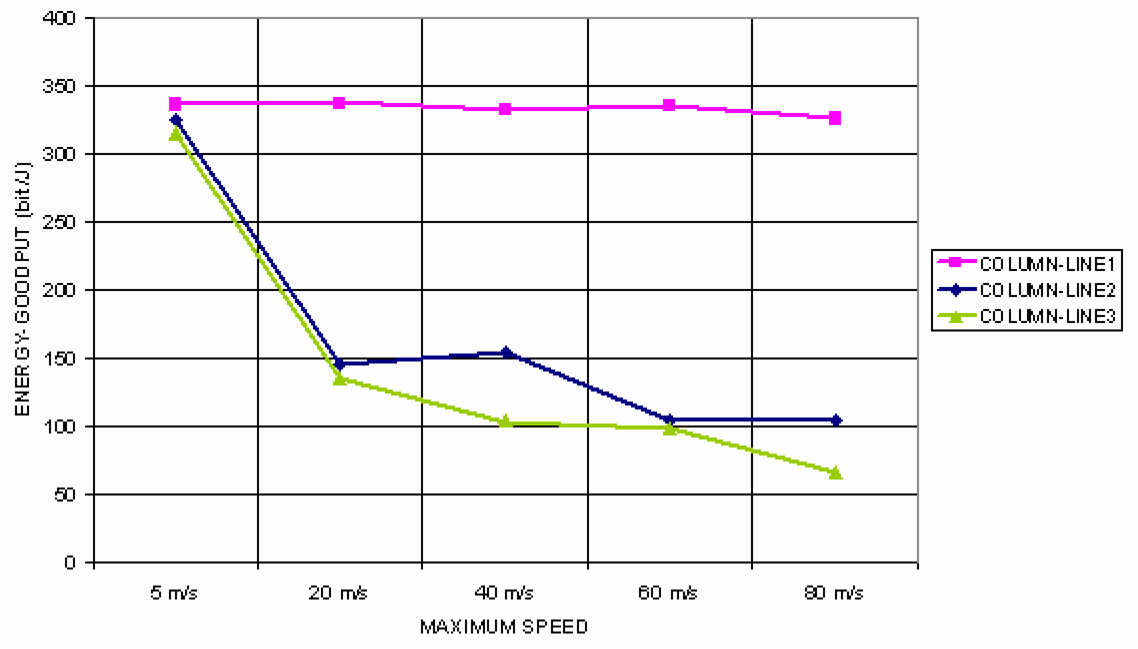

Figure 5.45. Energy-Goodput Analysis of AODV using Column Mobility Model for Various Group Scenarios

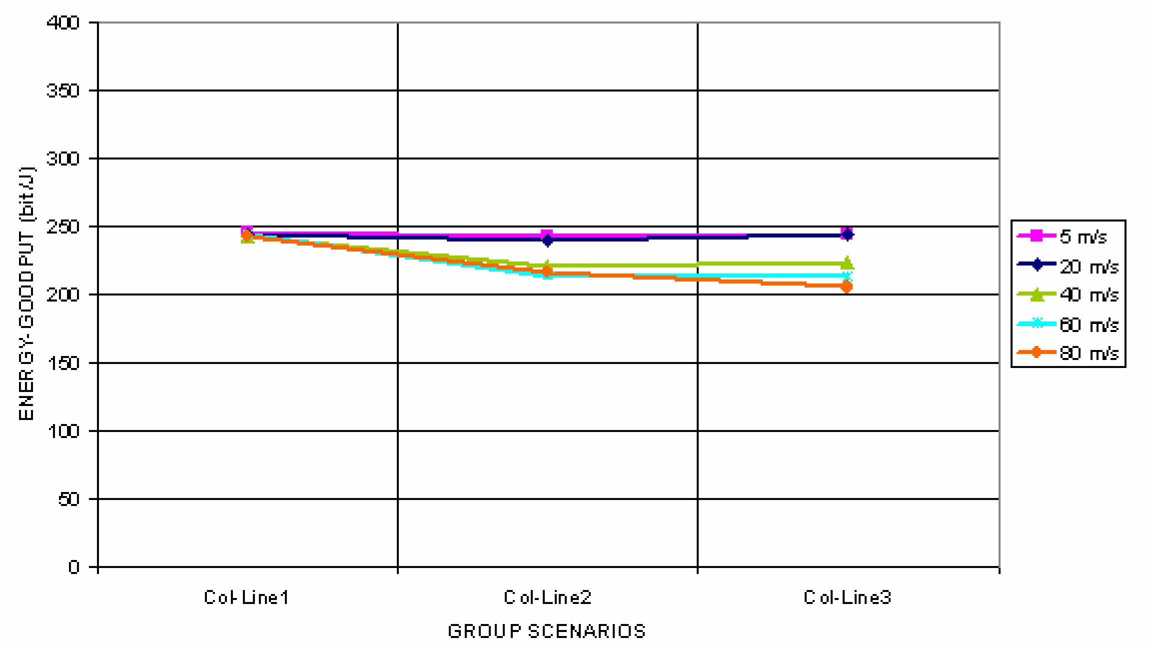

Figure 5.46. Energy-Goodput Analysis of DSDV using Column Mobility Model for Various Speeds

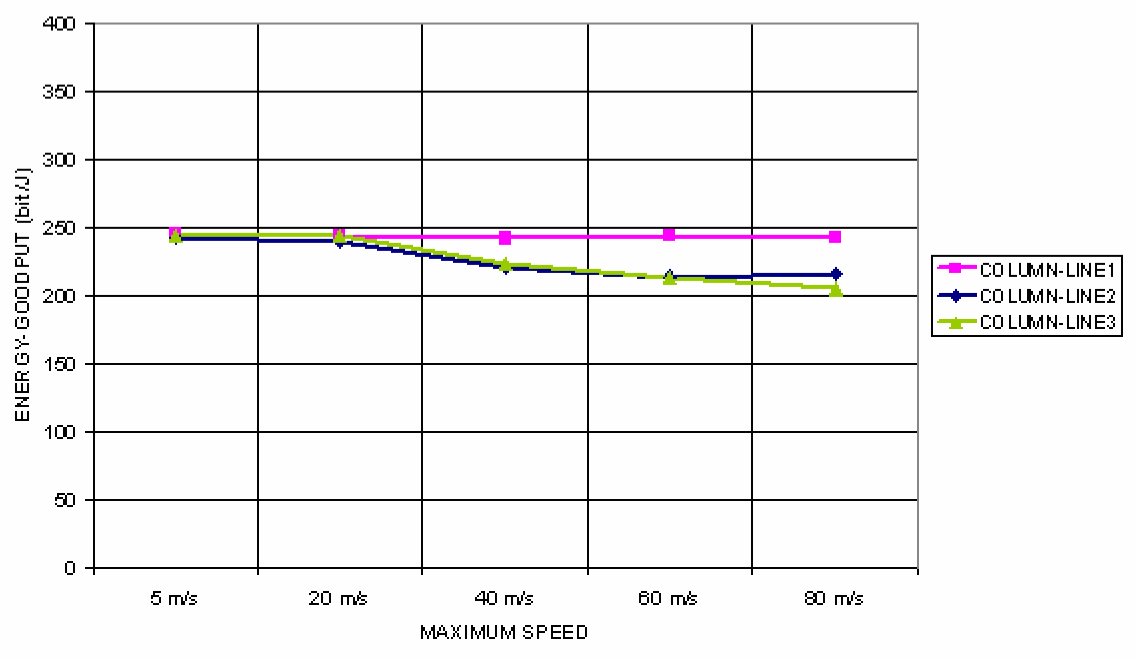

Figure 5.47. Energy-Goodput Analysis of DSDV using Column Mobility Model for Various Group Scenarios

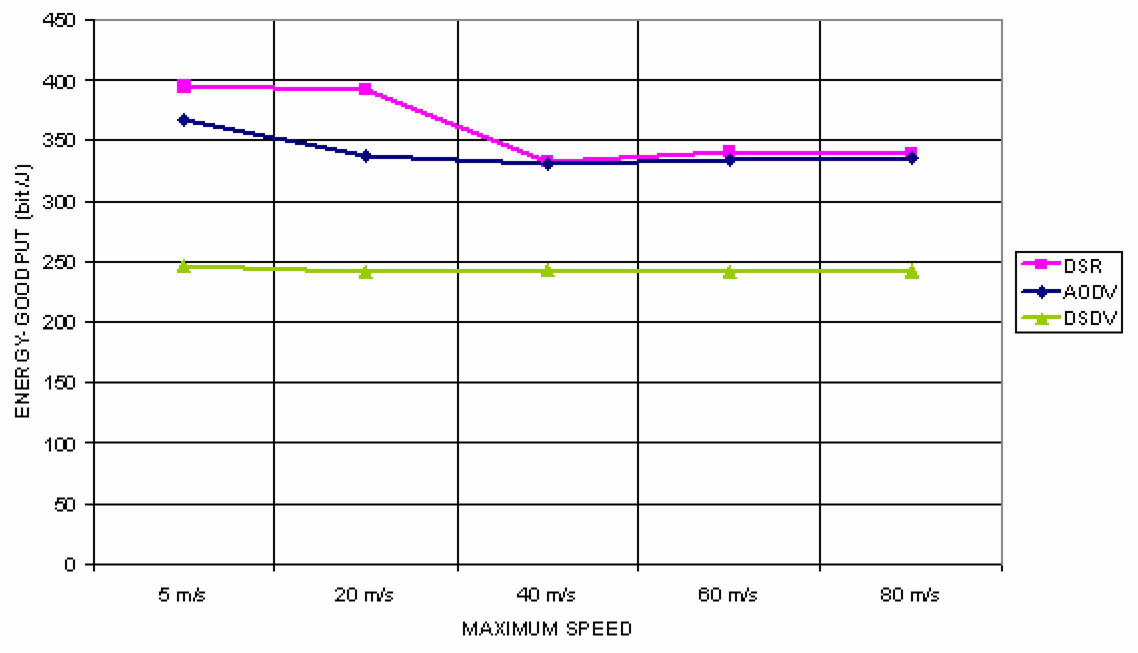

Figure 5.48. Energy-Goodput Analysis of Various Routing Algorithms using Pursue Mobility Model

DSR shows excellent energy performance at lower speeds with Pursue mobility model. Even though at higher speeds the energy-goodput decreases slightly, DSR shows better performance compared to AODV. As discussed previously DSR performs better with mobility models that have more homogeneity. It is believed that as speed increases and the pursuer nodes catch up more closely with the pursued node, there is more closer route formations with the pursued node and hence homogeneity decreases (or the degree of spatial dependence of velocity decreases) and hence the energy performance of DSR diminishes as shown in Figure 5.51. The same explanation applies to the drop in energy-goodput in AODV. DSDV shows the worst performance of the three routing protocols. But the energy-goodput of DSDV remains constant for all speeds from 5 m/s to 80 m/s.

5.3 Summary

In this chapter we analyze the scalability of MANETs using entity and group mobility models. We also study the energy performance of ad hoc networks in detail. The effect of realistic mobility characteristics on the overall performance of mobile ad hoc networks was explored.

Chapter Six

Conclusions and Future Work

6.1 Conclusions

The protocol performance such as, scalability and energy utilization of a mobile ad hoc network is affected by the movement pattern of mobile nodes in realistic environments. The effect of realistic mobility characteristics such as temporal dependence of velocity, spatial dependence of velocity and geographic restrictions on the protocol performance is studied in detail. From the performance analysis carried out, the following conclusions can be made:

When there are *geographic restrictions* associated with the movement of a mobile node in a MANET, as in Manhattan Grid model, or when there is a high *degree of temporal dependence of velocity*, as in Gauss Markov model, there are more link breakages and hence there are more packets being dropped. When more packets are dropped more retransmissions takes place leading to the generation of more control packets and hence lower PDR values as speed increases.

One main reason for this performance drop in DSR can be attributed to the fact that control overhead increases more drastically as speed increases from 5 m/s to 20 m/s, when MG model or GM model was used instead of RW model. AODV and DSDV are more stable when operating with mobility models that have less homogeneity such as MG, GM and also group mobility models with multiple groups. We observe that DSR performs better with mobility models where the nodes have more *homogeneity (higher degree of spatial dependence of velocity)*.

In RPGM model and Column model as the network transforms from being a single group scenario to multiple group scenarios, there is lesser homogeneity and hence there is less route formations between nodes in different groups. This results in longer route formations to transmit data across nodes of different groups. In Pursue model, the distribution of nodes is more homogeneous and hence there are shorter route formations between nodes.

Although DSR has a high PDR and low control overhead at lower speeds, it has to be noted that there is a drastic drop in performance as speed increases and hence we need to consider the consistency of the protocol performance when the mobile ad hoc network is scaled to include more number of nodes and operate in high mobility conditions. As speed increases more route changes take place and hence more routing packets are transmitted which in turn has an effect on the packet delivery of the network. DSR performs better with group mobility scenarios which have high degree of spatial dependence than with those which are less homogeneous (multiple groups).

DSDV seems to be more reliable routing protocol to be used in group mobility scenarios with less homogeneity (multiple groups) as there is no severe effect on protocol performance when speed increases or when the degree of spatial dependency decreases. As speed increases, more route changes take place and hence there is a need for more frequent updates of the routing table which increases routing overhead and hence reduces PDR values but in DSDV, when degree of spatial dependency (homogeneity) decreases, all the route formations within a group are usually stable even when mobility increases as the nodes are more closely packed among themselves and hence these routes need not be updated frequently. This helps to maintain the control overhead constant or at the least there is less variation of control overhead. Hence even when the single group transforms to multiple group scenarios, there is very little performance drop. AODV performs similar to DSDV when the degree of spatial dependence of velocity (homogeneity) decreases, but there is a more visible drop in protocol performance than DSDV.

6.2 Future Work

Previously, most of the simulations of MANETs were done using Random Waypoint mobility model as a default model. But the scenarios in which Ad hoc networks are implemented are not random in nature as in most cases the mobile nodes are operated by humans whose movements may more likely follow a certain deterministic pattern. Hence it is necessary to evaluate MANET performance with realistic mobility models. Simulations are a valuable tool for learning and comparing wireless protocols and techniques, but simulations generally succeed because we will always be able to find the right protocols and configure it to work well in any particular scenario.

Real-world ad hoc networks face problems that don't generally occur in simulation. It is true that unlike simulator experiments, test-bed experiments cannot be perfectly reproduced. Interference and radio propagation conditions change between each experiment, and are out of the experimenter's control. However, experimental results are generally repeatable, and executing the same experiment many times produces more consistent results [73]. The realistic movement patterns used in our simulations can be integrated into a suitable testbed such as Ad hoc Protocol Evaluation (APE) Testbed [74] or Network Emulation Testbed (Netbed) [75].

We can incorporate error models in our simulations to understand the effect of packet loss on the performance of the network. By doing this we will be able to mimic the realistic ad hoc environment more effectively. Error model simulates link-level errors or loss by either marking the packet's error flag or dumping the packet to a drop target. We also need to study the effect of node density on the scalability of a network in any mobility conditions.

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