Performance Analysis of Mobile Ad Hoc Network Routing Protocols Using ns-3 Simulations

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Abstract

Mobile ad hoc networks (MANETs) consist of mobile nodes that can communicate with each other through wireless links without reliance on any infrastructure. The dynamic topology of MANETs poses a significant challenge for the design of routing protocols. Many routing protocols have been developed to discover routes in MANETs through various mechanisms such as source, distance vector, and link state routing. In this thesis, we present a comprehensive performance comparison of several prominent MANET routing protocols. The protocols studied are Destination-Sequenced Distance-Vector (DSDV), Optimized Link State Routing (OLSR), Ad Hoc On-Demand Distance Vector protocol (AODV), and Dynamic Source Routing (DSR). We consider a range of network dynamicity and node density, model three mobility models: Steady-State Random Waypoint (SS-RWP), Gauss-Markov (G-M), and Lévy Walk, and use ns-3 to evaluate their performance on metrics such as packet delivery ratio, end-to-end delay, and routing overhead. We believe this study will be helpful for the understanding of mobile routing dynamics, the improvement of current MANET routing protocols, and the development of new protocols.

I would like to dedicate this work to my parents for their unconditional and continuous support for me to chase higher achievements as a graduate student and researcher.

Acknowledgements

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Contents

List of Figures

List of Tables

Chapter 1

Introduction and Motivation

Mobile ad hoc networks (MANETs) are self-organizing networks that consist of mobile nodes communicating with each other through necessary multi-hop wireless links without the need for supporting infrastructure such as base stations. Being infrastructure-free is an important feature of MANETs, which leads to potential applications in remote environments, disaster area recovery, and battlefields. In MANETs, each node acts not only as a host but also a router. Node mobility leads to the constantly changing topology and link states of MANETs. These characteristics pose a critical challenge for routing protocol design. Conventional routing algorithms do not perform well in MANETs as they assume a stable topology. Over the years, several routing protocols have been developed for MANETs. Based on the update mechanisms they can be categorized to proactive and reactive protocols. Algorithms such as source routing, link-state routing, and distance vector have been adopted into MANET routing protocols. More detailed introduction to the protocols is provided in Chapter 2.

The performance of MANET routing protocols on metrics such as average end-to-end delay, routing overhead, and packet delivery ratio (PDR) is affected by both the design of the protocols and the network scenarios. As a result, analyzing the performance of the protocols in various scenarios, and finding the relationship between the results and the mechanisms of the protocols, is important to achieving deeper understanding of mobile routing dynamics. Assumptions can be made by reviewing the nature of the protocols. For example, it is expected that reactive protocols have more latency than proactive protocols in highly dynamic scenarios as there is higher delay involved to allow the route discovery process. However, such assumptions can only be validated efficiently through simulation studies.

Many factors such as node mobility, traffic pattern, propagation model, channel characteristics, and MAC effects have a significant impact on the performance of routing protocols. Moreover, the interplay of these factors is rather complex [2]. In this thesis, we focus on two important factors that are network dynamicity and node density. In simulation studies, network dynamicity is influenced by choice of mobility models and parameter settings in each model, while node density is directly related to the total number of nodes in the network, simulation area, and transmission range of the mobile nodes. A variety of network scenarios in this study are created by varying some of these parameters to provide comprehensiveness in our performance analysis of MANET routing protocols. We hope that this thesis can provide more insights into mobile routing dynamics, and help the development of new protocols as well as the improvement of existing protocols.

1.1 Contributions

The main contributions of this thesis are:

- Compare and analyze performance of prominent MANET routing protocols with respect to network dynamicity and node density.

- Analyze impact of mobility models on MANET routing protocol performance.

1.2 Problem Statement

Evaluating the performance of MANET routing protocols is a challenging task due to the inherent complexity of MANETs and the random nature of node mobility and traffic [3]. Network simulation is the predominant evaluation approach for MANET routing studies [4]. One of the reasons behind the popularity of simulations studies on MANETs is the difficulty of creating repeatable scenarios involving tens or hundreds of mobile nodes [5]. Additionally, few of the prominent MANET routing protocols have seen significant actual implementation. On the other hand, there have been successful and detailed implementations of multiple MANET routing protocols and mobility models on a variety of simulation platforms that provide a powerful tool for MANET simulation studies. The ns-3 simulator is our choice of simulation platform in this thesis to analyze MANET routing performance. The four protocols studied have all been implemented in ns-3. Both DSR and DSDV have been implemented by researchers from the ResiliNets research group with extensive documentation providing implementation details such as header formats, control packet formats, and default values of the parameters. However, to our best knowledge,the AODV and OLSR models lack such comprehensive documentation. More importantly, some significant implementation details may heavily impact the simulation results. For example, it is unclear from the implementation whether OLSR maintains a send buffer or not. Buffering can affect the variation of end-to-end delay as has been pointed out by previous studies. The buffering behaviors of the four protocols are tested, and the results will be discussed in Chapter 4.

We analyze and compare the performance of prominent MANET routing protocols through ns-3 simulations. Even though simulation is a powerful tool for studying MANET protocols, there are challenges to achieve insightful and credible results. Simulation studies should be completed in a valid experiment, with sources of randomness such as seeds generated with random number generator (RNG) being used [6]. Previous studies on MANET routing performance using simulation tools have problems such as the lack of repeatability and comprehensiveness. In addition to the design and mechanisms, protocol performance is influenced by the underlying settings. As a result, repeatability of the simulation studies is very important for the results to be readily understood and validated by fellow researchers, and requires detailed documentation. Unfortunately, the lack of detailed documentation is a widespread problem in research on MANETs [7]. To guarantee repeatibilty for this study, we provide complete documentation on parameter settings in protocol implementation, mobility models, and all protocol layers in our ns-3 simulations. The lack of comprehensiveness is explained in detail in Section 2. We attempt comprehensiveness by using different mobility models and creating a wide range of conditions in the simulations. Moreover, we expect to achieve a more detailed understanding of MANET routing protocol performance by carefully investigating the parameter settings of the protocols in the simulation tools while reflecting on the design of the algorithms. To the best of our knowledge, this is the first study of MANET routing that covers a variety of of both protocols and mobility models.

1.3 Organization

The rest of this thesis is organized as follows. Chapter 2 presents the background of this study and an overview of related work. The protocols and mobility models used in our ns-3 simulations are introduced. In Chapter 3, we explain our choices of simulation parameters and introduce our data-collection method. Simulation results and analysis of MANET routing performance with different network dynamicity and node density are presented in Chapter 4. Chapter 5 presents the conclusion and the potential future work following this study.

Chapter 2

Background and Related Work

Routing in MANETs is non-trivial because of the infrastructure-free nature and the highly-dynamic topologies of mobile wireless networks. Many protocols have been proposed over the years that can be classified based on their mechanisms of exchanging routing information among mobile nodes. There have already been many performance analysis and comparison studies on MANET routing protocols. Although we have observed problems such as the lack of comprehensiveness and repeatability in many of them, they provide helpful insights and guidance for our research.

In this chapter, we present an overview of MANET routing protocols in different categories. The basic mechanisms in different stages of routing including route discovery and route maintenance in each protocol are introduced. In addition, we present an introduction to the mobility models used in our simulation studies. A discussion of previous studies on MANET routing performance analysis is also provided.

2.1 MANET Routing Protocols

Over the years there has been significant research on routing protocol design for MANETs. The protocols proposed can be classified into topology-based and position-based routing protocols.

2.1.1 Topology-Based Routing Protocols

Topology-based routing protocols perform packet forwarding using the information of links in the network [8]. They can be classified into proactive (or table-driven), reactive (or on-demand), and hybrid protocols based on their update mechanisms This classification is used in this section to introduce MANET routing protocols. In some previous studies, the protocols are also categorized into hello protocols and flooding protocols while analyzing their performance [9].

2.1.1.1 Proactive Routing Protocols

Proactive routing protocols calculate paths between node pairs with routing information kept in forwarding tables. There is little communication setup latency in this kind of protocol since paths are computed regardless of the need of data transmission. However, the overhead of maintaining routes that may not be needed is high, especially when routing information needs to keep up with the changing topology. Examples of proactive routing protocols include DSDV (Destination-Sequenced Distance-Vector protocol) [10] and OLSR (Optimized Link State Routing protocol) [11].

DSDV is one of the first MANET routing protocols [12] [13]. It is a hop-by-hop proactive routing protocol that uses the Bellman-Ford algorithm to calculate paths based on the metric of hop counts. Each node maintains a table with entries for all nodes in the network and is required to broadcast routing updates periodically to propagate changes. Periodic updates contain the entire routing table of each node, and a node may further propagate triggered updates if changes in the routing table are invoked by periodic updates. Routing tables contain the information of routes to every possible destination, which includes the next hop to the path and the number of hops to each destination. The next hop on the shortest path is determined by comparing the distances received for each destination. DSDV uses sequence numbers as a mechanism to determine most recent route updates and to prevent routing loops that the Bellman-Ford algorithm may produce. Each node in the network advertises a monotonically increasing even sequence number for itself, and the sequence number is incremented each time a periodic update is made by a node.

DSDV is similar to wired distance vector protocols such as the Routing Information Proctol (RIP) [14]. One of the disadvantages of DSDV is that it has high routing overhead when the size of the ad hoc network is large as it involves frequent network-wide essages. In addition, a path may have stale routing information before route updates propagation in the network, which may cause packets to be forwarded along the wrong path.

OLSR is a proactive protocol that belongs to the second generation of MANET routing protocols. It uses the link-state algorithm for path calculation. Paths to all destinations in the network are calculated and maintained before a data packet is sent from a source node. Nodes use Hello messages for neighbor discovery. Topology control (TC) messages are used to discover and broadcast link-state information throughout the network periodically [13]. Multipoint relays (MPRs) is an important concept in this protocol [15]. For a given node, all other nodes in the network can be divided into a neighbor set, a two-hop neighbor set, an MPR set, and an MPR selector set. The MPR set is a subset of neighbors of the selected node that can reach all two-hop neighbors. Link state advertisements (LSA) are only flooded to MPR set to reduce overhead. MPR selection is important in OLSR because a smaller MPR set leads to lower overhead. OLSR has lower overhead than other proactive algorithms because of MPR flooding optimization that will be introduced further in Chapter4, and is scalable to large networks because it introduces a kind of hierarchy to the network. It does, however, maintains routes that are not needed.

2.1.1.2 Reactive Routing Protocols

Proactive protocols borrow mechanisms such as periodic updates from conventional routing algorithms, which lead to certain problems including increased routing overhead. As a result, a novel approach of routing in MANETs was proposed in which mobile nodes use request packets to discover routes when they are ready to communicate with others [16]. This is the main idea behind reactive routing protocols in which paths are computed only when needed. When routing request packets are generated at a relatively low rate, this type of protocol provides lower overall overhead. However, reactive protocols require higher communication-setup latency as communication is delayed by the time it takes to discover routes unless there is a cached route between the specific pair of nodes. The AODV (Ad Hoc On-Demand Distance Vector) protocol [17] and DSR (Dynamic Source Routing) protocol [18] [19] are prominent examples of on-demand protocols in MANETs.

AODV is a reactive successor to DSDV. As is explained by its reactive nature, routes are discovered only when needed in AODV. There are four types of messages in this protocol: route request (RREQ), route reply (RREP), route error (RERR), and route reply ACK (RREP-ACK). The route discovery process is initiated when the source node has no routing information about the destination node [20], which means that either the destination was previously unknown to the source, or the previous valid route has expired. Additionally, if the previous valid route has been marked as invalid by a RERR message, a new route needs to be discovered.

AODV uses flooding as its route discovery mechanism. The source node floods RREQ messages in the network using the broadcast IP address. AODV adopts the concept of sequence number from DSDV. Sequence numbers are used at each destination node to determine the freshness of routing information and to prevent routing loops [21]. Route table entries are used to store routing information, such as sequence numbers in AODV. When an RREQ message is received by an intermediate node that possesses a route entry to the desired destination, the destination sequence number in the route entry is compared to the one in the RREQ. An RREP message is created and forwarded back to the source node when the destination sequence number of the route entry is equal to or greater than the one specified in RREQ. Otherwise, the RREQ is rebroadcasted by the intermediate node. In addition, a reverse-route entry for the source node is created by each node receiving the RREQ in the route table [22]. Periodic Hello messages are used in AODV to detect broken links. Failure to receive a certain number of consecutive Hello messages is an indication of link breakage between neighbors [12] [23]. Link-layer acknowledgments can be used as an alternative for link failure detection. It costs far less latency, which has been observed in our ns-3 simulation results. AODV provides RERR messages for notifying nodes of link breakages. RERR packets in AODV are intended to inform all sources sending data packets using the failed link [21]. A RERR message includes a list of destinations that have become unreachable due to the broken link [22]. However, RERR was not used in AODV route maintenance when the protocol was first introduced. Instead, when a link failure happened, the node upstream of the broken link propagated an unsolicited RREP with a fresh sequence number and infinite hop count to all the upstream nodes that had recently forwarded packets to a destination using that link [12,20]. AODV has a relatively simple algorithm, and it maintains paths only when needed. However, its performance suffers significantly from high mobility and episodic connectivity. Flooding RREQ control messages causes high overhead in large networks. Periodic Hello messages also lead to unnecessary bandwidth consumption.

The DSR protocol allows nodes to dynamically discover a source route across multiple network hops to any destination in the ad hoc network [19]. The use of source routing is a distinguishing feature of DSR, which simplifies routing at intermediate nodes by placing all responsibility for route selection at the source node [24], and allows the source to know the complete hop-by-hop route to the destination in DSR [21]. The control message types in DSR are the same as the ones in AODV. In DSR, a route cache is used to store routes that are already discovered. The first step of route discovery is to broadcast RREQ to the whole network. Any node that receives an RREQ messages will examine their route cache to find out if there is existing routing information for computing the route to the destination. If no useful routing information is found, the RREQ packet will be sent further on after having the address of the current node added to the hop sequence stored in the RREQ packet header, whose length is proportional to the number of hops. An RREP is generated when the RREQ packet reaches the destination or an intermediate node with routes to the destination cached. Routes are cached when RREP messages are received by source nodes. Route caching can significantly reduce flooding of control messages in the network, but mobility and episodic connectivity have a significant impact on DSR. Another disadvantage is that the header length grows with network size, which leads to higher overhead in every packet in a large network.

2.1.1.3 Hybrid Protocols

Hybrid routing protocols combine the advantages of both reactive and proactive protocols with the potential to provide better scalability than pure reactive or proactive protocols. This is because of their attempt to minimize the number of rebroadcasting nodes by defining a structure allowing nodes to collaborate, which helps to maintain routing information much longer [25]. Zone Routing Protocol (ZRP) [26] is a prominent hybrid routing protocol which has a zone based structure and reduces overhead for intra-zone nodes. ZRP aims to address the problems of proactive and reactive routing protocols by combining the best properties of both approaches [27]. It has a structure with a routing zone for each node in the network, which has a radius d expressed in hop count. ZRP consists of three components: the proactive IntrA-Zone Routing Protocol (IARP), the reactive IntEr Zone Routing Protocol (IERP), and Bordercast Resolution Protocol (BRP) [28]. IARP is a family of limited-depth, proactive link-state routing protocols, which maintains routing information for nodes that are within the routing zone of the node. Correspondingly, IERP is a family of reactive routing protocols that offer enhanced route discovery and route maintenance services based on local connectivity monitored by IARP [27]. The zone radius has a significant impact on the performance of ZRP for given node density. This is because ZRP reduces latency and overhead for RREQ for intra-zone nodes, but in the meantime it causes more traffic and higher overhead for maintaining the view of the zones. Zone overlap also contributes to the higher overhead in ZRP. There has not been an implementation in ns-3 releases yet.

2.1.2 Position-Based Routing Protocols

Position-based routing algorithms eliminate some of the limitations of topology-based routing by using additional location information [8]. In contrast to topology-based routing methods, they make decisions based on the geographical coordinates of the nodes [4], which are determined using GPS or other positioning services. Position-based routing protocols thus do not require traditional route establishment or maintenance. Nodes storing routing tables and routing information update messages are also not needed [8]. As a result, they may be more efficient than topology-based routing protocols in highly dynamic scenarios.

The ns-3 implementations of position-based routing protocols including Location-Aided Routing (LAR) [29] and Simple Forwarding over Trajectory (SiFT) have been developed by the ResiliNets research group. The comparative study with other MANET routing protocols will be completed in future work. This thesis focuses on prominent topology-based routing protocols.

2.2 Mobility Models

MANETs are often studied through simulation as is shown by previous studies. While trace-driven mobility patterns that are observed in real-life systems provide accurate information, MANETs are not easily modeled if traces are not yet created [30]. Therefore, the performance of routing protocols is heavily dependent on the mobility model used in the simulation that governs node movements [31]. Most previous studies on MANET routing use only one mobility model. In this thesis, several mobility models are used to create a variety of network scenarios. The mobility models introduced in this section are Steady-State Random Waypoint (SS-RWP), Gauss-Markov (G-M), and Lévy Walk. The Random Waypoint (RWP) model is most commonly used in MANET simulation studies. On the other hand, Lévy Walk captures the statistical features of human mobility and was recently implemented in ns-3 by the ResiliNets research group. We hope that by using various mobility models, we can get better insight into the relationship between MANET routing protocol performance and node mobility.

2.2.1 Steady-State Random Waypoint

The steady-state initialization is a method to improve the accuracy of RWP simulations, which leads to the creation of SS-RWP. The RWP model is a relatively simple and memoryless model that is more realistic in many scenarios than other models such as random walk. It is the most common mobility model used in ad hoc network simulations [31]. A node uniformly chooses a point in the area as the destination position of its next movement and moves towards this position at a velocity randomly chosen from an interval that is predefined by the model. After reaching each destination, a new speed is chosen from the interval, and a new destination point is uniformly chosen from the area. The node pauses its movement for a specific amount of time that is the given pause time before starting to move to its next destination. Note that the selection of speed and destinations are independent of each other, and is independent of the choices of previous movements as well.

In the implementation of RWP in both ns-2 and ns-3, the mobility model begins with all nodes paused at their initial positions. The problem of this kind of implementation is that it takes some time for the mobility model to converge. As the routing performance metrics are heavily influenced by the distribution of speed and location [31], the convergence stage of the mobility model may lead to the simulation results not accurately reflecting the long-term values. This is the reason why some of the previous studies [12] had a considerable warm-up time that takes up 20 percent of the total simulation time before the actual transmission of data packets. The SS-RWP model is a modification of the RWP model that eliminates the convergence stage so that the movements of the nodes are converged to the steady-state distribution from the start of the simulation. Some of the nodes start in a paused state while other nodes start in a moving state, chosen based on a probability distribution. Therefore we use the SS-RWP model in stead of RWP in this thesis.

The wide acceptance of the RWP model and its variants are a result of its simplicity of implementation and analysis [32]. However, because of its simplicity, the RWP mobility model may not provide adequate accuracy in modeling realistic movements. One of the limitations is that the average node movement speed will drop over time. It also has been noticed by previous studies that the stationary distribution of the location of a node is more concentrated around the center of the area in which the nodes move [31]. In addition, some extreme mobility behaviors such sharp turns frequently happen because of the memoryless feature.

2.2.2 Gauss-Markov

In the Gauss-Markov (G-M) mobility model, nodes have memory from their previous movements. The parameter α determines how much memory there is, and a time step dictates how frequently node velocity and direction are updated. G-M is more suitable to be used to model realistic movements with fewer sharp and abrupt turns. In this model, each node is assigned with the initial speed and direction, as well as the average speed and direction. A new set of speed s_n and direction d_n is calculated for each node after one time step [33]:

$$s_n = \alpha s_{n-1} + (1-\alpha)\bar{s} + \sqrt{(1-\alpha^2)}s_{x_{n-1}} \quad (2.1)$$

$$d_n = \alpha d_{n-1} + (1-\alpha)\bar{d} + \sqrt{(1-\alpha^2)}d_{x_{n-1}} \quad (2.2)$$

where $\bar{s}$ and $\bar{d}$ are the mean speed and direction parameters, and Gaussian variables $s_{x_{n-1}}$ and $d_{x_{n-1}}$ give randomness to the new velocity and direction parameters [34].

2.2.3 Lévy Walk

The RWP model and the G-M model are simple enough to be theoretically tractable and emulated in network simulators in a scalable manner. However, the accuracy of these models has not been validated by any empirical evidence [35]. Some of the tendencies of human mobility are not captured by these two models. The Lévy Walk mobility model was introduced to emulate the statistical features and evaluate the impact of the tendencies of human mobility on routing protocol performance. Analysis in previous studies shows that there is a similarity between the statistical features of human mobility and Lévy walks [35]. In addition, flights and pauses can be best characterized by heavy-tailed distributions, which are not produced by commonly used mobility models such as RWP and G-M.

2.3 Related work

The novel challenges and requirements of routing in MANET started to draw attention from researchers in late 1990s. A guideline for routing performance evaluation studies was proposed regarding important aspects that should be considered [36]. There have been many studies that analyze and compare MANET routing protocol performance using simulation. One of the early studies of MANET routing protocol performance comparison was done by Broch, et al. [12], whose purpose was to evaluate the ability of various protocols to react to network topology changes while successfully delivering data packets. The protocols evaluated in this study were AODV, DSDV, DSR, Temporally-Ordered Routing Algorithm (TORA) [37], and the RWP mobility model was used to simulate the movement of 50 wireless nodes in a flat space. Performance metrics such as packet delivery ratio and routing overhead were summarized and analyzed using ns-2 simulations.

Several researchers later completed similar studies on MANET routing protocol performance evaluation. Some of them focused on analyzing and comparing on-demand protocol performance. Performance comparison of AODV and DSR was performed by Perkins, et al. [21] and provided detailed analysis of the results. On-demand Multipath Distance Vector protocol (AOMDV) [38] was later added in MANET routing studies as well [39]. While these studies only focused on one category of MANET routing protocols, they evaluated the performance of the protocols on various metrics. Some studies later were carried out in similar simulation scenarios with DSDV, DSR, and AODV while evaluating performance on various metrics [40] [41]. Location-based protocols were later included in performance analysis studies with the performance of AODV, DSR, TORA, and LAR being compared using the QualNet [42] and ns-2 simulators [43]. In addition, performance comparison of MANET routing protocols is beneficial for selecting a proper protocol in real-life scenarios. Some studies performed scenario-based MANET simulations. Network sizes and parameter settings in mobility models are set to simulate real-life scenarios, such as disaster area recovery and archaeological sites [44] [45]. With the completion of implementation of DSDV and DSR in ns-3, comparison studies on MANET routing protocols using this newer simulation platform emerged in recent years, analyzing the performance of prominent protocols [46] [47]. Unfortunately, however, many of these studies provide very limited analysis of the simulation results. Simulation analysis of multiple protocols has been implemented in these studies, but many failed to cover all the prominent protocols, and some important performance metrics have been overlooked. Another noticeable problem is the lack of comprehensiveness in the mobility models used in these studies, with RWP commonly used, and only a few using G-M highly dynamic scenarios. Pause time is widely used in these studies as the only parameter to be varied to create more dynamic topologies. Therefore, a comprehensive performance comparison of MANET routing protocols on a sufficient number of performance metrics with different mobility models to simulate the movement of nodes needed. Previous studies have used ns-2 and GloMosim as the simulation tools. In this thesis, simulation is carried out using the advanced ns-3 platform.

Chapter 3

Simulation Methodology

In this chapter, we present the simulation setup and data-collection methods for our MANET routing protocol simulations in ns-3. In Section 3.1, we explain our choices of parameter values for the simulations. We investigate the implementation of each mobility model used in the simulations and explain how the parameters in each model affect node movement. Then we explain how we create different network scenarios by changing the values of the parameters. In Section 3.2, the detailed data-collection methods for calculating packet delivery ratio (PDR), average end-to-end delay, and routing overhead are introduced. A brief introduction to ns-3 is also presented in this section. In addition, routing protocol send buffer settings heavily affect routing performance. We carry out simulation experiments to test the effect of buffering behaviors of each protocol.

3.1 Simulation Parameters

In the implementation of SS-RWP (Steady-State Random Waypoint), G-M (Gauss-Markov), and Lévy Walk mobility models in ns-3, there are several parameters that are configurable to change node movement in simulations. In this section we explain our choices of mobility model parameters that we vary to evaluate routing protocol performance. Additionally, a brief introduction to the implementations of mobility models in ns-3 is presented in each subsection.

3.1.1 Network Dynamicity

The frequently changing topologies of MANETs pose a significant challenge for routing protocol design. Protocol performance can be heavily affected by network dynamicity. Node mobility affects the average number of connected paths and average link durations, which in turn affect the performance of the routing protocols [48] [49]. As a result, one important part of this study is to investigate how the dynamicity of networks affects routing performance. Creating proper scenarios by varying the parameters in each mobility model in the simulations is very important.

3.1.1.1 Steady-State Radom Waypoint

In the implementation of the SS-RWP model in ns-3, parameters including simulation area, pause time, and node speed are configurable. Most previous studies using RWP or SS-RWP only vary pause time to change node mobility, and use the same range of varying pause times [21] [12] [50]. In this thesis, we vary both pause time and node velocity (v) to create network scenarios with different dynamicity to make them distinctive. Node velocity is defined as a uniform random variable in SS-RWP. Some of the parameters in the SS-RWP implementation in ns-3 are listed in Table 3.1. Previous studies set the interval as from almost zero (0.01) to the given node speed [4]. If we use this range when tuning node velocity, the expected value would only be half of the given velocity in each scenario. Instead, we set the interval of node velocity to be $[v-1, v+1]$, where v is the given velocity.

Table 3.1. Parameters of SS-RWP in ns-3

Parameter	Description
MinSpeed	Minimum speed value [m/s]
MaxSpeed	Maximum speed value [m/s]
MinPause	Minimum pause time value [s]
MaxPause	Maximum pause time value [s]

In many previous studies, 20 m/s, which is comparable to traffic speeds inside a city [21], is set as the maximum node velocity in simulations. We vary node velocity from human walking speed (1.5 m/s) to high-speed railway speed (100 m/s) to create a wider range of network scenarios. The case of highly mobile airborne networks is beyond the scope of our work, and has have been studied along with the proposal of a 3-D G-M mobility model [33] [34].

3.1.1.2 Gauss-Markov

Table 3.2. Simulation setup for testing G-M parameters

Parameter	Value
Area	1500×300 [m^2]
Simulation time	200 [s]
Number of nodes	50
Link layer	802.11b DSSS rate 11 [Mb/s]
Packet size	64 [Byte]
Packets per second	4
Maximum node velocity	20 [m/s]
Transmission Range	250 [m]
Traffic model	Constant bit rate (CBR)

There are many parameters in the G-M model that affect network dynamicity, and the relationship among those parameters is rather complex [34] [51]. Setting

α between 0 and 1 allows for varying degrees of randomness and memory [34]. There is less randomness and more predictability in the node paths as α increases [51]. TimeStep is another important parameter that affects node mobility in G-M, a new movement is set up after each TimeStep. Although both parameters have a significant impact on the linearity and randomness of node movement, our simulation studies show that varying α or the TimeStep will not result in a trend in the performance metric values. Simulation parameters are listed in Table 3.2 below.

Simulation results are presented in Figures 3.1, 3.2, 3.3, 3.4, 3.5, and 3.6. The results show that the parameters α and TimeStep mainly affects the trajectory shapes rather than network dynamicity. As this study focuses on the performance of MANET routing protocols in network scenarios with different dynamicity, we will only vary the velocity in the G-M model for our simulations.

3.1.1.3 Lévy Walk

The Lévy Walk mobility model was first implemented in ns-3 by the ResiliNets research group [52]. In the initial implementation, there is only one parameter v that is configurable, which does not facilitate our study on routing performance as it is very difficult to predict the differences in the scenarios created by varying v. As α and its impact on node mobility in Lévy Walk is well-studied [35], it is added to the implementation as a second reconfigurable parameter. Varying α affects the diffusivity of the network, which leads to changes in the distributions of route hop-counts and path durations. Hop-counts and path duration have a significant impact on MANET routing protocol performances.

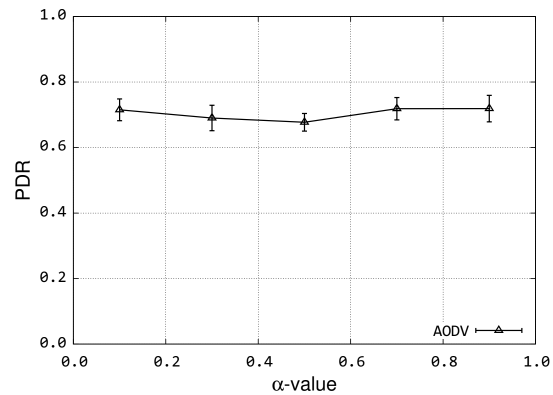

Figure 3.1. PDR varying α-value in G-M

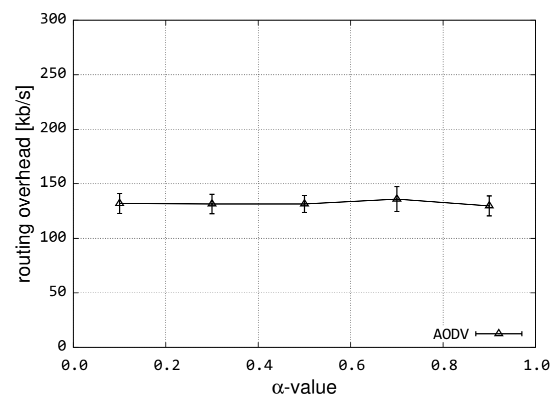

Figure 3.2. Overhead varying α-value in G-M

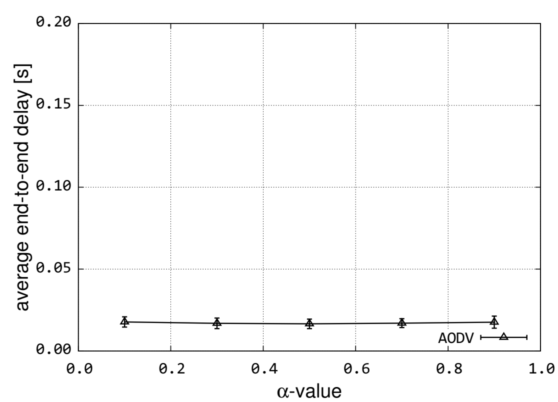

Figure 3.3. Delay varying α-value in G-M

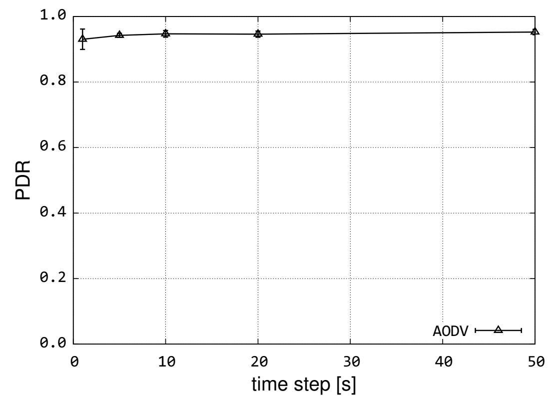

Figure 3.4. PDR varying TimeStep value in G-M

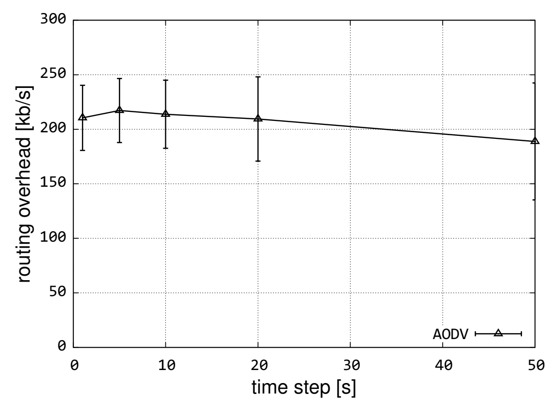

Figure 3.5. Overhead varying TimeStep value in G-M

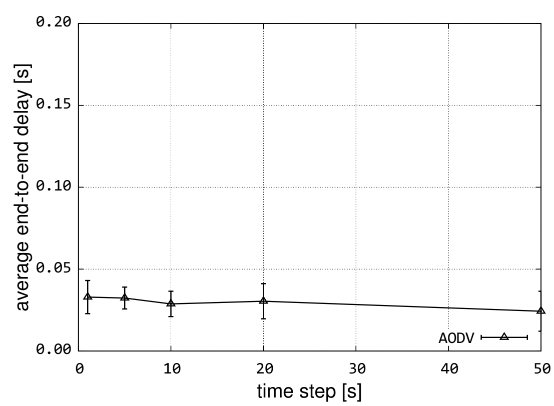

Figure 3.6. Delay varying TimeStep value in G-M

3.1.2 Node Density

Node density is affected by three parameters of the network including the total number of nodes, area, and transmission range. In a very sparse network, the number of possible connections between any node pair is very limited [48]. We use the degree of connectivity to measure node density in this thesis. The calculation of the degree of connectivity d is :

$$d = \frac{N\pi r^2}{A} \tag{3.1}$$

where N is the total number of nodes in the area, r is the transmission range of the nodes, and A is the simulation area. From this calculation, we can see that varying any one of transmission range, area, and the number of nodes, can achieve the same effect in varying node density of the network. We choose to vary transmission range in our MANET routing simulations as there have been studies focusing on optimum transmission radius [22] [53].

3.2 Data-Collection Methods

In this thesis, three important performance metrics of routing protocols are evaluated:

- **Packet delivery ratio (PDR)** – The ratio of the total number of data packets received by destinations to those sent by sources.

- **Average end-to-end delay of data packets** – The average time it takes for a data packet to be transmitted from the application at the source to the application at the destination node.

- **Routing overhead** – The total number of overhead bytes generated by routing protocols to transfer routing information. The total overhead is averaged over time.

PDR and average end-to-end delay are the most important for best-effort traffic. Average end-to-end delay in our simulation studies consists of transmission delay, queuing delay, retransmission delay, and propagation delay. Extra bytes generated by routing protocols consume network resources. In this section we present a brief introduction to the ns-3 simulator and the implementation of MANET routing protocols on this platform. Our data-collection method in ns-3 simulations for calculating the performance metrics listed above is also presented.

3.2.1 Implementation of MANET Routing Protocols

We use ns-3 [54] as the simulation tool in this study. It is an open-source discrete-event network simulator for research on Internet systems. It is a replacement for ns-2, which has been widely used in previous MANET routing studies. The ns-3 project aims to develop an open, preferred simulation environment for networking research [54], and relies on C++ for the implementation of the simulation models. The problems caused by the combination of oTcl and C++ in ns-2 is eliminated in ns-3 as oTcl is no longer used to control the simulations [55]. Additionally, there are many other improvements in ns-3 compared to its predecessor, including modular extensibility, mixed wired and wireless models, and arbitrary mix of link types and routing algorithms [4].

In the early releases of ns-3 the implementation of MANET routing protocols only included AODV and OLSR. The implementations of DSDV and DSR were developed by the ResiliNets group along with detailed documentation [13] [50].

They defined the modules and configurable parameters of both protocols and explained how the protocols function in the ns-3 documentation [56].

We have made the following changes to some of the default parameters in the implementation of MANET routing protocols in ns-3 to make the comparison fair across protocols. For AODV, we change the RreqRetries value, which defines the maximum number of retransmissions of RREQ to discover a route [56], from 2 to 16 to be the same as the default value in DSR. In addition, DeletePeriod is the upper bound on the time for which an upstream node can have a neighbor as an active next hop while this neighbor has invalidated the route to the destination. We change its value from 15 to 300 to match the RouteCacheTimeout in DSR.

Buffering is a very important setting for MANET routing protocol implementations. AODV, DSDV, and DSR all have specifically implemented send buffers, whereas the OLSR model does not provide any information about its buffering. Buffering or queueing time and the length of the buffer (queue) are configurable in AODV, DSDV, and DSR. A simulation experiment is carried out to test the effectiveness of buffering mechanisms in the protocols. The values of parameters in this experiment are listed in Table 3.3.

Table 3.3. Simulation setup of the buffering test experiment

Parameter	Value
Area	1200×1200 [m^2]
Simulation time	200 [s]
Link layer	802.11b DSSS rate 11 [Mb/s]
Packet size	64 [Byte]
Packets per second	1
Source node position	(0,0)
Destination node velocity	20 [m/s]
Transmission Range	1000 [m]
Traffic model	Constant bit rate(CBR)

The two nodes in this scenario are implemented with different mobility models. The source is set static using ns3::ConstantPositionMobilityModel and allocated with a position at the center of the area using ns3::ListPositionAllocator, transmitting to the destination node from this position. The destination node is implemented with the G-M mobiltiy model, with trajectory is set as a straight line at the angle of 180 degrees by changing the MeanDirection. The node will bounce back when it hits the bounds of the area. Based on the simulation parameters, the destination node will go out of the transmission range of the source node at time 50 seconds and will come back in range at time 70 seconds. ASCII tracing is enabled for reviewing the packets transmitted and received at each node after the simulation.

We observe the following pattern from the trace files from each protocol. Both AODV and DSR stop transmitting data packets after a failed transmission. They both start the route discovery process after the destination node comes back within transmission range of the source node, which transmits a burst of data packets within a short interval that is less than one second. These are the data packets buffered when route error was detected. However, neither DSDV nor OLSR show this kind of pattern in their respective trace files. Data packets are transmitted one per second even within the time that the destination is out of reach of the source node. The results of packet delivery ratio show that these packets are simply dropped. Both AODV and DSR have a buffer as is documented in their ns-3 source code, but we observe that OLSR does not have a send buffer, which is consistent with the fact that the mechanism is not mentioned in the RFC [11] nor the implementation source code in ns-3. DSDV send buffers only functions when there is no route available in the routing table and, therefore, we are not able to see its effect in this experiment.

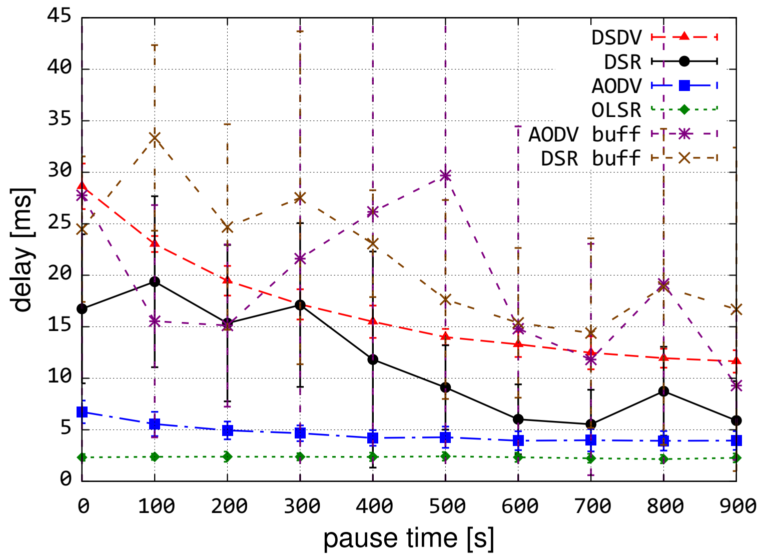

Figure 3.7. Delay varying pause time in SS-RWP [1]

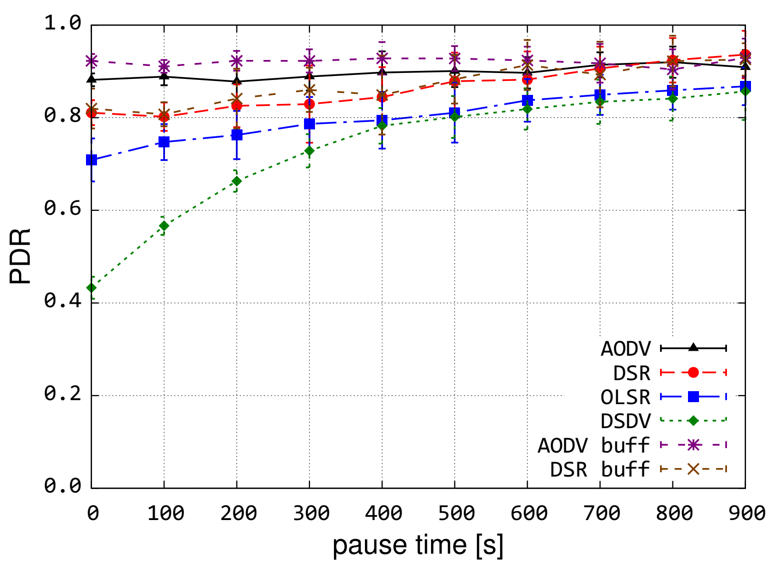

Figure 3.8. PDR varying pause time in SS-RWP [1]

The effect of send buffers on routing performance can be seen in Figures 3.7 and 3.8. Figure 3.7 reveals that send buffers cause significant variations in average end-to-end delay, especially for reactive protocols. This is because when the send buffer is on, the time for a data packet to get delivered can be delayed considerably because of link breakages, as is indicated by the results of our buffering test experiment. In high mobility scenarios, send buffers provide improvement in PDR as we can see from Figure 3.8. This is also consistent with the result of the buffering test experiment. The variations in the delay results makes it hard to study the impact of other factors on protocol delay performance. Additionally, fairer comparison among all the protocols is certainly beneficial for this study. Therefore, for the simulation studies on the impact of network dynamicity, we disable send buffers of AODV, DSR, and DSDV. We do, however, keep the send buffer in DSDV when studying the impact of node density to understand its effect, which will be further explained in Chatper 4.

3.2.2 Data-Collection Methods

The two factors needed for calculating PDR are the number of data packets transmitted by the source nodes and the number received by the destination nodes. We obtain both factors using the ns-3 tracing system. The tracing architecture is one of the main distinct features of ns-3 compared to ns-2, which uses a callback-based design that decouples trace sources from trace sinks. In this way, customization of the tracing or data output is enabled [57]. An introduction to the mechanism of the tracing system is provided in the ns-3 manual [58]. Trace sources in ns-3 provide access to interesting underlying data that are indications of events that happen during simulations. Trace sinks are the entities that consume trace information, and a trace source can be connected to multiple trace sinks through an ns-3 Callback.

As we use the ns3::OnOffApplication to generate traffic from the source nodes, the ns3::OnOffApplication/Tx trace source [59] is used to retrieve the total number of transmitted data packets by all the traffic sources. The variable onOffTx is implemented in a callback function, which is invoked by the trace source whenever a new data packet is created and sent by the application so that the value of the variable is increased by one. The total number of data packets transmitted by traffic sources are stored in this variable at the end of the simulation. Similarly, we connect the trace source ns3::PacketSink/Rx to another callback function that has the variable sinkRx to record the total number of data packets received by destination nodes, invoked whenever a data packet is received by the sink. PDR is calculated at the end of the simulation by dividing the value of onOffTx by sinkRx.

We calculate the average end-to-end delay in a similar method but with the help of the ns3::DelayJitterEstimation class in ns-3. The member function PrepareTx is implemented in the same callback function as onOffTx and is connected to the OnOffApplication/Tx trace source. This member function is invoked once on each data packet and records the transmission within the packet by storing it as a ns3::Tag [56]. The transmission time is used to calculate the end-to-end delay upon packet reception. The RecordRx member function of the DelayJitterEstimation class is implemented in the same callback as sinkRx and is connected to the trace source PacketSink/Rx, invoked when a data packet is received at the destination to update the delay. The GetLastDelay member function can return the updated delay after the RecordRx gets called, which is added and recorded by the variable delay. Average end-to-end delay is calculated by dividing delay by sinkRx at the end of each simulation run. This calculation also reveals that the performance metrics are not completely independent as, for instance, lower PDR means that average end-to-end delay is calculated with fewer samples [21].

MANET routing protocols use different port numbers for transferring routing information, including 654 for AODV, 269 for DSDV, and 698 used by OLSR. We use this feature to record the control packet overhead for these three protocols in our simulations. A callback function is connected to the trace source Ipv4L3Protocol/Tx so that it is invoked when an IPv4 packet is sent to the outgoing interface. This includes both data packets and control packets of the routing protocols. The GetDestinationPort function in the callback function examines the destination port number in the UDP header of the packet. By checking the destination port number, the callback function can determine whether the packet being sent is a control packet. The size of a control packet is added to the variable recording the total routing overhead.

The DSR header resides between IP header and UDP header in both data and control packets, consisting of two parts: DSR fixed-size header and DSR options header [50]. The message id in the DSR fixed-size header indicates the type of message this DSR header is carrying: a control packet is indicated by message id of 1 while a data packet has an id of 2. If the packet is a data packet, we only add the size of the DSR header to the total routing overhead, whereas the full size of control packets is added. In this thesis, the total routing overhead and control packet overhead of DSR are both presented in the simulation results.

Chapter 4

Simulation Analysis

In this section, we present our ns-3 simulation results and performance analysis of routing protocols including AODV, DSDV, DSR, and OLSR. The mobility models used in the simulations are SS-RWP (Steady-State Randm Waypoint), G-M (Gauss Markov), and Lévy Walk. Our simulations focus on two important aspects of MANETs, network dynamicity and node density. They both have a heavy impact on the performance of routing protocols. In order to ensure comprehensiveness of scenarios covered in this analysis study, we create low, medium, and high network density cases to perform simulations varying network dynamicity. Network scenarios with low, medium, and high network dynamicity cases are created accordingly for simulations varying node density. The parameter values for low, medium, and high dynamicity and density cases are shown in Tables 4.1 and 4.2. Parameters used in our simulation studies are presented in Table 4.3.

We choose 64 bytes as the packet size in our simulations, and each source node transmits 4 packets per second. This combination leads to fairly low traffic that does not invoke network saturation. Simulation studies on saturated cases are left for future work. The simulation area is set as rectangular instead of square to have

Table 4.1. Parameters for different scenarios varying dynamicity

Dynamicity	Pause time	Velocity	Real-life speed
Low	300 [s]	1.5 [m/s]	5.4 [km/h], human walking
Medium	75 [s]	40 [m/s]	144 [km/h], high-speed cars
High	0 [s]	100 [m/s]	360 [km/h], high-speed railway

Table 4.2. Parameters for different scenarios varying density

Density	Transmission range	Degree of Connectivity
Low	120 [m]	5
Medium	170 [m]	10
High	250 [m]	22

Table 4.3. Simulation parameters

Parameter	Value
ns-3 version	ns-3.27
Link layer	802.11b DSSS 11Mb/s
RTS/CTS enabled?	no
Packet fragmentation?	no
Propagation loss model	range
Routing protocol	AODV, DSDV, DSR, OLSR
Transport layer protocol	UDP
Application type	ns3::OnOffApplication
Mobility model	SS-RWP, G-M, Lévy Walk
Number of simulation runs	10
Total number of nodes	50
Number of flows	10
Simulation time	900 [s]
Warmup time	50 [s]
Simulation area	1500×300 [m^2]
Data packets per second	4
Data packet payload size	64 byte
Node velocity	1.5, 5, 10, 20, 40, 60, 80, 100 [s]
Transmission range	93, 131, 161, 207, 268, 317 [m]
Degree of connectivity	3, 6, 9, 15, 25, 35

a diversity of both long and short routes in terms of hop counts [4]. Parameters of the network are needed for performance analysis of routing protocols, and are presented in Table 4.4.

Table 4.4. Parameters of the network

Parameter	**Discription**
N	Total number of nodes
d	Degree of connectivity
h	Average route hop counts
p	Number of data packets per second from one source node
s	Number of source nodes

4.1 Varying Network Dynamicity

Widely varying mobility characteristics are expected to have a significant impact on the performance of routing protocols [49]. In this section, we analyze the performance of MANET routing protocols with varying network dynamicity. The mobility models used are SS-RWP, G-M, and Lévy Walk. Low, medium, and high network density cases are created and used to make network scenarios more diverse.

4.1.1 PDR Performance

Figures 4.1, 4.2, and 4.3 show the PDR performance of routing protocols in low, medium, and high node density cases as the network dynamicity increases using SS-RWP. The three reasons packet drops occur in MANETs are: 1) full interface queues caused by congestion, 2) packets being forwarded along a path that no longer exists due to topology changes, and 3) lack of established routes due to low connectivity. In our simulation settings, the interface queue of each node is 100 packets long. Given the low traffic rate in the network, interface queues being full is very unlikely to happen. The other two reasons then become the main causes for packet drops. In the low density case, limited network connectivity significantly reduces the chance of paths being established, resulting in poor PDR performance of all four protocols. The protocols perform similarly as low connectivity is the dominating factor in low density scenarios. In the medium density case, AODV performs a lot better than the other three protocols in terms of PDR. This performance superiority is observed in most of our simulation results. The reason is that AODV benefits from its on-demand nature and frequent reinitialization of route discovery process to adapt to fast topology changes. Since we removed the send buffer for both on-demand protocols, data packets rely on paths that are already established, which are stored in table entries and route cache for AODV and DSR respectively. PDR performance of DSR suffers from stale route cache in dynamic scenarios, whereas routing table entries in AODV are only valid for a much shorter time. The value of ActiveRouteTimeout, which is the period of time during which the route is valid [60], is only 3 seconds by default. This allows the route table entry to be fresh for most of the time during the simulations. Frequent topology changes increase the chance of a cached route being no longer valid in DSR. PDR performance of the protocols is similar in the highly dense case with OLSR performing significantly worse in more dynamic scenarios. In the highly dynamic scenario with no pause time and a node velocity of 100m/s, AODV and DSR outperform DSDV and DSR due to their reactive nature that helps adapt to rapid topology changes. Simulation results using the G-M mobility model, which are presented in Figurse 4.4, 4.5, and 4.6, show very

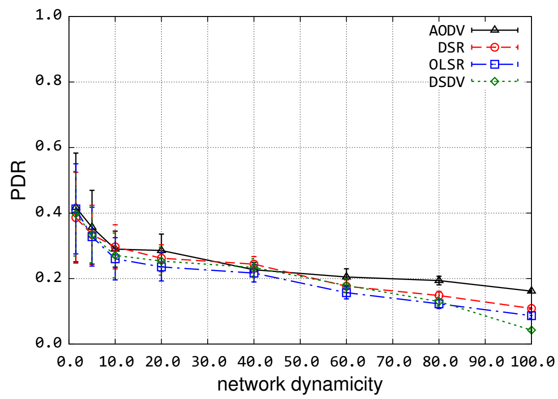

Figure 4.1. PDR varying dynamicity – SS-RWP, low density

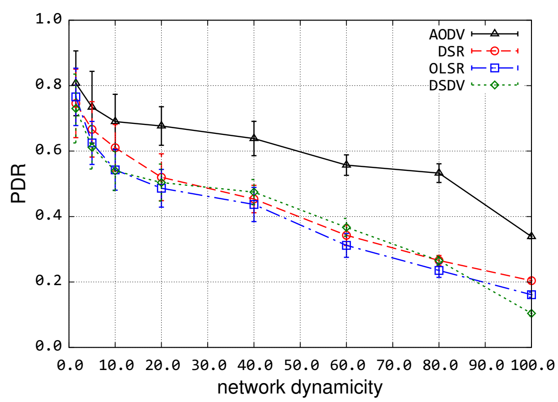

Figure 4.2. PDR varying dynamicity – SS-RWP, med. density

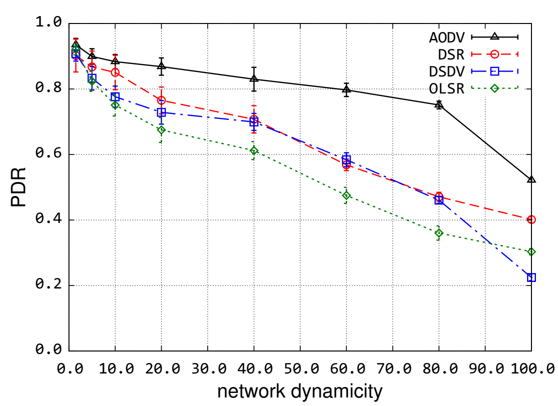

Figure 4.3. PDR varying dynamicity – SS-RWP, high density

similar trends and relative performance.

From the results we can see that PDR decreases for all the protocols with increasing network dynamicity, which implies that packet drops are happening more frequently. High network dynamicity causes link breakage to happen at a higher frequency, which then leads to shorter path durations. Path duration is modeled as the longest time interval during which all the links along a path exist [2]. Higher network dynamicity reults in lower average path duration in the network [61]. Low path duration increases the chance of data packets being transmitted along paths that are no longer existing and getting dropped eventually. The simulation results indicate that frequent updates that can keep up with topology changes in highly dynamic scenarios are important to achieving reasonable PDR performance.

The simulation results using the Lévy Walk mobility model shown in Figures 4.7, 4.8, and 4.9 show consistency with our analysis above. In the Lévy Walk simulations, we investigate how PDR performance changes when varying the value of the α variable in the mobility model. Larger values of α lead to higher average path duration in the network [35], which causes lower network dynamicity. Results in this study show that PDR decreases with decreasing α value, which is consistent with our analysis of the results using other mobility models and results in previous studies. However, relative PDR performance of the protocols is different from the results using other mobility models. AODV does not show superior performance in the Lévy Walk scenarios. We have not yet achieved an explanation for this result, and it will be studied further in future work.

4.1.2 Routing Overhead Performance

Figures 4.10, 4.11, and 4.10 show the routing overhead performance of the protocols as the network dynamicity increases under SS-RWP. The simulation results with G-M are shown in Figures 4.13, 4.14, and 4.15. We present both total routing overhead and control packet overhead of DSR. The main components of routing overhead are different for each protocol. In DSDV, routing overhead consists of periodic updates and triggered updates. Nodes advertise their entire routing tables in periodic updates, which are broadcasted after each periodic update interval. Triggered updates are small updates in-between the periodic updates, and are sent out whenever a node receives a DSDV packet that caused a change in its routing table [62]. Flooding of RREQ is the main component of routing overhead in AODV, and could contribute to 90% of total overhead in terms of the number of routing packets generated [21]. For DSR, both the source route header and the control packets (RREQ, RREP, and RRER) contribute to routing overhead. From the results, we can see that the routing overhead performance of DSR is largely dominated by source headers. The control packet overhead is much smaller compared to the overhead of AODV, which shows the effectiveness of route cache in reducing flooding of route requests. However our results reveal that the total overhead of DSR is larger in most of the scenarios compared to other protocols. Source route header overhead was not studied in most previous research. Previous research also argue that it is unclear whether reduction of overhead is significant for real world operations when considering the comparison of the source route overhead to control packet overhead, as transmitting a packet is more costly in terms of power consumption and network utilization [12]. However, we believe that source route header overhead is an important part of the total routing over-

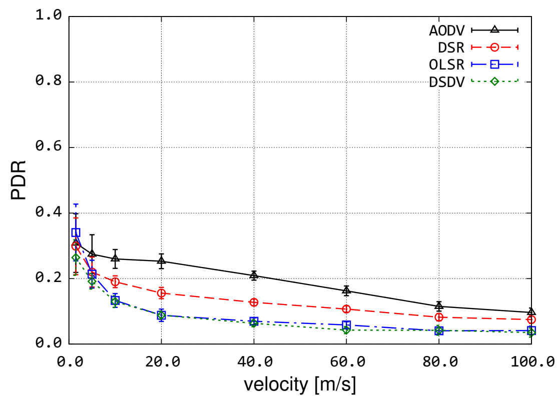

Figure 4.4. PDR varying dynamicity – G-M, low density

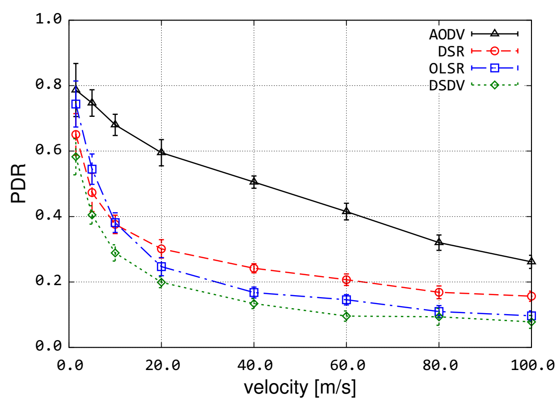

Figure 4.5. PDR varying dynamicity – G-M, med. density

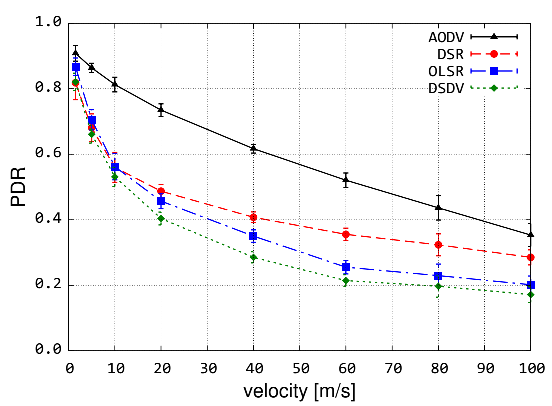

Figure 4.6. PDR varying dynamicity – G-M, high density

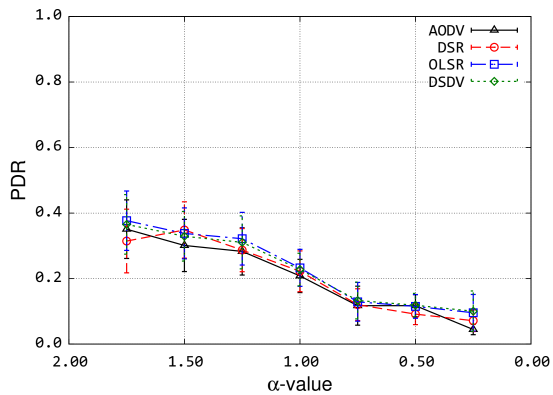

Figure 4.7. PDR varying dynamicity – Lévy, low density [1]

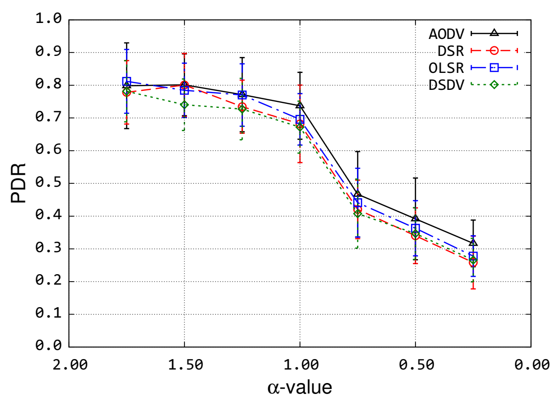

Figure 4.8. PDR varying dynamicity – Lévy, med. density [1]

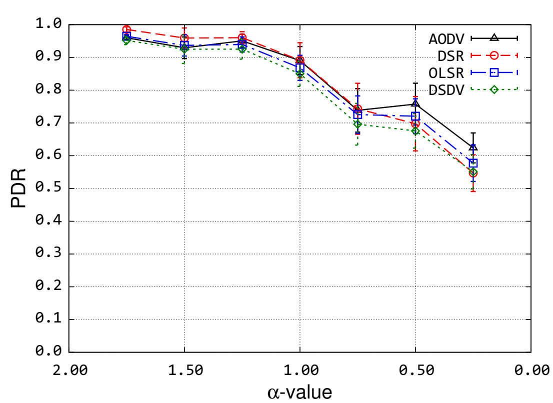

Figure 4.9. PDR varying dynamicity – Lévy, high density [1]

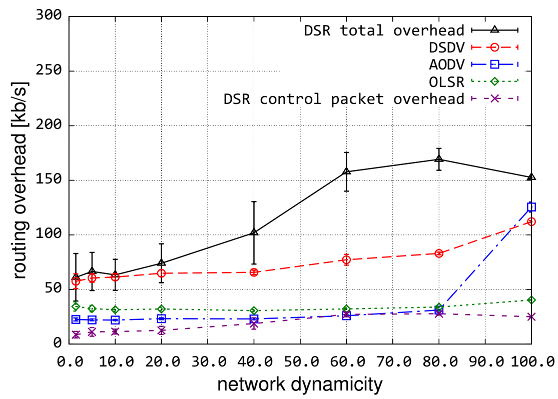

Figure 4.10. Overhead varying dynamicity – SS-RWP, low density

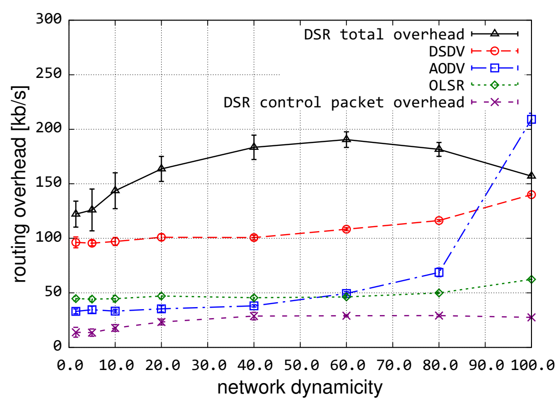

Figure 4.11. Overhead varying dynamicity – SS-RWP, med. density

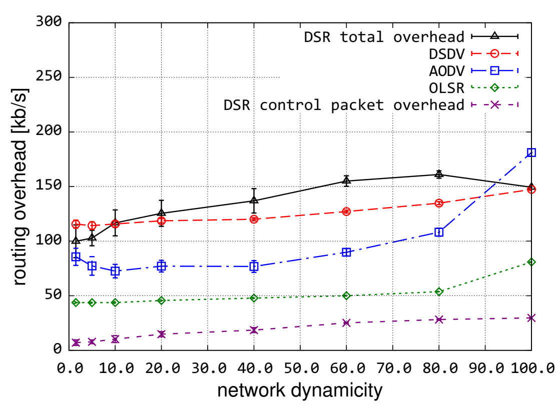

Figure 4.12. Overhead varying dynamicity – SS-RWP, high density

head as it consumes energy and bandwidth, which are both valuable resources in MANETs.

All protocols generate fairly low overhead in the low density case because of the limited connectivity of the network. DSDV and OLSR deliver fairly stable overhead performance with varying dynamicity of the network as the overhead mostly consists of periodic updates. There is a small increase in DSDV routing overhead with higher node mobility. because rapid topology changes lead to nodes sending more trigger updates. In the presence of high mobility, link failures can happen very frequently, which trigger new route discoveries in AODV since there is at most one route per destination in its routing table [21]. OLSR delivers better performance in terms of routing overhead due to the optimization schemes in the design of the protocol [63]. First, the flooding of topology control (TC) packets is limited to MPR nodes. This mechanism is referred to as MPR flooding. A node retransmits a broadcast packet only when it receives its first copy from a node for which it is a MPR. Our results in all scenarios show the effectiveness of these methods. Simulation results reveal that these mechanisms are very effective in reducing routing overhead caused by broadcasting control packets.

Routing overhead in DSR consists of both control packets and source route headers, and the latter is the dominating component. Source route header overhead is affected by route hop counts, as well as how many hops a data packet can be forwarded before getting dropped or eventually delivered during transmission. Here we propose a simple model to help analyzing this type of overhead in DSR. The parameters needed are listed in Table 4.5.

Previous studies suggest in dynamic cases, the deviation in the distribution of route hop counts is small [35], so here we assume uniform route hop count in the

Table 4.5. DSR parameters

Parameter	Discription
R_s	source route header overhead
θ_i	% data packets dropped after i hops
θ_0	% data packets dropped due to no route being available
l	length of one address in DSR source route header
D_r	packet delivery ratio

network. Then the total overhead of source route header can be formulated as:

$$R_s = sphl(\theta_1 + 2\theta_2 + \cdots + hD_r) \tag{4.1}$$

$$\theta_0 + \theta_1 + \theta_2 + \cdots + D_r = 1 \tag{4.2}$$

where s is the number of source nodes, p is the number of data packets transmitted per second by one source node, h is the average route hop counts from Table 4.4, and l and its description is listed in Table 4.5. We can see that the DSR source route header overhead is heavily dominated by route hop counts because of the h^2 factor in the formulation. DSR total overhead increases with network dynamicity in low node density cases as is shown in Figures 4.10 and 4.13. This is because low node density leads to poor connectivity, which significantly reduces the chances of routes being established and makes θ_0 the most influential factor in the above equations. A certain level of node mobility increases the ability of setting up routes in the low connectivity cases between sources and destinations, and reduces θ_0 with the source route header overhead then increases accordingly. However, further increase of network dynamicity causes DSR total overhead to go down because high mobility causes more packets to be dropped after a small number of hops.

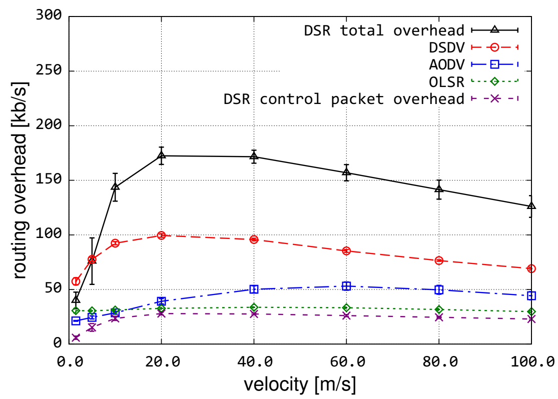

Figure 4.13. Overhead varying dynamicity – G-M, low density

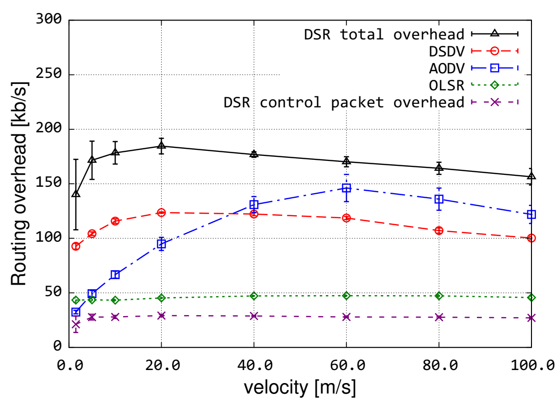

Figure 4.14. Overhead varying dynamicity – G-M, med. density

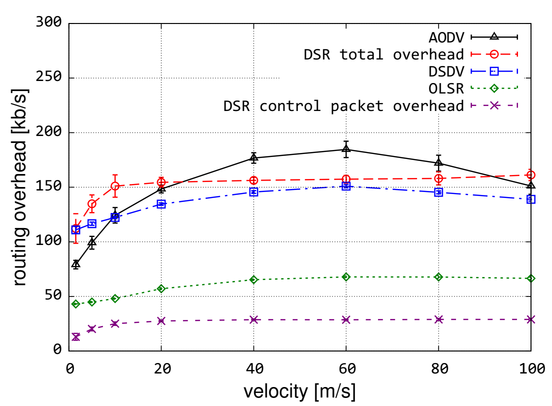

Figure 4.15. Overhead varying dynamicity – G-M, high density

Routing overhead performance using G-M in low, medium, and high density scenarios are shown in Figures 4.13, 4.14, and 4.15. Routing overhead of AODV, DSDV, and DSR show an interesting trend that is first increasing then decreasing with increasing dynamicity. We believe that this performance trend is related to the node distribution in the G-M model. However, unlike previous studies on RWP that focus on node distribution, there has been very little research on G-M that focus on this. Further studies on G-M in future work should find an explanation for this performance trend.

Simulation results of routing overhead performance using Lévy Walk in low, medium, and high density scenarios are shown in Figures 4.16, 4.17, and 4.18. Decreasing α value in Lévy Walk makes the nodes less spread out in the network, which can be shown by the distribution of route hop counts and route life time [35]. A higher α value indicates a greater chance of establishing routes with more hops and longer path duration. This explains why DSR total overhead is decreasing with smaller α values as there are fewer paths with higher hop counts, which leads to smaller h in Equation 4.1 that has a positive h^2 factor. Large α makes nodes more spread out in the network, and limits the knowledge of each node on the network topology, which proactive protocols can benefit from to optimize broadcasting and reduce the number of transmissions [64]. Thus DSDV and OLSR generate more routing overhead in scenarios with larger α.

Energy is a limited and valuable resource in many the scenarios that MANETs can be deployed. For example, power consumption is very important for mobile battery-powered devices. In our research, energy consumption is not directly studied as a performance metric. However, routing overhead performance can show some insight into energy consumption as transmitting overhead bytes consumes

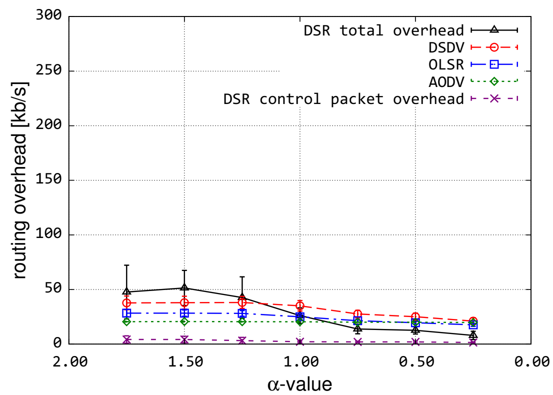

Figure 4.16. Overhead varying dynamicity – Lévy, low density [1]

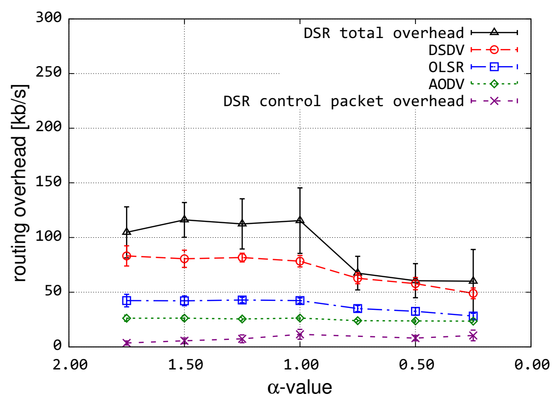

Figure 4.17. Overhead varying dynamicity – Lévy, med. density [1]

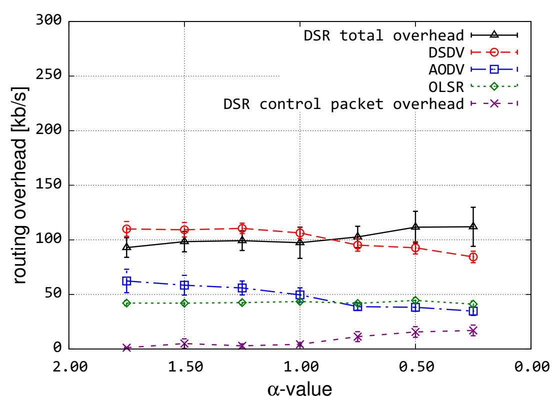

Figure 4.18. Overhead varying dynamicity – Lévy, high density [1]

energy of mobile nodes in the network. In addition to the overhead results analyzed above, we also show routing overhead fraction O of total traffic in the network using SS-RWP. The calculation is:

$$O = \frac{R}{R + D} \tag{4.3}$$

where R is the routing overhead traffic and D is the data packet traffic. From Figures 4.21, 4.20, and 4.19 we can see that in highly dynamic scenarios, routing overhead contributes to approximately 80% of the total traffic in the network for DSR, AODV, and DSDV. Moreover, routing overhead of DSR is greater than 80% of the traffic in most scenarios. Our results suggest that there needs to be further optimization to reduce routing overhead and energy consumption in MANET routing protocols. These results show the effectiveness of MPR flooding in OLSR in reducing routing overhead.

4.1.3 End-to-End Delay Performance

Average end-to-end delay performance in low, medium, and high density cases under the SS-RWP model are presented in Figures 4.22, 4.23, and 4.24. In addition to transmission delay, the main components of end-to-end delay are route-setup latency, retransimission delay, queuing delay, and propagation delay. As we use the ns3::ConstantSpeedPropagationDelayModel in the simulations, propagation delay is very small because the default value of speed is the speed of light in vacuum space [65]. There is no route-setup latency as we have disabled the send buffers. Queuing delay is an influential component in congested scenarios. Congestion has heavy impacts on delay of DSR and AODV while AODV has a good mechanism to mitigate the impact of congestion as nodes only reply to the first received RREQ

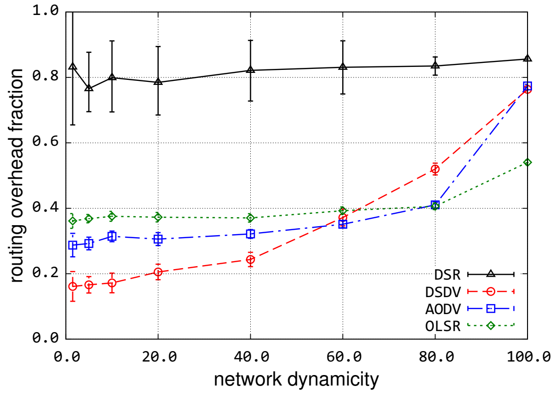

Figure 4.19. Overhead fraction – SS-RWP, low density

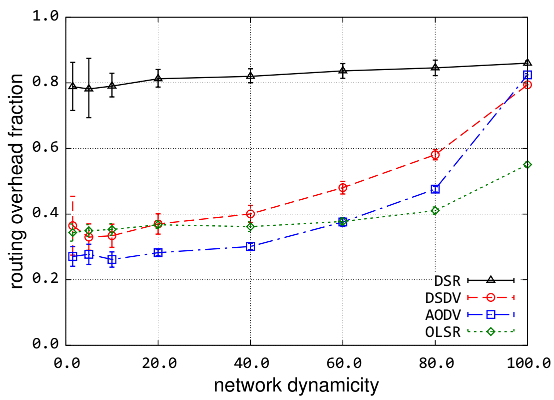

Figure 4.20. Overhead fraction – SS-RWP, med. density

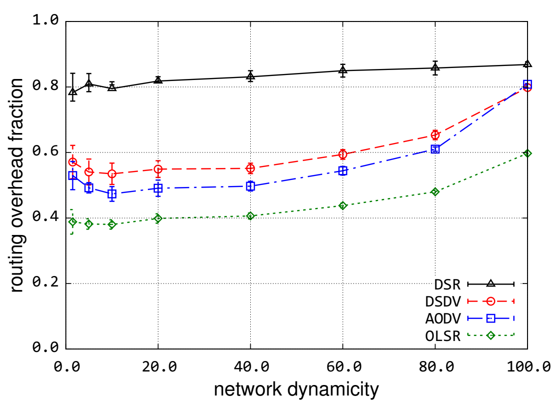

Figure 4.21. Overhead fraction – SS-RWP, high density

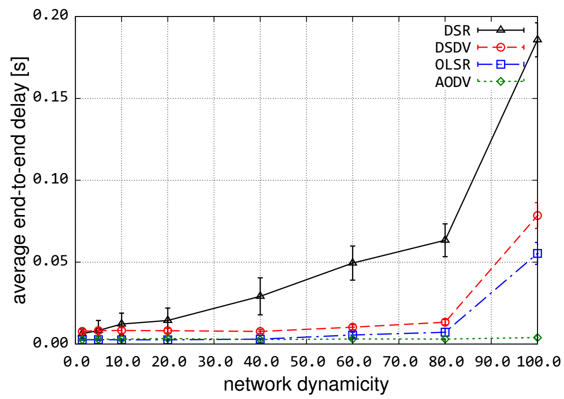

Figure 4.22. Delay varying dynamicity – SS-RWP, low density

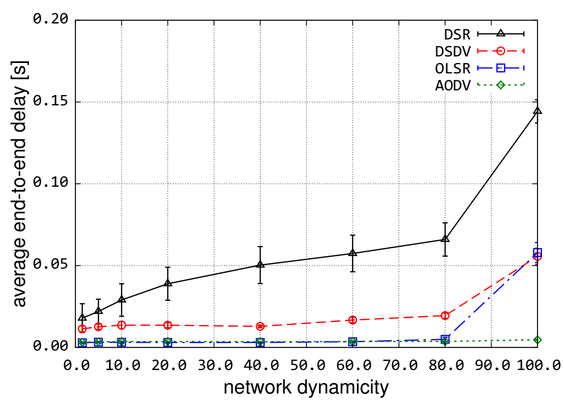

Figure 4.23. Delay varying dynamicity – SS-RWP, med. density

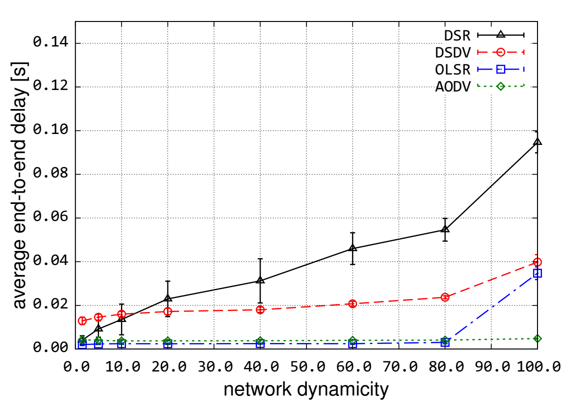

Figure 4.24. Delay varying dynamicity – SS-RWP, high density

packet [21]. However, in this thesis we consider the impact of queuing delay to be minimal because of the low traffic rate. Traces reveals that retransmission delay can be up to approximately 40 ms, which is significant compared to the end-to-end delay. Mobility has a large impact on overall retransmission delay in the network. High network dynamicity leads to frequent topology changes in the network, which result in more retransmissions of data packets. Thus end-to-end delay increases for all the protocols as network dynamicity increases because of higher retransmission delay.

Delay performance of DSR is significantly worse than other protocols because of the salvage mechnism. DSR can keep multiple routes cached for one destination and uses a hop-by-hop mechanism for route maintenance. If the data packet fails to get to the next hop after retransmissions, it will not be dropped immediately. Instead, the sender starts finding alternative routes to the destination in the route cache. If no alternative route is found, or the data packet has already been salvaged for MaxSalvageCount times, this data packet will be dropped [50] [66]. This process cause extra delay in data transmission.

AODV has the best delay performance because of frequent initialization of route discovery that helps the protocol adapt to fast topology changes. Of the proactive protocols, OLSR has better performance in end-to-end delay than DSDV. We have not yet found an explanation for this result. Previous research suggests that keeping track of other nodes available via one- and two-hop neighbors leads to less end-to-end delay in OLSR [67]. However, further validation is needed for this explanation in future work. The results of simulations using G-M are presented in Figures 4.25, 4.26, and 4.27. Delay performance of the protocols using G-M shows consistency with performance under SS-RWP and supports our analysis above.

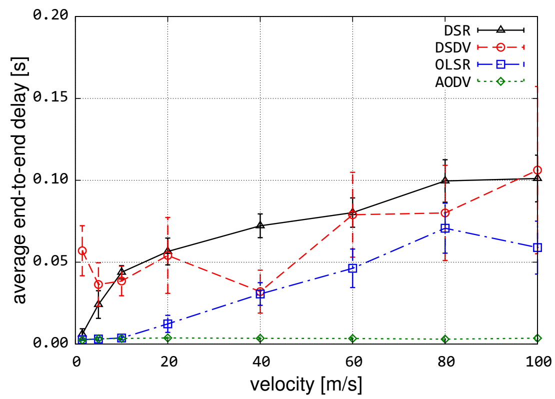

Figure 4.25. Delay varying dynamicity – G-M, low density

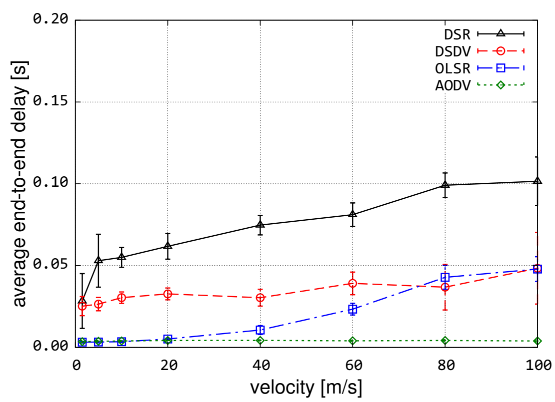

Figure 4.26. Delay varying dynamicity – G-M, med. density

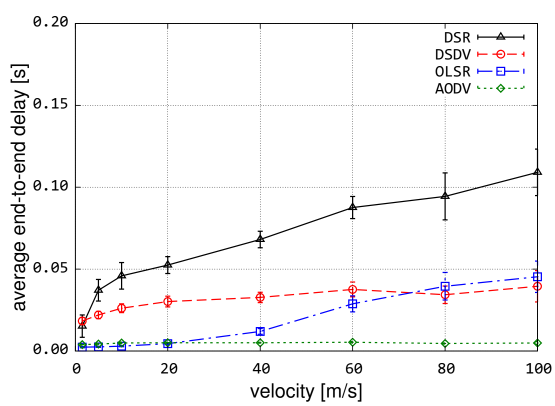

Figure 4.27. Delay varying dynamicity – G-M, high density

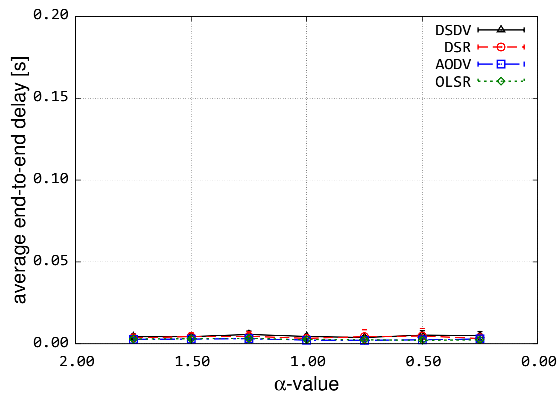

Figure 4.28. Delay varying dynamicity – Lévy, low density [1]

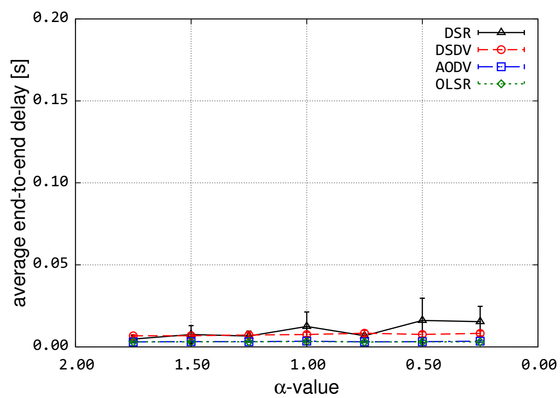

Figure 4.29. Delay varying dynamicity – Lévy, med. density [1]

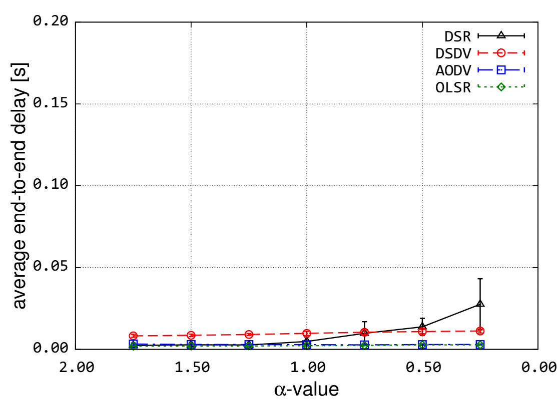

Figure 4.30. Delay varying dynamicity – Lévy, high density [1]

Figure 4.28, 4.29, and 4.30 show delay performance of protocols under the Lévy Walk model. Delay performance does not show a clear trend in the low and medium density scenarios. Data packets experience only small delay and one retransmission could significantly increase end-to-end delay. However, in the high density scenarios, delay increases as α value increases due to longer path durations that result in fewer retransmissions and salvaging processes.

4.2 Varying Node Density

Node density is the other important factor in MANETs that affects routing performance. The immediate impact of node density is affecting the chance of establishing paths. We vary transmission range in this thesis to vary node density.

4.2.1 PDR Performance

PDR performance of routing protocols in low, medium, and high network dynamicity scenarios is shown in Figures 4.31, 4.32, and 4.33. From the results we can see that PDR increases as degree of connectivity increases. This is because higher node density increases the chance of paths being established and leads to longer path duration. The protocols achieve reasonable PDR performance in high density scenarios even with high network dynamicity as high degree of connectivity can mitigate the impact of node mobility on PDR. AODV still shows superior performance, particularly in the medium and high dynamicity scenarios due to its ability to adapt to rapid topology changes. Proactive protocols perform worse as they rely on periodic updates. PDR performance of all four protocols shows consistency with our observations in the previous section. The send buffer of DSDV can only provide very minimal PDR performance improvement.

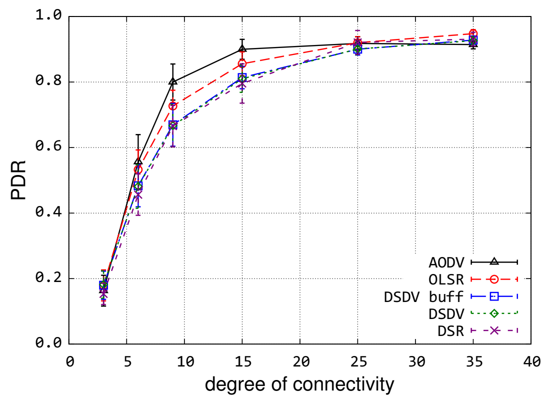

Figure 4.31. PDR varying density – SS-RWP, low dynamicity

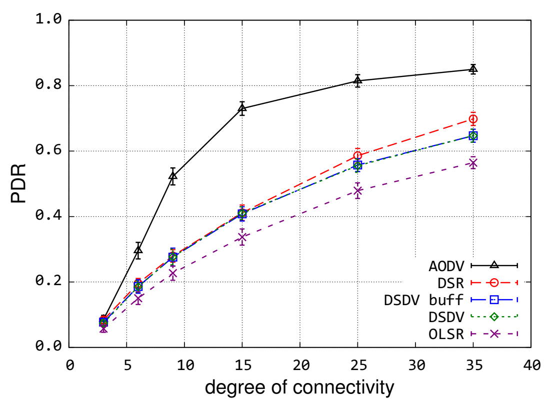

Figure 4.32. PDR varying density – SS-RWP, med. dynamicity

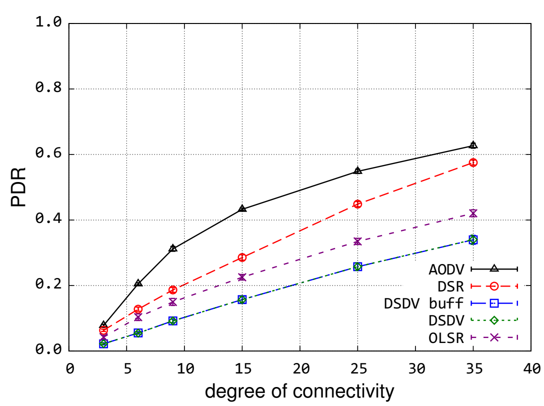

Figure 4.33. PDR varying density – SS-RWP, high dynamicity

4.2.2 Routing Overhead Performance

Routing overhead of the protocols in low, medium, and high network dynamicity scenarios is shown in Figures 4.34, 4.35, and 4.36. The overhead of AODV increases with degree of connectivity in low and medium dynamicity scenarios. As mentioned in the previous section, routing overhead generated by AODV is dominated by RREQ flooding. Assuming each traffic source generates a RREQ packets per unit time on average, routing overhead generated by AODV can be modeled by:

$$as(d-1)N \tag{4.4}$$

where s is the number of source nodes, N is total number of nodes, and d is the degree of connectivity in Table 4.4. We assume a to be fairly stable when varying the degree of connectivity in the low and medium dynamicity scenarios. We can make this assumption because when node mobility is low, increasing node density will not have the effect of mitigating the impact of network dynamicity on the frequency of topology changes. AODV routing overhead then has a linear relationship with degree of connectivity based on this assumption. The routing overhead of OLSR and DSDV do not show this linear relationship as both protocols can limit unnecessary retransmissions during broadcast of updates. OLSR routing overhead is lower due to the MPR flooding optimization, as described in Section 4.1.

In high dynamicity scenarios, we can not make the assumption that a is a constant. Let b denote the number of link breakages per unit time during the simulations. The relationships among factors a, b, and d can help explain overhead performance of AODV. a has a positive correlation with b in all scenarios. In low connectivity scenarios ($d \leq 9$), link breakages occur at a very high rate because of high dynamicity. So a is large because of a high value of b, which leads to AODV overhead increasing rapidly with d. However, increasing d will limit the number of link breakages, thus b has a negative correlation with d. When the network has reasonable connectivity ($d > 9$), the negative correlation between b and d starts to become the dominant factor and causes a to decrease with increasing d, with overhead then decreases.

DSR routing overhead can be divided into two parts based on the degree of connectivity in the medium and low dynamicity scenarios. In the first part ($d \leq 9$), a higher degree of connectivity leads to more routes being set up, which leads to more source route header overhead. Routing overhead increases with degree of connectivity primarily because of the large increase in the source route overhead. In the second part ($d > 9$), the network has reasonable connectivity, which can also be shown by the PDR performance results shown in Figures 4.31 and 4.32. In these scenarios, the source route overhead is fairly stable. On the other hand, the control packet overhead slightly decreases as the cache hit ratio increases with better connectivity of the network, which leads to the decreasing total overhead.

4.2.3 End-to-End Delay Performance

End-to-end delay in low, medium, and high network dynamicity scenarios varying network density is shown in Figures 4.37, 4.38, and 4.39. DSDV with send buffers enabled has significantly higher delay in the extremely low density scenarios. This is because the send buffer allows a certain number of data packets to be queued when there is no route available. The send buffer of DSDV does not provide good performance improvement, and its negative effect is significant in

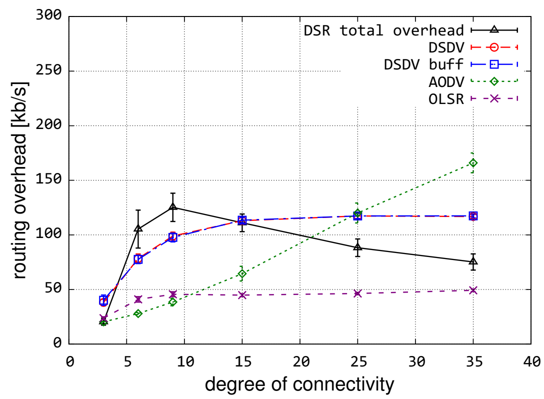

Figure 4.34. Overhead varying density – SS-RWP, low dynamicity

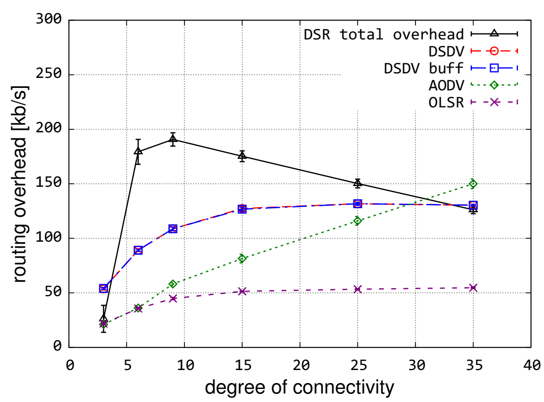

Figure 4.35. Overhead varying density – SS-RWP, med. dynamicity

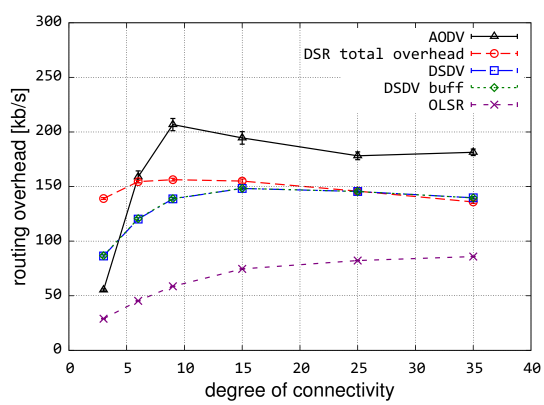

Figure 4.36. Overhead varying density – SS-RWP, high dynamicity

low connectivity scenarios. Further optimization is needed for buffering mechanisms in DSDV. In the low and medium dynamicity scenarios, delay of DSR first increases, and then decreases as d increases. This is because in low density scenarios the salvaging process is happening significantly less frequently due to the lack of established paths. Then when the network has reasonable connectivity, the lack of established paths is no longer the dominant factor. Increasing network density reduces link breakages and leads to lower delay as the number of retransmissions and the number of salvaging processes are decreasing. Both OLSR and AODV achieve very desirable delay performance, which is consistent with the results in Section 4.1. The delay of AODV shows a slight increase when node density is increasing. Further study of AODV delay performance in future work should find an explanation to this performance trend.

4.3 Performance Summary

To summarize our analysis of routing protocol performance, we focus on the protocols' ability to adapt to rapid topology changes, and scalability to larger and denser networks. Additionally, our analysis reveals the fundamental performance tradeoff between adaptation to rapid topology changes and routing overhead. Improving the ability to adapt to topology changes can lead to higher routing overhead when designing and optimizing protocols.

AODV delivers good performance throughout our simulation studies. It has better PDR performance than all other protocols in dynamic scenarios because of the ability to adapt to topology changes. This ability comes from its frequent initialization of route discovery, which also leads to desirable delay performance in all scenarios. However, the problem with AODV comes from frequent flood-

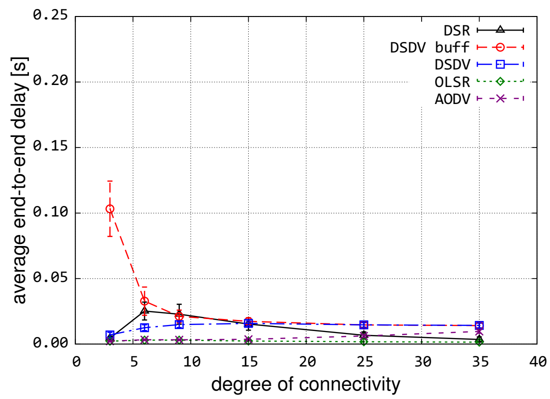

Figure 4.37. Delay varying density – SS-RWP, low dynamicity

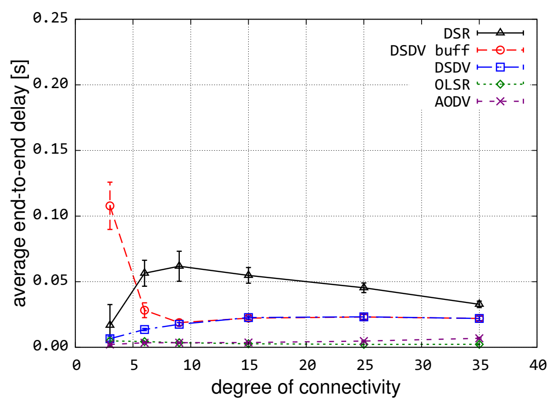

Figure 4.38. Delay varying density – SS-RWP, med. dynamicity

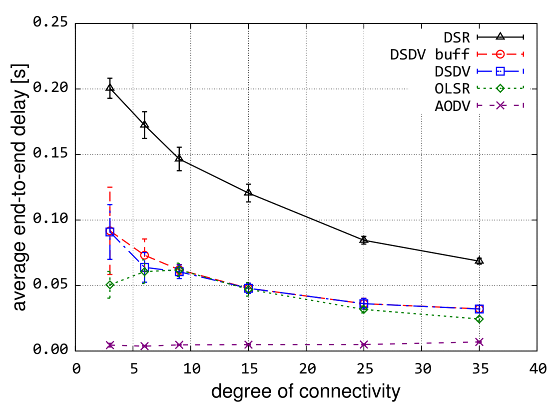

Figure 4.39. Delay varying density – SS-RWP, high dynamicity

ing of RREQ packets, which results in linearly increasing routing overhead with increasing degree of connectivity. This significantly limits AODV scalability to denser and larger networks. It also causes AODV to generate high overhead in extremely dynamic scenarios in which many extra route discovery processes are triggered. Even so, AODV appears to be the best choice in most of the scenarios. For DSR, the distinctive features are the aggressive use of route cache and the use of source routing. However, the performance of DSR suffers from both features in many of the scenarios. Aggressive use of cache causes stale routes, which hurts DSR performance on PDR and delay. Even though route caching effectively helps reduce flooding of control packets, injecting source route header in data packets results in high total overhead and will cause extra processing burden in real implementations. Apparently, further optimization of DSR is needed based on our results and ananlysis. Firstly, the impact of the salvage mechanism needs to be examined in future works. The salvaging limit should be chosen appropriately in different scenarios to improve delay performance. Secondly, better route caching strategies can be proposed in future work to achieve better overall performance.

DSDV, as expected, does not adapt well to frequent topology changes as it is a proactive protocol relying on periodic updates. On the other hand, DSDV does show reasonable scalability in high density scenarios. However, DSDV has higher delay and the overall performance does not stand out in any of the scenarios. OLSR, which is also a proactive protocol, delivers better delay and overhead performance than DSDV in most cases. OLSR optimization schemes are very effective in limiting routing overhead, making it a good choice for low and medium dynamicity scenarios. Reducing the intervals between periodic updates in proactive protocols can improve their PDR performance, but at the cost of higher routing overhead, which shows the performance tradeoff in protocol design. Table 4.6 summarizes our discussion on the ability to adapt to rapid topology changes and scalability to denser and larger networks of the protocols.

Table 4.6. Performance summary of protocol abilities

Protocol	**Adapting to topology changes**	**Scalability**
AODV	Good	Fair
OLSR	Fair	Good
DSDV	Fair	Fair
DSR	Poor	Fair

It should be noted that the above performance evaluation is made under the default parameter settings with only a few changes. Parameters such as route-cache timeout, periodic-update interval, active-route timeout, and salvaging limit, are expected to have some impact on performance of routing protocols. Carefully setting the parameters to proper values based on network cases is very helpful to achieve better performance in real-life scenarios.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

In this thesis, we analyzed the performance of prominent MANET routing protocols (DSDV, AODV, DSR, and OLSR) using ns-3 simulations. Routing protocol performance was evaluated for three mobility models (SS-RWP, G-M, and Lévy Walk). Both network dynamicity and node density of MANETs have a significant impact on routing performance.

According to our results and analysis, AODV is the best choice in most of the scenarios. OLSR performs better than its fellow proactive-protocol DSDV in most scenarios. DSR performance could suffer from the use of route cache and source routing.

5.2 Future Work

Given the scope of this thesis and our observations from the simulation results, more can be achieved in future work. We present our thoughts on the future outlook of simulation-based MANET routing studies in this section.

Future work can aim to provide more comprehensiveness. First, more performance metrics can be evaluated in future studies on MANET routing protocols, especially underlying metrics that provide more insight into node movement and routing performance. For example, route life time and route hop counts studied in [35] are good indicators of the dynamics of mobile wireless networks. In addition, presenting the distributions of metrics should be considered in performance evaluation. In this thesis, we use connected data points with confidence interval (CI) estimates in our presentation of the results. CI is a range of likely values for a parameter [68]. For performance metrics such as PDR and routing overhead, this is a simple, sufficient, and straightforward way to present results. But for end-to-end delay, route life time, and route hop counts, presenting the distribution reveals more statistical characteristics and could provide more insights on MANET routing performance. Second, more protocols can be included in the comparison studies. These protocols include hybrid protocols such as ZRP, and location-based protocols such as DREAM (Distance Routing Effect Algorithm for Mobility), GPSR (Greedy Perimeter Stateless Routing), SiFT, and LAR. In addition, more mobility models can be used, especially group mobility models such as the Reference Point Group Mobility (RPGM) model [30]. Lastly, more network scenarios should be created to evaluate routing performance in future studies. Congestion is not considered in this thesis with the network being far from saturated in our simulations because we first want to understand routing performance and dynamics isolated from the effects of congestion and collisions. However, congestion can have a significant impact on routing performance, and saturated scenarios should be implemented in future work. In addition, MANET routing protocols are generally designed based on the assumption that all participating nodes are fully cooperative [69]. Most simulation studies are carried out in scenarios based on this assumption as well. However, a node may be misbehaving by agreeing to forward packets and then failing to do so, because it is overloaded, selfish, malicious, or broken [70]. Studying the impact of misbehaving nodes and mitigation approaches is a good topic for future work and will be helpful especially for actual implementation of MANET routing protocols.

There have been previous studies on MANET routing protocols that try to establish detailed mathematical models to reveal the relationship among routing performance metrics, node mobility, and parameters of the mobile networks [2], [3]. These models provide helpful insights and are good examples of exploiting mathematics to evaluate routing performance. However, validation of their models is only done on a limited number of scenarios. Developing comprehensive mathematical models would be helpful for in-depth research on MANET routing protocols.

Future studies of MANET routing can also focus on the implementation of protocols in ns-3. Current ns-3 releases only have proactive and reactive protocols implemented for MANET routing. This can be extended by adding implementations of hybrid protocols such as ZRP. In addition, implementations of AODV and OLSR lack detailed documentation. Studies on their implementations can analyze and test the parameters and justify the default values. Research on protocol implementation will be helpful for research on new protocol development.

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