Impact of Varying Offered Data Load on Density-Based Routing in Mobile Ad-hoc Networks

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ABSTRACT: *We present a new algorithm called Density-based probabilistic routing algorithm (AODV–Probabilistic) for efficient data transmission in mobile ad-hoc networks. We also define a new metric for routing called traffic density to represent the degree of contention at the medium access control layer. To evaluate the performance of our proposed protocol, we identify three different environments: a high density, a variable density and a sparse density. Simulation results show noticeable improvement under the three environments. Under the settings we examine, our proposed algorithm achieve up to 22 percent higher percentage of average data throughput for different offered data loads and speeds than AODV and 30 percent higher than OLSR at the three environments without incurring any additional routing overheads or intense computation.*

Keywords: Mobile Ad-hoc Networks, Density Based Probabilistic Algorithm, Nodes Density, Nodes Connectivity Management, Broadcast Management

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1. Introduction

Mobile ad-hoc networks (MANET) are non-infrastructure based networks with an undefined network size. The ubiquitous nature of the MANET allows any device to be attached to a certain network at any time. The range of wireless transmission only limits the network, which is approximately a few hundred meters. Many problems and issues need to be addressed for a MANET protocol to be implemented for mobile applications and devices. One of the main issues that needs to be addressed for MANET is the movement and the dynamic changes that occur in the connectivity over a certain period.

Deploying MANET in real life scenarios with a mixture of vehicular and pedestrian traffic or disaster areas would result in node distributions that lack uniformity. A non-uniform distribution of nodes imposes a problem for MANET since the nodes are required to be near each another in order to communicate. This issue was discussed in our previous papers [E. Natsheh and T. Wan, 2008] [E. Natsheh et al., 2008] [E. Natsheh et al., 2007] [E. Natsheh et al., 2006]. Also, this scenario was discussed in [S. HeimLicher et al., 2009][J. Haillot, 2010] to determine the necessary scenarios studying partially connected networks. The uneven distribution of nodes in an area was identified as a contributive factor for poor or limited connectivity in a multi-hop wireless network such as MANET.

Frequent solicitation of routing information via broadcasts performed by MANET nodes in densely populated areas exposes the network to a problem known as “broadcast storm”. This event occurs when a high number of broadcast activities are performed simultaneously at a certain point in time and trigger torrents of redundant broadcast requests and replies that will eventually lead the contention based link layer of MANETs to suffer a blackout [S. Ni et al. 1999]. In networks with varying node densities, such problems are expected to occur more frequently since MANET nodes will be forced to retransmit broadcasts whenever there is a broken link or when the destination could not be found after a certain period. The performance of the communications link in the network would eventually decline due to aggressive broadcast activity [A. Siddique et al, 2007] [T. Lin et al, 2010] [A. Waluyo et al, 2004].

In short, the problems found in MANET networks with varying node distributions are the following: low packet delivery ratio, low data throughput rate, high end-to-end delays and potential “broadcast storm” problems due to an unmanaged network broadcast generating a high number of retransmissions.

The research objective of this work was to study the behavior of MANET protocols encountering non-uniform node distribution in a given area and to address the issues caused by non-uniformity. A suitable quantitative estimate of node density in a given area was found to be dense with the assumption that all of the nodes had an identical transmission range. This estimate was used to provide node density awareness for nodes within this network. In addition, an enhanced MANET routing protocol was developed to address the problems arising from node density variations. The performance of the enhanced protocol was compared with existing MANET protocols for different levels of node density to determine the effectiveness of the new protocol.

The rest of this paper is organized as follows: Section 2 summarizes related work on the nodes density effects; then, the proposed density based probabilistic algorithm, performance analyses of the proposed algorithm, simulation results and evaluations, and finally, the conclusions will be presented.

2. Node Density Issues

The nature of our proposed scheme is the issue of node connectivity (density) and, hence, the definition of *Sparse* and *Dense* regions. In this section, we conducted a discussion for this issue.

2.1 Node Density

The optimum density of MANET was studied in [E. Royer et al, 2001], which discussed the tradeoffs between network density and node connectivity in the face of increasing node mobility. This study also proposed a search for an optimal node density value in order to maintain connectivity in a stationary network. However, the results were inconclusive regarding the optimal density for maintaining connectivity in highly mobile environments. When neighbor nodes were saturated, they yielded very similar results. Nonetheless, E. Royer et al. (2001) concluded that both transmission power and the node densities needed to increase when the nodes experience increasing mobility in order to maintain connectivity.

The node density for an entire network can be identified as the number of nodes that populate over a certain area or region of a MANET. Therefore, the node density can be equated to:

ρ Node Density

n Number of nodes

A Size of Network Area

$$\rho = \frac{n}{A} \tag{1}$$

The relationship of the node density in MANET should consider the extent of the nodes’ transmission range throughout the network area. Including the transmission range coverage of the nodes provides a better estimation for node density and will help identify how well the network is connected. In a large network area, even though there are many nodes scattered around, the nodes that are far from their respective transmission ranges would not allow the network to be classified as Dense. Therefore, the network area has considered the transmission range to provide a better estimate of node density.

2.2 Connectivity and Connection Probability

The probability of connectivity is defined based on the homogenous transmission range of the nodes, which is denoted as *P(k-*

con) [C. Bettstetter, 2002] [C. Bettstetter and J. Zang, 2002]. The definition of connectivity of a network is defined by the following characteristics:

- The number of neighbors surrounding a node is denoted by its degree (d)
- A node that has a degree $d = 0$ is said to be isolated from the rest of the network
- The minimum degree of nodes (d_{min}) is considered to be the smallest degree of all the nodes in the network
- A network is said to be connected when every pair of nodes has a path between them; otherwise, the network is disconnected
- A connected network always has a minimum degree $d_{min} > 0$, but the reverse trend is not necessarily true
- A network is *k*-connected if at least a *k* mutually independent path connecting each pair of node exists

The formula for *P* (*k-con*) proposed in [C. Bettstetter, 2002]:

$$P(k\text{–}con) = \left(1 - e^{-\mu}\sum_{i=0}^{k-1}\frac{\mu^{i}}{i\,!}\right)^{n} \tag{2}$$

The connection probability of *P(k-con)*could also be derived from transmission radius of a single node r_0 in [C. Bettstetter, 2002] with the assumption that the network has at least one mutually independent path connected to the node in a given area, which is formulated as $P(1{-}con)$. The derivation of $P\ (1{-}\ con)$ is as follows:

$$r_0 \cong \sqrt{\frac{1n(1{-}P(1{-}\ con)^{1/n})}{-\ p\pi}} \tag{3}$$

$$r_0{}^2 = \frac{ln\ (1{-}P\ (1{-}con)^{1/n})}{-\tilde{n}\eth}$$

$$-\tilde{n}\ \eth\ r_0{}^2 = ln\ (1{-}P\ (1{-}\ con)^{1/n})$$

$$Given\ \mu = -\tilde{n}\ \eth\ r_0{}^2,\ substituting\ into\ (2) \tag{4}$$

$$\mu = ln\ (1-\ P(1-\ con)^{1/n})$$

$$e^{-\mu} = 1-\ P\ (1{-}con)^{1/n}$$

$$P(1{-}con)^{1/n} = 1-\ e^{-\mu}$$

$$P(1{-}con) = (1-\ e^{-\mu})^{n} \tag{5}$$

The denotation of the variables used to derive $P(1{-}\ con)$ are:

- r_0, Radius of the transmission area
- n, Number of nodes
- A, Area of the network
- ρ, Physical node density equivalent to n/A

The variable ρ is equivalent to the node density of the network. The node density also takes into account the transmission range, which is denoted by $\pi\ r_0{}^2$. The transmission range coverage was assumed to be similar for all nodes. Therefore, the number of nodes *n* multiplied the range. Thus, the variable μ is the size of the transmission coverage over the size of the network area with a node density estimate based on the transmission range of each node and not just the number of nodes.

In this paper, the focus was on determining at least one viable route connecting a source to a destination within the MANET. Therefore, the value of *k* was set to 1 to identify that the network contained at least one mutually independent path connecting the nodes in a given area. This *k* value means that in any particular network that has a high degree of node density, there is a connection probability of $P(1{-}con)$. Thus, there is at least one mutually independent path connecting the nodes in a particular network area. This type of network is categorized as (almost surely) 1-connected with a connection probability of 0.95 or higher ($P(1- con)$ 0.95) based on the definition of [C. Bettstetter, 2002].

2.3 Sparse and Dense Region Definition

The calculations for the degree of node density of the network areas in this study were based on the formula provided for $P(1-con)$. in Equation 5. Based on p (1-con), two levels of node density were identified: Dense and Sparse. The definitions for the two levels of node density have been defined.

The node density of the MANET region is considered Dense based on the following conditions:

- The density has at least one mutually exclusive path to other nodes in the same area that is independent of another path
- $P(1- con) \geq 0.95$

The node density of the MANET region is considered Sparse based on the following conditions:

- Nodes in a sparse node density neighborhood cannot guarantee at least a single connection in the network
- $P(1- con) < 0.95$
- The minimal neighbor node degree for sparse areas could be $d_{min} = 1$. Thus, the node should not be disconnected from the network (isolated nodes were not considered in this paper)

3. Proposed MANET Protocol Extensions for Non-Uniform Density Environments

3.1 Non-Uniform Network Density Enhancements

Existing MANET routing protocols lack awareness of the network's surroundings when transmitting broadcasts. A node would not be able to discern if the default broadcast transmission rate was suited to the size and node density of the MANET or whether it would degrade the performance of the network by retransmitting broadcasts incessantly. The literature reviews in the previous section explained how unmanaged broadcasts impair the performance of the network. Currently, no existing MANET protocols for routing address this issue.

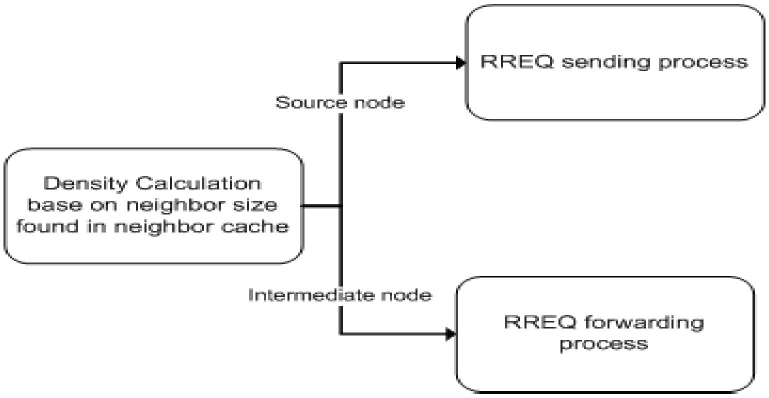

Figure 1. Non-uniform density aware MANET routing algorithm

To address the issue of non-uniform density environments for MANET, the proposed MANET routing protocol enhancement should possess the following capabilities:

- Estimation of the surrounding node density
- The MANET protocol should retransmit broadcasts based on the estimation of node density information
- Improve the available route repair time of the MANET routing protocol

Figure 1 shows a block diagram of the proposed MANET routing protocol enhancement where the RREQ (Route Request) sending and forwarding is determined by the node density estimation of the proposed MANET routing protocol. The node density estimation is based on Equation 5.

3.2 Proposed Enhancement to AODV

AODV-P introduces a new broadcast management scheme for the Route Discovery phase of AODV to address problems with the existing broadcast transmission scheme when dealing with non-uniform density topologies. The broadcast management scheme utilizes neighbor estimation as well as node density estimation to perform broadcast management. The density estimation that was performed prior to sending and forwarding RREQ broadcast packets as shown in Figure 1, and it was based on Equation 5. The neighborhood size was determined from the amount of one-hop neighbors of the sending or forwarding node.

3.3 Route Discovery Process

Figure 2 shows the message parsing for AODV, which highlights the type of messages involved in the route discovery phase. Essentially, the implementation of AODV-P only involved the handling of RREQ messages sent and forwarded to the destination node. Based on the message-parsing diagram, the RREP had to traverse back to the source in order for the link to be established. Thus, the destination node would have to perform its own RREQ, which has the RREP traveling on it if there are no reverse routes to the source node.

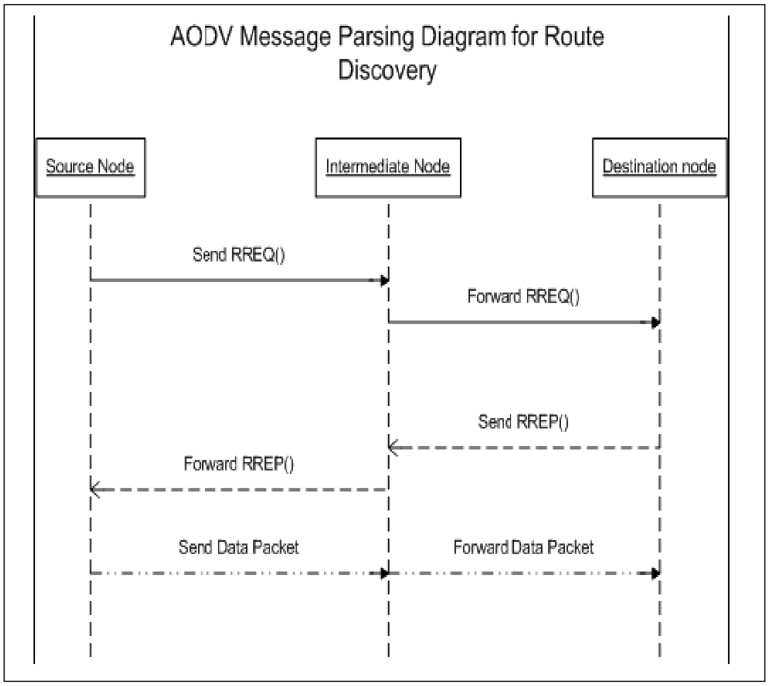

Figure 2. Message parsing diagram for AODV-P protocol for Route Discovery

Therefore, the RREQ propagation could also be bi-directional when the destination route does not have a reverse route to the source. This is inherent in the current AODV design. The implementation of AODV-P here, however, treats every RREQ broadcast as a mutually independent broadcast and does not consider if the RREQ is from the source or the destination.

3.3.1 Neighbor Cache Strategy

The sending or forwarding node obtains its neighbor information from the HELLO message that is stored in a neighbor cache. Each HELLO message is equal to one single hop neighbor that resides in the same area. The HELLO messages will only be valid until its lifetime expires. The lifetime for the HELLO message, however, will not be a concern for the AODV-P since it is already handled by the current AODV implementation. The extension will be implemented on top of the Expanding Ring Search, which is the incumbent broadcast management for the Route Discovery phase of AODV.

The Route Maintenance mechanism in AODV-P remains unchanged, and only the HELLO messages are stored in memory as a neighbor size cache that was described earlier. Route error notification and link repair were not considered and these situations were handled by the current AODV implementation. Other outstanding issues apart from those that affect the implementation of the extension were assumed to be inherited from the available implementation based on RFC 3651 [C. Perkins et al., 2003].

In Figure 3, the neighbor node information acquisition is based on the assumptions that the neighbor node *id* is unique when the addition of the neighbor count is added. The HELLO Reply packet was used to update the neighbor cache and the neighbor count.

3.3.2 Node Density Estimation

Using the neighbor cache information in Subsection 3.2.1, the proposed AODV-P would use the neighbor count as the node number represented by n in *Equation 5*. The node density estimation would be used to determine the timing for RREQ packets to be generated, and the RREQ packet generation mechanism for AODV-P will be discussed in the next section.

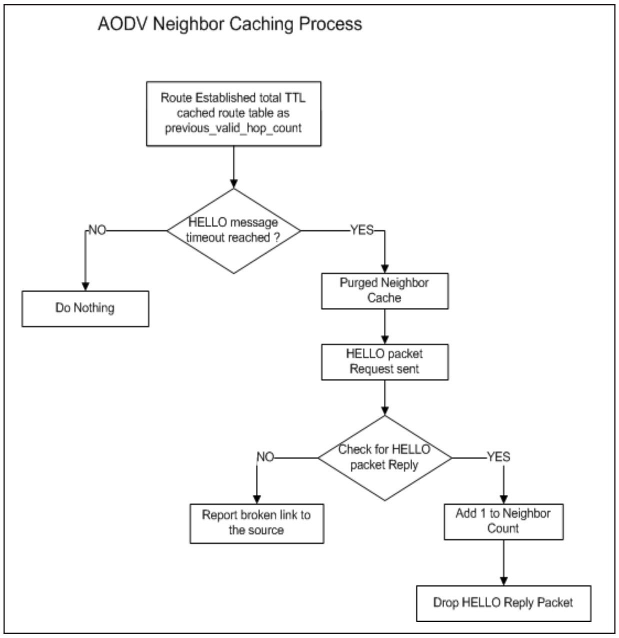

Figure 3. Neighbor node information acquisition mechanism for AODV-P

3.3.3 AODV-P Route Request (RREQ) Sending algorithm

The pseudocode below *Listing 1* is the AODV-P RREQ algorithm based on the following Time to Live (TTL) assumptions (values were chosen based on [AODV-UU, 2006] implementation).

- The NETWORK DIAMETER is 30 hops (TTL)
- The starting try is 5 hops (TTL)
- The increment is 2 hops (TTL)

```
Upon initiating a Route Discovery when RREQ packet is sent
    Access Neighbor Cache
    If Neighbor not equal to null
        Increase neighbor count.
        Return neighbor count
    If RREQ Count = 1
        Broadcast packet with TTL_START (2 hops)
    Else
    If DENSITY (calculated with neighbor count) is less than 0.95
        If TTL is less than THRESHOLD (7 hops)
            Increase the hop count by 2
        Else TTL value equals TTL THRESHOLD + previously used hop count
            If TTL value > 30 hops
                    TTL value equals 30 hops
    Else
    Broadcast with NETWORK DIAMETER (simple flooding 30 hops)
```

Listing 1 AODV-P RREQ Sending Algorithm Pseudocode

The algorithm in Listing 1 begins by obtaining the number of single hop neighboring nodes that resides in its neighbor cache. The neighbor information determines the number of neighboring nodes available to the source node (which is the node initiating the Route Discovery). The number of neighbor nodes will be used to calculate the node density in the area based on Equation 4. Note that each of the neighbor nodes has to be somehow involved in previous links that are associated with the source node.

The assumption here is that each neighboring node will have a unique id so no neighbor node with a similar id will be added twice or more times. We also assumed that continuous Route Discovery activities would help the source node improve the efficiency of its neighbor node information as it becomes increasingly aware of new nodes available in the network (if there are any).

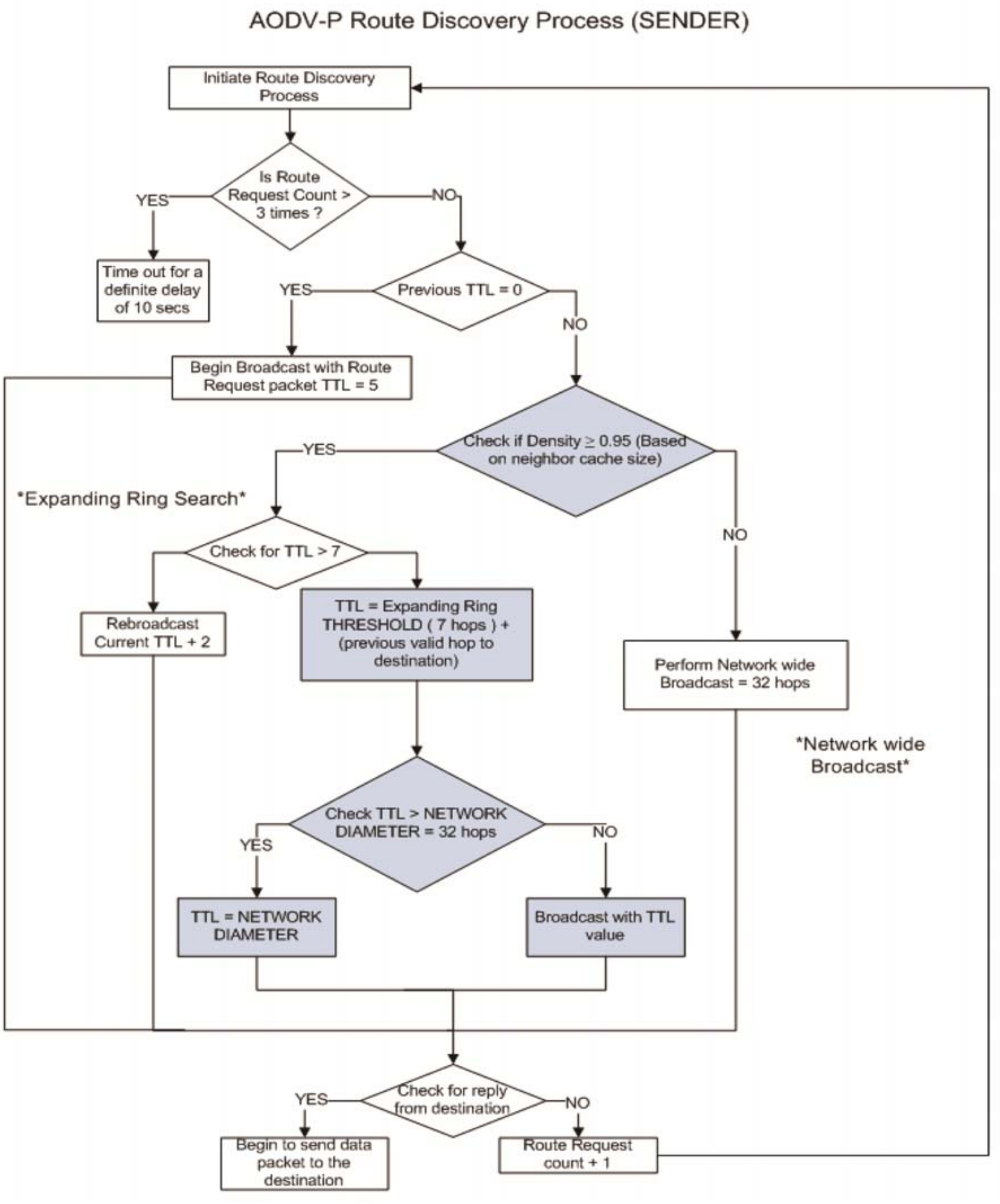

Figure 4. RREQ broadcast packet sending mechanism for AODV-P protocol

Figure 4 shows the Route Discovery phase of the proposed AODV-P. The configuration of TTL would be similar to assumption of Listing 1. Figure 3 shows the Expanding Ring search [J. Hasan et al, 2004] that is used with the current algorithm for AODV to perform RREQ broadcast management. The idea was to limit the range of the broadcast packet from the source to the other nodes in the area. After certain iterations of low TTL broadcast, the source node would flood the network if the destination node was still not found.

Figure 4 shows the augmented AODV-P protocol with a node density awareness based probabilistic algorithm running on top of the Expanding Ring Search algorithm. During the RREQ sending phase, given that the TTL is not zero or, in other words, a RREQ broadcast has taken place beforehand, the node will decide if the current MANET was Dense based on its available neighbor node information. If the MANET region was Sparse, a network wide broadcast would occur based on the NETWORK DIAMETER (assumed TTL = 30 hops).

Otherwise, if the source node detected that the area had Dense node density, it would check if the maximum TTL has been reached. If the maximum TTL was not reached, the existing TTL would be incremented by 2 hops. If the maximum TTL had been reached and it was less than the NETWORK DIAMETER, the TTL THRESHOLD would be added to the previous valid hop number (if available) at the destination. The previous valid hop number is the number of hops taken by the source to a similar destination based on previously known routing information. In the case where the addition of hops for TTL THRESHOLD and previous valid hop exceeds the NETWORK DIAMETER, the RREQ broadcast will be based on the NETWORK DIAMETER.

The motive of the extension in the AODV-P RREQ broadcast mechanism was to limit the range of the RREQ broadcast propagation when there was Dense node density in the network. This was an attempt to enhance the current methods in order to address the "*broadcast storm*" problem. The extension was implemented in order to perform the following:

- Limiting the range of propagation that would stop redundant packets being forwarded to other areas of the network, which may have other RREQ broadcasts at the same time
- The proposed extension was assumed to allow the source node not to contaminate the network with bad RREQ packets, which may have non-reachable destinations being propagated around it
- The source node has more refined node density information (based on transmission range) to rely on when deciding to perform a RREQ broadcast
- This method was aimed at reducing the amount of routing packets per data packet and avoided too many packet drops

Given the benefits that the protocol extension provides, the actual improvement also depended on other factors as well. There will be instances where the number of available single hop neighbors does not represent the actual number of nodes available in the area. Single hop neighbors refer to the neighboring nodes that reside within the transmission range of the source node. However, not all of these nodes are taken into account since only those that have taken part in routes that were previously known to the source were considered. Other single hop neighbor nodes that may receive the broadcast and forward the packet would be added as a part of the neighbor cache only when the route was successfully established and at least one round of Route Maintenance has taken place

3.3.4 AODV-P Route Request (RREQ) Forwarding Algorithm

For AODV, the packets that were received were forwarded when the RREQ broadcast packet receiving node was not the destination node. In that case, the packet would be forwarded to the next hop neighbor, but if the packet was traversing a known route (destination is similar), it would be forwarded the packet next to the known neighbor. Otherwise, the packet would continue to be broadcasted with a decreased TTL. The AODV-P added a condition to the forwarding mechanism by having to use routing information similar to the RREQ sending phase.

Before forwarding the packet or broadcasting the packet, the AODV-P would check on the node density using an algorithm based on Equation 5. The condition was based on whether the current intermediate node resided in a Dense or Sparse MANET region. If the MANET region was Dense, the packet forwarding would be imposed with a random delay and if the region was Sparse, the packet would be forwarded without delay to the routing layer. The MAC [IEEE Std 802.11b, 1999] layer, however, would still perform a collision avoidance check before sending out the packet.

```
The AODV-P RREQ forwarding algorithm is shown in Listing 2:
Upon initiating a Route Discovery when RREQ packet is to be forwarded
      Access Neighbor Cache
      If Neighbor not equal to null
            Increase neighbor count.
            Return neighbor count
      If DENSITY (calculated with neighbor count) is less than 0.95
            Forward the packet with a random delay
      Else
            Forward the packet without any delay (Subject to MAC Layer CCR)
Listing 2 AODV-P RREQ forwarding algorithm pseudocode
```

The AODV-P RREQ forwarding process was based on the information provided by the neighbor cache that was described earlier in Subsection 3.2.1. Based on Listing 2, the packet would be forwarded without delay when the MANET region was Sparse. The immediate forwarding of the data packet in such conditions would be similar for known next hop neighbors as well as for broadcasting the forward packet again.

Figure 5 shows the RREQ packet forwarding implementation for AODV-P. Immediate broadcast of the forwarding packets in Sparse regions of the network area was designed to improve the link repair time of the intermediate nodes and hasten the process of invalidating broadcast packets that could not reach the destination. In Sparse regions, broken links are frequent due to high mobility. Therefore, the RREQ packets need to be forwarded quickly in order to accommodate the constant change in topology. Immediate forwarding allows intermediate nodes to quickly detect the broken links or unreachable destinations and repair the broken link or notify the source that the current link is already invalid. This process would allow the initiation of a new Route Discovery process.

The broadcast of RREQ packets in a Sparse MANET region was immediate and may raise some concerns for possible packet collision due to hidden nodes. However, the 802.11 MAC layer (CCR) [IEEE Std 802.11b, 1999] and the routing information of the AODV-P was expected since it was created to minimize the problems associated with immediate forwarding. The routing information in AODVP based on the neighbor cache would be refined as the intermediate node becomes more aware of its neighbors' presence and would have a more accurate picture of the actual node density in the MANET area over time.

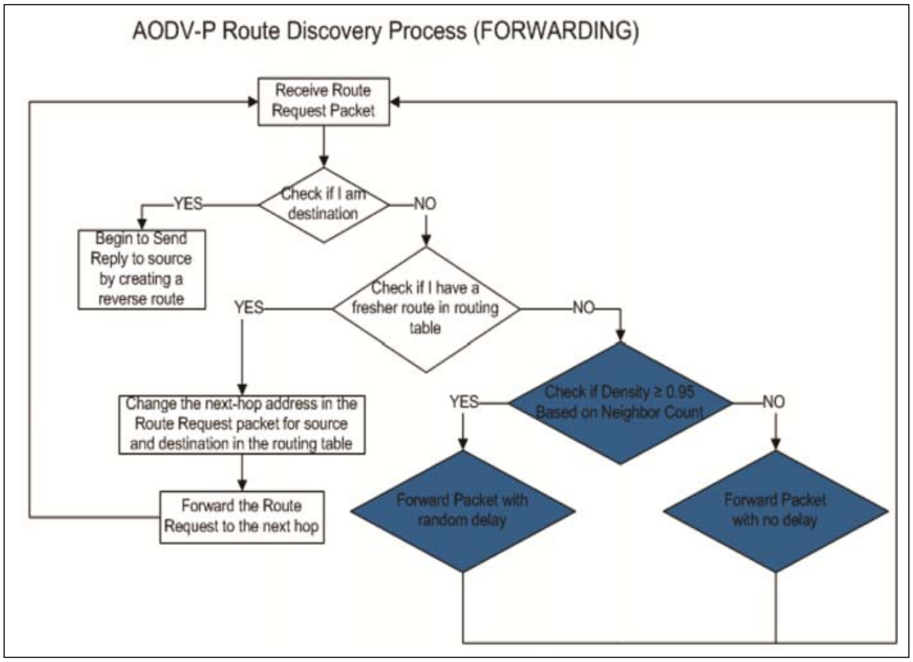

Figure 5. RREQ broadcast packet forwarding for AODV-P protocol

4. Simulation Environment

In this section, the simulation approach for comparing the behavior of AODV-P, AODV and OLSR in network topologies with varying degrees of node densities is described. The simulation framework and details of various models are given was well as the formulas used for important simulation metrics.

4.1 Simulation Environment configurations

The MANET routing protocols studied was based on the available implementation for NS-2. The simulated AODV protocol extension (AODV-P) was modified based on the original NS-2 based implementation of AODV-UU (AODV-UU, 2006). The AODV-UU version that was used was based on Version 0.9.1 with a patch for NS-2 Version 2.31. OLSR was an implementation designed by the MASIMUM group [MASIMUM, 2012]. A performance comparison in a real-world environment between AODV and OLSR protocols can be founded in [E. Kulla, 2010].

The environment configurations were defined using the scenario generator module, which was part of the NS-2 package. The topology of the MANET was redesigned using the scenario generator in the NS-2 in order to simulate the following MANET environments: variable degrees of node density (a mix of Sparse and Dense node density) topology, Dense node density topology and Sparse node density topology.

4.1.1 MANET Simulated Topology Configuration

The proposed topology for simulation was configured based on the degree of node density defined in Section 2 (Equation 5). Three types of topologies were studied. The definitions of these topologies are listed in Table 1.

Dense node density (HD) topology	All nodes located in this topology complied with the connection probability of $p\ (1\text{-}con) \geq 0.95$ (*Dense* MANET region)
Variable node density (VD) topology	This is a hybrid topology with two different degrees of node density (*Dense* and *Sparse* MANET region) combined together as shown in Figure 6
Sparse node density (SD) topology	This is also a hybrid topology that was similar to the concept for variable topology but it has a larger area, which is shown in Figure 7. It was used to simulate sparse topology where many of the mobile nodes had a connection probability of $p\ (1\text{-}con) < 0.95$ (*Sparse* MANET region)

Table 1.Types of density used in this study

The HD topology based on Table 1 had at least one mutually exclusive path connecting each node within the area. So, the connection in this topology was almost guaranteed and would be susceptible to “broadcast storm” issues.

The VD topology is illustrated in Figure 6, where the topology is divided into a 3 by 3 grid comprised of nine areas with two types of areas. The areas at each corner of the topology have Dense node density, whereas the other areas of the topology have Sparse node density. This topology setup would simulate the scenario with non-uniform distribution with the different levels of node density distributed over the area.

The SD topology is illustrated in Figure 7 where the topology is divided by a 6 by 6 grid comprised of 36 areas with two types of areas. The areas at each corner of the topology have Dense node density, whereas the other areas of the topology have Sparse node density. This topology setup would simulate a scenario with non-uniform distribution with the different levels of node density distributed over the area.

4.1.2 Mobility Model and Traffic Sources

The mobility model that was used is the Random Waypoint model since it has been evaluated with non-uniform node distribution, and it is also a widely used mobility model for MANET research. The nodes in the Random Waypoint mobility model move from one waypoint to another with an initial trajectory and the nodes will stop at the waypoint for a specified period of time. After the

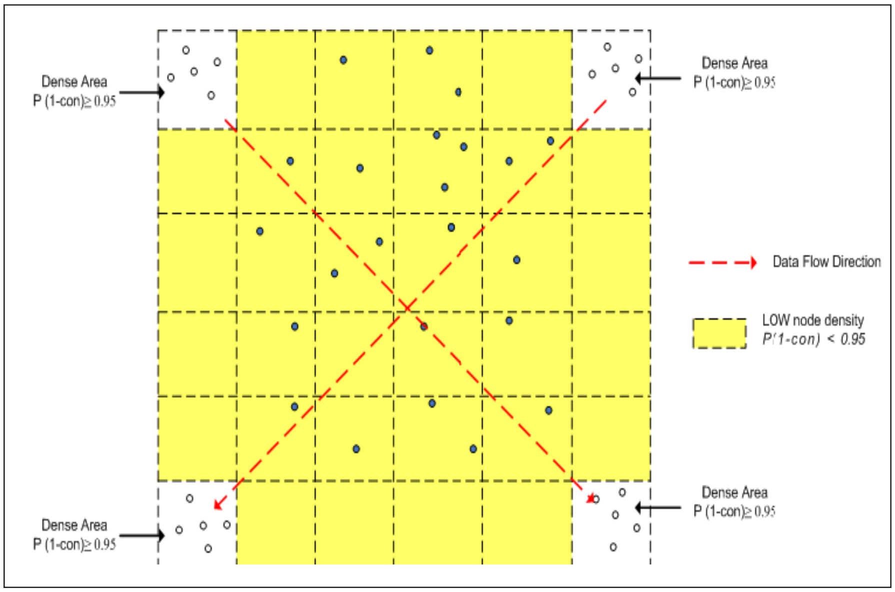

Figure 6. Example of varying density MANET region topology (VD)

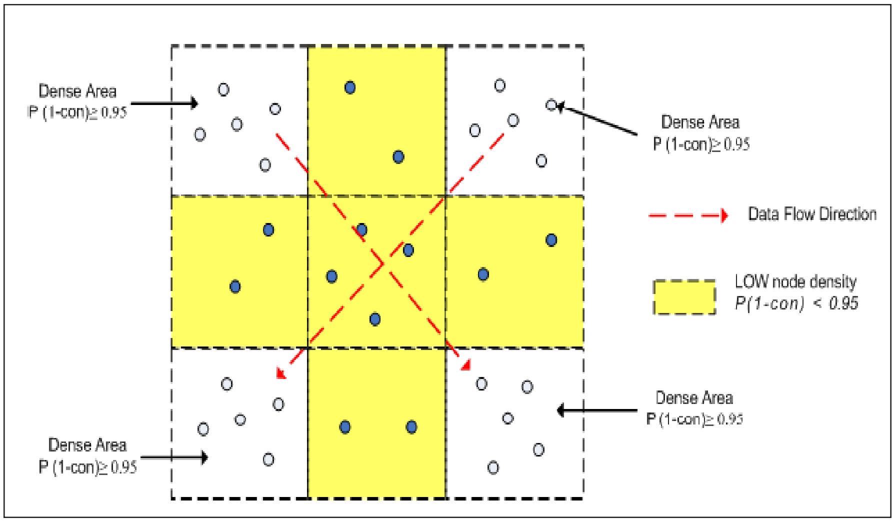

Figure 7. Example of *Sparse* MANET region topology (SD)

end of the pause, the nodes move again with a new trajectory until the simulation ends. The mobility of the nodes in the experiments was different for the three different topologies. The mobility for HD was constant and there were no stationary nodes and no pause time. In VD topology, the Dense regions had a pause time of 250 seconds and the speed of the nodes were 1 m/s, whereas the nodes in the Sparse region were constantly moving without pause (no pause time). The mobility for SD was similar to VD, but there was a larger area. Therefore, the mobility of the three topologies is stated below:

- In HD topology, the nodes were moving with no pause time
- In the VD and SD topologies, the Dense area nodes were almost moving at 1 m/s with a 250 second pause time and the Sparse area nodes were moving at different speeds with no pause time

In VD and SD topologies, the nodes in the Dense regions remained in the respective regions throughout the entire simulation. The nodes in the Sparse regions did not cross into the Dense regions, but the nodes could cross over to other Sparse regions.

The data packet size used in this experiment was 128 bytes. The packet size was chosen to mimic real-time data traffic protocols such as VOIP. Five traffic sources were used and the sources were distributed equally among the four dense regions of the VD and SD topologies. In HD topology, the sources were distributed evenly in the HD topology area. The data traffic pattern used in this experiment was the CBR (Constant Bit Rate).

4.2 Main Simulation Configurations

The simulation runs in the experiment included ten runs per protocol for each individual scenario. Three different network sizes were modeled: 1000m×1000m map size with 50 nodes, 1500m×1500m map size with 50 nodes and 3000m×3000m map size with 80 nodes representing HD, VD and SD topologies, respectively. Each simulation run takes 500 simulated seconds.

The Broadcast diameter hop count in NS-2 defaulted to 32 hops for AODV-P, AODV and OLSR. The configurations of Start TTL (5 hops), TTL increment (2 hops) and TTL Threshold (7 hops) were based on the default AODV configurations, which were used by AODV-P and AODV. OLSR does not utilize these parameters since it is a link state algorithm.

The link layer protocol used for this study was the IEEE 802.11b protocol with channel bandwidth equals to 2 Mbps. The maximum transmission range was 250 m for each node.

The NS-2 physical layer model based on the two-ray ground reflection model was considered both the direct path and a ground reflection path. It was selected since large simulation areas were used and these areas required long distance radio signal propagation.

4.3 Definition of Parameters

The parameters measured in the study focused on individual protocol efficiency in the various scenarios that were described previously. Measurement of network latency and bandwidth utilization were in terms of Average End to End Delays and Throughput. In addition, overheads that were incurred during Routing Discovery were also evaluated. The measured parameters were used to compare the performance of AODV-P against AODV and OLSR.

The Average End to End Delay per packet was measured as the time taken by each data packet to traverse from source to destination, which included the forwarding of packets as well.

Data throughput was measured by using the size of each data packet traversing from source to destination divided by the overall simulation time. This measurement only accounted for packets that successfully arrived at the destination, and excluded the MAC headers.

The Packet Delivery Ratio was the percentage of successfully delivered data packets from source to destination. This measurement correlated with the measurement of the Data Throughput.

Normalized Routing Overheads were measured via the ratio of the number of routing packets sent to the number of data packets received successfully. The Normalized Routing overheads showed how well the protocols utilized the bandwidth available in the network.

Average Hop Count measured the path optimality of each protocol by taking into account the number of hops taken by a single packet to reach its destination from the source. A large number of hops meant that the current path was not optimized enough or the current protocol was not efficient enough to generate a better path to the destination for each transmitted packet while there were changes to the connectivity.

5. Analysis and Discussion

This section presents an analysis of the MANET routing under varying offered data loads. The analysis investigated the performance of the three MANET routing protocols with different types of topology: HD, VD and SD.

The offered data load was measured at 51.2 kbps, 1024 kbps, 253.6 kbps, 204.8 kbps, 256 kbps and 358 kbps. The measurements also took place in different environments with VD, HD and SD topology. To measure the network capacity, the speed of the nodes were fixed at 2 m/s, 6 m/s and 10 m/s, which represent pedestrian, moderate and vehicular speeds in urban environments.

The simulation runs performed on each offered load included ten runs for each speed. The results were based on the average total of each data points with a 97.3% confidence interval based on the values of the data points that were obtained. The simulation was designed to evaluate the performance of the MANET protocols in handling different packets with the HD, VD or SD topologies.

5.1 Network Capacity Under Varying Offered Data Load for HD Topology

The average delays for high node density with varying offered loads are shown in Figure 8. In HD topology, the behavior of slow moving nodes 2 m/s and fast nodes of 10 m/s were quite similar. Medium speed nodes had much better performance since when there was an offered load more than 350 kbps, there was a spike for AODV-P and OLSR. The delay was much smaller at that point since the nodes were not subjected to any mobility limitations.

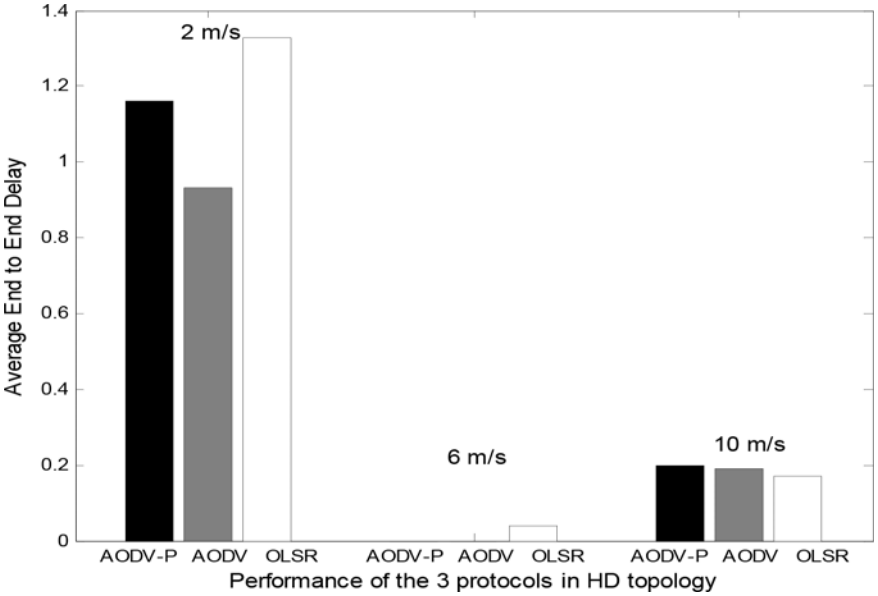

Figure 8. Average delay for varying offered loads in the HD topology

The average hop count for a high node density is shown in Figure 9. The average hop count for nodes at 2 m/s and 10 m/s were quite similar. Thus, this finding leads to the assumption that hop counts for low speed and high speed nodes encounter similar mobility problems. For node speed of 6 m/s, the average hop count fell below 3 hops for all of the offered data loads. Our observations also found that 6 m/s was an ideal speed for nodes to move and communicate simultaneously.

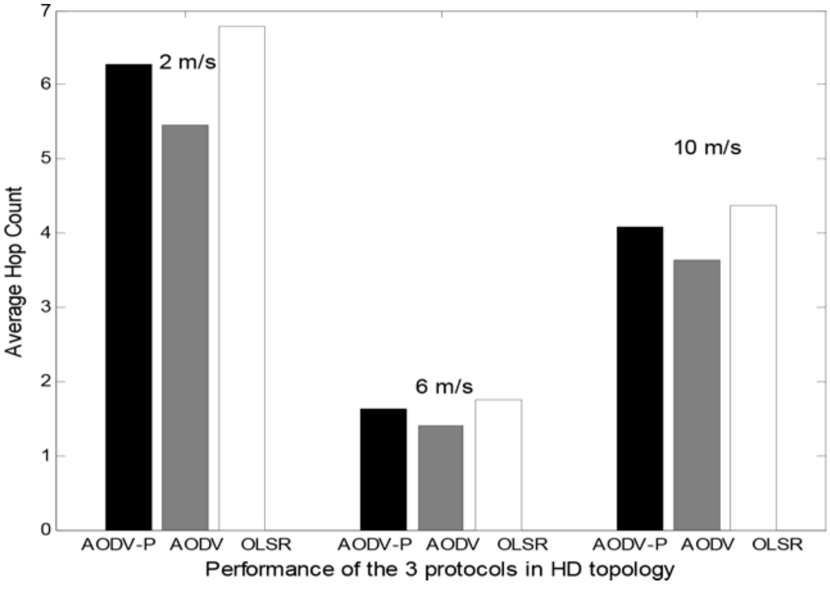

Figure 9. Average Hop Count for varying offered load in HD topology

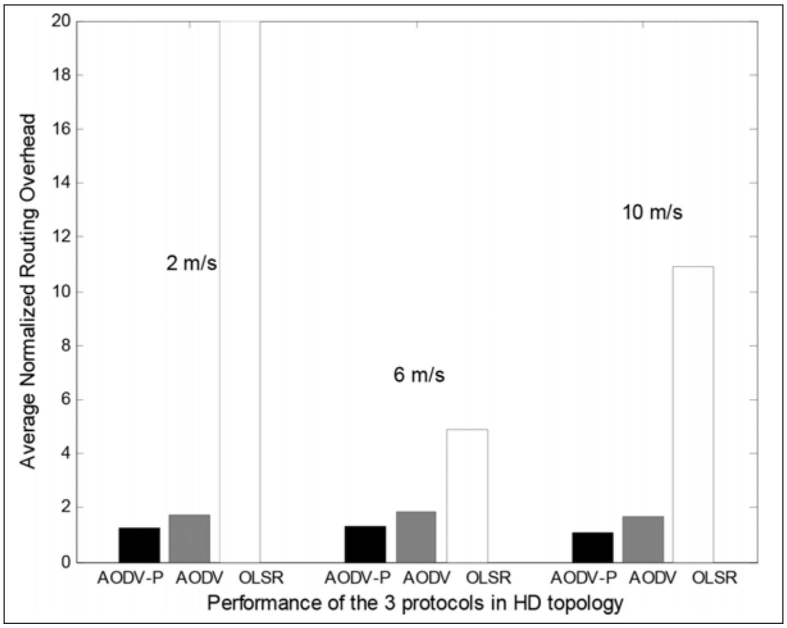

Figure 10. Normalized Overhead for varying offered loads in the HD topology

Figure 10 shows that the routing overheads for OLSR was significantly higher compared to AODV-P and AODV. However, the average overhead is truncated in the graph. The number of overheads incurred for each data packet received for OLSR ranged from five to one hundred packets. The overheads seemed to be similar for different mobility environments. The AODV-P performed consistently better than the AODV for all of the offered data loads, even though the improvement was less than one routing packet sent per data packet.

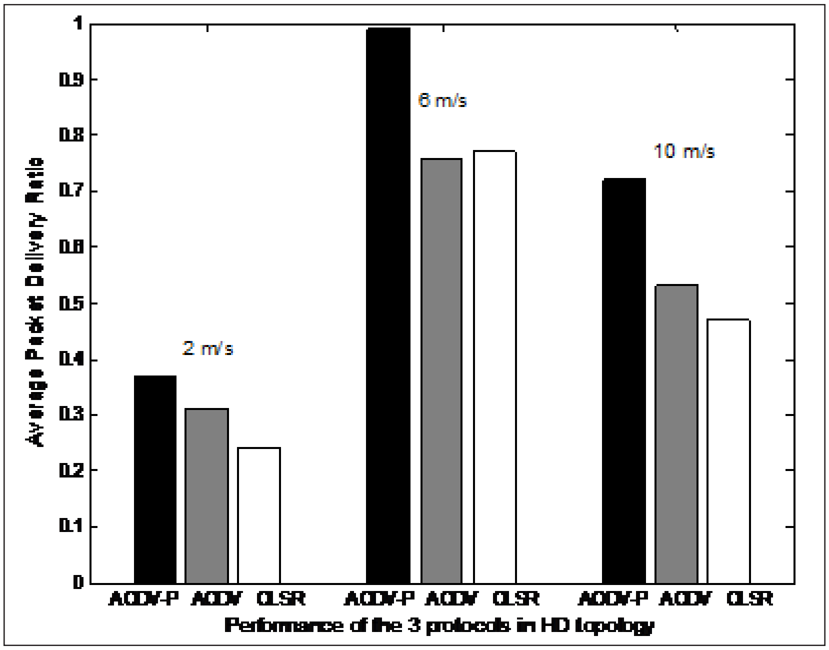

Figure 11. Packet Delivery for varying offered load in HD topology

The packet Delivery Ratio for the high node density topology was shown in Figure 11. The packet delivery reflected the performance of other metrics that were shown earlier when the slower and faster nodes were declining due to the increasing number of offered data loads. At medium speed (6 m/s), the Packet Delivery Ratio for AODV-P showed almost 100 % delivery. For the other protocols, the delivery success fell below 85 % for 102.4 kbps of offered data load and above.

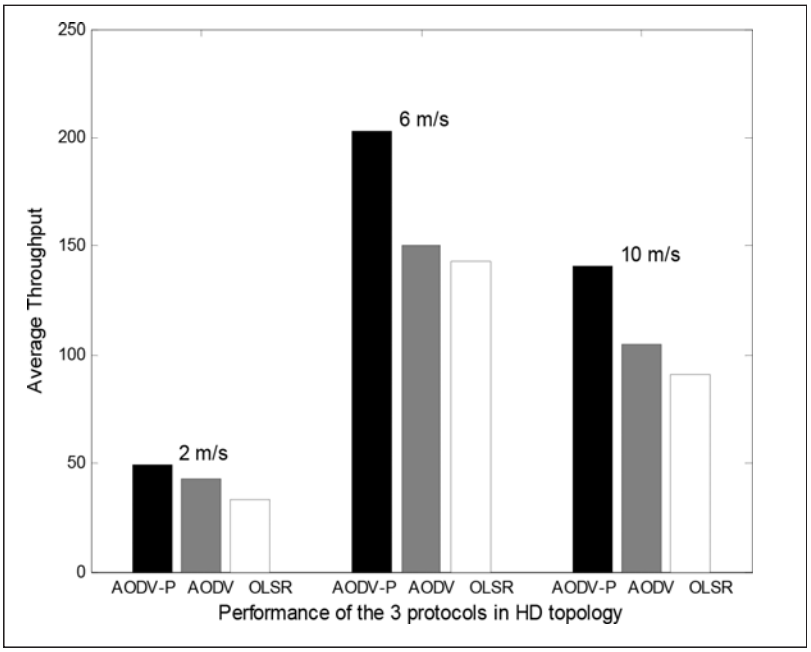

Figure 12. Data Throughput for varying offered load in HD topology

The throughput of high node density shown in Figure 12 reflected the results observed in the Packet Delivery Ratio. At a node speed of 2 m/s, the throughput never exceeded 70 kbps and at 6 m/s, the AODV-P correlated with the offered data load. This finding is an indication that the AODV-P was better at handling on the usage of the route discovery process and maintenance compared to the other two protocols.

As expected from the analysis of the offered data load in environment with varying densities, the protocols' performance depended on the node speed. At the 2 m/s speed, the throughput dropped significantly as well as the performance of other parameters. Low mobility in a HD topology was found to be quite susceptible to link breakages if there were too many intermediate nodes. One possible situation that could be hypothesized is that the environment was too crowded and a broadcast storm could have occurred since the nodes repetitively broadcast their routing packets.

The behavior of the protocols towards different offered data loads depended on the speed of node movements in environments with variable densities. In these environments, speed plays an important role in the network for determining the Average Data Throughput. For slower speeds, the performance of OLSR dropped in terms of Average Data Throughput and AODV-P performed better than the AODV. For all speeds, the performance of AODV-P was better than AODV until the offered load reached 256 kbps. At that point, the performance difference between the two protocols decreased until there was a small difference of less than 10% for Packet Delivery Ratio.

As the speed increased, the AODV-P performed better at 6 m/s, which was identified optimum speed for the HD topology since the amount of throughput achieved was almost 100% compared to the throughput offered in the network. The other two protocols faced some issues for achieving a good delivery since the offered load grew higher. The other metrics did not show any significant differences between the three protocols except that the routing overheads for OLSR were higher than the other two protocols. These results were obtained even though there is no guarantee in a HD topology that packets sent at a high offered data rate would achieve a good success rate.

5.2 Network Capacity Under Varying Offered Data Loads for VD Topology

Figure 13 shows the Average End to End Delay for the three routing protocols in an environment with variable node density. Based on the results, the offered data load of 204.8 kbps was the highest offered data load where the delay of the network was minimized. Beyond 204.8 kbps, the End to End Delays increased rapidly, which suggested that significant network congestion and buffer overflows were occurring. The node speed at 6 m/s had the lowest average delay, which suggested that network links were more frequently available and that they had longer average link lifetimes compared to the other speeds.

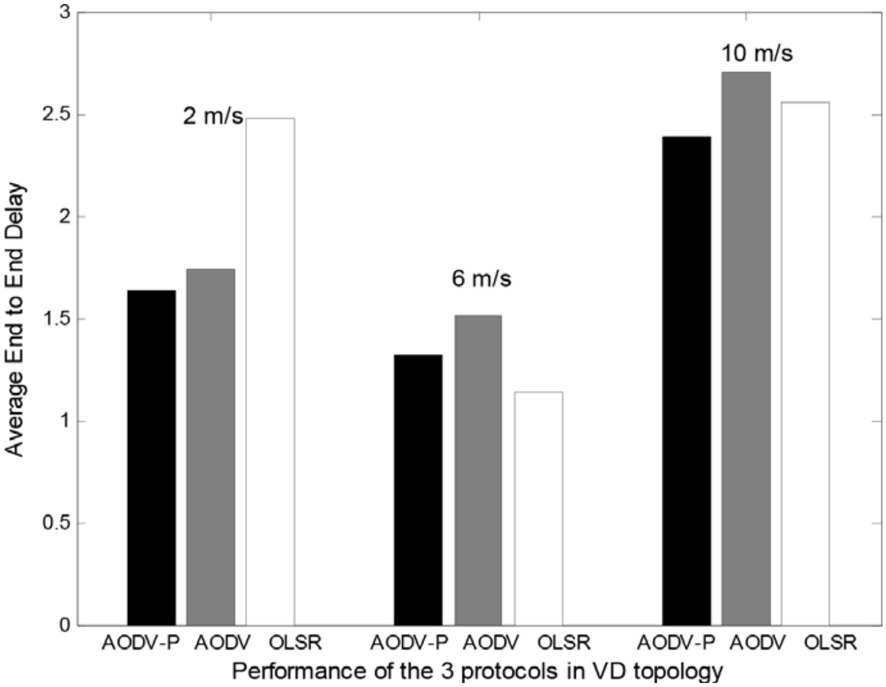

Figure 13. Average delay for varying offered load in VD topology

The Average Hop Count measured from Figure 14 for the three protocols in the variable node density topology was approximately 3 hops and above. Once again, the performances of the three protocols were much better at a speed of 6 m/s compared to the protocol performances at the two other speeds. At the 10 m/s speed, the average hop taken by AODV-P was much lower than the other two protocols for different offered data loads. AODV-P performed better by roughly 2 hops. The difference between the three protocols in the Average Hop Counts increased with the speed of the nodes. This result shows that there was a more direct relationship between mobility and hop count than the relationship between offered data load and mobility.

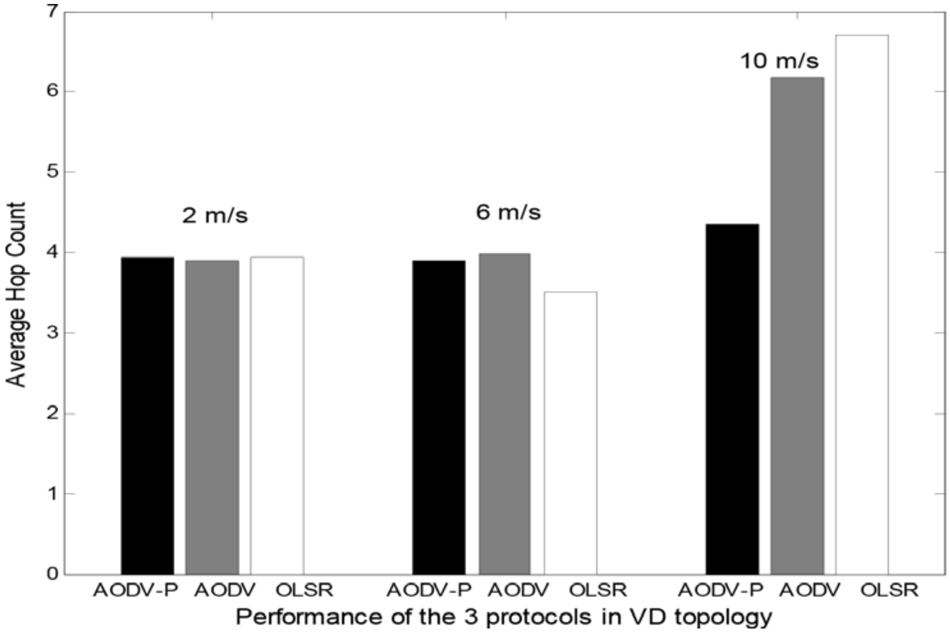

Figure 14. Average Hop Count for varying offered loads in the VD topology

The Normalized routing overheads illustrated in Figure 15 show that among the three protocols that were observed, OLSR had significantly higher overheads compared with AODV variants. Thus, for presentation reasons, the OLSR results were

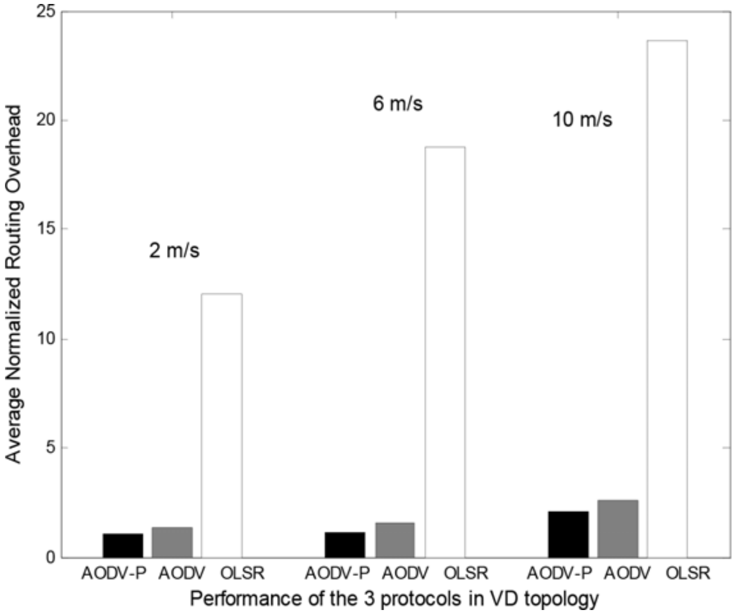

Figure 15. Normalized Overhead for varying offered load in VD topology

truncated since the numbers far exceeded the values of the AODV variants. The number of overheads incurred for each data packet received for OLSR ranged from 5 to more than 50 packets across different mobility speeds. This finding shows that link state protocols were not suitable for an environment with different densities even with a low mobility and a low offered data rate. There was a slight increase in the amount of overheads observed for the AODV variant protocols at the node speed of 10 m/s for the higher offered data loads. The AODV variant of the routing protocols showed that in sub-optimal environments, on demand routing is better.

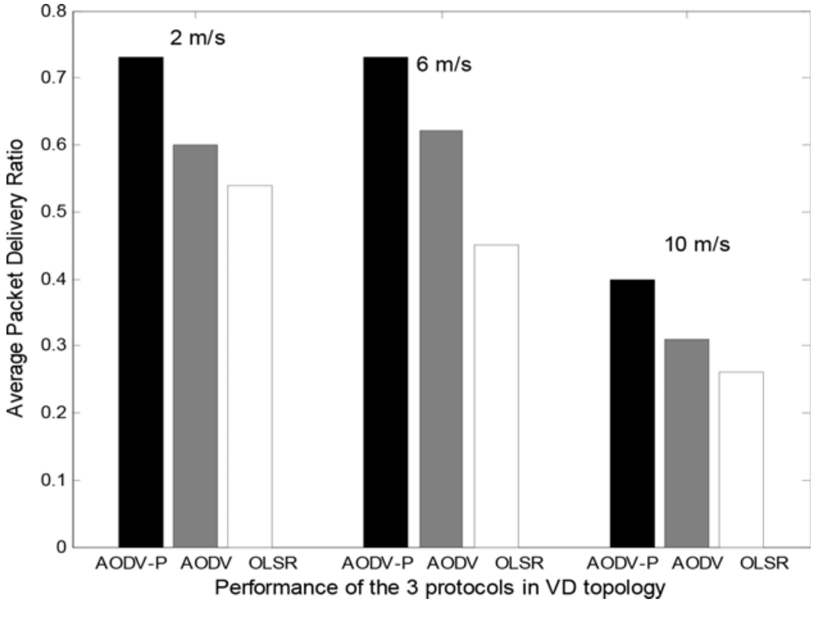

Figure 16. Packet Delivery for varying offered load in VD topology

The Packet Delivery Ratio shown in Figure 16 shows that the overall performances for the three simulated protocols were, ranked from highest to lowest, AODV-P, AODV and OLSR. For lower offered data loads, such as 51.2 kbps, OLSR managed to perform significantly better than AODV. This result could be due to the relay nature of OLSR communication compared to AODV. AODV-P caused less route discovery overheads compared to the other two protocols. But, at high speeds, when more data is pumped into the network, the difference was much less since the results of all three protocols suffered a gradual decline.

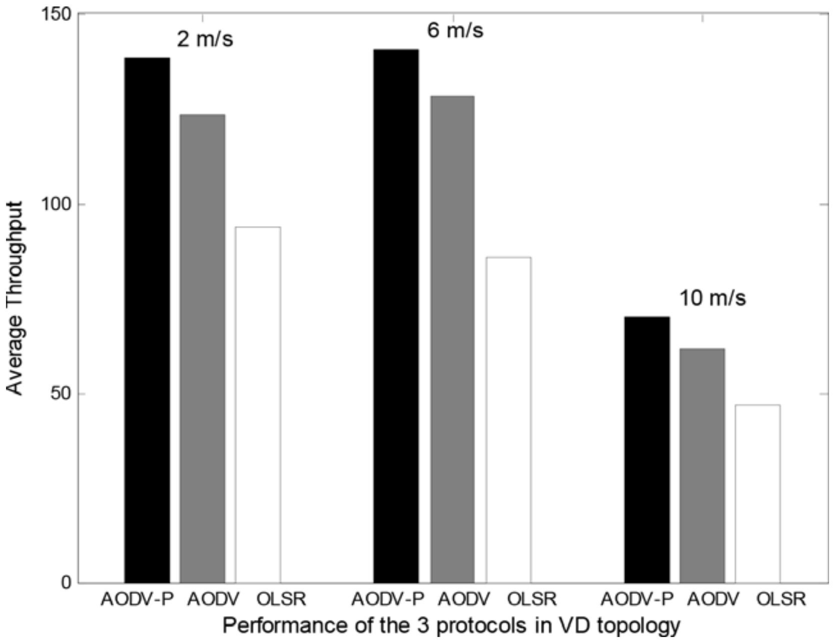

Figure 17. Data Throughput for varying offered load in VD topology

The throughput examined for different offered data loads is shown in Figure 17. The AODV variants had better throughput compared to OLSR. Additionally, the performance of AODV-P and AODV were especially close at values of 204.8 kbps of offered load and higher. The performance became a flat line below 100 kbps and from 204.8 kbps onwards for a node speed of 10 m/s.

Based on the other metrics, the performances of AODV-P and the AODV were almost the same with minimal differences. In contrast, the OLSR seemed to have routing overheads that grew exponentially. The AODV variants had very low overheads in comparison and produced less routing overhead packets so that the amount of data transferred was around one routing packet per data packet sent. From the results, the offered data load of 204.8 kbps was the threshold for the proposed environment before the performance of the three protocols began to drop at a similar rate

5.3 Network Capacity Under Varying Offered Data Load for SD Topology

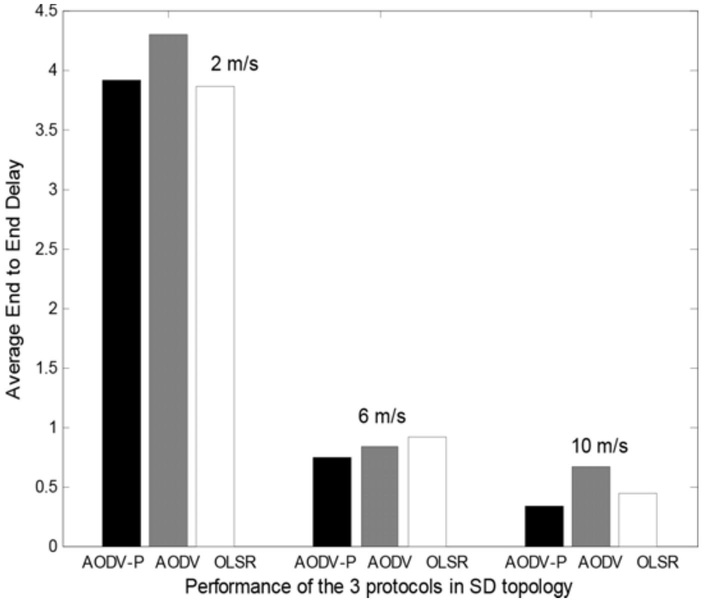

Figure 18. Average delay for varying offered loads in the SD topology

The average delay for the SD topology is shown in Figure 18. The delay shown here was significantly higher than the delays for the other two environments. At 2 m/s, the delay was very high for the higher offered data loads and that trend was similar for the other two speeds as well. The three simulated protocols performed poorly. AODV-P edged out the other two protocols at offered loads higher than 350 kbps.

The Average Hop Count shown in Figure 19 also suggests that the packets of the three protocols needed at least 6 hops or more to reach its destination at a speed of 2 m/s in the SD topology. When the offered data rate was high, the number of hops increased significantly. However, for nodes moving at 10 m/s, the hop count remained at 2 hops for data rates of 102.4 kbps and above.

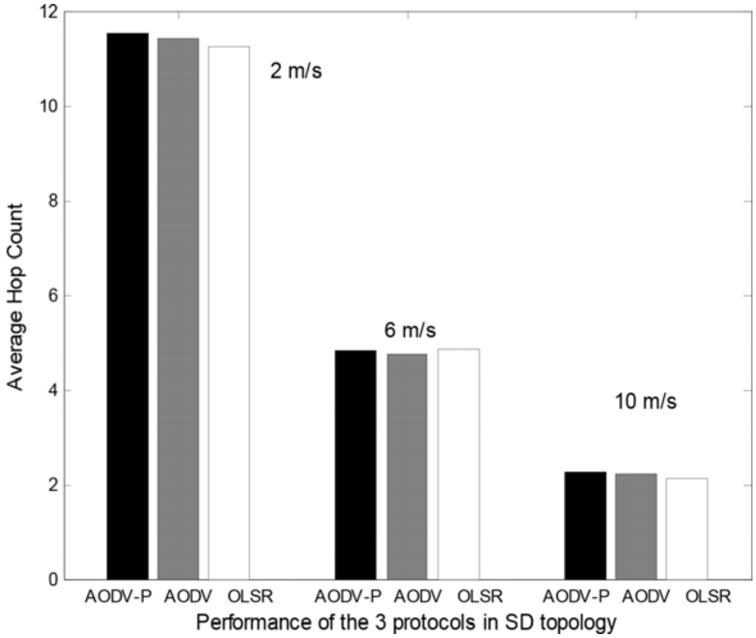

Figure 19. Average Hop Count for varying offered loads in the SD topology

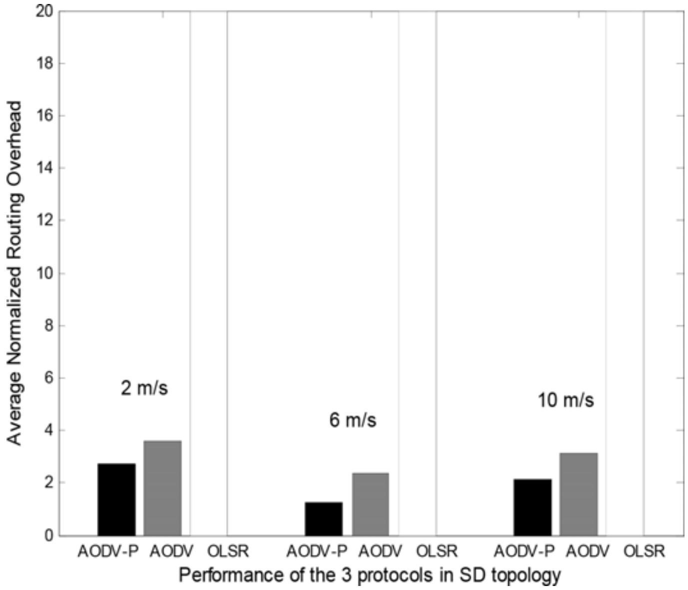

Figure 20. Normalized Overhead for varying offered load in SD topology

The normalized routing overheads for sparse node density shown in Figure 20 share a similar trend with the other two environments. OLSR used an even greater number of routing overheads for every successfully sent packet at the higher offered data loads. The number of overheads incurred for each data packet received for OLSR ranged from 9 to 1,000 packets. The data points for OLSR were not presented completely in the graphs since the numbers were far greater than the range of the AODV variants. However, the other two protocols had similar results compared to the other two environments that were discussed earlier. The results showed that AODV-P generated less control packets as compared to AODV despite the fact that the difference was around one packet per data packet sent.

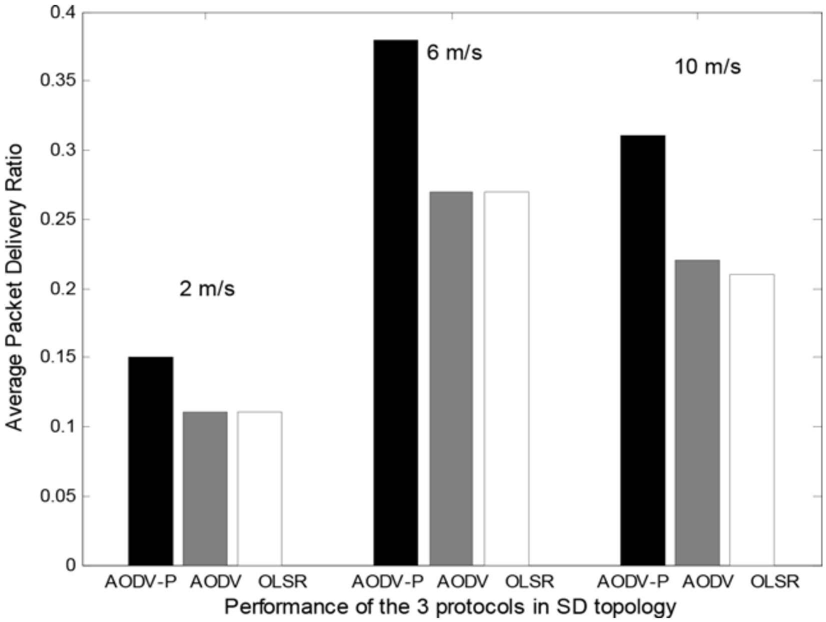

Figure 21. Packet Delivery for varying offered load in SD topology

Figure 21 shows the Packet Delivery Ratio in the SD topology. At speeds of 2 m/s and 10 m/s, the decline in performance for the protocols was more gradual compared to the 6 m/s speed in terms of packet delivery ratio. At 204.8 kbps, the network was saturated and could not achieve any further increases for the 2 m/s and 6 m/s mobility speeds. This finding could be due to a more aggressive approach in route forwarding where there were no delays for sparse areas in AODV-P. At a node speed of 6 m/s, the condition seemed to be more suitable for low packet traffic, but there was a stark decline as the amount of data traffic increased.

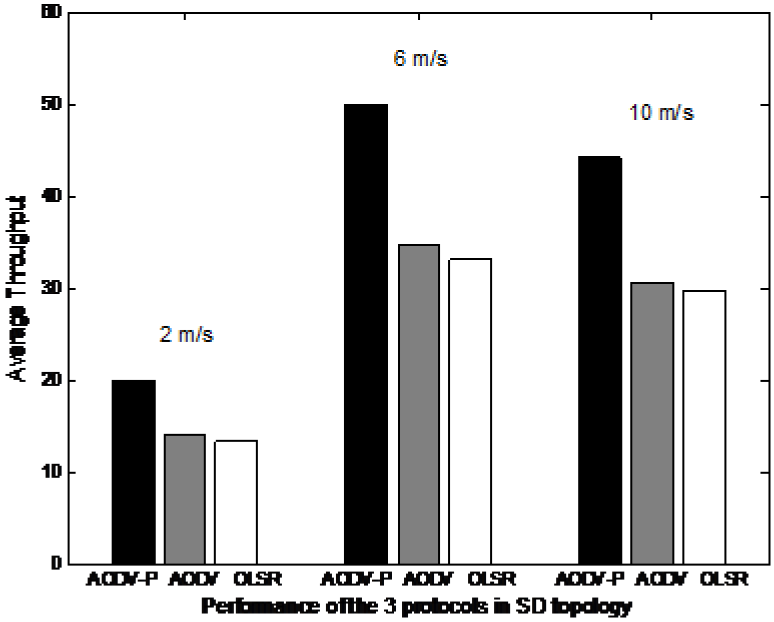

Figure 22. Data Throughput for varying offered load in SD topology

The throughput performance for the three routing protocols in sparse areas is illustrated in Figure 22. As expected, the performance of the throughput in this environment was a stark contrast to the performance in the HD topology with less than 70 kbps achieved over all traffic environments. Consequently, the offered data rates greater than 102.4 kbps were not sustainable in such topologies. Ultimately, 51.2 kbps was a practical maximum for offered data load since that load avoided extremely low Packet Delivery Ratios.

The results showed that in such an extreme environment, it was quite difficult to establish a proper communication between nodes. The throughput of the network remained around less than 50% at an offered rate of 150 kbps and above. The performance of the packet delivery worsened when the nodes began to move faster. Other metrics also showed that there was a declining performance in this environment. However, the amount of routing overheads that generated per successfully delivered packet was not substantial. But, the average delay and hop count increased significantly with the amount of offered data being pumped into the network. In terms of optimal path, as much as five times the original length was taken by each packet in order to reach its destination.

5.4 Summary of Results

The analysis of the network capacity measured the data throughput yield across different topologies and offered data loads. The key parameters were the effectiveness of bandwidth usage by the nodes for three MANET routing protocols. The protocols contribution to effective usage of the offered data load was reflected by the Packet Delivery Ratio for a certain offered data load. Table 2 shows the percentage of average Data Throughput for different offered data loads across all speeds. The average Data Throughput of the three different mobility scenarios were combined and compared based on the three different topologies.

s	Speed of Nodes
l	Data Load
Dt	Data Throughput
Ld	Offered Data Load

$$\frac{\sum^{s}\left(\sum^{l}\left(\frac{Dt}{Ld}\right)\right)}{l \times s} \times 100\% \qquad (6)$$

	AODV-P	AODV	OLSR
VD topology	61.67%	51.17%	41.70%
HD topology	69.47%	53.47%	48.99%
SD topology	28.14%	19.96%	21.18%

Table 2. Percentage of Average Data Throughput for different offered data loads and speeds

The analysis of the results for network capacity showed that, on average, AODV-P performed well for different offered data loads. This result demonstrates that AODV-P can handle the offered data load better since it achieved an average of 28% across the different offered data loads, even for the SD topology. The others measured parameters did not show any significant decline in performance for AODV-P. There were also encouraging results shown in terms of hop count, although the average delay was slightly higher for packet transfers.

6. Conclusion and Future Work

This study on the performance of MANET protocols in environments with different node densities highlighted some issues that were not previously observed in uniform density environments. A node density estimation formula was derived to characterize the topology that a mobile node was in and used to make suitable routing decisions in response to changes in node density. The incorporation of the node density estimation algorithm into AODV was based on an understanding that when there are a largenumber of nodes in a given area, there is no hurry or need to constantly discover new routes, especially since there were likely existing paths linking to all of the nodes and the paths were still valid. The overall performance for AODV-P showed that in all three environments (HD, VD and SD), there was an increase in performance in Packet Delivery Ratios, Normalized Routing Overheads, Data Throughput, and also a slight improvement in the delay for the SD topology. In *Dense* environments, the increase in performance was obvious with an improvement around 10% to 20% compared to AODV in the various environments that were simulated. Although the Average Hop Count may not be significantly better than AODV, the increase in average link lifetimes helped maintain the stability of the links and improved overall Data Throughput and Packet Delivery Ratios.

In our future work, we aim to collect supplementary information from previous node movements to build more sophisticated mobility prediction schemes. The location estimation scheme will be combined with a stability factor for each link to help the sender make better routing decisions. We also plan to investigate the relationship between node density and the performance of our routing protocol under more realistic mobility models of ad-hoc networks.

Acknowledgments

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