INVESTIGATING THE SCALABILITY OF THE FISH-EYE STATE ROUTING PROTOCOL FOR AD HOC NETWORKS

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ABSTRACT

The overall goal of this paper is to investigate the scalability of the Fish-eye State Routing (FSR) protocol under different network scenarios in mobile ad hoc networks (MANETs). This performance based study simulates FSR under practical network scenarios typical of MANETs, and measures selected metrics that give an introspective look into the performance of FSR. The FSR protocol is compared against the minimum hop-count based reactive Dynamic Source Routing (DSR) protocol. The implementations of both protocols are simulated for varying conditions of network density, node mobility and traffic load. The following performance metrics are evaluated: packet delivery ratio, average hop count per path, control message overhead and energy consumed per node. Simulation results indicate FSR scales relatively better compared to DSR and consumes less energy when operated with moderate to longer link-state broadcast update time intervals in high density networks with moderate to high node mobility and offered traffic load. FSR successfully delivers packets for a majority of the time with relatively lower energy cost in comparison to DSR.

Keywords: *Fish-eye State Routing, Dynamic Source Routing, Mobile Ad hoc Networks, Energy Consumption, Simulations, Performance Studies*

1. INTRODUCTION

A mobile ad hoc network (MANET) is a dynamic distributed system of wireless nodes where in the nodes move independent of each other. MANETs have several operating constraints such as: limited battery charge per node, limited transmission range per node and limited bandwidth. Routes in MANETs are often multi-hop in nature. Packet transmission or reception consumes the battery charge at a node. Nodes forward packets for their peers in addition to their own and hence are forced to expend their battery charge for receiving and transmitting packets that are not intended for them. Given the limited energy budget for MANETs, inadvertent over usage of the energy resources of few nodes at the cost of others can have an adverse impact on the node lifetime.

There exist two classes of MANET routing protocols [1]: proactive and reactive. The proactive routing protocols are table-driven protocols and can be of two sub-categories: Distance-vector based routing and Link-state based routing. In the distance-vector based routing approach, each node periodically exchanges its routing table for the whole network with all of its neighbors. The neighbor node that informs of the best path to a destination node is chosen as the next hop to reach the destination node. In the link-state based routing approach, each node periodically floods link-state updates, containing the list of its neighbors, to the whole network. The flooding is done in such a way that each node receives exactly one copy of the link-state update. Destination-Sequenced Distance Vector (DSDV) routing [2] and Optimized Link State Routing (OLSR) [3] protocols are the classical examples of the distance-vector based and link-state based proactive routing strategies. Proactive routing protocols are characterized by low route discovery latency as routes between any two nodes are known at any time instant. But there is a high control overhead involved in periodically propagating the routing tables or the link-state updates to determine and maintain routes. The reactive or on-demand routing protocols discover routes only when required. When a source node has data to send to a destination node and does not have a route to use, the source node broadcasts a Route-Request (RREQ) message in its neighborhood and through further broadcasts by the intermediate nodes, the RREQ message is propagated towards the destination. The destination node receives the

RREQ message along several paths and chooses the path that best satisfies the route selection principles of the routing protocol. The destination sends a Route-Reply (RREP) message to the source on the best path selected. The Dynamic Source Routing (DSR) [4] protocol and the Ad hoc On-demand Distance Vector (AODV) [5] routing protocol are classical examples of the reactive routing protocols. The reactive routing protocols are often characterized by low route discovery overhead as routes are discovered only when needed; but, the tradeoff is higher route discovery latency.

The Fish-eye State Routing (FSR) protocol [6] is a type of link-state based proactive routing protocol proposed to lower the traditionally observed higher control overhead with the proactive protocols. In FSR, a node exchanges its link-state updates more frequently with nearby nodes, and less frequently with nodes that are farther away. The number of nodes with which the link-state information is exchanged more frequently is controlled by the "Scope" parameter (basically the number of hops), while the frequency of updating the neighbors outside the scope is controlled by the "Time Period of Update" (TPU) parameter. The operation of FSR is basically controlled by these two parameters. As a result, a node maintains accurate distance and path information to its nearby nodes, with progressively less accurate detail about the path to nodes that are farther away. This is also the basic principle behind the vision system for fishes and hence the routing protocol is named after this principle. A scope value of 1 and a larger TPU value typically results in a lower control overhead at the cost of a higher hop count path (a sub-optimal path) between any two nodes. On the other hand, a scope value equal to the diameter of the network and a smaller TPU value basically transform FSR to OLSR, resulting in higher control overhead with the advantage of being able to use the minimum hop path between any two nodes. However, in this research, we find that FSR can be normally operated with a smaller scope, typically 1-hop, because even with larger TPU values, a data packet is more likely to get forwarded on a better path towards the destination as the packet approaches the destination.

Our contributions in this paper are as follows: Given that the scope parameter is normally set to 1-hop, the critical performance metrics for FSR such as the control overhead (number of link-state messages exchanged), the hop count of the paths and energy consumption are heavily dependent on the TPU parameter. To date, only a handful of performance studies [7][8][9] are available for FSR in the literature. To the best of our knowledge, we could not find a simulation study on the performance of FSR as a function of this TPU parameter. In addition, we conjecture that the proactive routing strategy based FSR may be preferable over DSR as the node mobility and network density increases. DSR and FSR have not been categorically studied for different levels of node mobility, network density and offered traffic load. The above observations formed the motivation for this paper. We present a scenario based performance analysis of the FSR protocol with respect to the TPU parameter under scenarios generated by different combinations of node mobility, network density and offered traffic load. For each of these scenarios, the performance of FSR is also compared with that obtained for DSR. We categorically state which of these two protocols can be preferred for each of the different scenarios.

The rest of the paper is organized as follows: Section 2 describes the simulation environment and the different scenarios considered. Section 3 defines the performance metrics evaluated. Section 4 illustrates the simulation results obtained for different scenarios; interprets the performance of FSR with respect to the TPU parameter and compares the performance of FSR vis-à-vis DSR. Section 5 concludes the paper.

2. SIMULATION ENVIRONMENT

The simulations of FSR and DSR were conducted in ns-2 [10]. The network dimensions are 1000m x 1000m. The transmission range of each node is 250m. We vary the network density by conducting simulations with 50 nodes (low density network with an average of 10 neighbors per node) and 75 nodes (high density network with an average of 15 neighbors per node). The simulation time is 1000 seconds. The scope value is 1-hop. If all the nodes flood their link-state updates at the same time instant, there would be collisions in the network. Hence, the TPU value for each node in the network is uniformly and randomly chosen from the interval [0…TPU_{max}]. The different values of TPU_{max} studied in the simulations are: 5, 20, 50, 100, 200 and 300 seconds and these translate to average TPU values of 2.5, 10, 25, 50 and 150 seconds respectively.

The node mobility model used in all of our simulations is the Random Waypoint model [11], a widely used mobility model in MANET simulation studies. According to this model, each node starts moving from an arbitrary location to a randomly selected destination location at a speed uniformly

Table 1: *Scenarios Studied in the Simulation*

Scenario #	Network Density	Offered Traffic Load	Node Mobility
1	Low (50 nodes)	Low (15 *s-d* Pairs)	Low (v_{max} = 5 m/s)
2	Low (50 nodes)	Low (15 *s-d* Pairs)	Moderate (v_{max} = 50 m/s)
3	Low (50 nodes)	Low (15 *s-d* Pairs)	High (v_{max} = 100 m/s)
4	Low (50 nodes)	High (40 *s-d* Pairs)	Low (v_{max} = 5 m/s)
5	Low (50 nodes)	High (40 *s-d* Pairs)	Moderate (v_{max} = 50 m/s)
6	Low (50 nodes)	High (40 *s-d* Pairs)	High (v_{max} = 100 m/s)
7	High (75 nodes)	Low (15 *s-d* Pairs)	Low (v_{max} = 5 m/s)
8	High (75 nodes)	Low (15 *s-d* Pairs)	Moderate (v_{max} = 50 m/s)
9	High (75 nodes)	Low (15 *s-d* Pairs)	High (v_{max} = 100 m/s)
10	High (75 nodes)	High (40 *s-d* Pairs)	Low (v_{max} = 5 m/s)
11	High (75 nodes)	High (40 *s-d* Pairs)	Moderate (v_{max} = 50 m/s)
12	High (75 nodes)	High (40 *s-d* Pairs)	High (v_{max} = 100 m/s)

distributed in the range [v_{min},…,v_{max}]. Once the destination is reached, the node may stop there for a certain time called the pause time and then continue to move by choosing a different target location and a different velocity. In this paper, we set v_{min} = 0 and pause time is 0 seconds. Each node chooses speed uniformly distributed between 0 and v_{max}. The v_{max} values used are 5 m/s, 50 m/s and 100 m/s; the corresponding average node velocity values are: 2.5 m/s, 25 m/s and 50 m/s representing mobility levels of low (school environment), moderate (downtown) and high (interstate highway) respectively.

Traffic sources are continuous bit rate (CBR). Number of source-destination (*s-d*) sessions used is 15 (low traffic load) and 40 (high traffic load). The starting times of the *s-d* sessions is uniformly distributed between 1 to 20 seconds. Data packets are 512 bytes in size; the packet sending rate is 4 data packets per second. While distributing the source-destination roles for each node, we saw to it that a node does not end up as source of more than two sessions and also not as destination for more than two sessions. The queue size at the nodes is 200 and priority is given to the control packets over the data packets. The control packets are the link-state updates in the case of FSR or the RREQ-RREP messages in the case of DSR. For each class of packets, the queue operates in FIFO fashion.

Each node is initially provided energy of 1000 Joules to make sure that no node failures happen due to inadequate energy supply. The transmission power loss per hop is fixed and it is 1.4 W and the reception power loss is 1 W [12]. The Medium Access Control (MAC) layer model used is the standard IEEE 802.11 model [13] wherein the access to the channel per hop is accomplished using a Request-to-send (RTS) and Clear-to-send (CTS) control message exchange between the sender and the receiver constituting the hop in a path. The different combinations of simulation scenarios used in this paper are summarized in Table 1.

3. PERFORMANCE METRICS

The following performance metrics are evaluated for each of the 12 scenarios (refer Table 1) and each of the five TPU values considered.

(i) Packet Delivery Ratio – the ratio of number of actual data packets successfully disseminated from the source to destination to that of the number of data packets originating at the source.

(ii) Average Hop Count per Path – the average number of hops in the route of an *s-d* session, time averaged considering the duration of the *s-d* paths for all the sessions over the entire simulation time.

(iii) Control Message Overhead – the ratio of the total number of control messages (route discovery broadcast messages for DSR or the link-state update broadcast messages for FSR) received at the nodes to that of the actual number of data packets delivered to the destination across all *s-d* sessions. Note that we take into consideration the number of control messages received rather than transmitted because a typical broadcast process involves a node transmitting the control message and all of its neighbors receiving the control message. The energy expended to receive the control message, summed over all the nodes, is far less than the energy expended to transmit the message.

(iv) Energy Consumption per Node – the average energy consumed across the nodes in the network. Energy consumed for transmission

Table 2: *Control Message Overhead (Control messages received per data packet delivered) for Maximum TPU Value of 5 Seconds*

Maximum Node Velocity (v_{max})	Low Density, Low Traffic Load	Low Density, High Traffic Load	High Density, Low Traffic Load	High Density, High Traffic Load
5 m/s	178	64	585	220
50 m/s	182	69	640	235
150 m/s	180	67	660	250

Table 3: *Energy Consumption per Node at Maximum TPU Value of 5 Seconds*

Maximum Node Velocity (v_{max})	Low Density, Low Traffic Load	Low Density, High Traffic Load	High Density, Low Traffic Load	High Density, High Traffic Load
5 m/s	104 Joules	126 Joules	212 Joules	230 Joules
50 m/s	110 Joules	129 Joules	235 Joules	250 Joules
150 m/s	109 Joules	129 Joules	240 Joules	255 Joules

and reception of data packets, periodic broadcasts and receptions (in the case of FSR), and route discoveries (in the case of DSR) all contribute to the energy consumed at a node.

4. SIMULATION RESULTS

Each data point in Figures 1 through 16 and Tables 2 and 3 is an average of data collected using 5 mobility trace files for each value of v_{max} and network density, and 5 sets of randomly selected 15 and 40 *s-d* sessions. To present the results of FSR (with larger TPU values) and DSR in a comparable scale in the figures, we present the control message overhead and energy consumption per node at FSR for maximum TPU value of 5 seconds in Tables 2 and 3 respectively.

4.1. Low Network Density and Low Traffic Load (Scenarios 1 through 3)

4.1.1. Packet delivery ratio

The packet delivery ratio (refer Figure 1) of FSR decreases with increase in the TPU value. This can be attributed to the inaccuracy in the routing information stored at the intermediate nodes for certain destination nodes. However, it should be noted that FSR still consistently maintains a packet delivery ratio of above 90% even for TPU values exceeding 200 seconds. An interesting observation for both FSR and DSR is that as node mobility is increased from 5m/s to 50m/s, there is an increase in the packet delivery ratio. In low density networks, spatial distribution of network nodes plays a critical role in the effectiveness of a routing protocol. Nodes are sparsely distributed in a low node density network and if nodes are also characterized with low mobility, they tend to experience higher rates of network disconnection. Consequently, since the nodes are relatively static and do not change their positions frequently, this disconnected state persists, and as such, packet delivery is adversely impacted. In contrast, as node mobility increases, nodes are redistributed and move to new locations, thus increasing the probability that they move within the transmission range of each other. As a result, the probability of network connectivity increases, thus increasing the likelihood of a node successfully routing a packet to its destination.

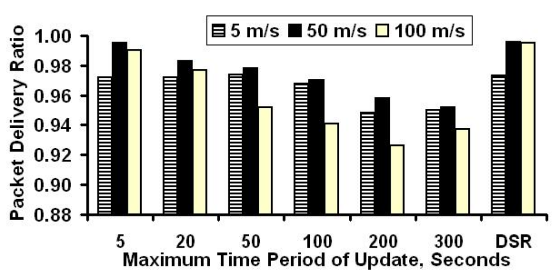

Figure 1: *Packet Delivery Ratio for FSR and DSR (Low Network Density, Low Traffic Load Scenario)*

4.1.2. Average hop count per path

In the low node mobility scenario, FSR was observed to yield a more optimal minimum hop path than DSR for a time period of update (TPU) value of 5 seconds (refer Figure 2). Beyond a TPU value of 5 seconds, DSR maintained a lower average hop count compared to FSR. The results discovered relative to FSR's performance is expected due to the following reasons. FSR, as a proactive protocol, periodically broadcasts routing information to nodes within a network. DSR is assumed to under perform compared to FSR because of the characteristic low node density of the simulated network. In low node density networks, nodes are sparsely distributed, and availability of routes between *s-d* pairs is not always guaranteed. At low mobility, nodes are less likely to change their location, which hinders them from discovering more optimal routes to destinations. In addition, DSR tends to maintain its current minimum hop path route until a link failure is detected, predisposing it to retain sub-optimal routing information in low node density scenarios. Consequently, since FSR proactively maintains more accurate topology information at lower TPU values, it outperforms DSR by determining more optimal minimum hop paths. In contrast, at higher TPU values, FSR propagates routing information infrequently, thus DSR outperforms FSR at these TPU values. The degradation in the performance of FSR can be attributed to routing inaccuracy as a result of longer link-state update time intervals utilized to exchange broadcast messages on network topology.

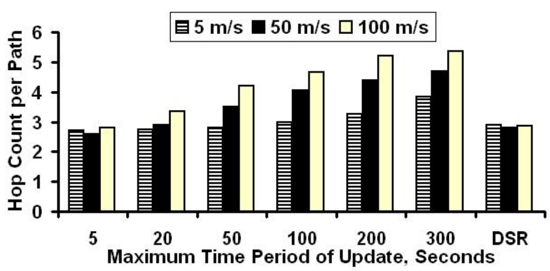

Figure 2: *Average Hop Count per Path for FSR and DSR (Low Network Density, Low Traffic Load Scenario)*

4.1.3. Control message overhead

FSR, as expected, incurs a significantly higher control overhead over DSR at a lower TPU value of 5 seconds (refer Table 2 and Figure 3). FSR periodically generates network wide broadcasts at a selected TPU value with the purpose of establishing routes for every node in a network. This process of periodic broadcasts generates high control overhead especially if it is done rather frequently as in the case of a TPU value of 5 seconds. In contrast, DSR incurs less overhead than FSR because it generates less control packets in a low network density scenario. DSR performs network wide flooding only when a route is needed for a data transmission session, and thus its control overhead depends on the traffic load (number of *s-d* pair sessions).

For TPU values beyond 20 seconds, a decreasing trend is observed in the number of control messages generated by FSR (refer Figure 3). This is attributed to the fact that higher TPU values translate to longer intervals between periodic broadcasts of control messages. Thus, FSR does not frequently generate periodic broadcast messages, and as a result, the amount of control overhead reduces significantly. In comparison to DSR, FSR generates less overhead for TPU values ranging from 50 seconds to 300 seconds. With respect to node mobility, the amount of overhead generated appears to grow with increasing mobility in DSR. However, FSR remains unaffected by variations in node mobility.

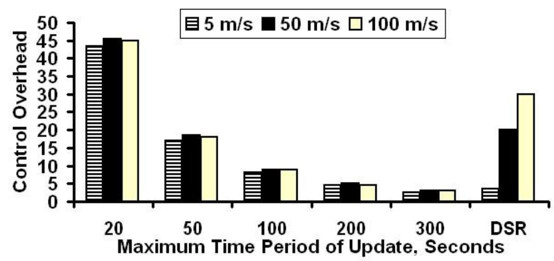

Figure 3: *Control Message Overhead for FSR and DSR (Low Network Density, Low Traffic Load Scenario)*

4.1.4. Energy consumption per node

As clearly illustrated in Figure 4 and Table 3, it can be concluded that DSR consumes less energy per node, relative to FSR. This is expected because DSR, a reactive protocol, should incur less energy consumption as a result of less control overhead generation, when compared to a proactive routing protocol like FSR. However, we do notice that operating FSR under higher TPU values helps to minimize energy consumption per node. Figure 4 illustrates that contrary to expectations, FSR loses less energy per node relative to DSR in high mobility scenario cases of 100m/s, corresponding to TPU values of 100 seconds and 200 seconds respectively. However, some researchers can argue that minimizing energy consumption at these high TPU values comes at a cost of reduced routing accuracy. Figure 1 contradicts this argument by showing that the packet delivery ratios of FSR corresponding to TPU values of 100 seconds and 200 seconds in a characteristic high mobility scenario of 100m/s are 94.14% and 92.69% respectively, when compared to the DSR's packet delivery ratio of 99.38%. These results clearly indicate that FSR can be utilized for applications requiring optimized energy consumption at high node velocity scenarios and can tolerate a packet delivery ratio of approximately 94%.

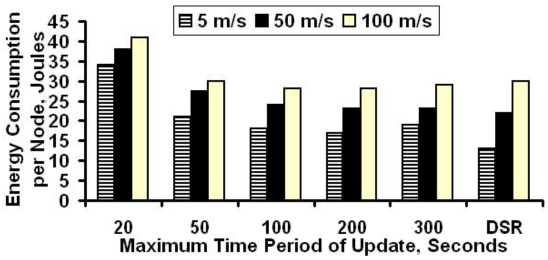

Figure 4: *Energy Consumption per Node for FSR and DSR (Low Network Density, Low Traffic Load Scenario)*

4.2. Low Network Density and High Traffic Load (Scenarios 4 through 6)

4.2.1. Packet delivery ratio

For this simulated scenario, as observed in Figure 5, both DSR and FSR exhibit an appreciable increase in their respective packet delivery ratios at low node mobility of 5m/s. However, as node mobility is increased to 50m/s and 100m/s respectively, both protocols experience a slight decrease in their packet delivery ratios. This observation is justified for the following reason: In networks of low density and high traffic load, the number of neighbors per node is significantly smaller compared to the number of active source-destination pairs. As a result, there is more demand placed on a few nodes to successfully route packets to their destinations. This obviously results in more packets getting dropped at each node and hinders the ability of both protocols to successfully route packets to their destinations at a higher rate.

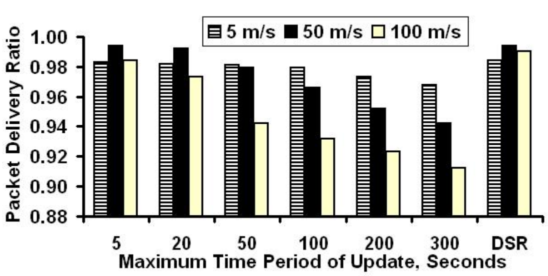

Figure 5: *Packet Delivery Ratio for FSR and DSR (Low Network Density, High Traffic Load Scenario)*

FSR has comparable packet delivery ratios, although DSR slightly outperforms FSR. As the TPU value for FSR is increased, FSR exhibits a decreasing trend in its packet delivery ratio. This can be attributed to the fact that at higher TPU values, FSR does not provide accurate routing information due to infrequent propagation of topology updates. Consequently, packets get misrouted, leading to lower packet delivery ratio.

4.2.2. Average hop count per path

As the velocities of nodes are increased from low to high, FSR incurs a higher hop count value compared to DSR. This observation holds true except for the TPU value of 5 seconds (see Figure 6). The hop count of DSR is not much affected by the node velocities.

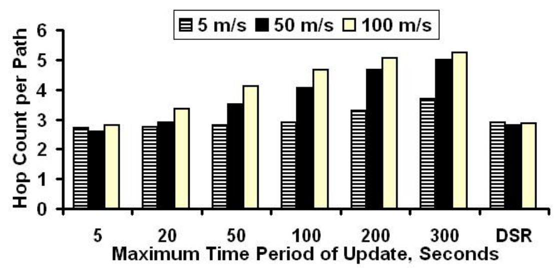

Figure 6: *Average Hop Count per Path for FSR and DSR (Low Network Density, High Traffic Load Scenario)*

4.2.3. Control message overhead

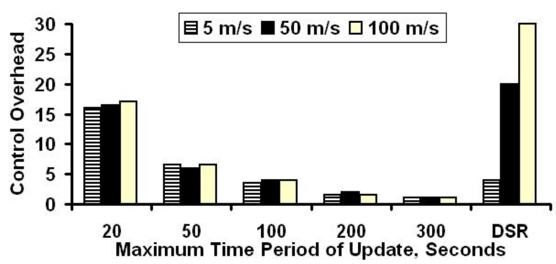

Figure 7: *Control Message Overhead for FSR and DSR (Low Network Density, High Traffic Load Scenario)*

As illustrated in Table 2, FSR is observed to incur a higher control overhead than DSR at a low TPU value of 5 seconds due to frequent network-wide broadcasts. However, DSR incurs significantly more overhead than FSR as traffic load is increased to 40 *s-d* pairs (refer Figure 7) for TPU values of 20 seconds and beyond. This observation can be attributed to the reactive nature of DSR and the low node density of the network. DSR only determines routes as needed. With an increasing need to determine routes for a growing number of *s-d* pairs, DSR invokes its route discovery mechanism frequently, which floods the network with broadcast messages. The amount of route discoveries increases with increasing mobility to determine routes for *s-d* pairs, and thus DSR incurs a higher control overhead compared to FSR. FSR remains largely unaffected by increasing rates of node mobility.

4.2.4. Energy consumption per node

In a low node density network characterized by high offered traffic load, the amount of energy consumed by both protocols (refer Figure 8) is observed to be appreciably larger than that observed in networks with low traffic load (refer Figure 4). The spike noticed in energy consumption can be attributed to factors such as the number of data and control packets flowing through the network. An increase in the offered traffic load at low network density is analogous to an increase in the number of active *s-d* pairs wishing to establish sessions. Consequently, this corresponds to an increase in the number of data packets flowing through each node in the network, which contributes to the observed increase in the energy consumption at each node. In addition, in a low density network, the probability of route failures is rather high. This is attributed to the fact that nodes could be sparsely distributed, and as a result, will be unable to find paths to route data packets successfully to their designated destination. Thus, there will be an observed increase in the amount of control overhead generated to maintain and establish routes for the voluminous amount of data traffic. FSR's energy consumption is significantly less when compared to DSR in moderate to high mobility scenarios for a TPU value of 100 seconds.

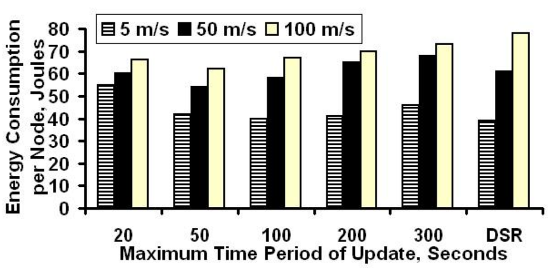

Figure 8: *Energy Consumption per Node for FSR and DSR (Low Network Density, High Traffic Load Scenario)*

4.3. High Network Density and Low Traffic Load (Scenarios 7 through 9)

4.3.1. Packet delivery ratio

In networks of higher density, the packet delivery ratios incurred by both FSR and DSR are relatively larger than those incurred in networks of lower density (compare Figures 1 and 9). For low mobility scenarios of 5m/s, both FSR and DSR deliver packets at approximately 100%. FSR maintains this perfect packet delivery rate for low node mobility as TPU values are increased from 5 seconds up to 200 seconds. However, for a TPU of 300 seconds, the packet delivery ratio of FSR slightly decreased to 99.4%. The better performance of both protocols regarding packet delivery ratio can be attributed to the fact that in higher density networks, a node has more neighbors within its transmission range, to route messages along a given source-destination route. This distribution almost always guarantees that a packet will be successfully routed to its destination.

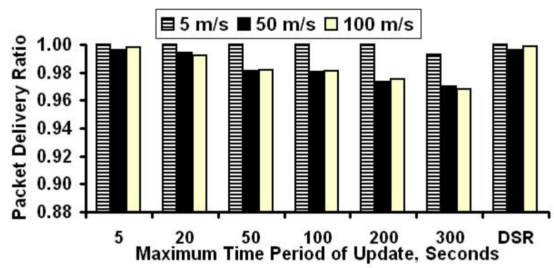

Figure 9: *Packet Delivery Ratio for FSR and DSR (High Network Density, Low Traffic Load Scenario)*

For moderate and high node mobility levels, the packet delivery ratio of DSR and FSR (at TPU value of 5 seconds) is almost the same. However, as the TPU parameter is increased beyond 5 seconds, DSR exhibited a relatively higher packet delivery ratio. This trend is once again indicative of the routing strategy inherent in FSR. FSR maintains routing information about its topology more frequently at lower TPU values. At higher TPU values, FSR maintains routing information less frequently, and as such this adversely affects the accuracy of routes. Consequently, this will reduce the packet delivery ratio as the number of packets successfully routed to their destinations decreases due to the persistence of stale routing information leading to inaccurate routes.

4.3.2. Average hop count per path

In the case of high network density, some interesting observations have been made. It has been observed that the average hop count per path values for both FSR and DSR shown in Figure 10, reduced appreciably compared to the low network density scenarios in Figures 2 and 6. This noticeable trend is attributed to the fact that nodes in a high density network tend to have more neighbors, and as a result have better path alternatives to choose from among optimal routes to any given destination. Thus, nodes in a high density network have more routing alternatives between a given *s-d* pair, which allows them to select shorter routes for routing packets relative to a low density network. As indicated in Figure 10, in low mobility scenarios, FSR outperformed DSR at TPU values of 5 seconds and 50 seconds. Beyond a TPU of 50 seconds, DSR performed better than FSR. This performance can be attributed to FSR losing routing accuracy due to infrequent topology wide broadcasts. For scenarios of moderate to high mobility, FSR outperformed DSR only at a TPU value of 5 seconds. Again, this observation is attributed to loss in routing accuracy on the part of FSR due to prolonged intervals between topology updates.

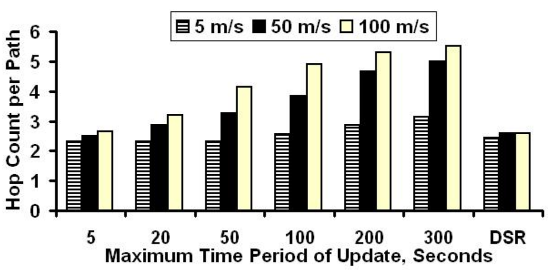

Figure 10: *Average Hop Count per Path for FSR and DSR (High Network Density, Low Traffic Load Scenario)*

4.3.3. Control message overhead

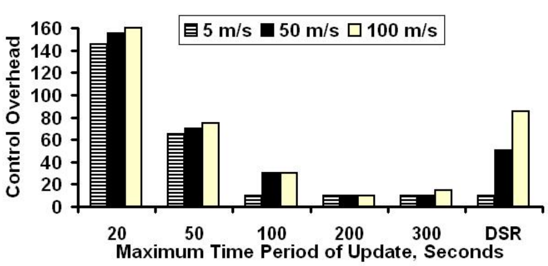

Figure 11: *Control Message Overhead for FSR and DSR (High Network Density, Low Traffic Load Scenario)*

FSR and DSR are observed to incur significantly higher control overhead in networks characterized with high node densities. This is because each node has a denser neighborhood, and thus generates more broadcast messages are received due to an increase in the number of neighbors. As illustrated in Table 2 and Figure 11, FSR generates more broadcast messages than DSR for TPU values of 5 seconds, 20 seconds and 50 seconds. Beyond a TPU of 100 seconds, FSR incurs less control overhead than DSR due to less frequent broadcast message propagations.

4.3.4. Energy consumption per node

According to Figure 12, it is observed that the energy consumed per node by both protocols is lower in magnitude for high density networks, compared to that consumed in lower density networks (see Figures 4, 8, 12 and 16) except for the first case of FSR with a TPU value of 5 seconds. This decreasing trend in energy consumption can be attributed to the fact that a node has more neighbors, and as a result is able to efficiently route data along optimal paths in high density networks. In low node mobility scenarios, DSR significantly outperforms FSR in terms of energy consumption due to its reactive nature. This is because FSR incurs a fixed energy cost due to periodic network broadcasts. DSR, on the other hand, incurs minimal energy consumption due its ability to discover routes only as needed. However, as illustrated in Figure 12, at higher node mobility scenarios, it can be observed that as node mobility increases, energy consumption of FSR converges to that of DSR, and actually outperforms DSR at TPU values: 100 seconds for high rates of mobility of 100m/s, and 200 seconds for moderate to high rates of mobility of 50m/s and 100m/s. This suggests that FSR can be employed as a suitable routing alternative in networks characterized with high node density and moderate to high node mobility.

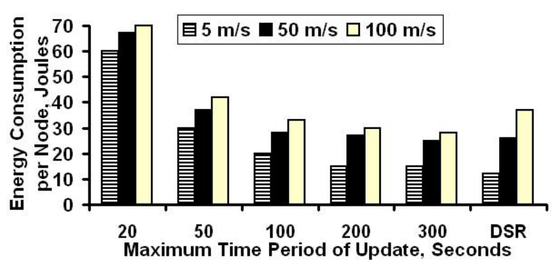

Figure 12: *Energy Consumption per Node for FSR and DSR (High Network Density, Low Traffic Load Scenario)*

4.4. High Network Density and High Traffic Load (Scenarios 10 through 12)

4.4.1. Packet delivery ratio

FSR and DSR maintained a near perfect packet delivery ratio of 100% as illustrated in Figure 13. In FSR, this trend stayed the same as TPU values were varied from 5 seconds to 50 seconds for low node mobility scenarios. However, the packet delivery ratio of FSR dropped to 99.97%, 99.95%, 99.94% for TPU values of 100, 200 and 300 seconds respectively. This decrease is very small in magnitude, and as a result is considered insignificant.

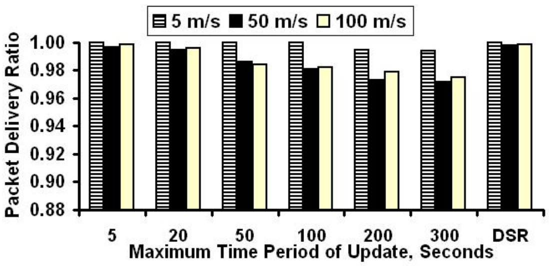

Figure 13: *Packet Delivery Ratio for FSR and DSR (High Network Density, High Traffic Load Scenario)*

For moderate to high node mobility, the discrepancy between FSR and DSR in terms of packet delivery ratio increased, as the TPU parameter values were increased from 50 seconds to 300 seconds, DSR yielded a higher packet delivery ratio. This observation is attributed to the effect of high traffic load on the FSR protocol coupled with stale routing information. As the offered traffic load is increased, increasing demand is placed on the nodes to route data packets to their destination. As TPU values are increased, nodes in high traffic scenarios are not guaranteed to maintain accurate routing information in this environment. This results in a decrease in the packet delivery ratio. It should be noted that although the packet delivery ratio decreases in FSR with increasing TPU values, FSR is still able to maintain a packet delivery ratio above 97% even at a high TPU value of 300 seconds.

4.4.2. Average hop count per path

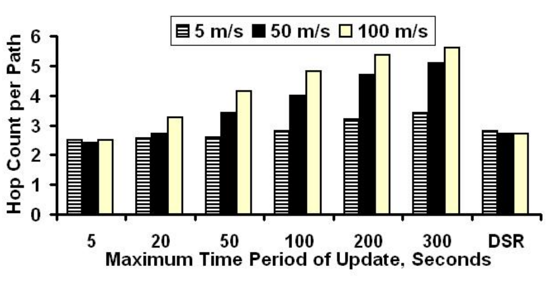

Figure 14: *Average Hop Count per Path for FSR, DSR (High Network Density, High Traffic Load Scenario)*

The hop count trends graphically displayed in Figure 10 are also noticed in the performance of FSR and DSR in Figure 14. FSR outperforms DSR in low node mobility scenario at a TPU 5 seconds. Beyond 5 seconds, DSR discovers more optimal minimum hop paths compared to FSR, due to the discovery of inaccurate routes in FSR. One major difference observed is the increase in the magnitude of the hop count discovered by both protocols as compared to the high network density low traffic load scenario.

4.4.3. Control message overhead

As illustrated in Table 2 and Figure 15, FSR scales considerably better than DSR at TPU values beyond 50 seconds. This is because FSR proactively maintains routing information and is not affected by increasing network density. DSR, on the other hand, will generate more overhead due to increasing demands for route discoveries for *s-d* sessions. Thus, DSR floods the network using its route discovery messages, which account for the generation of excessive control overhead when compared to FSR. Variations in mobility do not have an effect on FSR, but have a significant effect on the amount of control messages generated by DSR in high node density and high traffic scenarios.

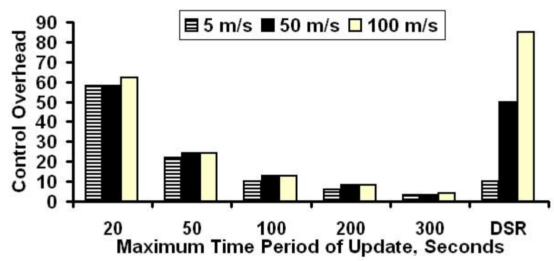

Figure 15: *Control Message Overhead for FSR and DSR (High Network Density, High Traffic Load Scenario)*

4.4.4. Energy consumption per node

For the high network and offered traffic load simulations, it is observed from Table 3 and Figure 16 that the energy consumption of both protocols exceeded that of the high network density and low traffic load scenario (refer Figure 12). This is justified by the increase observed in the number of communicating *s-d* pairs. More packets are routed in the network due to data and control overhead, and as a result nodes expend more energy associated with routing a larger amount of packets. As illustrated in Figure 16, energy consumption trends per node are observed to increase with an increase in the mobility levels of nodes within the network. When compared to DSR, FSR consumes less energy in moderate to high mobility scenarios at TPU values ranging from 20 seconds to 300 seconds. Thus, it can be suggested that for high mobility and high-density scenarios, FSR can be configured to a lower TPU value of 20 seconds while minimizing energy consumption. For moderate node mobility high density-high traffic load networks, FSR can be selected over DSR by configuring the former with a TPU value of 50 seconds.

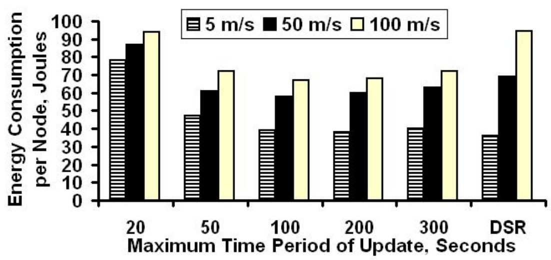

Figure 16: *Energy Consumption per Node for FSR, DSR (High Network Density, High Traffic Load Scenario)*

5. CONCLUSIONS

This paper explores the performance and tradeoffs associated with the FSR protocol relative to DSR in MANETs under varying scenarios of network density, node mobility, and traffic load using simulation based analysis. Conclusions and suggestions are made for the configuration of the FSR protocol to yield better performance than DSR under specific scenarios based on the results observed in the simulations.

A significant tradeoff has been observed in the performance of FSR regarding the hop count per path. For lower Time Period of Update (TPU) values, FSR has been discovered to obtain optimal minimum hop paths due to the increased frequency of route update messages. As the TPU value is increased, FSR has been observed to incur higher hop count values due to lower update frequency. Consequently, this leads to the persistence of stale routes, which generates longer hop paths. We have identified the TPU values that will generate paths with hop count comparable to DSR. It has been discovered that at low mobility levels, FSR yields more optimal paths.

An interesting observation has been made regarding packet delivery ratio, control message overhead and node energy consumption. FSR has been observed to maintain a close to perfect packet delivery ratio of 90% or above in high density networks characterized with high traffic load, even at higher TPU values. This suggests that the control message overhead can be significantly minimized while maintaining close-to-accurate routing information to deliver packets to their respective destinations. The same trend has been noticed in terms of energy consumption at moderate to high node mobility values with FSR losing less energy for routing and topology maintenance as compared to DSR.

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