Improvement of Robustness for Ad Hoc Networks Through Energy-Aware Routing

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ABSTRACT

A major restriction in ad hoc networks is the limited battery energy resource of a mobile node. Designing a routing protocol for ad hoc networks that is robust, dynamic, and efficient in power consumption is a major challenge. In this paper we present the Max-Min Energy (MME) algorithm that improves the robustness of the routing protocol by introducing fairness in power consumption. A robust protocol should be capable of initiating traffic with minimum 'connection time' delay and maintain connectivity as long as possible by seeking alternative routes if there is movement of active nodes in the network. Most of the studies in this area of power conservation have been evaluated on stable conditions like low or zero movement. However, the actual performance of the proposed algorithms will be more evident especially during an adverse situation like disconnectivity due to movement leading to route failures.

During the earlier part of the paper, a performance analysis was conducted in three ad hoc routing protocols: AODV, DSDV, and DSR. The results show that DSR performs best for the given partitioning scenario. The MME algorithm was implemented in ns-2 code for DSR protocol. A performance evaluation of both the versions of DSR was conducted for the several instances of the partitioning scenario. MME- DSR routes the traffic through nodes having higher remaining battery energy. The simulation results demonstrate that MME-DSR maintains connectivity for a longer interval of time as compared to DSR. The overall throughput of MME-DSR was higher or comparable to DSR. Work [1] independently proposed a modification to DSR termed MMRP that seeks to prolong the lifespan of the network by making remaining energy-aware routing decisions. When compared to the protocol proposed in this paper, MMRP exhibits longer route establishment times and results in higher reduction in network throughput.

KEY WORDS
Wireless networks, ad hoc networks, energy-aware routing, robustness.

1 Introduction

In an ad hoc network the mobile nodes agree to serve as both routers and hosts. The nodes can dynamically join and leave the network, frequently without warning, and possibly disrupting communication amongst other nodes. Moreover, the limitations on power consumption imposed by portable wireless radios result in a node transmission range that is typically small relative to the span of the network. This limits the propagation range of a mobile node. In such an environment, it may be necessary for one mobile host to enlist the aid of others in forwarding a packet to its destination. One of the main challenges in the design of ad hoc networks is the development of dynamic routing protocols that can efficiently find routes between two communicating nodes.

Several aspects of the physical layer such as propagation effects, network interfaces, transmission power, antenna gain, and receiver sensitivity play an important role in the performance of ad hoc networks. Apart from the physical aspect, the wireless topology can change rapidly in unpredictable ways or remain relatively static over long periods of time. It is common for a parent network to split up into sub-networks due to the common kind of operation taking place within those groups of nodes. This demands that the routing protocol be robust in continual route discovery and maintenance. The routing protocol should be able to detect the change in the topology of the network and efficiently reroute the traffic without causing degradation in throughput. It should also be able to detect congestion in the network and discover or cache alternate routes to the destination or distribute the load through multiple routes to the destination. There also may be situations where the node or group of nodes again comes within the range of the parent network. In such situations the routing protocol must be capable of being robust enough to adapt to the changes in the network. The protocol should also be able to keep the connection alive as long as possible during adverse conditions of node separations. Also, in a wireless environment the mobile nodes have limited battery energy, which needs to be utilized efficiently to route traffic through them. The severity of the problem escalates when there is movement in the network that leads to disconnectivity. At such instances it is essential for the nodes to have enough energy remaining to assist in rerouting traffic that had been disrupted due to movement in the network. A mobile node that is running low on battery energy can hardly be of any assistance for maintaining connectivity during separation. Due to this constraint, the robustness of a routing protocol is restricted by the remaining energy of the nodes that fall in the category of edge nodes during movement. By edge nodes we mean the nodes that are located at the outer edge of the network or subnetworks. Robustness could be enhanced at the cost of some kind of periodic signaling and updates over the constrained channel. The efficiency of the existing protocol could also be enhanced at the cost of the increase in computational complexity at the nodes. Hence there is always a trade-off between robustness and computational overhead involved.

2 Background and motivation

The issue of energy[1] conservation in ad hoc networks has stirred up a significant amount of interest amongst many research groups. Numerous protocols have been proposed to address this problem. Metrics that have been proposed for improving the battery life of a mobile node can be broadly classified into two major categories: power-aware and cost-aware. Power-aware metrics aim at minimizing the total power. Here the important point to note is that the term power implies power consumed by the node in routing a packet between a source and its destination. Cost-aware metrics look at methods that extend the nodes' battery lifetimes [2]. We are also aware of the recent development of Yu and Lee along the same lines of our proposed algorithm [1]. However there are striking differences between the two approaches and also in the actual purpose behind proposing both the algorithm. The differences are discussed in the subsequent sections.

2.1 Robustness and energy efficiency

The term robustness refers to the ability of a routing protocol to induce minimum initial set- up delay and maintain connectivity without a significant degradation in throughput even when there is movement of nodes that are actively participating in the communication. A robust protocol must also find an optimal path to the destination based on several other factors apart from the traditional 'number of hops' metric. A route is said to be optimal based on factors like the least number of hops and the minimum energy consumed. This will avoid the inclusion of redundant nodes and hence minimize consumption of energy per end-to-end connection. The routing protocol must also be robust enough to rediscover the optimal route to the node if there is a better route that might become available later in time. However, the proposed routing protocol must not degrade the throughput of the network. This requires that during an unexpected route failure, the routing protocol must be robust enough to discover a new route in a minimum time. Considering all these factors, one has to strike a balance between finding the optimal route, improving robustness, and avoiding degradation of throughput even during stable network states.

For example, in practical applications it is very common for a group of nodes to split into several subgroups that gradually move out of each other's range. In such adverse conditions the routing protocol must stand the test of maintaining the connection as long as possible with minimum loss of throughput. This requires that the energy of potential edge nodes must be conserved during the stable condition so that they can stay alive as long as possible to maintain connectivity between subgroups. The MME-DSR protocol proposed in this paper attempts to address these issues and helps in improving the robustness of an ad hoc network during adverse conditions. It induces fairness in route decision and helps in load distribution of the traffic even during stable conditions without increasing the computational or control overhead in the network during an adverse condition. One such frequently encountered adverse scenario is the partitioning problem described in the next section.

2.2 The network partitioning problem

The partitioning problem refers to a scenario where nodes in an ad hoc network divide into two or more clusters that eventually lead to loss of connectivity. Such adverse scenarios can be observed in practical situations while maintaining connectivity among troops in a battlefield. For example, during combat operations, groups of nodes are eventually formed within an ad hoc network. The groups are a result of assignment to a common task in the battlefield. Grouping of mobile nodes may result in partitioning of an ad hoc network into multiple groups. In such situations, the approach adopted by the routing protocol to maintain connectivity for as long as possible plays a very important role. Later, these groups might converge again to re-form the original ad hoc network. During such transient conditions, almost every node in the network contributes towards maintaining connectivity amongst the subgroups. It is essential to introduce some sort of fairness in route decisions so that every node gets an equal opportunity to conserve its energy. This will be very beneficial in the case of partitioning where some nodes will have to serve as edge nodes and assist in maintaining connectivity.

In this paper, we consider the following model scenario: The topology the network comprises of twelve nodes forming two hexagonal clusters partially overlapping each other as shown in Figure 1. Nodes 0 to 5 and nodes 6 to 11 form the two hexagons that are denoted as cluster 1 and cluster 2 respectively. There are intra-cluster and inter-cluster communication within the network. During the time of active communication between the two clusters, clus-

[1]The term energy refers to the remaining energy of the battery of the mobile node [1, 2, 3].

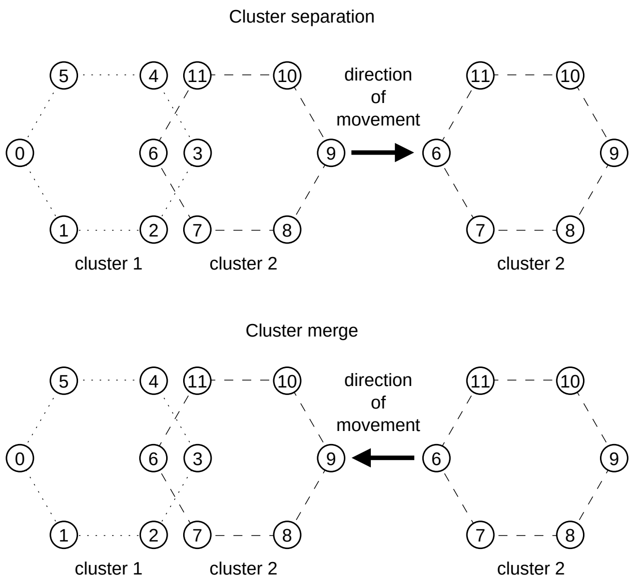

Figure 1. Network partitioning scenario.

ter 2 starts moving away from cluster 1, while the individual intra-cluster formations are maintained. This leads to a separation of the parent network into two non-overlapping hexagonal clusters. It is also possible that later the nodes of cluster 2 come back into range of cluster 1 to form a single network again.

A routing protocol that would be deployed in such a scenario certainly needs to be very robust and energy efficient. The MME-DSR algorithm proposed here is one such solution to deal with the challenges faced by an ad hoc network during such transient conditions.

Before incorporating the MME algorithm in DSR, we first conducted a study of the performance of different routing protocols in ad hoc network scenarios. The routing protocol that performed the best during these evaluations was then further studied and modified to choose an optimal route to the destination and implement fairness in route decisions.

3 Protocol Performance During Network Partitioning

The work underlying this paper commenced with a detailed evaluation of the various routing protocols that have been used widely amongst various research groups for performance study. Network Simulator (ns) [4] was chosen as a simulation and evaluation tool. We also studied the results of several research papers that have discussed about performance evaluation of the existing routing protocols [5, 6].

A step-by-step approach was used to understand how MAC and routing protocols have been implemented in the Network Simulator . Several simple and basic scenarios were simulated for wireless ad hoc networks. These scenarios were then subjected to various adverse conditions, such as congestion, node movements, and link disconnections. These results were helpful in justifying several unexpected behaviors observed in larger networks. The routing protocols studied were Dynamic Source Routing (DSR) [7], Ad hoc On-Demand Distance Vector (AODV) [6], and Destination Sequenced Distance Vector (DSDV) [8].

3.1 Performance Metric

The aim here is to find the most robust protocol amongst those selected as reasonable candidates for ad hoc networks, which relates to the ability of the routing protocol to maintain the connectivity for as long as possible even during adverse situation. This also implies that the protocol should avoid any sort of degradation in the throughput of the network during adverse conditions. Hence, throughput was chosen as the metric to assess the robustness of the protocol. The average throughput was calculated separately for every connection in the network. The average throughput of a given connection in an ad hoc network can be calculated as follows:

$$Average\ throughput = \frac{total\ number\ of\ bits\ received}{defined\ time\ interval}$$

In some cases the instantaneous throughput of a given connection proved to be the best measure to identify exactly where the throughput degraded. Instantaneous throughput of a given connection in an ad hoc network can be calculated as follows:

$$Instant.\ throughput = \frac{packet\ size\ in\ bits}{packet\ interarrival\ time}$$

Note that the count of the total number of received packets (bits) includes only the data packets (bits) that were received by the destination node. Hence, the control overhead is not included during the calculation of throughput.

3.2 Evaluation of ad hoc routing protocols with respect to robustness

Five different experiment scenarios were developed to reveal the behaviors of the selected routing protocols under adverse conditions. The first two experiments were conducted to observe the effect of re-routing of a UDP connection due to a link loss from node movement. The experiments were performed for different bit rates and for two different queue lengths of 4 and 50. If the bit rate is increased, the queue will be filled at a faster rate. Hence, a different queue size would impose different levels of congestion at the same bit rate. This will affect the throughput of the network. Moreover, the movement of an active node would cause the routing protocol to re-route the traffic through other alternative routes. Hence, our aim was to study the behavior of the different routing protocols during movement of mobile nodes in the network and how each of them to re-route the traffic efficiently to maintain the throughput of the network. The experiment was repeated for DSR, DSDV and AODV to observe the change in the throughput for these protocols.

In the next experiment we simulated the partitioning scenario in the larger network of mobile nodes and studied how the three routing protocols chose an optimal route during the start of transmission, perform considerably well during an unexpected change in the topology and maintain connectivity between parting nodes for the maximum amount of time. The experiment was performed for different bit rates.

An important observation is that most of the routes were concentrated through several central nodes. Here by central nodes we imply the nodes that are located centrally in the network. Nodes that were located around the edge of the parent network were not so actively participating in carrying the traffic. This is because the shortest routes for intercluster traffic share only a few edge nodes. Hence, the routing protocols based their route decisions only on the minimum number of hops and often chose a path that was shortest but contained the nodes that were running low on battery energy. In an adverse case where a node is completely drained of its battery resource, this causes a severe degradation in throughput. Buffer overflows at several nodes were observed for most of the simulations performed. Such a condition is highly undesirable in emergency situations since it would result in degradation of the performance of a routing protocol or possibly lead to network disconnectivity.

A performance comparison of the protocols revealed that DSR adapts more dynamically to a change in the topology. DSR initiates a route discovery only when the existing route breaks. DSR uses the least hop count to find the best route to the destination. AODV is not as robust as DSR. There is a significant delay in discovering a new route to the destination and also in setting up the initial connection. DSDV finds a better route eventually, but this happens only when a route table update is propagated throughout the network. However, there is a significant overhead involved due to the route table updates. On demand routing protocols are more efficient in terms of the routing overhead.

Since the DSR protocol performed the best among all three routing protocols in the given scenarios, it was chosen as the protocol for further study and enhancement. DSR considers a metric which usually is number of hops to compute the best route. This algorithm performs well during periods of zero mobility and in lightly loaded networks. During adverse scenarios, such as the partitioning problem discussed above it is essential that protocols, such as DSR, assist energy conservation in the nodes with rapidly depleting batteries. Incorporating this feature in DSR without involving extra overhead would help to improve the performance of the DSR protocol.

4 Description of the DSR protocol

The Dynamic Source Routing protocol (DSR) introduced by Johnson et al. [7] is a simple, efficient routing protocol designed specifically for use in multi-hop wireless ad hoc networks of mobile nodes. The DSR protocol comprises two basic steps for discovery and maintenance of source routes.

Route Discovery: This helps the source node discover a route to the destination when it needs to communicate. The source node first checks its route cache for any previously established routes to the destination node. However, if the source does not have any previously used routes then it broadcasts a route request packet to all of its next hop neighbors. The route request contains a record of all the nodes that this packet traverses before reaching the destination. Every intermediate node checks whether or not it is the destination for the route discovery. If the node is the destination, then it returns a route reply message to the source that has a copy of the route record. Multiple copies of the same route request are dropped. When the source node receives this route reply, it stores this record in its cache and uses it to send the subsequent packets to the destination.

Route Maintenance: This helps the source node to discover a new route when the existing route to the destination is disrupted. This is done either by using the link level acknowledgment frame that is defined by IEEE 802.11 [9] or by using the passive acknowledgment [4] method.

Apart from these two modes, DSR also exhibits robustness due to its promiscuous mode of operation. Every node examines (decodes) any packet going through it and adds the routing information contained therein to its own cache. This helps in automatic route shortening during the time of communication.

Thus the DSR routing protocol is robust in maintaining connectivity during adverse conditions. The route shortening in DSR inherently helps in power conservation by avoiding the usage of the energy of a mobile node. However, if the topology does not permit route shortening then the nodes stand a very small chance of conserving their battery energy. Hence we propose a modification to the DSR protocol which will help introduce fairness in power conservation in an ad hoc network.

5 Proposed energy-conserving enhancement to the DSR protocol

The DSR protocol does not directly take into account the limited energy resource of a mobile node. Thus, a route discovered by DSR may inadvertently include nodes that are on the brink of failure. The DSR protocol commonly performs route discovery and maintenance based on the shortest path metric [10]. Before explaining the MME-DSR protocol, it is worthwhile to acknowledge recent work [1] that proposes a DSR based energy-aware routing protocol. The key idea behind the max-min routing protocol

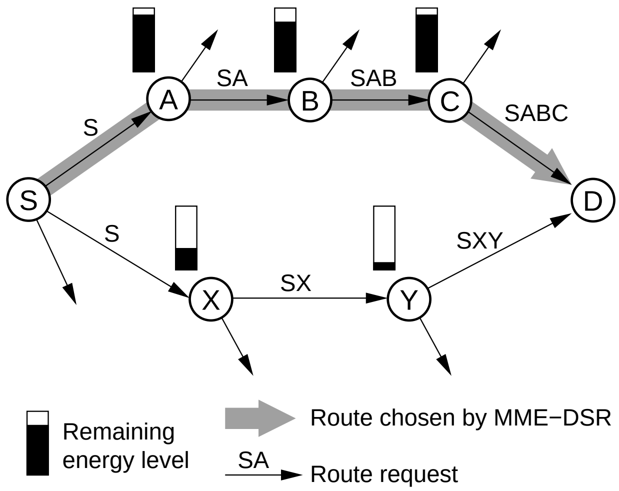

Figure 2. An example of a route selection in MME-DSR.

is to let the destination node decide which route request contains node with maximum among the minimum energy node. This is contrary to the basic route discovery method in DSR where the source node makes the decision about the best route to the destination. The algorithm proposed in this paper does not change the basic route discovery feature. The procedure for route request remains the same as before. The MMRP has a predefined timer and a counter mechanism which controls the duration for which the destination should hold off before sending out the route reply. This introduces delay in the route discovery. In case of MME- DSR there is no delay in route discovery. The source node uses the first arrived route reply to start the communication. If it later receives multiple route replies, it computes the best path and then continues communication through it. MMRP has demonstrated some potential in regards to power conservation and robustness, however the issue of robustness has not been addressed completely in the paper. Another distinctive feature is that if there are multiple identical minimum energy values among paths, then the next smaller value is compared. In MME DSR, if there are routes with the same minimum values then the shorter route is chosen.

Figure 2 demonstrates route discovery for the MME-DSR protocol. The source node starts communicating as soon as it receives the first valid route reply. However, once the source S receives the next route reply, it runs a max-min energy routing algorithm, which is described as follows with reference to Figure 2.

The modified DSR protocol finds the optimal route by searching the node with the minimum remaining energy in each route reply (except the source and destination node). In the example S has route replies for destination D. Considering an ideal environment with no congestion or packet losses, S will first receive the route reply as X→Y→D. The second route reply will be A→B→C→D. The max-min algorithm is run on both route replies. Y has the minimum energy amongst X and Y. B has the least energy among A, B, and C. The next step is to find the maximum among all the minimum energies,. So the remaining energies of Y and B are compared. Since B has a higher remaining energy than Y, the second route reply (A→ B→C→D) is chosen as the optimal route to the destination. To maintain the throughput of the protocol, the data packets received before the arrival of the second route reply are not kept on hold. The max-min energy routing scheme is used for all packets that are sent after the arrival of the second route reply. In the case of disruption of the route due to any adverse conditions, the algorithm deletes the obsolete route and reinitiates the route discovery.

6 Comparison of performance of both versions of DSR protocol

The MME algorithm was incorporated in the DSR protocol in ns and several simulations were run to verify that the MME-DSR protocol behaves the same as DSR for change in queue length, congestion and performs error propagation, or route shortening. Once this was accomplished, the next step was to evaluate the performance of the network during adverse conditions and observe if there is an improvement in the robustness of the network. Robustness is directly linked to the ability of the network to maintain connectivity as long as possible and also restore connectivity after a disruptive event. During such conditions, the edge nodes of the various clusters play an important role in routing the majority of the traffic. However, choosing routes based on the fewest hops criterion will lead to choice of a group centrally located nodes to forward the majority of the traffic. This will lead to the early depletion of their batteries and hence they will not be able to assist to maintain connectivity during adverse situations like that described in the partitioning problem. The modified protocol gives every node a fair chance to conserve its energy. Hence, the scenarios used for the experiments involved movement and temporary disconnectivity due to nodes with depleted energy. The results of the experiments presented below show that the modified protocol helps to improve the robustness of the network in adverse scenarios such as the partitioning problem described previously.

Experiment 1: MME-DSR under partitioning

The topology of the network that was implemented to evaluate the performance of the MME-DSR is same as that described in Section 2.2. The scenario illustrated in Figure 1 comprises twelve nodes with different remaining energies. Nodes 0, 1, 4, 7, 9, and 10 have 1000 J of initial energy. Nodes 2, 5, 8,and 11 have 900 J of initial energy. Nodes 3 and 6 have the least initial energy of 700 J. The area of simulation was defined as 1200 * 1200 m^2. The speed of movement was set to 5 m/s. The buffer length of the mo-

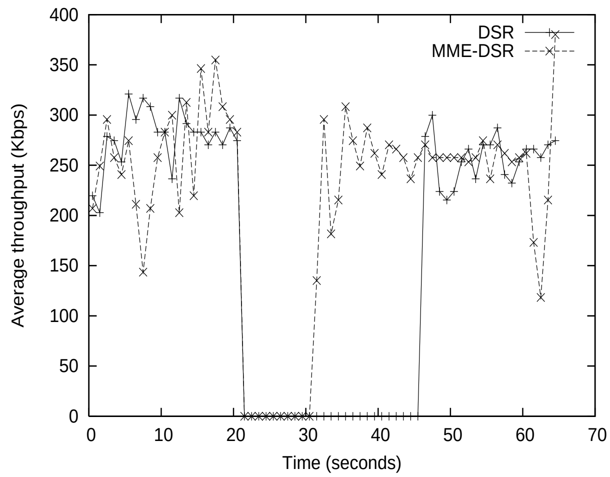

Figure 3. Average throughput for connection from node 4 to node 8.

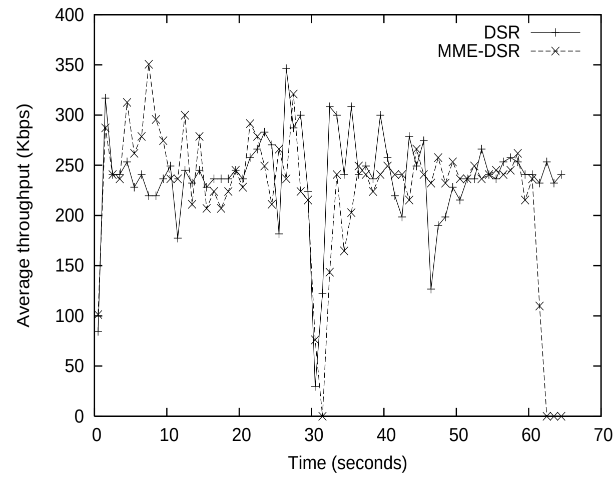

Figure 4. Average throughput for connection from node 10 to node 1.

bile nodes was set to 50. The bit rate was set to 266.66 kbps which corresponds to interpacket gap of 15 msec. The underlying MAC protocol used was IEEE 802.11 for WLANs. The type of traffic was CBR with a packet length of 500 bytes. CBR traffic was initiated from node 4 to node 8 and from node 10 to node 1. At time $t = 8.0$ sec, cluster 2 starts moving away from cluster 1. This leads to a separation of the parent network into two hexagonal clusters. At time $t = 20$ sec the nodes reverse direction of movement and come back into range to form a single network. The aim is to determine which routing protocol chooses the most efficient route, has the maximum throughput, and is more robust when the nodes move apart.

DSR routes the traffic from node 4 to 8 through node 3. The MME-DSR routes the traffic through node 11 to get to node 8. As observed from the Figure 3, the throughput for both versions of DSR was exactly the same before separation. At $t = 21$ sec, the two clusters are out of range, hence the throughput for both routing protocols is zero. At time $t = 30$ sec. MME-DSR restores connectivity while DSR is able to reconnect the network only at $t = 45$ sec. Hence, the overall throughput of MME-DSR is higher than that of DSR for the connection from 4 to 8.

Figure 4 shows the graph of throughput for the traffic from node 10 to node 1. The throughput for both versions of protocol remained the same till time $t = 30$ sec. In the case of DSR there is a sharp drop of throughput at time $t = 30$ sec. In case of DSR the throughput drops to zero for an instant at time $t = 31$ sec. Also there is an intermittent drop of throughput for DSR at approximately $t = 46$ sec. Hence the overall throughput for the connection from nodes 10 to 1 for both the versions of DSR is almost the same.

As an additional step to verify the results, the same experiment was repeated with the traffic flowing from node 4 to node 9 and from node 10 to 1. As observed in Figure 5 the throughput for the connection from node 4 to node 9 is the same for both versions of DSR till time $t = 31$ sec, after which it drops to zero. In case of MME-DSR the connectivity is restored at time $t = 33$ sec, while DSR is unable to restore the connectivity till time $t = 41$ sec. An interesting observation is that once the connection is reestablished, the throughput for MME-DSR is lower than that for DSR. Hence the overall throughput for both versions of DSR is almost the same. Similar results are observed for the connection from nodes 10 to node 1 in Figure 6.

Experiment 2: MME-DSR Performance Under Critical Battery Conditions

The purpose of this experiment was to observe the behavior of the two routing protocols in a network where several nodes are running low on battery energy. The simulated scenario makes clear the importance of energy conservation and awareness in ad hoc routing protocols. This experiment involves multiple connections as in the previous experiment.

The topology of the network is same as that of the previous experiment. The only difference from the previous experiment is that the initial energies of nodes 3 and 6 are critically, i.e., 2 Joules. The aim was to emphasize how important it is to conserve energy of those nodes running low on battery during stable conditions so that these nodes are able to assist in keeping connections alive as long as possible during unfavorable conditions, e.g., if they should become edge nodes.

Observations: DSR routes the traffic from node 4 to 8 through node 3. MME-DSR routes the traffic through node 11 to get to node 8. However, as node 3 is low on initial battery energy, it dies out and is unable to forward any traffic. As observed in Figure 7, the throughput of the connection when using DSR drops to zero even before the nodes move apart. The connectivity is then reestablished

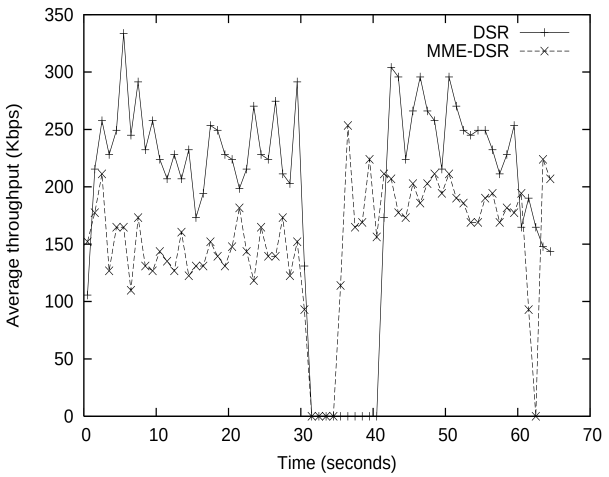

Figure 5. Average throughput for connection from node 4 to node 9.

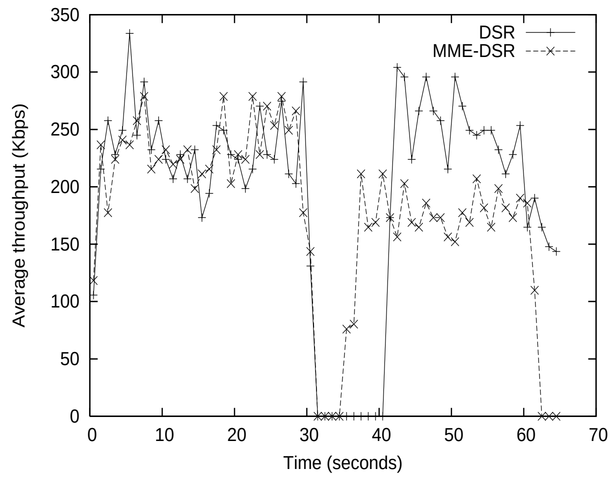

Figure 6. Average throughput for connection from node 10 to node 1.

through other nodes. As the two clusters of nodes move out of range, both versions of DSR experience a loss of connectivity at 30.5 sec. However, later when the nodes come again into communication range, MME-DSR quickly reestablishes the connectivity through the edge nodes 3 and 6 at 40.5 sec. On the other hand DSR fails to reestablish the connection at all. This is because in the case of DSR, the nodes 3 and 6 had been depleted of their remaining energy resources at the start of the communication, hence they could not assist in reconnecting the network like MME-DSR. Also in the case of DSR the other nodes that had assisted in reconnecting the network from $t = 4.0$ sec to 30.5 sec did not come into range of each other after the movement was initiated. Thus, the throughput of the MME-DSR is higher than DSR and MME-DSR is more robust than DSR.

As seen in Figure 8 the throughput of MME-DSR was higher than that of DSR for the traffic from node 10 to node 1 for both versions of the DSR protocol. In the case of DSR node 3 and node 6 acted as forwarding nodes and were completely drained of battery energy by time $t = 4.0$ sec. For the same reason mentioned above, the MME-DSR was able to maintain the connection for a longer duration of time than DSR during separation of the clusters.

Summary of Experiments

From the observations of both sets of experiments it is evident that MME-DSR does not lose DSR's unique quality of quick adaptation to change in the topology and minimum delay in initial connecting time. Moreover, it avoids routing through nodes with lower energy and hence increases the chance to keep the connection alive for a longer period during movement. The algorithm proposed is simple and adds an overhead of no more than just a couple of bytes to the DSR route reply packet. Also the computational overhead is not increased, since we are just changing the metric that the source node will use to compute the best route to the destination.

The results of the experiments presented in this chapter, reaffirm the importance of robustness as a performance objective for ad hoc networks. The experiments also give a concrete example of the importance of the conservation of battery energy in mobile nodes. The necessity of keeping key connections alive as long as possible becomes more imperative in life-critical situations where ad hoc networks are potentially employed. The proposed protocol demonstrates one mechanism for achieving more robust routing solutions. It has been demonstrated that the shortest route to the destination is not always the best routing solution if robustness is an issue in network operations.

7 Conclusions

The research carried out for this paper was aimed at making contributions in two areas. First we performed a detailed performance evaluation of three major ad hoc routing protocols: DSR, AODV, and DSDV. Second, we proposed a max-min energy routing scheme that will not only improve the robustness of the routing protocol but will also help in energy conservation of the mobile nodes.

The performance comparison of these routing protocols was conducted under several adverse scenarios. The results of the performance evaluation suggest that DSR is more robust than AODV or DSDV in maintaining connectivity during adverse situations. Hence, we chose to implement and validate the max-min energy routing scheme by modifying the DSR protocol.

The behavior of the DSR protocol was studied and it was verified that the implementation of the route discovery and route maintenance of DSR in ns was according to the DSR draft [7]. We then incorporated the max-

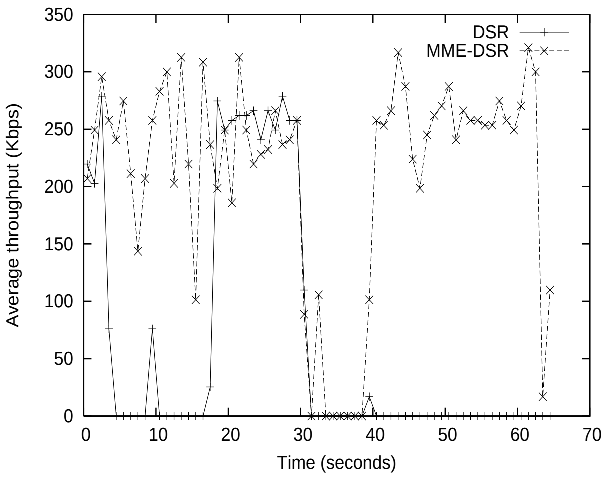

Figure 7. Average throughput for connection from node 4 to node 8.

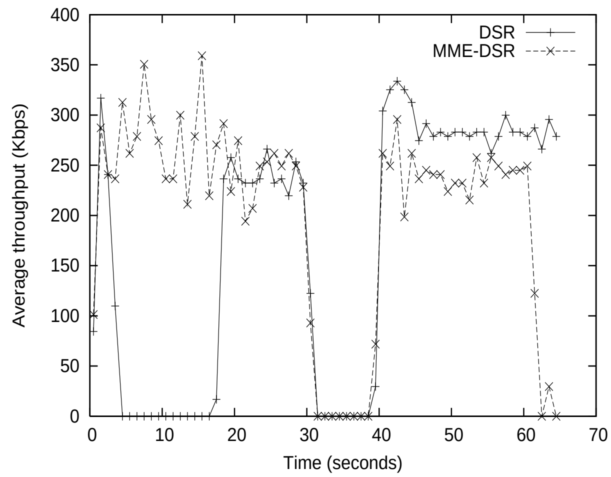

Figure 8. Average throughput for connection from node 10 to node 1.

min routing scheme in the DSR protocol. The MME-DSR protocol was simulated in several scenarios and its basic functionality was verified with reference to DSR. We then conducted performance evaluations of both versions of the protocol under simulated adverse scenarios. The results showed that the MME-DSR might prevent accelerated battery depletion of key mobile nodes serving as relay points for large volumes of traffic. The throughputs of the nodes in the network were either the same or higher than the values achieved with the DSR protocol. After a link breakage, the MME-DSR was able to reconnect the network faster than conventional DSR. Hence, the proposed routing scheme improved the robustness of the network and we were able to accomplish the goal that we had defined at the beginning of this endeavor.

A practical implementation of the scenarios defined in the simulations would certainly bring out some issues that might have been overlooked. Another interesting project would be the incorporation of the max-min routing algorithm in any other routing protocol that is capable of identifying multiple routes to a common destination.

The alternative routing criterion solution proposed is certainly not an ultimate solution for improving the energy efficiency of the mobile nodes or even for enhancing the robustness of the currently existing routing protocol. We will be pursuing the research in our future work that will introduce dynamic route switching even before link breakage. We also aspire to further enhance the min-max algorithm to compute the best path based on the combination of remaining energy and least number of hops. We also aspire to explore the tradeoff due to delay that is introduced due to MMRP Vs Least hop path and optimize the algorithm to strike a efficient balance between them.

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