Implementing Distributed Multicost Routing in Mobile Ad Hoc Networks Using DSR

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ABSTRACT

In this work we study the distributed implementation of multicost routing in mobile ad hoc networks. In contrast to single-cost routing, where each path is characterized by a scalar, in multicost routing a vector of cost parameters is assigned to each link, from which the cost vectors of the paths are calculated. These parameters are combined according to an optimization function for selecting the optimal path. Up until now the performance of multicost routing in ad hoc networks has been evaluated either at a theoretical level or by assuming that nodes are static and have full knowledge of the network topology and nodes' state. In the present paper we assess the performance of multicost routing, based on energy-related parameters, in mobile ad hoc networks by embedding its logic in the Dynamic Source Routing (DSR) algorithm, which is a well-known distributed routing algorithm. We compare the performance of the multicost-DSR algorithm to that of the original DSR algorithm under various node mobility scenarios. The results confirm that the multicost-DSR algorithm improves the performance of the network in comparison to the original DSR, by reducing energy consumption overall in the network, spreading energy consumption more uniformly across the network, and reducing the packet drop probability and delivery delay.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless Communication; C.2.2 [**Network Protocols**]: Routing Protocols

General Terms

Algorithms, Experimentation, Measurement, Performance

Keywords

ad hoc networks, routing, multicost, DSR

1. INTRODUCTION

An ad hoc network is a set of nodes that have the ability to communicate wirelessly without the existence of any fixed infrastructure. Nodes in an ad hoc network use other nodes as intermediate relays to transmit packets to their destinations. This makes routing a pivotal issue for these networks. Node mobility which is a common feature of these networks adds complexity to the routing problem since the network topology is subject to frequent changes. The routing algorithms designed for such networks either use periodical updates of the routing information collected, or discover routing paths on-demand. The DSR algorithm [5], which the present work extends, falls in the on-demand category of routing algorithms.

Most routing algorithms proposed to date use the single-cost approach. In single-cost routing each path is characterized by a scalar, which is the sum of the costs that characterize each of its constituent links. The link costs can be a function of several network parameters but they are still scalar. Routing algorithms of this kind calculate the path with the minimum cost for each source-destination pair. In most cases in ad hoc networks this metric is the hop count resulting in minimum-hop routing.

Multicost routing, presented in [1], is a generalization of the multi-constrained problem [15][3], where no constraints exist. In the multicost routing approach, a cost vector V_l consisting of several cost parameters is assigned to each link l. The cost vector of a path is constructed by combining component-wise the cost vectors of its links, according to some *associative operator*. The cost parameters on the links can be either *additive* or *restrictive* parameters. For an additive parameter the path cost is given by adding the corresponding parameters of the path's links. Typical examples of such parameters are the transmission delay and the energy consumption on a link, where the total delay and the total energy consumption on a path is the sum of the delay and the energy expenditure on its constituent links, respectively. For restrictive parameters the path cost is obtained as the minimum value among the corresponding parameters of the links on the path. For instance the capacity and the residual energy of a path are given by the "bottleneck" link, that is, the one with the minimum value of the corresponding parameter.

A key concept in the operation of multicost algorithms is the *domination relation* between paths. We will say that a path p_1 dominates another path p_2 that has the same source-destination pair, if p_1 is better than p_2 with respect to all the cost parameters. The set of non-dominated paths P_{n-d} for a given source-destination pair is then defined as the set of paths with the property that no path in P_{n-d} dominates another path in P_{n-d}. The multicost routing algorithm consists of two phases: it first computes a set of candidate non-dominated paths for a given source-destination pair, and then it selects the path that minimizes a certain optimization function. Different optimization functions give rise to different routing algorithms.

Apart from the aforementioned phases, the collection of the network link information also has to be performed, and has not been addressed in previous works on multicost routing [13][7][6]. Multicost routing was implemented in a centralized manner assuming global knowledge of the network state and topology by all network nodes at every instance. Node mobility was also neglected when evaluating the performance of multicost routing. The present work is, to the best of our knowledge, the first to examine distributed multicost routing for mobile ad hoc networks in a realistic scenario. Specifically, we embed multicost routing into a traditional mobility aware routing algorithm for ad hoc networks, namely Dynamic Source Routing (DSR) [5]. This way the multicost algorithm makes use of the DSR's mechanisms for path discovery and maintenance in order to learn and update the information regarding the path cost vectors. The operation of the multicost routing algorithm is fully distributed at each node.

The cost parameters considered for each network link are the transmitter node's residual energy and the transmitter node's transmission power, thus yielding an energy-aware mobility-enhanced multicost algorithm. The reason we included energy related cost parameters is that energy efficiency in mobile ad hoc networks is a top priority given that the nodes of such networks are usually battery-operated, and energy is a scarce resource limiting the performance and lifetime of the network.

The proposed multicost-DSR algorithm is compared to the original DSR algorithm through simulations. The results show that the multicost-DSR algorithm enhances the performance of the network not only by reducing energy consumption overall in the network, but also by spreading energy consumption more uniformly across the network as well. This prolongs the lifetime of the network and reduces the packet drop probability. Furthermore, the delay suffered by the packets that are delivered to their destination by the multicost-DSR algorithm is shown to be lower than in the case of the original DSR algorithm. We also observe in our results that the multicost-DSR algorithm uses alternate paths to route traffic reducing the congestion in the network.

The remainder of the paper is organized as follows. In Section 2 we report on previous work. In Section 3 we describe the basic steps of the implementation of the multicost-DSR algorithm. In Section 4 we discuss the simulation environment, where we conducted the experiments and the results obtained. Finally, Section 5 concludes the paper.

2. PREVIOUS WORK

Several works have dealt with modifying traditional routing algorithms for ad hoc networks, like DSR and AODV, in order to extend their functionalities and improve their performance. In [10] a link breakage prediction algorithm is incorporated in DSR, which makes use of link signal power strength information in order to proactively search for alternate routes. In [11] the ability to store and use more than one alternate paths was added to the DSR algorithm, improving its performance and balancing traffic load. In [9] the DSR algorithm is modified in order to achieve energy efficiency by taking into account node residual energy and transmission power. These metrics, however, are combined in a single scalar metric characterizing each path resulting in a single-cost routing algorithm. The authors of [16] modify the DSR algorithm by prefering nodes with higher residual energy when forwarding packets. This way the performance of DSR is enhanced resulting in longer network lifetime and higher packet delivery probability.

Regarding the extensions proposed for the AODV algorithm, [2][8] modified the AODV algorithm to include the source route accumulation mechanism of the DSR algorithm, resulting in better performance over the traditional AODV algorithm. In [14], a location-aware version of AODV is presented that proposes appropriate locations where the network nodes should move in order to improve the performance of the network. In [17] AODV is modified to take into account hop-count, node stability and load when selecting appropriate routes. Even though [17] uses more than one link cost parameters, as in our multicost routing approach, these are combined into a scalar metric and single cost routing is used. The results in [17] show an enhancement in the performance compared to the original version of the AODV algorithm. In [4] AODV was modified to incorporate node caching and load balancing techniques.

All the aforementioned papers focus on certain aspects of the operation of the DSR or the AODV algorithm and make appropriate modifications to improve their performance. Our work is different in that it uses DSR just as a building block for implementing a novel algorithm. The multicost-DSR algorithm that we propose incorporates the update mechanisms provided by DSR, but apart from that follows a totally independent way of operation.

Multicost routing was first presented in [1] where it was applied to wireline max-min fair share networks. Multicost routing is a generalized version of the multi-constrained problem [15][3], where no constraints exist. In [13][7][6] multicost routing was examined for wireless ad hoc networks under different assumptions for the network model, and using various link cost metrics and optimization functions. The cost metrics used for the network links were the residual energy of the nodes, the link transmission power and the interference caused by the transmission on a link. In all cases, multicost routing was shown to outperform traditional minimum-hop routing in terms of energy consumption dispersion, packet delivery capability and network lifetime. However, a common assumption of the aforementioned works is that nodes are static and have at any instance global knowledge of the network state. In contrast, in the present paper multicost routing is implemented in a fully distributed fashion, and mobility is taken into account both in the implementation of the algorithm and in the performance results taken.

3. IMPLEMENTATION MODEL

The routing process consists of two types of functions: the routing information collection function and the path selection function. Routing information protocols deal with collecting and disseminating network state information, while routing algorithms compute the optimal path(s) using this information. The DSR algorithm [5] provides a Route Request/Route Reply mechanism for the first function and uses the minimum-hop routing for the second.

So far, multicost routing has been studied focusing only on the routing function [13][7][6]. Regarding the collection and dissemination of the network state information, all the aforementioned works assume that the network topology and the nodes' state information is globally and instantly known to every network node. Thus, multicost routing in the aforementioned papers deals only with enumerating the set of candidate (non-dominated) paths for each source-destination pair and choosing the optimal one based on a certain optimization function that combines the cost parameters.

In this paper a fully distributed mobility-enhanced version of multicost routing algorithm for wireless ad hoc networks is implemented by embedding the multicost routing approach into DSR. The multicost-DSR algorithm consists of three phases: a) collection and update of the information regarding the path cost vectors, b) calculation and formation of the set of non-dominated paths to every destination, and c) selection of the optimal path to a destination by applying an optimization function to the candidate (non-dominated) paths. The multicost-DSR algorithm makes use of the route discovery and maintenance mechanisms of the DSR algorithm for the first phase, that is for collecting the necessary information. In doing so, these mechanisms are modified in order to include the link cost parameters and the ability to store multiple paths per destination. The formation of the set of non-dominated paths and the selection of the optimal path are functionalities that were added to the original DSR algorithm since they are specific to the multicost-DSR algorithm. Below the implementation of each of the aforementioned building blocks of the multicost-DSR is described. It is important to note that these changes do not add overhead in terms of computation or energy consumption on the network nodes.

3.1 Collection of network topology and cost metrics information

The path discovery and maintenance mechanisms of the DSR algorithm have been augmented to incorporate the node cost parameters used by the multicost-DSR algorithm and the ability of each node to store in each cache multiple paths per destination.

In the original DSR algorithm when a node receives a Route Request (RREQ) packet destined to another node, it simply adds its unique identification number (ID) to the under-construction path node array and then broadcasts it to its neighbors until the destination node or a node knowing a path to it is reached. Then a Route Reply (RREP) packet is sent back to the origin node, which stores the newly found path in its route cache. When the information about another path to the same destination reaches the origin node, the two paths are compared and the one with the minimum hop count is kept in the cache.

In the multicost-DSR algorithm the information kept for each route includes not only the IDs of the nodes on the path, but also the cost parameters related to them. So, each node when adding itself in an under-construction path's node array it also adds its own cost parameters. In this way when the path construction process is completed, all the necessary

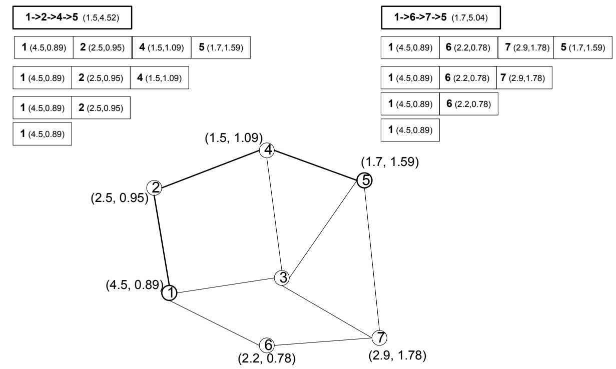


Figure 1: Illustrates the path construction mechanism of the multicost-DSR algorithm for paths $1 \rightarrow 2 \rightarrow 4 \rightarrow 5$ and $1 \rightarrow 6 \rightarrow 7 \rightarrow 5$. The link's cost vector are in the form of (R_i, T_i), where i is the link, R_i its origin node's residual energy and T_i its origin node's transmission power. The path node array is expanded to include in every entry, apart from the node ID, the corresponding link's cost vector as well. Finally, when the path is constructed the path cost vector is produced according to the associative operators of each cost parameter. The path's residual energy is given by the minimum residual energy on the path, while the path transmission power by the sum of the transmission powers of its nodes.

for the multicost-DSR algorithm information is gathered and thus the rest of its operation can be carried out. By combining component-wise the parameters of the path's links, the path cost vector is obtained and then by applying an optimization function the cost of the path is produced, based on which the optimal path is selected. Figure 1 summarizes all the above.

When the information on another path to the same destination reaches a node, the domination relation between them is first checked, as described below, and if they are non-dominated to each other, they are both stored in the cache. If one of them proves to be dominated by the other, then it is discarded.

In the present work the parameters used are the node residual energy and the node transmission power. The node residual energy is used as a restrictive parameter, that is the minimum residual energy of the path's nodes represents the path's residual energy. The node transmission power is used as an additive parameter, that is the transmission power cost metric of a path is the sum of the transmission powers of its nodes.

3.2 Updating the cache

The multicost-DSR algorithm relies only on the path discovery and maintenance processes of the DSR in order to gather network topology and state information. In DSR when a path enters the route cache of a node it is used until the node finds out it is not valid anymore. Until then no new route discovery process to the same destination is initiated by the node. This on-demand nature of the DSR algorithm means that there can be no guarantees for multicost-DSR regarding the frequency of the cache updates.

However, the accuracy of the information regarding the paths stored in each node's cache is indispensable for the multicost-DSR algorithm to perform efficiently. Apart from the possibility that some paths stored in the cache may become invalid, some of the parameters taken into account, in the general case, can change over time. In the present work the only time varying parameter is the node residual energy. Thus, even if the paths in the cache remain connected, their residual energy related information becomes obsolete. This way the multicost-DSR algorithm can not be accurate in selecting the most energy efficient path.

In our effort to improve the accuracy of the information kept in each route cache, whenever a node discovers a new route or overhears a route being used, it also updates accordingly the information of the newly found route's nodes in all the routes in its cache. Furthermore when the optimal path is chosen, the energy that is going to be expended on its nodes is calculated and the information on the residual energy of these nodes in all the paths stored is proactively updated.

3.3 Domination relation

A key aspect of the multicost approach is that only the non-dominated paths between a certain source-destination pair are taken into account in the final stage of the algorithm. A path P_1 is said to dominate another path P_2, when P_1 is better than P_2 with respect to all the parameters in use. In our case, let us assume two paths $P_1(r_1, tx_1)$ and $P_2(r_2, tx_2)$ between two network nodes with r_i the minimum residual energy on the nodes of path P_i, tx_i the total transmission power expended on path P_i and $i \in 1, 2$. Path P_1 dominates path P_2 if $r_1 > r_2$ and $tx_1 < tx_2$.

The original DSR algorithm stores, in its routing cache, only one path per destination, that is the one with the minimum hop count. In multicost-DSR multiple paths for each destination are kept in a node's route cache. When a node initiates a path discovery process to a certain destination, it usually receives many Route Reply packet responses from different nodes. In multicost-DSR before a node adds a discovered path in its route cache, it checks if this path dominates or is dominated from a path to the same destination already in the cache. If the newly found path is dominated by an existing path in the cache, the path is discarded. If the newly found path dominates paths already in the cache, then those paths are discarded, and the new path is stored in the cache. The same process is followed also when a node overhears about a route being used by other nodes. This way a node keeps in its route cache only the non-dominated paths to a destination.

3.4 Selection of the optimal path

The final step of the multicost-DSR algorithm is performed when a node wants to route a packet to a destination node. Then the source node selects the optimal path for the destination node from the set of non-dominated paths stored in its cache. In doing so, it applies an optimization function to the cost vectors of the candidate paths, producing the paths' costs. The path with the minimum cost is then selected as the optimal path to be used.

In this work the optimization function we use is

$$f(T, R) = \frac{\sum_{i \in P} T_i}{\min_{i \in P} R_i},$$

Parameter description	Value
Number of nodes	49
Nodes' transmission range	50m-250m (uniformly)
Number of packets per session	50
Packet size	1024 bytes
Packet transmission interval	1 second
Number of sessions	20-100 (step 20)
Node initial energy	10/50/500 Joules
Maximum node speed	2-12 meters/sec (step 2)
Node pause period length	1 second

Table 1: List of simulation parameters

where P is the path, i is iterating through the path nodes, T_i is the transmission power of node i and R_i the residual energy of node i.

4. PERFORMANCE RESULTS

In our simulations we use the Network Simulator (NS) [12]. Specifically, the implementation of the multicost-DSR algorithm is built upon the native DSR implementation of the NS (original DSR algorithm). The experiments were conducted on a network of 49 nodes, initially placed along the points of a $7x7$ grid with 100m distance between neighboring nodes. The network nodes move following the Random Waypoint model [5]. According to this model a node selects uniformly a destination point and moves towards it with a certain speed. When it arrives there, it stays for a pause period and then follows the same procedure. In our experiments the speed assigned to each node is uniformly distributed between 1 and a maximum value, which in the experiments was taken equal to 2 to 12 m/sec, at step 2. The pause time was 1 second for all nodes.

All the nodes have equal initial energy, which is either equal to 10 Joules, equal to 50 Joules, or equal to 500 Joules. The nodes' transmission range is uniformly distributed between 50m and 250m. The energy expended for a transmission is given by multiplying the source node's transmission power with the duration of the transmission. We assume that energy expended for packet reception is constant and that no energy is expended when a node is moving, remains static, or idle. The two algorithms were evaluated against an increasing number of sessions. Specifically, the number of sessions created in the network were 20 to 100, at step 20. Each node with a session generates 50 packets of 1024 bytes each, with an interval of 1 second between two successive packet generations. The source and destination node of the packets in each session are uniformly distributed over all nodes. Table 1 summarizes the parameters used in our simulations. Each experimental scenario was run 10 times, using an independent random seed and the values depicted in the figures below are the averages of these runs.

The metrics of interest are the average number of hops of the paths selected by the algorithms, the average residual energy left at the network nodes in the end of the experiment and its variance, the probability of a packet being dropped and the packet delay. These metrics were evaluated for different number of generated sessions per node and different levels of node maximum speed.

Figure 2 shows the average residual energy left at the network nodes at the end of the experiments, for the all

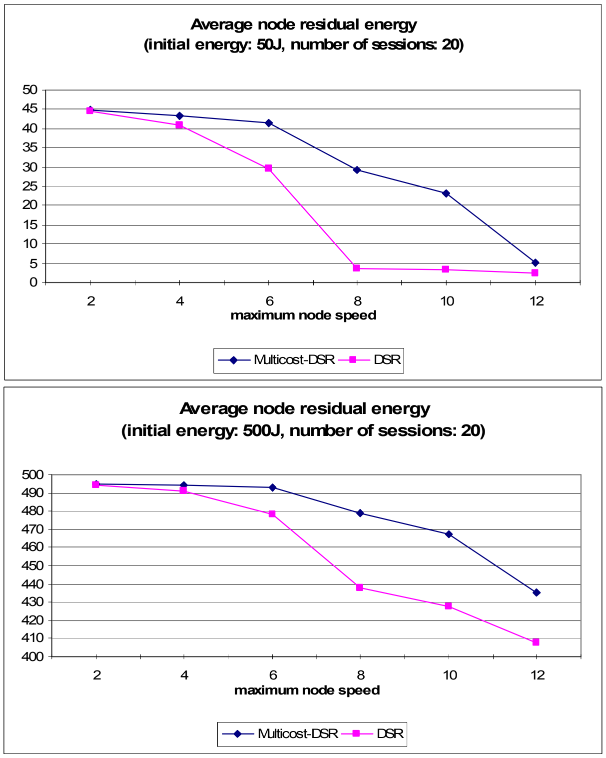


Figure 2: Illustrates the average residual energy left at the network nodes for the multicost-DSR algorithm and the original DSR algorithm with 20 sessions in the network in the cases of node initial energy of (a) 50 Joules, and (b) 500 Joules.

the cases of initial energy. We observe that the multicost-DSR algorithm achieves larger average residual energy than the original-DSR algorithm, since it selects energy efficient routes. The hop count that is the only criterion for the path selection in the original DSR algorithm, also takes part in the path selection process in the multicost-DSR algorithm, even indirectly, given that the transmission power cost metric of a path is taken to be the sum of the transmission power expended on each of its links. However, its use ensures that the paths used for the packet transmissions are the most energy efficient, whereas in the original DSR algorithm this is not always the case. For example when choosing between two paths of the same hop count, a minimum hop routing algorithm like the original DSR selects arbitrarily, while the multicost-DSR algorithm selects always the one that is more energy efficient. It is worth noting that the multicost-DSR algorithm results in higher average residual energy than the original DSR algorithm while in the same time successfully delivering more packets to their destinations (Figure 4).

Furthermore, it is important to underline the effect of the node mobility on the performance of the multicost-DSR algorithm. Due to the on-demand nature of the DSR algorithm, a node is triggered to discover a path to a destination only when it needs to, i.e. when a packet towards a destination with no known route is created or when the path currently in use becomes invalid. The increased node mobility leads to many path disconnections and hence route discovery initiations. As a result, the nodes end up having more accurate knowledge of the time-varying parameters regarding the nodes' state that take part in the routing decisions made by the multicost-DSR algorithm. This is why the difference in the performance of the two algorithms grows with the node mobility.

In the cases of restricted initial energy, however, when the mobility grows above a certain limit the two algorithms behave similarly because many nodes run out of energy. As it can be seen in Figure 2, the average node residual energy decreases as the node mobility grows. This is because the frequent changes in the network topology trigger the exchange of more control messages, in order to re-establish feasible paths to the destinations. This results in the increase of the number collisions, the packet retransmissions and thus in the increase of the energy consumption. On the other hand in the case of non-restricted energy reserves (Figure 2b) the multicost-DSR algorithm results in higher average residual energy than the original DSR algorithm for all the node mobility scenarios.

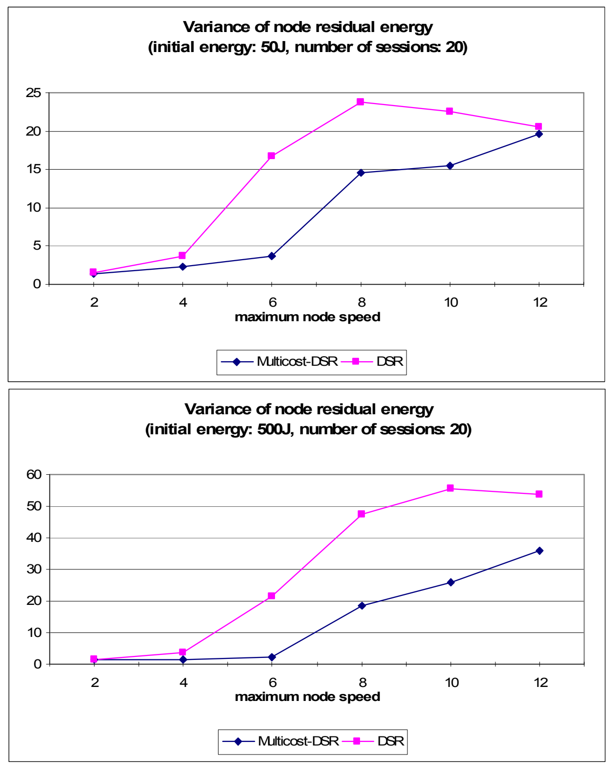


Figure 3: Illustrates the variance of the residual energy left at the network nodes for the multicost-DSR algorithm and the original DSR algorithm with 20 sessions in the network in the cases of node initial energy of (a) 50 Joules, and (b) 500 Joules.

Figure 3 shows the averaged over all experiments variance of the residual energies of the nodes at the end of the experiment. It can be observed that regardless of the initial energy or the node mobility level, the multicost-DSR algorithm results in lower variance of the node residual energy than the original DSR algorithm.

The difference between the two algorithm is obvious for all the scenarios. Only when the mobility is too low or the high mobility expends much of the nodes restricted energy reserves the original DSR algorithm approaches the multicost-DSR algorithm. In all the other cases the node mobility favors the multicost-DSR algorithm since it forces the network nodes to initiate path discovery processes more frequently and thus have a better view of the nodes's state which is necessary for the efficient operation of the multicost-DSR algorithm.

The multicost-DSR algorithm manages to spread energy consumption more evenly across the network by storing a set of non-dominated paths for each destination in the route cache of each node instead of just the one with the minimum hop-count that the original DSR algorithm stores. Then an optimization function is applied to the set of non-dominated paths to select the optimal path. This way the algorithm can select different paths for the same source-destination pair, since the the energy related cost parameters (e.g., node residual energy) of the multicost-DSR change over time. As a result the energy consumption is spread more uniformly, over a larger number of nodes, leading to lower variance of the node residual energy. On the other hand in the classical minimum hop count routing (like in the original-DSR) a source node routes packets using always the same path as long as it remains connected.

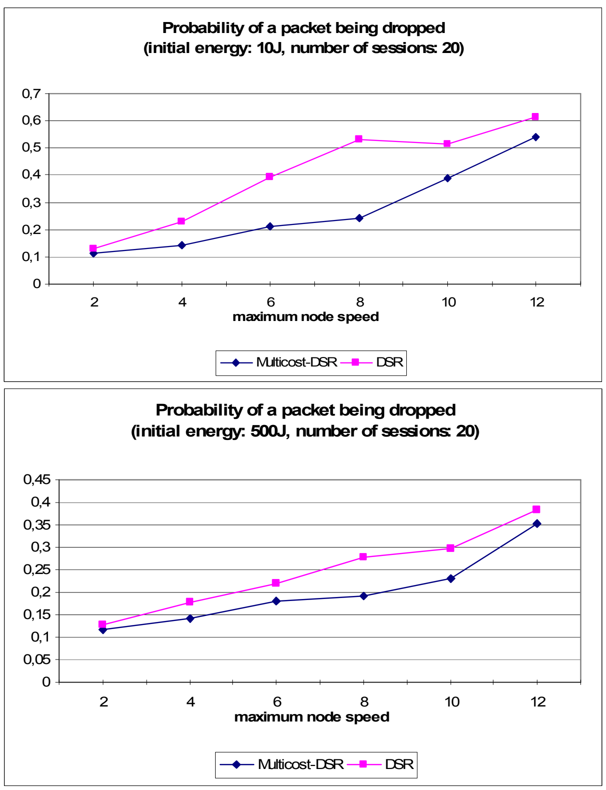


Figure 4: Illustrates the probability of a packet being dropped for the multicost-DSR algorithm and the original DSR algorithm with 20 sessions in the network in the cases of node initial energy of (a) 10 Joules, and (b) 500 Joules.

Figure 4 shows the probability of a packet being dropped. A packet is dropped because it is located in or destined to a node that runs out of energy, or because the maximum number of its retransmissions is reached. This is why as it can be observed in Figure 4 both algorithms perform better as the node initial energy grows. Similarly as the node mobility grows higher the probability of a packet being dropped increases in all cases since establishing a stable path for transmission becomes more difficult.

However, in all figures the multicost-DSR achieves lower values than the original DSR, meaning that more packets are delivered to their destination. This is because as shown in the results regarding the residual energy (Figures 2 and 3) the nodes have higher energy reserves and energy is more uniformly distributed among the nodes using the multicost-DSR. This means that the network lifetime is prolonged and thus paths remain connected during more time. As a result with multicost-DSR more packets reach their destination than with the original DSR.

The difference between the two algorithms is more obvious when the node mobility is neither too low or too high. In the former case the topology changes are not often enough to trigger frequent path discovery initiations that are the only means for information update for the multicost-DSR algorithm. In the latter case the mobility causes so many topology changes that the update mechanisms provided by the DSR protocol can not maintain an efficient operation for the multicost-DSR algorithm. However even for these unfavorable cases the multicost-DSR algorithm succeeds in delivering more packets to their destination than the original DSR algorithm.

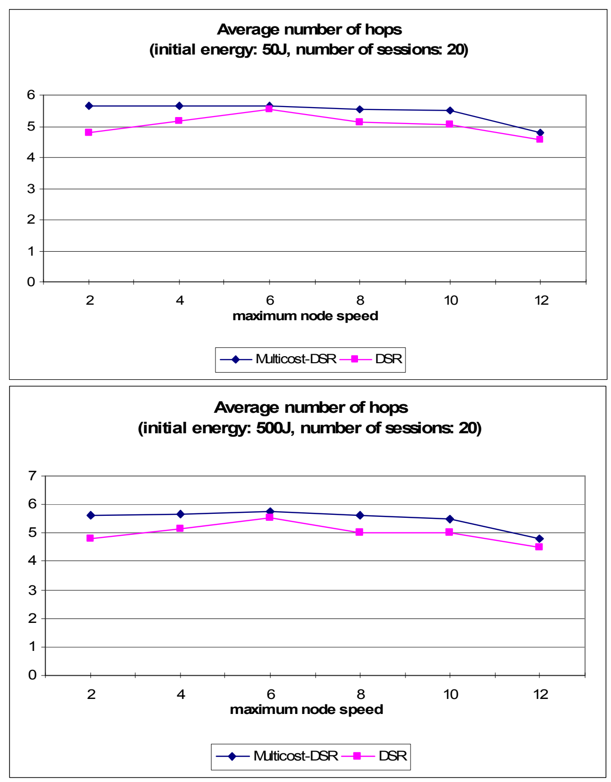
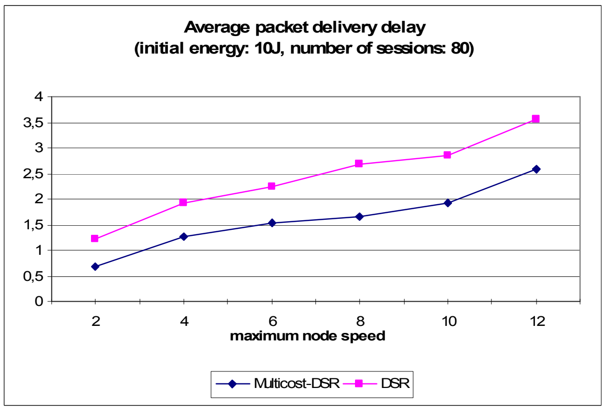


Figure 5: Illustrates the average number of hops for the multicost-DSR algorithm and the original DSR algorithm with 20 sessions in the network in the cases of node initial energy of (a) 50 Joules, and (b) 500 Joules.

Figure 5 shows the average number of the hops on the paths selected by the algorithms. We observe that in all cases the original DSR algorithm selects shorter paths than the multicost-DSR. This is expected given that the only criterion that the original DSR uses for the path selection, is the hop count. On the other hand the multicost-DSR algorithms selects the optimal path based on the path cost vector, consisting of the transmission power and residual energy path parameters.

An additional point to note is that for all cases when the node mobility grows above 10 meters/second, the average number of hops decreases slightly for both algorithms. This is because at high mobility rates the longer a path the higher the probability that it will get disconnected. Hence the paths followed by the packets reaching their destination are on average smaller than in the cases of lower mobility. This however affects both algorithms the same.



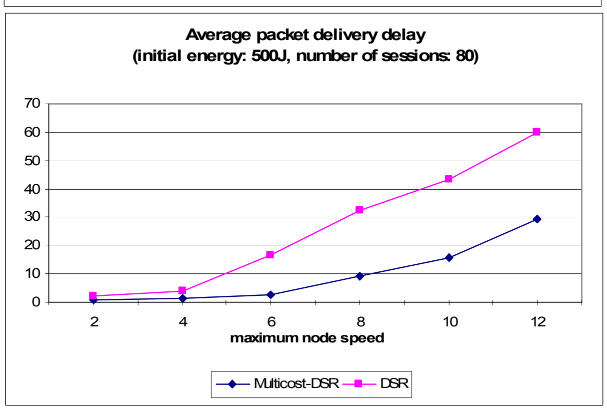


Figure 6: Illustrates the packet delivery delay for the multicost-DSR algorithm and the original DSR algorithm with 80 sessions in the network in the cases of node initial energy of (a) 10 Joules, and (b) 500 Joules.

In Figure 6 the results regarding the packet delivery delay are shown. We define the packet delivery delay as the time that elapses between the departure of the packet from the origin node and its arrival at the destination node. Only the packets having reached their destination are taken into account.

In all the scenarios the multicost-DSR algorithm outperforms the original DSR algorithm in terms of the packet delivery delay. The multicost-DSR algorithm results in lower average packet deliver delay as the node mobility grows in all cases of node initial energy. This is justified by the general argument already mentioned above that the increased mobility makes the multicost-DSR algorithm more accurately informed about the network nodes' state because the path discovery processes are more frequently initiated. This way the routing decisions made by the multicost-DSR algorithm lead to better results as it was also shown regarding the node residual energy and the packet drop probability.

Another factor resulting in lower average packet delivery delay for the multicost-DSR algorithm compared to the original DSR algorithm is that the multicost-DSR algorithm stores a set of candidate paths instead of just one, which is the case for the original DSR algorithm. As a result, when a path gets disconnected another path already stored in the cache can be used saving the delay caused by discovering a new route to the destination.

Furthermore, the multicost-DSR algorithm directs the traffic through less congested paths across the network than the original DSR algorithm. The latter selects and uses a single path to a destination for as long as it remains connected, while the former alternates between the non-dominated paths. This benefits the performance of the multicost-DSR algorithm in terms not only of uniform spreading of the energy consumption (Figures 2) but of lower average packet delivery delay as well. The intermediate nodes' buffers are not that congested and thus the packets reach their destinations sooner.

We should underline that the average packet delivery delay grows with the node initial energy because the network lifetime is prolonged and thus more packets are taken into account. In situations of high node mobility this increased number of packets reaching their destination has suffered long delays due to the difficulty of establishing and maintaining a stable route.

5. CONCLUSIONS

We have implemented a fully distributed multicost routing algorithm, multicost-DSR, without assuming any sort of global knowledge on network topology and state by embedding it into the original DSR algorithm. The multicost-DSR algorithm relies only on the DSR's mechanisms of route discovery and maintenance in order to collect the information regarding the network topology and state which is necessary for the enumeration of the set of candidate (non-dominated) paths for every destination. The cost parameters taken into account by the multicost-DSR algorithm for each network link are the transmitter node's residual energy and the transmitter node's transmission power. A path's residual energy is taken to be the minimum residual energy of its nodes, while a path's transmission power is taken to be the sum of the transmission powers of its nodes. The optimization function used in order to determine the cost based on which the optimal path is selected, combines the paths cost parameters in the following manner:

$$f(T,R) = \frac{\sum_{i \in P} T_i}{\min_{i \in P} R_i},$$

where P is the path, i is iterating through the path nodes, T_i is the transmission power of node i and R_i the residual energy of node i.

The multicost-DSR algorithm, due to the energy-related cost metrics it takes into account, makes better use of the disposed energy reserves of the network nodes in comparison to the original DSR algorithm resulting in lower energy consumption and more uniform energy consumption in the network. The paths used by the multicost-DSR algorithm are energy-efficient, whereas the original DSR algorithm is only based on the hop count. Therefore multicost-DSR reduces overall energy consumption in the network, in spite of delivering more packets and using longer paths. The multicost-DSR algorithm also manages to spread energy consumption more evenly across the network by alternately using a set of non-dominated paths for each destination, instead of just the one that is the case for the original DSR. This way the network lifetime is prolonged and more packets are successfully sent to their destinations.

The fact that the multicost-DSR algorithm stores multiple paths per destination means that the packets encounter less congested queues on their way to their destination and that when a path gets disconnected another path already stored in the cache can be instanty used saving the delay caused by discovering a new route to the destination. Therefore the packets suffer lower delay in their way to their destination.

Node mobility improves the performance of the multicost-DSR algorithm in comparison to the original DSR algorithm regarding all metrics of interest. As mobility grows the path disconnections due to topology changes become more frequent, and therefore the path discovery processes are performed more often. The multicost-DSR algorithm is based on these procedures in order to acquire the necessary information regarding the link cost parameters. As a result, the information on the time-varying cost parameters stored in each node's cache becomes more up-to-date and thus the operation of the multicost-DSR algorithm more efficient.

However, in the scenarios of low mobility the path discovery mechanisms are not called sufficiently often in order to provide the multicost-DSR algorithm with up-to-date information on the time-varying cost parameters Due to the on-demand nature of the DSR algorithm, these mechanisms are only called when a path to a destination becomes invalid. Therefore in the cases of low mobility the operation of the multicost-DSR algorithm becomes static and its performance degrades to that of the original DSR algorithm. On the other hand when the node mobility increases beyond a certain point, the topology changes become so frequent that the update mechanisms provided by the DSR protocol can not ensure the accuracy of the information. Therefore in scenarios of extremely low or high mobility the difference between the two algorithms decreases.

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