An Extended Dynamic Source Routing Scheme in Ad Hoc Wireless Networks*

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Abstract

In this paper we consider a multipath extension to the *dynamic source routing* (DSR) protocol proposed by Johnson and Maltz, an on-demand routing protocol for ad hoc wireless networks. This extension keeps two node-disjoint paths between the source and destination of a routing process without introducing extra overhead. Unlike other multipath extensions where node-disjoint paths are selected at the destination or at the reply phase, our approach generates two node-disjoint paths during the query phase of the route discovery process by restricting the way the query packet is flooded. Several optimization options are also considered. Simulation is conducted to determine the success rate of finding node-disjoint paths.

Key words: Ad hoc wireless networks, dynamic source routing (DSR), multipath routing, optimization, simulation.

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1 Introduction

Recent advances in technology have provided portable computers with wireless interfaces that allow networked communication among mobile users. The resulting computing environment, which is often referred to as mobile computing, no longer requires users to maintain a fixed and universally known position in the network and enables almost unrestricted mobility. An *ad hoc wireless network* [4] is a special type of wireless mobile network in which a collection of mobile hosts with wireless network interfaces may form a temporary network, without the aid of any established infrastructure or centralized administration. The applications of ad hoc wireless networks range from civilian (e.g., distributed computing, sensor networks) to disaster recovery (search-and-rescue) and military (battlefield).

An ad hoc wireless network can be represented as a simple directed graph $G = (V, E)$, where V is the vertex set representing a set of wireless mobile hosts (also called nodes) and E is a set of edges representing a set of links (channels). An edge (v, u) from v to u indicates that host u is within the wireless transmitter range of host v. Such a graph is also called *unit disk graph*, or simply, unit graph.

Routing is a process of sending a message from one mobile host in the network to another (it is also called *unicast*). Routing protocols for ad hoc wireless networks normally call for *mobility management* and *scalable design*. Mobility management is done through information exchanges between moving hosts in the ad hoc wireless network. In general, when information exchanges occur frequently, the network maintains accurate information of host locations and other relevant information. However, frequent information exchanges can be costly, because they consume communication resources including bandwidth and power. With less frequent information exchanges, these costs diminish but there is more uncertainty about the host's location. Scalable design (one that works for large size networks) requires both routing protocols and resource consumptions to be scalable.

Routing in the ad hoc wireless network poses special challenges because of its infrastructureless network and its dynamic topology. The tunnel-based triangle routing of mobile IP [15] works well if there is a fixed infrastructure to support the concept of the "home agent". However, when all hosts move (including the home agent), such a strategy cannot be directly applied. Traditional routing protocols for wired networks, that generally use either *link state* [10] or *distance vector* [5], are no longer suitable for ad hoc wireless networks. In an environment with mobile hosts as routers, convergence to new, stable routes after dynamic changes in network topology may be slow and this process could be expensive due to low bandwidth. Routing information has to be localized to adapt quickly to changes such as hosts movement.

Routing protocols for ad hoc wireless networks can be roughly divided into *proactive* and *reactive*. In proactive routing, each host continuously maintains complete routing information of the network. Both link state and distance vector belong to proactive routing. The reactive scheme, on the other hand, invokes a route determination procedure only on demand through a query/reply approach. Dynamic source routing (DSR) protocol [7] is a reactive routing protocol. The source determines the complete path for each routing process. The approach consists of *route discovery* and *route maintenance*. Route discovery allows any host to dynamically discover a route to a destination host. Each host also maintains a route cache in which it caches source routes that it has learned. Unlike regular routing-table-based approaches that have to perform periodic routing updates, route maintenance only monitors the routing process and informs the sender of any routing errors. Without the use of routing tables to keep track of routes, mobility management and scalable design can be relatively easy to manage.

However, the efficiency of DSR depends largely on the "hit ratio" of route cache. That is, the probability a route to the destination exists in the cache. When a miss occurs, the system has to invoke a relatively expensive route discovery process via flooding. In this paper, we propose a novel approach to reduce the frequency of invoking the routing discovery process. The idea is to keep two node-disjoint routes to each destination in the route cache. One route is designated as the primary and the other the backup. When the primary route fails, the alternative route can be used without invoking a route discovery process. Another alternative is to use both paths at the same time and packets are split along paths.

Two node-disjoint routes are constructed during the route discovery process *by restricting the way the query packet is flooded in the network in the query phase and the way routes are stored in the route cache of each node in the route reply phase*. Other than the color mark of each node along a route and a dirty bit associated with each route in the route cache, the construction process does not introduce additional overhead, compared with the regular route discovery process. Several optimization options are also considered. Simulation is conducted to determine the success rate of finding node-disjoint paths. Note that DSR also provides an option of constructing edge disjoint paths, so that an alternate path can be used when the primary path fails. However, too many paths are maintained in DSR in a trivial matter, without any regard to their ultimate usefulness.

The paper is organized as follows: Section 2 gives preliminaries and related work on multipath routing. Section 3 proposes the extended dynamic source routing. Several optimization options are studied in Section 4. Section 5 shows some simulation results on the effectiveness of the proposed approach in finding two node-disjoint paths. Section 6 concludes this paper.

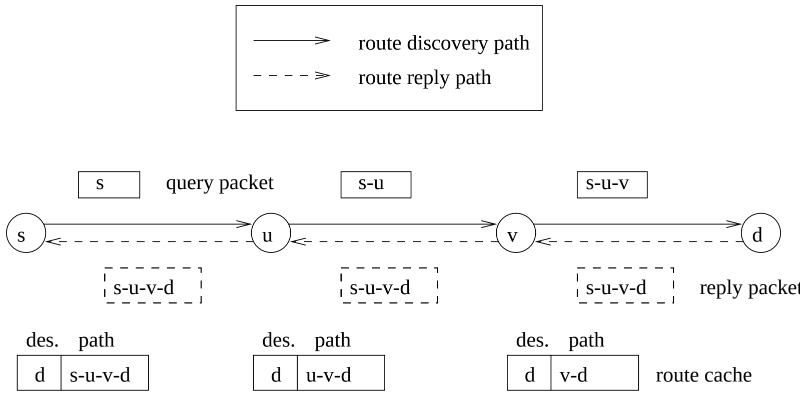


Figure 1: The query and reply phases in the route discovery process.

2 Preliminaries

2.1 DSR

Dynamic source routing protocol (DSR) [7] is a reactive routing protocol. Unlike other protocols, DSR requires no periodic packets of any kind at any level within the network. The approach consists of route discovery and route maintenance. Route discovery allows any host to dynamically discover a route to a destination host. Each host also maintains a route cache in which it caches source routes that it has learned. The source determines the complete path for each routing process. When the source cannot find a route to the destination from its cache, it initiates a route discovery process that consists of two phases: query and reply. First, a *query* packet initiated from the source floods the network in seeking of a route to the destination. When the destination receives a query packet, it replies with a *reply* packet that copies the route from the query packet and traverses it backwards (or via a different route back to the source). Route information to the destination is stored in route cache of each node as learned from the reply packet. Note that more than one route reply packet may be generated at the destination. However, the destination can control the number of reply packets. Route reply packets can also be generated at an immediate node where the route to the destination exists in the route cache. In this case, the number of reply packets is difficult to control. Route maintenance maintains source routes to arbitrary destinations. Other details of route maintenance are of no interest here and, hence, they will not be discussed further.

Figure 1 shows a routing example in a simple linear network. Source s first sends out a query packet. A sequence of network hops is accumulated during the query process. Once the packet reaches destination d, d replies with a reply packet that copies the complete route $s-u-v-d$ and traverses the route backwards. Route information to d is stored in route cache of each intermediate node (including the source). For example, u includes route $u - v - d$ in its route cache. Since links in the network can be unidirectional, the reply phase may have to use a different route to send out the reply packet to the source.

2.2 Related work

Multipath routing is one of the favorite mechanisms to balance network traffic and to provide fault tolerance and quality of service (QoS). Mathematical analysis has proven that splitting the traffic over the two or more paths is more efficient, and provides shorter delays overall [6]. Once multiple paths are constructed, there are in general two ways of using them: (a) One path is selected as a primary and all the rest are backups [8]. Only the primary path is used to transmit packets. Backups are used only when the primary path fails. (b) All paths are used at the same time and packets are split along paths. To tolerate packets loss, special codes, such as m-for-n [18], can be used where each original packet is split into n blocks. By adding m overhead blocks, $m + n$ multiple paths offer protection against m lost blocks. A hybrid approach is to use multiple paths in a round-robin fashion to distribute load [19].

Multipath routing has been extensively studied in wired networks [1], [2], [13], [16], and [17]. Most approaches use either link state or distance vector to compute multiple paths. Zaumen and Garcia-Luna-Aceves [21] proposed a multipath routing using diffusing computation for packet switching networks. In general, multipath routing is based on constructing first either *edge disjoint paths* or *node-disjoint paths* with the former being a special case of the latter. The multipath routing is also captured in OSPF [11], a link state routing protocol in Internet, by the notion of "equal cost multipath", where traffic should be split equally between all the equal cost paths.

Multiple path construction in a proactive approach, as used in wired networks, is not suitable for ad hoc wireless networks because of its excessive overhead. Some protocols for ad hoc wireless networks maintain multiple paths. Other than DSR, the Temporally Ordered Routing Algorithm (TORA) [14] maintains a directed acyclic graph (DAG) for each destination with the destination being the sink of the DAG. In this way, edge disjoint paths are maintained for each destination.

Nasipuri, Cartaneda, and Das [12] proposed a multipath extension to DSR by constructing node-disjoint paths. The destination keeps a record of the first arrived packet (including the complete path record initiated from a particular source). The subsequent packets arrived will be discarded until a packet with a node-disjoint path with respect to the first one arrives. All subsequent packets are discarded. Lee and Gerla ([8] and [9]) also provides two extensions to DSR. The first one gives a simple extension without extra overhead. Basically nodes in the neighborhood of intermediate nodes of a path are used to form a mesh structure providing alternate paths (but not node disjoint). The second approach is similar to the one proposed by Nasipuri, Cartaneda, and Das. The only difference is that each intermediate node can cancel a route if its length exceeds the length of the first-received route. Still the destination selects two node-disjoint routes. In all the existing multipath extensions to DSR, no information from route cache can be used to construct multiple paths.

Another way of constructing node-disjoint paths in DSR is based on the following strategy ([3] and [20]): In the query phase, each node still forwards the query packet the first time it receives. Instead of dropping all late-received query packets, these packets are cached for the later use. In the reply phase, the packet can be *re-directed* to the source based on the cache information stored at intermediate nodes. That is, the selected path can be altered during the reply phase. This approach, however, requires storing a good amount of route information at the cache storage of each node.

Unlike the approach in [12] and [9] where node-disjoint paths are selected at the destination or the approach in [3] and [20] where node-disjoint paths are selected during the reply phase, *our approach generates two node-disjoint paths during the query phase of the route discovery process by restricting the way the query packet is flooded.*

3 Extended Dynamic Source Routing

In DSR, route discovery tries to find a path to a destination by first sending out a query through flooding. If the route discovery is successful the source receives a route reply packet listing a sequence of network hops through which it may reach the destination. However, DSR is not suitable for constructing multiple node-disjoint paths. Suppose source s has multiple node-disjoint paths to destination d (see Figure 2). During the query phase, among three neighbors of s, suppose w_3 forwards the query packet before w_1 and w_2, both query packets initiated from w_1 and w_2 will be terminated. All paths generated at the destination share the common intermediate node w_3. This problem is called *single query domination.*

In the proposed extended dynamic source routing (EDSR), the probe/reply phases are constructed in a special way so that two node-disjoint routes (if they exist) are constructed as the result of a route discovery. Specifically, one route is called the *black route* with all nodes along the route colored black and another one is called the *white route* with all nodes along the route colored white. A node that has a white color, a black color, or both colors is said to be *marked* (for a particular route request); otherwise, it is *unmarked.* Initially, all nodes except the source

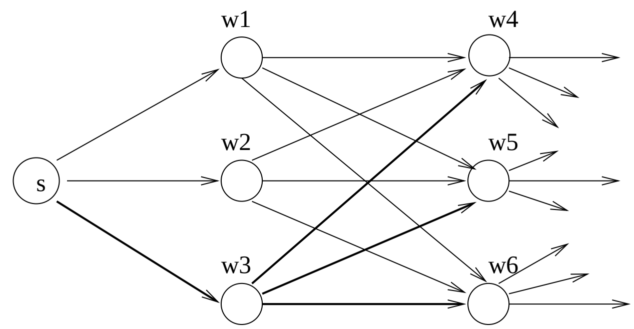


Figure 2: The *single query domination* problem in DSR.

node are unmarked. The source is initially marked both white and black. Color white is said to be complement to color black, and vice versa. We denote $white^{'} = black$ and $black^{'} = white$. In order to detect duplicate route requests received, each host in the ad hoc wireless network maintains a list of $(source, destination, request\_id, color)$ tuples that it has received. $request\_id$ is a sequence number maintained at the sender. Each intermediate node can be colored only once for each $(source, destination, request\_id)$ and the destination can be colored twice with one for each color. To avoid the "single query domination" problem, upon receiving the query packet for the first time, each intermediate node waits for a Δ units of time before committing to a particular color.

Each sender s initially broadcasts two requests (s, d, id, $black$) and (s, d, id, $white$). Both requests have the same id, i.e., the same sequence number maintained locally at s. When an intermediate host v (excluding destination) receives a route request packet (s, d, id, $color$), it processes the request as follows:

- If v has been marked for (s, d, id), then the request will be discarded.
- If v is unmarked for (s, d, id) and v received the request for the first time, then the request is kept for Δ units of time before marking v for (s, d, id).
  - If v does not receive a route request packet of (s, d, id, $color^{'}$) before the expiration of Δ units of time, v is marked $color$ for (s, d, id).
  - If v receives a route request packet of (s, d, id, $color^{'}$) before the expiration, v is randomly marked either white or black without further delay.

Once it is marked, v performs one of the following actions:

- If a route to destination d can be determined at v, a *route reply* packet to the source of the route discovery is sent from v. A route can be determined if v is the destination or a route with a matching color from v to the destination exists in the route cache of v (such a route is called *cached route*).
- Otherwise, v appends v's host's own address to the route record in the route request packet, and forwards the request with the committed color.

The destination node accepts the first black route and the first white route (i.e., the destination node is colored twice). Then a route reply packet to the source is sent from the destination node. A route reply packet (sent from either the destination or an intermediate node with a cached route to the destination) keeps the complete route information. Route information to the destination are stored in route cache of each intermediate node (including source) as learned from the reply packet.

In the above algorithm, the use of Δ is to ensure that the selection of a color is a random process, like flipping a coin. Note that the color of each node for each request is a conceptual notion. Each node has multiple colors with one for each request.

Like DSR, EDSR uses its caches routes to avoid propagating a route request packet received all the way to the destination. The color of the selected route in the route cache is important in this case. Suppose each route can select any cached route without considering its marked color, a white route may stop at u with a black cached route $u - v - d$ and a black route may stop at v with a black cache route $v - d$ which is a subpath of $v - u - d$. In this case, two routes are not node disjoint.

Therefore, a black route request initiated from s to d will stop at v only if a *black route* from v to s exists in the route cache. Similarly, a white route request initiated from s and with the same id will stop at u only if a *white route* from u to s exists in the route cache. When a node v has both black and white routes (e.g., v has initiated a route discovery process to the current destination), then pick the one with the matching color.

Figure 3 shows a sample ad hoc wireless network with eight nodes. Initially, all nodes excepts source s are unmarked. To simplify the discussion, it is assumed that the route cache of each node is empty, i.e., each route will not send its route reply before reaching the destination node. Assume that among neighbors of source s, w_2 and w_3 are marked black and w_1 and w_4 are marked white. The subsequent broadcasts mark w_5 black (by w_2) and w_6 white (by w_4). Finally, destination d is marked white by w_6 and black by w_5. The resultant node-disjoint paths are $s - w_1 - w_6 - d$ and $s - w_2 - w_5 - d$ as shown in Figure 3.

During the route reply phase, route information to destination d is stored in route cache of each

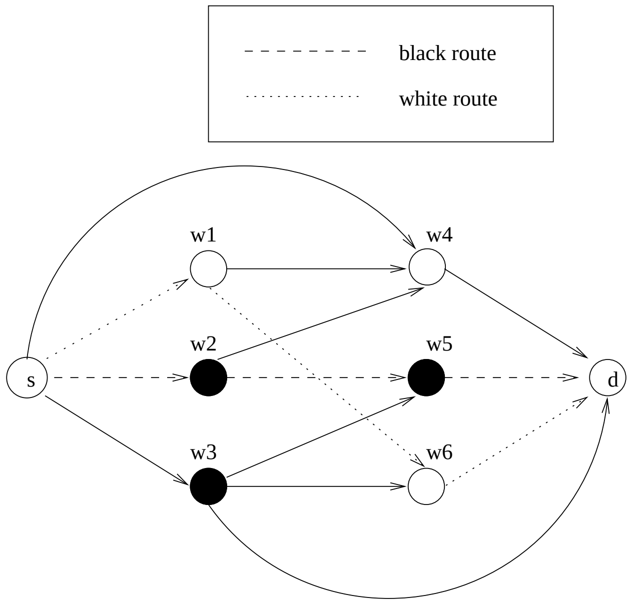


Figure 3: A sample multipath routing.

intermediate node (including source) as shown in Figure 1. When a network has unidirectional links, not all nodes on the route discovery path can cache route information during the route reply phase, since a different route might be used in the reply phase. Figure 4 (b) shows such an example. It is clear that only nodes (v in the figure) that are on both route reply path and route discovery path can cache route information. Such nodes are called *cache nodes*. In the subsequent discussion, we assume that links in the network are bidirectional. Therefore, the route reply path is the reverse of the route discovery path and all nodes on the path are cache nodes. When a route discovery path is disconnected (because of host movement) during the route reply phase, the path is simply discarded. Note that when a node caches route information, ($color$, TTL) is associated with each route. TTL (Time-To-Live) is a timed value. When time-out occurs, the corresponding route entry is removed from the route cache. That is, *each route to a particular node in the route cache is colored and is time-sensitive.* For example, in Figure 1, when node s caches $s - u - v - d$ with a white color, routes $s - u$, $s - u - v$. and $s - u - v - d$ are all considered white.

4 Optimizations

When route cache is used, the node disjoint property of black and white routes is difficult to enforce. Consider an example shown in Figure 5 where route query for white route stops at v since v has

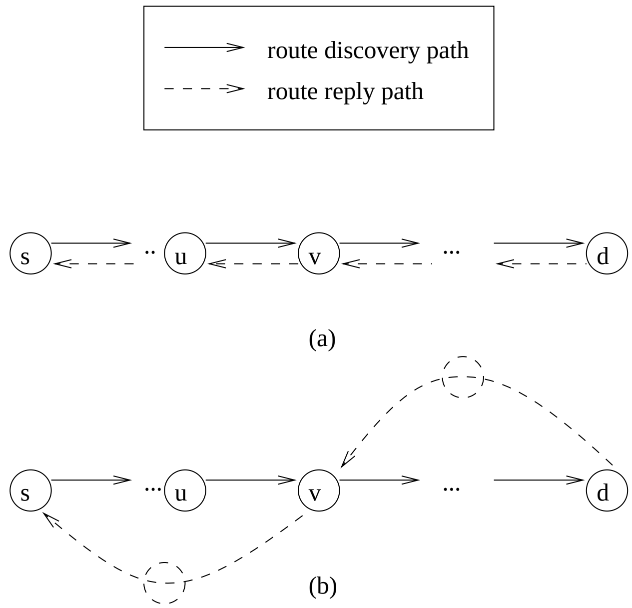


Figure 4: The relationship between route discovery path and route reply path: (a) route reply path is the reverse of route discovery path and (b) route reply path is not the reverse of route discovery path.

a white cached route to destination d. Similarly, route query for black route stops at u with a matching cached route at u. However, the color-matching requirement is still not sufficient. In Figure 5, paths $s-v-d$ and $s-u-d$ are not necessarily node disjoint. In fact, subpaths $s-v$ and $s-u$ are guaranteed to be node disjoint since they are generated from the current query phase, but not necessarily for $v-d$ and $u-d$ because they can be generated from two different sources, say $s^{'}$ and $s^{''}$ (see Figure 5). Therefore, $v-d$ and $u-d$ are not guaranteed to be node disjoint even though they have different colors. Two paths are said to be *overlapping* if they have the same destination and they share at least one intermediate node that is not the source of each path. In Figure 5 paths $u-w-d$ and $v-w-d$ are two overlapping paths and node w is called an *overlapping node*.

To ensure the property of node disjointness, we consider two solutions. In the first solution, overlapping paths are prevented from being generated; while in the second solution, overlapping paths are allowed, but they are tagged with "dirty bits".

In the first solution, we forbid to caching route information whenever two overlapping paths of different colors are detected: *During the route reply phase for a path from d back to s, if at intermediate node v (excluding source s) a route of the other color to destination d exists in the* *route cache of v, any cache node on the path after v (closer to source s than v) is not allowed to cache route information.* Note that the current node v is still allowed to cache the route information.

Consider the example shown in Figure 5. Suppose route information of white route $s^{'}-v-w-d$ initiated from $s^{'}$ has been cached on each node on the path before the reply phase of black route $s^{''}-u-w-d$ (initiated from $s^{''}$) starts. If w is the *last overlapping* node (the closest overlapping node to the destination), any node between w and d (including w) will be able to cache route information, but not the other nodes on the path.

In the second solution, instead of disallowing caching routing information, an extra bit called "dirty bit" is added to each route record. The dirty bit is set after the last overlapping node w is detected in the route reply phase. In the example of Figure 5, nodes in subpath $s^{''}-u-w$ (excluding w) still cache route information with their dirty bits being set. Note that the notion of dirty bit is different from the one used in traditional cache memory. A route with its dirty bit set indicates the existence of another route of different color to the same destination and that these two routes are not node disjoint.

The dirty bit alone does not distinguish the second approach from the first one. The difference occurs when *each dirty bit is associated with a TTL to indicate the life time of the dirty bit.* That is, the dirty bit itself is time-sensitive. When the TTL of a dirty bit expires, the dirty bit is removed and the corresponding path becomes clean. Note that each route still has its own TTL. TTL of the dirty bit of a black (white) route at node u is the maximum TTL value of any white (black) route to the same destination d cached at a overlapping node in subpath $u-w$ (see Figure 5). In other word, TTL is the longest time a overlapping white (black) cached route can live! Note that there are several ways to keep track of the maximum TTL value of a route. For example, the TTL value can be initiated at the destination. Each intermediate node records the TTL value of the corresponding route during the route reply phase. The TTL of a dirty bit will be timed with the remaining time registered at the overlapping node.

To generate two node-disjoint routes, the route discovery protocol can be slightly modified as follows:

- The white route accepts only *clean white route* (route with its dirty bit unset) while the black route accepts *clean black route* (route with its dirty bit unset).
- A clean white (black) route is found at v if v is destination d or a clean white (black) route from v to d exists in the route cache of v.

Note that if the above approach fails, the routing policy can be dynamically switched back to the regular DSR where any route, without considering its color and dirty bit status, to the

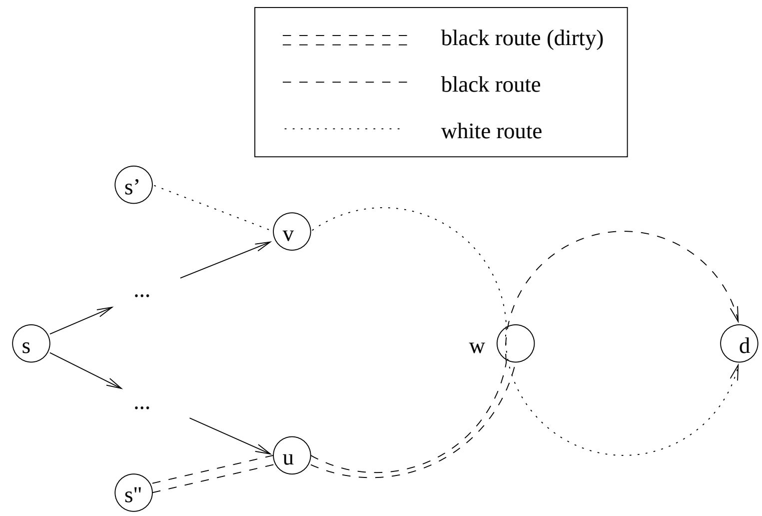


Figure 5: Overlapped paths.

destination can be selected. However, information about route color and dirty bit status is still maintained in case the routing policy is switched back to EDSR later.

When route cache is used more than one black (white) route can be generated at the end of the query phase by the destination and intermediate nodes with cached routes to the destination. A special delay mechanism similar to the one used in DSR can be used to avoid too many simultaneous replies for both white and black routes. This is done by selecting a delay period which is a monotone function of h, the number of hops for the route to be returned to the source. That is, the host that is farther from the source has a longer delay than the one that is closer to the source. In this way, a route can be terminated during the reply by an intermediate node if this node can infer that the source has already received a reply giving an equally good or better route (e.g., this node has initiated or passed a shorter route to the same source).

5 Simulation

We have conducted a simulation study without using route cache. The simulation was conducted in a 100×100 2-D free-space by randomly allocating a given number of hosts ranging from 20 to 100. Graphs are generated in two ways: a fixed transmitter range (r) and a fixed average node degree (d). Three radii of transmitter ranges are considered: 18, 25, and 30 as well as three ranges of average node degrees: 5, 10, and 15. We test the performance of the EDSR algorithm based on different node transmitter ranges and average node degrees. These two parameters are indeed related to each other: The average node degree is the expected number of nodes (out of n) that are within a node's transmitter range. Specifically, the average node degree can be approximated as $d = (\frac{\pi r^2}{m^2})n$, where r is the transmitter range and m is the length of each side of the confined broadcast space. This approximation is fairly accurate, especially when $r \ll m$. For example, when $r = 18$ and $n = 50$, the corresponding degree node is $d = 5$; when $r = 18$ and $n = 100$, the corresponding degree node is $d = 10$. That is, the performance of EDSR should be similar for $r = 18$ and $d = 5$ when $n = 50$ and for $r = 18$ and $d = 10$ when $n = 100$. Basically, we measure the same feature from two different viewpoints and obtain the more sensitive parameter, r or d, under various simulations.

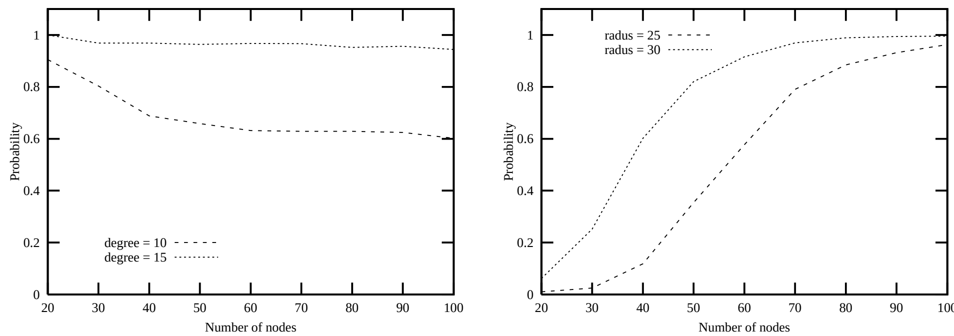
In the simulation, $rand(0, 1)$ is a random number generator that generates a random number in [0...1]. The one-hop transmission time (among neighbors) is $T_{min} + T_{range} \times rand(0, 1)$, where $T_{min} = 0.2$ and $T_{range} = 0.3$. Delay time Δ (i.e., waiting time between first receipt and color commitment at each node) is $D_{min} + D_{range} \times hop\_count \times rand(0, 1)$, where $D_{min} = 0.3$ and $D_{range} = 0.5$. The *hop_count* is the number of hops from the source. Intuitively, the farther a node from the source, the longer the delay. In addition, a wider range of arrival time is expected after routing packets have traveled multiple hops (than the ones that have traveled only a few hops).

Based on the Menger's node-connectivity (or simply connectivity) theorem, a graph G is k-connected, represented as $K(G) = k$, if and only if any two distinct nodes are connected by at least k node-disjoint paths. Therefore, if $K(G) > 1$ then two node-disjoint paths exist. Two sets of simulation are conducted:

1. The probability of $K(G) > 1$ is first calculated through simulation, given that G is connected. Then using EDSR the success rate of finding two node-disjoint paths when $K(G) > 1$ is determined.

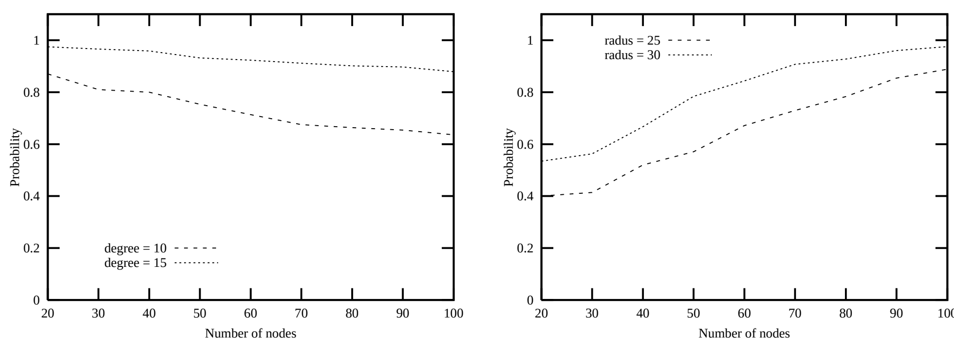
2. Given the source and destination, the probability of the existence of node-disjoint paths between them is determined. Note that such a node-disjoint path may exist even though $K(G) \leq 1$. Then using EDSR the success rate of finding two node-disjoint paths when they exist is determined.

In fixed-node-degree simulation, all probabilities decrease when the number of nodes increases. This is because the diameter of the network increases as the number of nodes increases. In fixed-transmitter-range simulation, all probabilities increase when the number of nodes increases. This



(a) (b)

Figure 6: Probabilities of $K(G) > 1$: (a) fixed-node-degree and (b) fixed-transmitter-range.



(a) (b)

Figure 7: Success rates of finding two node-disjoint paths when $K(G) > 1$ using EDSR: (a) fixed-node-degree and (b) fixed-transmitter-range.

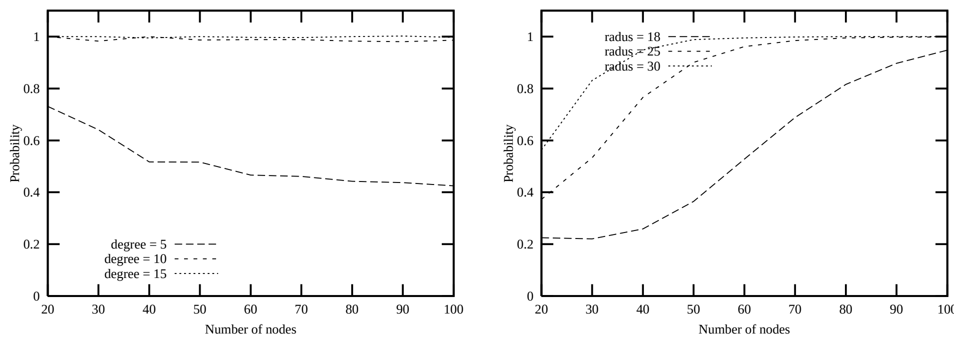
is because the graph under simulation becomes denser (i.e., the average node degree increases) as the number of nodes increases.

In the first set of simulations, the fixed node degree of 5 is too small to generate reasonable numbers of networks such that $K(G) > 1$. Therefore, we consider only networks with a fixed node degree of 10 and 15 (and a fixed transmitter range of 25 and 30). Figure 6 shows the probability of $K(G) > 1$ for unit graphs given the fixed node degrees (Figure 6 (a)) and the fixed transmitter ranges (Figure 6 (b)). It is clear that the probability of $K(G) > 1$ is high for a fixed node degree of 15. For a fixed transmitter range, the graph is relatively sparse when the number of nodes is small and, hence, the probability of $K(G) > 1$ is small.

Figure 7 shows success rates of finding two node-disjoint paths when $K(G) > 1$ exists using EDSR. Again the results show the approach is effective for networks with either small diameters (Figure 7 (a) with a relatively small number of nodes) or high densities (Figure 7 (b) with a relatively large number of nodes). This confirms the applicability of EDSR in networks with either relatively small diameters or high densities.

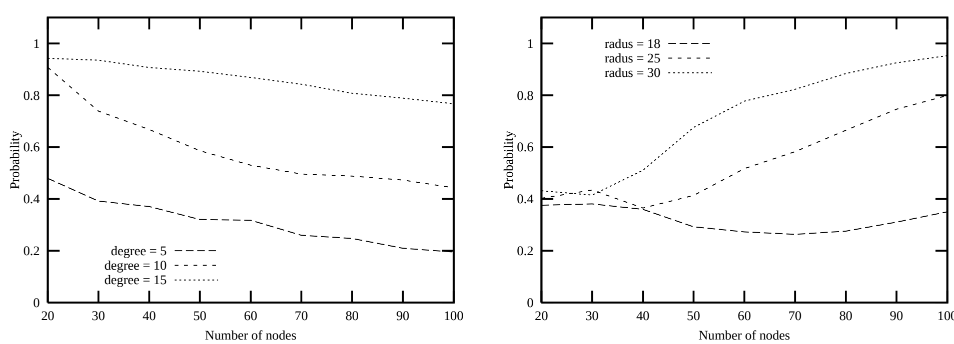
Both Figures 6 and 7 show results based on a strict requirement; that is, each pair of nodes has node-disjoint paths in a given graph. In the second set of simulation, we only consider the connectivity of two randomly selected nodes, without considering the connectivities of other nodes. Specifically, in this set of simulations, unit graphs under consideration are not necessarily 2-connected, but the source and destination are connected by two node-disjoint paths.

Figures 8 and 9 show simulation results of the second set of simulations. It is clear that the probability of node-disjoint paths between two nodes is higher than the probability of $K(G) > 1$ under both situations (fixed-node-degree and fixed-transmitter-range). In addition, the situations when $d = 5$ (fixed-node-degree) and $r = 18$ (fixed-transmitter-range) are shown. The curves for success rates of finding two node-disjoint paths when they exist using EDSR resemble the ones of the first set of simulations. The only exception is that the success rate does not pick up significantly for $r = 18$ when the number of nodes increases. Note that the performance of EDSR deteriorates significantly when the graph is either relatively sparse ($r = 18$) or with a relatively large diameter ($d = 5$).



(a) (b)

Figure 8: Probabilities of node-disjoint paths between two nodes: (a) fixed-node-degree and (b) fixed-transmitter-range.



(a) (b)

Figure 9: Success rates of finding two node-disjoint paths when they exist using EDSR: (a) fixed-node-degree and (b) fixed-transmitter-range.

6 Conclusions

We have proposed an extension to the DSR, called extended DSR (EDSR), by maintaining two node-disjoint paths as a result of each route discovery process. The virtue of this approach is that it does not introduce additional overhead other than maintaining the color of each node for each destination and a dirty bit associated with each route stored in the route cache. The simulation results have shown the potential of the proposed multipath construction process. Our future work includes an in-depth simulation on the effectiveness of the proposed approach when route cache is used and when unidirectional links exist.

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