Route Fragility: A Novel Metric for Route Selection in Mobile Ad Hoc Networks

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***Abstract*— A key factor deciding the performance of a routing protocol in mobile ad hoc networks is the manner in which it adapts to route changes caused by mobility.**

Exploiting the intuition that a *less* dynamic route lasts longer, we propose a new metric, the *Route Fragility Coefficient* (RFC), to compare routes. RFC estimates the rate at which a given route *expands* or *contracts*. Expansion refers to adjacent nodes moving apart, while contraction refers to their moving closer. RFC combines the individual link contraction or expansion behavior to present a unified picture of the route dynamics. We demonstrate that lower the value of RFC, more static (less fragile) the route. We then use this metric as a basis for route selection so that route discovery yields routes that last longer and hence increase throughput while reducing control overhead.

We provide a simple distributed mechanism to compute RFC, so that a Route-Request (RREQ) packet contains the metric for the path it traversed, when it reaches the destination. The Dynamic Source Routing Protocol (DSR) is enhanced with the proposed metric in the NS-2 simulation environment. Simulation results are provided to demonstrate improvement in throughput and reduction in routing protocol overhead with increased mobility.

I. INTRODUCTION

Mobile ad hoc networks (MANETs) promise to break many of the traditional requirements for building communication networks and make information exchange possible in a wide variety of situations. As such, there has been a lot of interest in the recent years to design and build efficient routing protocols to realize MANETs [14]. Such protocols attempt to build routes that can perform best, given the fact that some of the nodes in the route may move out of range, causing route failure. In this scenario, a route is "good" if it is short *and* lasts longer than alternative routes to the destination.

In a typical ad hoc network, the source broadcasts a route request packet which then ripples through the network till it reaches the destination. The destination replies to one or more of the requests depending on whether the protocol discovers multiple routes. Considering that a route may not be valid for a long time, there have been proposals to discover routes *on-demand* instead of computing them pro-actively. Accordingly, routing protocols for ad hoc networks are frequently classified as being proactive [12] [10] or reactive [1] [11] [13]. There have also been proposals which try to strike a balance between these two approaches by employing hierarchical routing and cluster-based routing [5] [8].

Uniformly, the performance of routing protocols depends on the quality of the routes chosen in terms of route longevity, the manner in which route failures are handled and the protocol overhead introduced in the process [2]. A protocol that discovers better routes also features a reduced rate of route failures and lesser route discovery traffic. Thus an important aspect of the decision process is to compare and pick the "better" route.

Intuitively, a route consisting of nodes that "stay together" while being mobile, will last longer. In other words, if the nodes in a route move such that they remain within the transmission range of the same neighbors for a longer duration, the route stays valid for a longer duration.

In this paper, we present the "Route Fragility Coefficient" (RFC), a metric which describes how dynamic a route is. More static routes (which last longer) are represented by a lower value of RFC. The computation of RFC proceeds in two phases.

First, on receiving a Route Request (RREQ) packet, each node on the route computes the extent by which the "link" to its previous hop is contracting or expanding. Assuming a free-space path loss model, we examine the received power of two successive packets. If the nodes are moving apart the second power measurement is lesser. The extent of expansion or contraction is captured by a function of the received power samples which represents the *relative speed* of the two nodes within a proportionality constant (§III). The result is then added to one of two counters in RREQ (one for expansion and the other for contraction).

Second, the destination collects multiple RREQs and employs a function of the number of hops and the value of RFC for the routes represented by each RREQ, to arrive at the best route (§III-D). Employing a simple inequality to decide which metric is better, the destination chooses the RREQ representing the best route and replies to it.

We note here that for the above technique to work, we only need the received power measurements (effects of various fading models on wireless channels is currently under study and is not a part of this paper). We do not need the location or velocity information of the nodes and hence do not need a global positioning system. We also do not need any time-bound measurements which means that we do not require a global clock in the network. There are no periodic beacon or hello packets needed since the power measurements are obtained from data packets. The state requirement (received power samples) is of the order of the number of neighbors of a node (typically about 6-8 for optimal operation [15]). The benefits of deploying RFC are demonstrated by extensive simulations using the NS-2 simulation environment with the DSR module enhanced with our metric. We demonstrate that appreciable improvement in throughput can be obtained in networks with higher mobility.

Thus the contributions of this paper are as follows: a) We provide a new metric to quantify the dynamic nature of a route

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and allow the routing protocol to choose the more static and long-lasting routes; b) Without requiring any global positioning information, clock synchronization or periodic beacon packets we provide a distributed mechanism to compute this metric; c) We verify the utility of the metric by enhancing a popular routing protocol (DSR [1]) and demonstrate the gains.

Rest of the paper is organized as follows. In §I-A we examine related work in literature. We present our assumptions and notations used in the rest of the paper in §II. The route metric is derived in §III and its performance is presented with simulations in §V. We conclude with a discussion of the results and future directions in §VI.

A. Related Work

Adapting route discovery to higher mobility involves quantifying the longevity of routes and enforcing a route selection process. Such a solution can be either *local* to the nodes in the route or *global* in the sense that one node makes a decision about selecting the route.

Signal Stability Routing [3] features a local mechanism wherein, each node forwards a route search packet along the link with the strongest signal. AODV [13] similarly tries to preempt a link failure by using periodic hello packets and propagating failure messages to sources using the route. Preemptive Routing [4] is an enhancement to DSR that enables nodes to estimate the time to link failure and propagate route failure information in advance. All the above mechanisms suffer from the fact that they are local to a node and not necessarily the right strategy for the route as a whole.

Proposals that attempt to view the route as a whole include the ones that use some kind of *mobility prediction*. For example, authors in [16] propose to send velocity and position information in packets to aid in estimating the time to link expiry. They require global clock synchronization and a positioning system for the network. Our work requires neither of these. Associativity-based Routing [17] (ABR) attempts to measure a route's goodness using "associativity ticks" which indicate how stable a route is. Although the proposal can select routes that are more stable, like [16] it cannot distinguish between an expanding, contracting or static route as a result of the fact that it does not capture the aspect of relative speed for the route. In addition, ABR needs periodic beacon messages to be transmitted.

Probabilistic prediction of link availability was proposed in [6] where, the probability of validity of a link is computed assuming an exponentially distributed mobility epoch. The route metric is the minimum of the link availability measures for all the links in the route. This proposal captures the dynamic nature of the links but selects routes based on the property of just the weakest link. Thus a route with all links equally "bad" will be treated as equivalent to a route which has just one link "bad". For protocols that feature route failure recovery, this means that the whole route may have to be recomputed. Our proposal does not have this drawback since it uses a measure which considers all the links in the route. A similar probabilistic treatment in [9] suffers from the same problems.

In summary, our work is distinguished by the ability to achieve the intuitive strategy of selecting a route that is "more" static, with minimal overhead.

CCM	Cumulative Contraction Metric
CEM	Cumulative Expansion Metric
CUM	Cumulative Uncertainty Metric
d_i	Distance between two nodes at time t_i
K	Constant dep. on antenna gain, wavelength
m_i	RFC for Route i
n_i	Node i
P_i, t_i	Received power and time of measurement
r	Transmission range
R_i	Route i
RFC	Route Fragility Coefficient
v	Relative speed w.r.t. neighbor

TABLE I

TABLE OF SYMBOLS AND THEIR MEANING

II. Notation and Model Assumptions

In the succeeding sections we assume a network model described below. The network is assumed to consist of a set of mobile wireless nodes. The nodes move according to the "random waypoint" model. Each node moves in a piece-wise linear trajectory with a constant velocity that is chosen randomly. The nodes pause for a set time before changing direction. The power at which the nodes transmit is assumed to be constant. A free-space path loss model is assumed to characterize the received power at a node.

In order to discover a route, each node is assumed to broadcast a route request packet. The route request packet is assumed to ripple through the network till it reaches the destination. The destination replies to one or more route requests.

The notations used in the paper are depicted in Table I.

III. Route Fragility

In this section we derive the metric used to describe the dynamic nature of a route. In order to compute this metric we estimate the rate at which the separation between each adjacent pair of nodes in the route is increasing (expansion) or decreasing (contraction). A measure of such an expansion or contraction is given by the relative speed of the nodes. We first present techniques to estimate relative speed of a pair of nodes (§III-A) and then discuss how to combine these measurements to get a single number representative of the whole route (§III-D). Some strategies for deploying the metric in certain reactive protocols are presented in §III-E.

A. Estimating Relative Speed

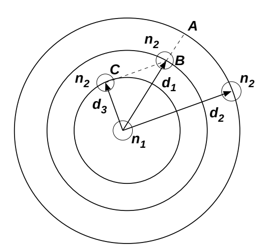


Fig. 1. Schematic showing two positions of node n_2 relative to node n_1.

Consider a node n_1 receiving packets from a node n_2. Let t_1 and t_2 be the times at which the last two packets from n_2 were received. Denote the received power for these packets as P_1 and P_2. We consider two possible situations, viz., the nodes are moving closer ($P_1 > P_2$) or are moving apart ($P_1 < P_2$).

B. Nodes Moving Apart

Fig. 1 indicates two nodes n_1 and n_2, with d_1 and d_2 being distances corresponding to the positions of node n_2 at received powers of P_1 and P_2. To estimate the relative speed of the nodes, we do not need the exact position of the two nodes as shown below. This is indicated by the two circles which indicate all the possible positions in which n_2.

Assuming a free space path loss model, we have:

$$P_i = \frac{K}{d_i^2} \Rightarrow \frac{d_i}{\sqrt{K}} = \frac{1}{\sqrt{P_i}} \tag{1}$$

Here K denotes a constant that depends on the antenna gains of the two nodes and the wavelength of the transmission.

Since the nodes are assumed to be moving with a constant velocity in a piecewise linear manner, we can then write the following.

$$\frac{d_2 - d_1}{\sqrt{K}} = \frac{1}{\sqrt{P_2}} - \frac{1}{\sqrt{P_1}} \tag{2}$$

$$\frac{v}{\sqrt{K}} = \frac{1}{(t_2 - t_1)} \left(\frac{1}{\sqrt{P_2}} - \frac{1}{\sqrt{P_1}} \right) \tag{3}$$

Equation(3) thus allows us to compute the relative speed v, normalized by the constant K.

C. Nodes Moving Closer

For the case where $P_2 > P_1$, i.e., n_2 is moving closer to n_1, a similar analysis holds. In Fig. 1 the circle of radius d_3 represents the new position of n_2 closer to n_1. Hence in the following paragraph, the power measurement P_2 corresponds to a distance of d_3. Again we assume that the node moves in a straight line.

Note that the node n_2 will stay in the range of n_1 for a longer time if it moves along a radial direction. The worst-case scenario is when n_2 starts moving away from n_1 just after time t_2. The line segment $\overline{BC}$ represents such a path. Using Pythagoras theorem we see $|\overline{BC}| = \sqrt{d_1^2 - d_3^2}$. We then obtain the relative speed, v as

$$\frac{v}{\sqrt{K}} = \frac{\sqrt{d_1^2 - d_3^2}}{(t_2 - t_1)} = \frac{1}{(t_2 - t_1)} \sqrt{\frac{1}{P_1} - \frac{1}{P_2}} \tag{4}$$

We thus have the means to compute an estimate of the relative speed (normalized by a constant) with just the received power measurements.

D. Route Fragility Coefficient

Equipped with a measure of expansion of the link between a pair of nodes, we now present a method to combine these values to obtain a single metric for the route. We introduce the following definition.

Definition 1: Consider a route R. Let E denote the set of node-pairs (n_k, n_j) such that they are adjacent nodes in R and are moving apart. The Cumulative Expansion Metric (CEM) is given by

$$CEM = \sum_{i \in E} \frac{v_i}{\sqrt{K_i}}$$

Let C denote the set of node-pairs (n_k, n_j) such that they are adjacent nodes in R and are moving closer. The Cumulative Contraction Metric (CCM) is given by

$$CCM = \sum_{i \in C} \frac{v_i}{\sqrt{K_i}}$$

Observe that CCM and CEM are positive quantities and higher values indicate that the route is more dynamic (more fragile). In order to capture these two measures in a single metric we consider a weighted sum. Note that a contracting link (neighbors moving closer) lasts longer than an expanding link. Thus a weighted sum would have to penalize expansion more than contraction.

In order to obtain this combined metric, we take recourse to the following intuition. Consider a pair of nodes n_1 and n_2 which are in each other's range at some point in time. Let d_1 indicate the distance between the nodes when they are closest. We can divide the period in which they are within range, into two parts - one, comprising of the time when they drawing closer till d_1; two, comprising of the time when they are moving apart. On the average we can consider these two distances to be equal. Thus, a contracting link eventually transforms into an expanding link, staying alive for approximately twice the time as compared to a link currently detected to be expanding. Hence we propose the following combined metric, which we call the "Route Fragility Coefficient"(RFC):

$$RFC = CCM + 2 * CEM \tag{5}$$

This reflects the intuition that an expanding link is roughly twice as bad as a contracting link. If the length of two routes is the same, we could simply choose the route with the lower RFC. However, if the routes are of differing length, choosing the route with a lower RFC would not be a valid alternative - we would almost always choose the shorter route.

To remove the bias against longer routes, we consider the following procedure to compare route metrics. Denote m_1 and m_2 to be the RFCs for two routes R_1 and R_2, obtained as in Equation(5). Let N_1 and N_2 denote the number of hops in the respective routes. Then we use the following condition to decide if R_1 is better than R_2:

$$\frac{m_1}{N_1} < \frac{m_2}{N_2} \tag{6}$$

We now have a procedure to quantify and compare the dynamic nature of two routes. We now examine some of the properties of RFC:

- **Best Route:** A route whose RFC evaluates to zero, features nodes that are moving with zero relative speed. Such a route would out-live any route with a positive value of RFC.
- **Penalizing Contraction and Expansion:** The metric penalizes both contraction and expansion in routes, since

eventually both cause route failure. Further, expansion carries a higher penalty.

- **Discovering Longer and More Static Routes:** The shortest route is not necessarily the best route. By employing a comparison strategy that normalizes the RFC by hop-length, we allow discovery of longer, but more stable, routes.

E. Implementing RFC

Here we consider some popular reactive routing protocols and present some strategies to enhance them with RFC.

- **AODV:** A source using AODV, broadcasts a route request (RREQ) packet. The packet then ripples through the network till the destination receives it and sends back a route reply packet. Thus deploying RFC involves three steps: a) Have each node receiving the RREQ update the fields pertaining to contraction and expansion information; b) Have the destination reply to the RREQ with the best RFC; c) Disable caching so that a route whose RFC is "stale" is not selected.
- **TORA:** In TORA [11], the source receives multiple route replies for a request. As mentioned above, the intermediate nodes would have to update the RREQ packet with fragility information. The difference will be that the destination replies to all the requests it receives. The source should then pick the route with the best RFC.
- **DSR:** The route discovery process in DSR [1] is very similar to that in AODV. The same three steps mentioned under AODV apply here. In §V we present results of enhancing DSR with RFC.

IV. A DISTRIBUTED ALGORITHM

In the previous sections we presented the means to compute RFCs and compare them. In this section we outline the algorithms that need to execute at each node. When the route request is received, the node uses received power information for the source of the route request and then computes the relative speed estimate. As the RREQ progresses towards the destination it accumulates the contraction and expansion metrics for each route. Finally the destination employs the strategy discussed in §III-D to arrive at the best route. We present per-node operation in §IV-A and the destination's operation in §IV-B

A. Per-Node Operations

The RREQ packet is enhanced with three additional fields, viz., a Cumulative Contraction Metric field (CCM), a Cumulative Expansion Metric field (CEM), and a Cumulative Uncertainty Metric field (CUM). CCM and CEM are defined in §III-D. CUM is used to indicate the number of links where there was just one or no received power measurements and computing CCM (or CEM) is not possible. Algorithm 1 outlines the operations performed at each node.

When a data packet is received at the node, the MAC layer records the received power for the source originating the packet. When a RREQ is received from a source, the MAC layer passes the previous received power information for this source and the received power for the RREQ packet. Thus the routing layer obtains two power samples for the previous hop.

To implement Algorithm 1 the MAC layer needs to maintain a table of power samples for its neighbors. This has very low state requirements since the typical number of neighbors is of the order of 6-8 for optimal operation of the network [15]. In order to avoid stale entries we periodically purge the contents of the table. The refresh period can either be set as a constant for all entries or can be computed as the time to link expiry using the relative speed estimate for the node-pair constituting the link and knowing the transmission range.

Algorithm 1 Algorithm to update RREQ packets with expansion or contraction information

```
Input: A RREQ packet from node s
Input: Last two received power measurements P1, P2, for node s
if No Power Samples then
    CUM ← CUM + 1; return
end if
if P2 < P1 then
    Compute relative speed estimate v from Equation(3)
    CEM ← CEM + v
end if
if P2 > P1 then
    Compute relative speed estimate v from Equation(4)
    CCM ← CCM + v
end if
```

B. Destination Operations

The destination processes a RREQ packet and sends a route reply packet in the reverse path. Thus the destination chooses a route for the source. In order to obtain the route with the best properties, the destination should not just reply to the first route request it receives. Instead, if it waits for a set amount of time and compares the RREQs it receives, it can do a much better job of choosing a good route. Thus we introduce a delay called the "Route Reply Latency" (RRL).

Higher the value of RRL, higher the number of RREQs at the disposal of the destination and higher the end-to-end latency of obtaining a route at the source. To set a value for this parameter we limit the routes that are examined to a specific number of hops. E.g., if the first RREQ packet represents a route of N hops (most likely, the least delay path), we set the maximum length route that will be considered as $N + k$. Observe that, to receive RREQs that pass $N + k$ hops we would have to wait for an additional time, equivalent to the delay experienced by a packet at k hops. A simple strategy to find this delay is to consider the worst-case delay that is experienced due to queuing at k hops, if delays due to contention and other MAC layer functions are ignored. Denote the buffer length at the MAC layer by B, the capacity of the wireless link by C, and the maximum size of packets transmitted by M; an estimate of RRL is then given by kBM/C.

In §III-D we demonstrated the means to obtain a single metric representative of the route and specified a strategy to compare two routes. Assuming that the destination waits for a duration specified by RRL after the first RREQ, Algorithm 2 specifies the operation performed when each RREQ is received. We first note that a route which does not have information about many of its constituent links is worse than a route about which there is information. The CUM value in the RREQ packet indicates the number of links about which there is no expansion or contraction information. If the best route received till now has a CUM value that is less than that of the RREQ received, the RREQ is ignored. Otherwise, the RFC for this route is evaluated using the CCM and CEM values and compared with that of the best route seen till that time (using Equation(6)). At the end of the duration specified by RRL, the destination sends a reply to the RREQ packet representing the best route seen till then.

Algorithm 2 Procedure executed at destination on receiving a RREQ packet

Input: m^*, N^* - RFC for the best route till now and its hop-length
Input: CUM^* - Cumulative Uncertainty Metric for best route till now
Input: RREQ packet
Extract CCM, CEM, CUM and N (hop-length) from the RREQ
if $CUM > CUM^*$ **then**
  /* Greater uncertainty; ignore this RREQ */
  return
end if
$m \leftarrow CCM + 2 * CEM$
if $m/N < m^*/N^*$ **then**
  /* Replace m as the best route till now */
  $m^* \leftarrow m$
  Save the RREQ packet.
end if

V. PERFORMANCE EVALUATION

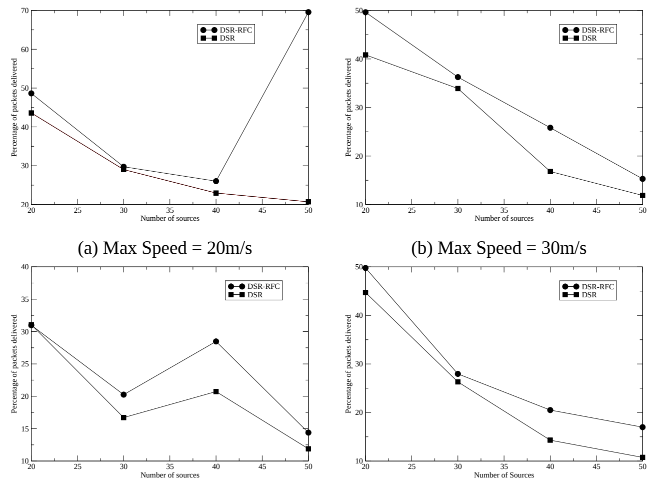
In this section we present the results of enhancing DSR with RFC. We used the NS-2 simulation environment. The objectives of the experiments were two-fold: a) to verify the relation of RFC with route longevity and the resultant gains in throughput, and b) to examine the gains in terms of reduced route overhead. We first specify the details regarding simulation setup and parameters used (§V-A). We then present the performance of DSR enhanced with RFC in terms of throughput (§V-B) and routing overhead (§V-C).

A. Simulation Setup

The simulation consisted of wireless nodes moving in an area of $1000m \times 500m$ according the the "random waypoint" model. The nodes move along piece-wise linear trajectories with velocities that are chosen randomly. The nodes pause for a set amount of time before changing direction. In all the simulations the pause time was set to $1s$. The traffic was generated by CBR sources.

The Route Reply Latency (RRL) was defined to be the time for which the destination waits before replying to the best available RREQ (§IV-B). In the simulations, the destinations wait for a delay equivalent to the worst-case queuing delay for one hop (assuming no contention delays), i.e., RREQs are received for paths at least 1 hop longer than the shortest path. In NS-2, the MAC layer buffer size is set at 64 packets, maximum packet size set to 1500 bytes and capacity of the wireless link is set at $2Mbps$. Hence we can compute the value of RRL as $64 \times 1500 \times 8/(2 \times 10^6) = 384ms$.

At each node, the received power samples are stored for the neighbors of the node. In the simulations, the samples were purged once in 100s.



(a) Max Speed = 20m/s (b) Max Speed = 30m/s

(a) Max Speed = 40m/s (b) Max Speed = 50m/s

Fig. 2. Percentage of Packets delivered with varying number of sources and Transmission rate = $10pkts/s$

B. Effect on Throughput

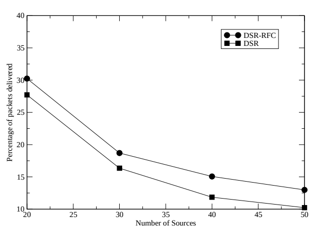
In order to measure the improvement in throughput, we examine DSR enhanced with RFC (DSR-RFC) and the original DSR with varying velocities, network size (number of sources) and transmission rates. Since we require route discovery to use the RFC of the route, we disable route caching in DSR-RFC. We however retain caching in the original DSR for the following reason. There is no appreciable difference in throughput between DSR with route caching and without route caching; however routing overhead is reduced when DSR has caching enabled [7]. Since we need to compare the routing overhead of DSR-RFC with that of DSR, we retain caching. So a lower routing overhead than DSR with route caching implies lower overhead than DSR without route caching.

The results of the throughput experiments are depicted in Fig. 2 and Fig. 3. The plots show percentage of packets delivered successfully against increasing number of sources. The plots in Fig. 2 feature simulations with transmission rate set at $10pkts/s$. We observe that DSR-RFC consistently outperforms DSR, across various network sizes. Further at higher speeds ($30m/s$ and above) and moderate network size (30 to 40 nodes), the gains with DSR-RFC are higher, indicating the fact that stable and less dynamic routes are being exploited. This is expected, since increase in mobility means the first RREQ packet is often not the best one. This can also be viewed as a cause of higher variance in node velocities. With higher variance, the spread in relative velocities is higher, implying the existence of more routes which are dynamic. The plots in Fig. 3 indicate results for a higher transmission rate ($20pkts/s$). DSR-RFC again out-performs DSR. The gains here are less pronounced due to the fact that, at higher rates, contention for medium access plays a more important role, limiting the overall network throughput. Most of the sources experience increased collisions and hence are in a state of backoff.

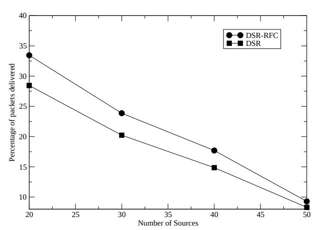
C. Effect on Routing Protocol Overhead

An important benefit of long-lasting routes is the reduced control overhead in terms of lesser route discovery iterations. Since route selection based on RFC leads to a choice of routes that are more durable, we would expect to see a reduction in the number of routing packets sent for every data packet transmitted. This is reflected in Fig. 4 (a). The plot shows the remarkable result that even in the face of increased node speeds, DSR-RFC maintains lesser routing overhead. In comparison, DSR incurs much higher overheads. We also note that these results are for DSR with route caching enabled. This demonstrates that RFC-based route selection is superior to route caching as a strategy to reduce routing overhead.

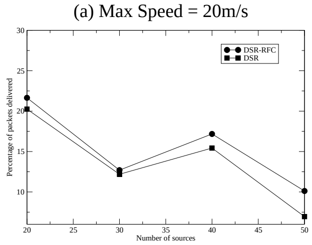
The plot in Fig. 4 (b) depicts the number or route errors generated as a percentage of data packets transmitted. Again DSR-RFC performs much better than DSR. There are multiple reasons for this gain. First, as noted earlier DSR-RFC chooses routes that last longer and hence reduces the number of route errors. Second, with higher mobility DSR cache has a lot of stale routes leading to increased route errors. Thus the gain in terms of reduced route errors increases with higher node speeds.



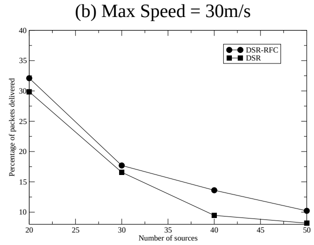
(a) Max Speed = 20m/s



(b) Max Speed = 30m/s



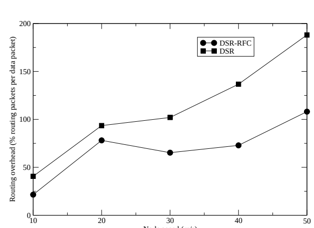
(a) Max Speed = 40m/s



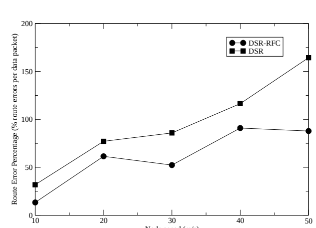
(b) Max Speed = 50m/s

Fig. 3. Percentage of Packets delivered with varying number of sources and Transmission rate = $20 pkts/s$

Clearly, preempting route failures and maximizing route lifetime pays rich dividends. The results presented in this section demonstrate that RFC-based route selection achieves these objectives to a large extent.



(a) Routing packets per data packet (%)



(b) Route Error packets per data packet (%)

Fig. 4. Routing Overhead and Route Error Comparison

VI. Conclusions

We presented a novel route metric which measures the *fragility* of a route. Noting that neighbors moving apart (expansion) or moving closer (contraction) captures the dynamic nature of a route, we provided a relative speed based measure. The measure distinguishes itself in its ability to differentiate between a static, expanding or a contracting route without requiring global positioning information or clock synchronization. A completely distributed algorithm was provided to compute the metric online so that a destination can receive the route metric as part of the Route Request packet. A simple strategy was evolved to compare route metrics without bias towards hop-length. The Dynamic Source Routing protocol (DSR) was then enhanced with the proposed metric. Simulation results were presented showing gains in throughput and reduction in routing overhead.

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