Electric-Field-Based Routing: A Reliable Framework for Routing in MANETs

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Abstract – Constructing multipath routes in MANETs is important for providing reliable delivery, load balancing, and bandwidth aggregation. However, popular multipath routing approaches fail to produce spatially disjoint routes in a simple and cost-effective manner, and existing single-path approaches cannot be easily modified to produce multiple disjoint routes.

In this paper we propose Electric-Field-Based Routing (EFR) as a reliable framework for routing in MANETs by applying the concept of electric field lines. Our location-based protocol naturally provides spatially disjoint routes based on the shapes of these lines. The computation is highly localized and requires no explicit coordination among routes. EFR can also be easily extended to offer load-balancing, bandwidth aggregation, and power management.

Through simulation, EFR shows a higher delivery ratio and lower overhead under high mobility, high network loads, and network failures compared to popular multipath and location-based schemes. EFR also demonstrates high resiliency to DoS attacks.

I. INTRODUCTION

Mobile users must communicate when no wired infrastructure is available, either because it may be economically impractical or physically impossible to provide the necessary infrastructure. In such situations, a collection of mobile hosts with wireless network interfaces may form an ad hoc network.

In an ad hoc network, each node communicates with the others via radio. These radio packets have a short propagations range, so the route must be multi-hop when the destination node is out of range.

Under high mobility and heavy traffic load, ad hoc routing algorithms based on a single path can experience problems. Ad hoc routing algorithms that use multiple paths can provide reliable delivery, load-balancing, and bandwidth aggregation under these conditions. However, multipath algorithms for wired networks are not readily adaptable to wireless situations. The fluidity of mobile environments and battery limitations make CPU- or communication-intensive algorithms infeasible. Also, spatially disjoint routes are more important because they can help to avoid radio collisions and regional failures.

Several on-demand routing protocols have been proposed. Protocols such as DSR [16], AODV [31], and their variants are built on demand. The source initiates a route request, which is flooded throughout the network. The request records all the intermediate nodes as it travels so that when it reaches the destination node, a complete route can be formed. A node can find multiple disjoint routes to the destination and switch among them if one is broken. These approaches rely on transient hop-by-hop routes. However, as mobility increases, these fixed node membership routes break more frequently. Thus, the performance of these protocols sharply declines with increasing mobility. Failure recovery is possible but incurs high overhead.

Some location-based approaches, such as GPSR [19], INF [11] and GFG [9], avoid hop-by-hop routing. In these protocols, packet-forwarding decisions are based on the locations of the current node and the destination. These protocols produce single routes and cannot be easily generalized to produce multiple disjoint routes. Even though some of these protocols provide guaranteed delivery, they still do not offer satisfactory results under high mobility or traffic load.

Other location-based multipath routing approaches [24] do not provide spatially disjoint routes in a simple and cost-effective manner.

In addition, we have found that existing protocols do not perform well when faced with high mobility or heavily loaded networks. Specifically, when the network communication is highly concentrated in a group of nodes, existing multipath ad hoc routing protocols perform poorly due to the lack of spatially disjoint routes to avoid the congested path.

In this paper we propose an electric-field-based multipath routing protocol (EFR). To our best knowledge, EFR is the first location-based protocol that provides the following desirable properties:

1. Spatially disjoint paths without explicit coordination
2. Simplicity
3. Stateless forwarding with localized information

4. Scaling in high mobility and heavy load environments
5. High resiliency against the DoS attack due to network failures and misbehaving nodes.

EFR can also be easily extended to provide load-balancing and bandwidth aggregation.

II. ELECTRIC FIELD ROUTING OVERVIEW

EFR is inspired by the characteristics of the force field lines for a pair of electric charges.

A. Review of Electric Fields [13]

Given a pair of electric poles with opposite charges, any charged point in space experiences two forces: a repulsive force emanating from the similar charge and an attractive force from the dissimilar charge.

A force is represented by a vector consisting of a magnitude and a direction. The magnitude of a force is inversely proportional to the square of the distance to a charged point, and the direction of the force is either directly away from or toward the point.

For a pair of unlike charges, the net force on a given point in space is the vector sum of the forces exerted by both charges. A straight line between any two adjacent points in an electric field line is always parallel to the direction of force.

B. Applying Electric Field Principles for Routing

Electric field lines have several intriguing characteristics. First, electric field lines are naturally disjoint, even when close to the causative charges. Second, coordination is achieved entirely by applying the equations of electric fields at individual points. Each point in space "knows" exactly how to participate in the global behavior based on only the knowledge of its position relative to the two poles. Third, one can reach the unlike charge from the like one by following any one of the field lines.

In EFR, the like and unlike charges are replaced by the source and destination nodes. Different field lines represent different propagation paths from the source to the destination. By choosing field lines with different initial angles at the source node, we can control the distance between disjoint paths, and thus control the spatial disjointness. An angle of 0 degrees represents the straightest and (most likely) the shortest path from the source to the destination, which is also the route produced by compass routing [21]. Fig. 1 shows a pair of communicating nodes using EFR. The five routes shown are based on electric field lines with different initial angles.

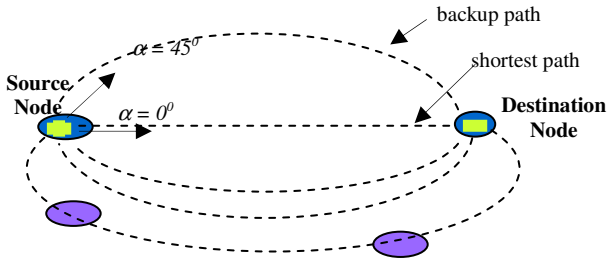

Fig. 1 – Routes Corresponding to Different Angles

Route forwarding is based on choosing a neighboring node that is close to the current field line and near maximum transmission range. Section III will discuss in more detail how EFR works.

C. Benefits of EFR

EFR, a stateless multipath location-based routing, can provide the following benefits:

1. Constructing disjoint routes requires no explicit coordination. Any intermediate node needs to know only its position relative to the source and destination to forward the data packet.
2. Intermediate nodes maintain no per-route state to forward data packets. A node participates in a route when a packet arrives there. Mobility and changing node membership are thus handled without explicit route reestablishment.
3. Since each forwarding node only keeps track of its neighbors, EFR scales well.
4. The quality of routes under EFR can improve as the number of nodes increases, while some existing routing approaches are likely to encounter scaling problems due to the number of control messages needed for coordination.
5. EFR allows flexible control over the number of redundant routes, their disjointedness, and the reliability of transmissions, thus providing a continuum of solutions for various constraints.
6. Spatially disjoint paths can be used for reliable delivery, load-balancing, bandwidth aggregation, and resiliency against certain network failures or misbehaving nodes.

7. Given that any packet can follow any field line to reach its destination, misrouted packets still have a high probability of delivery.
8. EFR also works for 3D environments.

D. Current Drawbacks of EFR

While EFR has many advantages over existing ad hoc routing solutions, it also has certain limitations. First, EFR must know the physical locations of the source and destination nodes. This is an inherent property of all location-based routing. Second, EFR does not guarantee delivery of all packets, even when some feasible path exists. Finally, EFR may not be optimal for stationary networks, since the combination of effective caching of static network topology and greedy routing can outperform EFR.

Nonetheless, EFR offers overall advantages compared to existing alternatives and performs better on key metrics in a variety of realistic cases.

III. EFR ROUTING PROTOCOL

The basic steps in the protocol are as follows:

1. The source finds the destination's location (as needed) using any location-discovery protocols.
2. On learning the position of the destination, the source probes the destination by sending requests along different electric field lines.
3. The destination sends an ACK for each request corresponding to different field lines.
4. To send data packets, the source selects the route with the smallest end-to-end delay.
5. The source periodically probes the destination at other angles and selects a new best route.
6. The destination periodically sends ACKs to refresh the route status.

A. Assumptions

For EFR to work, each source node needs to know only its own position and the destination node's position. A node does not need to know the position of all nodes in the network.

Since the primary purpose of this paper is to apply the concepts of electric fields for MANET routing, we are less concerned with optimizing location discovery. EFR can use any known location-discovery methods (e.g., [8, 23, and 33]).

For the current investigation, we chose a relatively simple approach in which each node finds its own geographic position via GPS [7 and 18]. The destination's position is then found through flooding. Clearly, a better location-discovery alternative would improve the performance of EFR.

B. Discovering the Destination's Location

The position of the destination is found using a basic flooding scheme. The location request is propagated from the source through the entire network (similar to the propagation of RREQ in DSR [16]). However, in contrast to DSR, this flooding needs to be done only once, at the beginning of the data session. The destination will periodically report its new location back to the source as it moves.

Each location request contains the source coordinates, a sequence number, and (if available) the timestamp of the last known destination location. Requests can be short-circuited; if an intermediate node has cached an up-to-date destination position, then that value will be returned immediately. In the absence of cached information, an intermediate node will forward the request to all its neighbors. Once the request reaches the destination node, it will send back its coordinates directly to the source.

C. Establishing Routes

After discovering the destination position, the source probes the destination for valid routes by sending route requests through different angles. Data packets can be aggregated in the request to save extra round trips at the cost of larger packet size. In our implementation, the source probes the destination by sending requests through three different angles. Route requests and data packets are routed in the same fashion, as described in III.D.

On receiving the request, the destination piggybacks an ACK to confirm the status of that angle. After receiving the first ACK from a route via an angle, the source starts to send subsequent data messages using that route. If multiple ACKs are received through routes of different angles, the source will choose the one with smallest end-to-end delay. Periodically, the source will request an ACK from the destination to refresh the status of the current active route and one alternative route (randomly chosen). This request is also aggregated to the data packet. A route

(corresponding to an angle) will be timed out if no ACK is received to refresh it.

In the current implementation, the source uses end-to-end delay as the routing metric to avoid congested paths. Other metrics could be used to offer load-balancing or power management.

D. Routing Data Packets

The source node, after deciding a routing angle, forwards the data packet to the neighbor node that is closest to the electric field line corresponding to that angle. For intermediate nodes, the ideal choice of the next hop is the node closest to the existing field line while near the maximum transmission range. Note that each intermediate node knows which field line to use to forward packets since it knows the locations of the source, destination, and the current node.

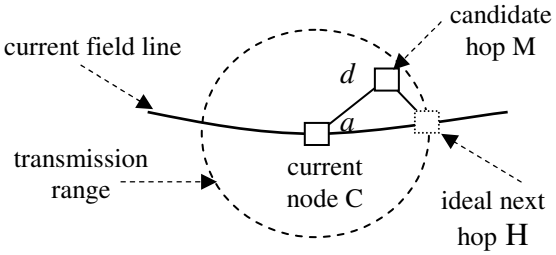

Fig. 2 – Finding the Ideal Next Hop

As shown in Fig. 2, H is the ideal neighbor node that lies on the intersection of the current field line and the maximum transmission range of current node C. If H does not exist, we have to find the candidate node M that minimizes *a*, the angle between the current field line and the direction of the next node, and maximizes *d*.

In our implementation, a node can experience a force by a pole proportional to $K\frac{Q_1Q_2}{r^2}$. This is known as Coulomb's law [13], where $K=\frac{1}{4\pi\varepsilon_0}$, where ε_0 is the permitivity of free space, with the value of $8.85*10^{-23}$. Q_1 and Q_2 are electric charges of two poles. Since the charge itself contains positive and negative signs, they will influence the direction of the resulting vectors. For simplicity of computations, we make $KQ_1Q_2 = 1$. Finally, r is the distance between the pole and the node. Intuitively, the $4\pi r^2$ term at the denominator reflects how electrical forces decay with the increasing spherical surface area relative to a charged point at the center of the sphere [13].

Assume that the current node C, the source node S and the destination node D are at (x_C,y_C), (x_S,y_S) and (x_D, y_D), respectively. The magnitude of the force exerted by the source is given by the formula

$$\left|\overline{E_{SC}}\right| = \frac{1}{4\pi\varepsilon_0}\frac{Q_S}{(x_C-x_S)^2+(y_C-y_S)^2}$$

and similarly for the force exerted by the destination:

$$\left|\overline{E_{CD}}\right| = \frac{1}{4\pi\varepsilon_0}\frac{Q_D}{(x_D-x_C)^2+(y_D-y_C)^2}$$

The angle of the force exerted by the source is:

$$\theta_{SC} = \sin^{-1}\left(\frac{y_C-y_S}{(x_C-x_S)^2+(y_C-y_S)^2}\right)$$

The angle due to the destination is:

$$\theta_{CD} = \sin^{-1}\left(\frac{y_D-y_C}{(x_D-x_C)^2+(y_D-y_C)^2}\right)$$

The magnitude of the combined force in the X and Y direction is given by:

$$E_{CX} = \left|\overline{E_{SC}}\right|\cos\theta_{SC} + \left|\overline{E_{CD}}\right|\cos\theta_{CD}$$

$$E_{CY} = \left|\overline{E_{SC}}\right|\sin\theta_{SC} + \left|\overline{E_{CD}}\right|\sin\theta_{CD}$$

Its angle can then be calculated as:

$$\theta_C = \sin^{-1}\left(\frac{E_{CY}}{|E_{CX}|^2+|E_{CY}|^2}\right)$$

It is this angle that is of interest in EFR, since it gives the tangent to the electric field line at that point. We must now find the next-hop node that is closest to that direction and at maximum range. In our implementation, we chose a simple approach in which we find all candidate neighbor nodes that are within a small angle range (e.g., 15 degrees). The node that makes the most progress toward the destination will be picked from these candidates.

In a mobile environment, it can be suboptimal to choose a node at the absolute maximum transmission range, since the node is more likely to move out of range before the arrival of the next location update or

due to link loss ratios as described in [10]. We can avoid this problem by reducing *d* by the product of the maximum node speed and the inter-update interval.

A data packet is forwarded to the neighbor node that is closest to the current field line formed by the source, the current, and the destination nodes. Therefore, data packets can jump from one field line to another during the transmission. As a result, the final route might not conform to the original chosen electric field shape. The initial angle and the electric field line are only guides to help the route form disjoint routes without explicit coordination.

To avoid packets wandering in the network, there is a maximum TTL and a threshold to prevent the next hop from deviating from the current field line. If no neighbor is found or the TTL has been reached, the data packet gets dropped. Currently, EFR does not offer guaranteed delivery if a feasible path exists. This is discussed further in Section VII.

E. Heartbeats

Each node caches the locations of neighboring nodes. Each node periodically broadcasts its location (heartbeats) to its neighbors to maintain the cache. If a cache entry is not refreshed within a timeout period, the entry is removed.

To reduce routing overhead, EFR eavesdrops on regular messages to extract location information, and a node that is transmitting data skips its heartbeat.

A failed neighbor can be detected by a heartbeat time-out or by notification from the MAC layer (through link-layer feedback from IEEE 802.11 [14] or by the absence of a passive ACK [17]).

Each node's location cache also stores the recently overheard locations of more distant nodes that have responded to location-discovery requests. The cache is used to reduce the amount of location request flooding and to update the destination coordinates in packets that pass through the node. If an in-transit packet contains newer location information, it will update the local location cache and vice versa. The timeout for location information is set to 30 seconds.

IV. PERFORMANCE

A. Tested Protocols

We compared EFR to several popular protocols. The applicability of our results is limited in three ways. First, among the large number of protocols, we can only choose a representative subset for comparison. Second, since different protocols have different implementation platforms and versions, we only selected ones that were publicly available and could be ported to ns-2 (version 2.1b9). Third, although location-based approaches primarily provide single-path routes, we also compared our multipath approach against location-based approaches to show a more meaningful overhead comparison with other stateless routing protocols.

We decided to compare EFR to four approaches: LAR [20], DREAM [1], GPSR [19], and AOMDV [26]. The first three are location-based approaches: DREAM uses flooding, LAR is source-routed, and GPSR provides guaranteed delivery. AOMDV is a multipath algorithm. We made minor modifications to the DREAM and LAR implementations [6] to port them to the latest stable version of ns-2.

The original GPSR assumed global knowledge, where an ideal location-management database provides the source nodes with the locations of the destinations at zero cost. To allow a fair comparison with LAR and DREAM, we modified GPSR to use the same location-discovery mechanism as EFR.

Existing multipath routing protocols [22, 26, 28, 34] are largely variants of AODV and DSR. To compare multipath results, we selected AOMDV, an AODV variant. We configured AOMDV to use three disjoint link routes, as in [26].

Since LAR and AOMDV are the enhanced versions of DSR and AODV, we did not include DSR and AODV in our benchmark. The simulation results from [6] and [26] also showed that LAR and AOMDV outperformed these two routing protocols.

B. Simulation Model

We evaluated all five protocols using the ns-2 simulator [12]. The CSMA/CA protocol and distributed coordination function of IEEE 802.11 [14] for wireless LAN were used. The radio model was similar to a commercial radio interface, Lucent's WaveLAN, with a nominal bit-rate of 2Mb/sec and radio range of 250 meters.

All protocols maintain a send buffer of 64 packets for data packets waiting for a route. Packets are dropped after 30 seconds of waiting. All packets sent by the routing layer are kept in the interface queue until the MAC layer can transmit them.

Scenario	Node Population	Area	Radio Range	Average Neighbors	CBR Pairs	Mobility Speed (m/s)
1	50	600m x 300m	100m	8	20	0 – 20
2	100	1000m x 1000m	250m	20	10 – 50	20
3	100	1000m x 1000m	250m	20	20	20

Table 1 – Simulation Parameters

To keep packets from unnecessarily wandering in the network, the maximum hop count was set to 32.

Our mobility and traffic models were similar to those in prior studies [6, 26]. The *random waypoint* model [5] was used to model mobility. As in [6], we fixed the pause time at 10 sec and varied the maximum speed of the nodes so that the protocols could be placed under stress.

As in [6], we used CBR and peer-to-peer traffic to stress the protocol. We varied the number of CBR pairs between 10 and 50 to test the behavior and scalability of the protocols under different network loads. The sources sent 64-byte packets at a rate of 4 packets per second. To avoid contention, we padded the transmission of data packets by 0.1 milliseconds for each of the CBR pairs. To avoid initial flooding by all nodes for route discovery, there was a 1-second window between each CBR pair before the first packet was sent. In our figures, each data point represents the average of 10 simulation trials at each speed setting and CBR load. Confidence intervals are shown at the 90% level, except when they are insignificantly small.

C. Simulation Scenarios

We evaluated the protocols in both small and large networks, and both rectangular and square simulation areas. We tested them for high mobility and heavy traffic by varying mobility speeds and the number of CBR. We tried both highly concentrated and equally distributed traffic loads. Table 1 describes the settings for each scenario.

Scenario 1:
This scenario was used to compare DREAM and LAR in [6]. The use of a rectangular area resulted in a larger hop count than that of a square with the same area. The total simulation time was 2000 seconds, which included 1000 seconds of warm-up time. Each routing protocol was simulated 50 times (5 speed settings x 10 mobility topologies).

This scenario is designed to test the performance of the protocols in a small and sparse network under varying mobility conditions.

Scenario 2:
This scenario with dense topology was also used in [6]. The simulation involved a square area. The square area allows nodes to move more freely and maximizes the benefit of spatially disjoint routes. The total simulation time was 1000 seconds, which included 250 seconds of warm-up time. Each protocol was simulated 50 times.

This scenario was designed to test performance in a large and dense network with high load. The traffic becomes more equally distributed as the load (number of CBR connections) increases.

Scenario 3:
We designed this scenario to show the advantages of EFR under a heavy load generated by a group of nodes. The settings were similar to those in Scenario 2, except that we fixed the number of CBR sources at 20. We increased the load by varying the data-sending rate of each CBR connection from 4 to 5 packets/second.

D. Performance Metrics

We used the following metrics to compare protocol performance:

(i) *Data packet delivery ratio* – ratio of the number of received data packets to the number originated by the source(s); (ii) *Hop count* – average hop count of all data packets received by the destinations; (iii) *End-to-end delay* – average end-to-end delay of all data packets received by the destinations; (iv) *Normalized routing load* – number of routing control packets transmitted per data packet delivered at the destination. Each hop-wise transmission of a routing control packet is counted as one transmission. Control packets used in the location discovery service were included.

E. Simulation Results

Scenario 1: (50 nodes – 600x300m – small-size and sparse topology)

Fig. 3a illustrates the data packet delivery ratio versus speed. Surprisingly, no protocol achieves a 100% delivery ratio at speed 0, even though the network is not partitioned. The node positions were generated randomly (using the *setdest* utility in ns-2), and we selected unpartitioned topologies from those generated. We found that when a topology contains narrow bridges that connect several groups of nodes, the tested protocols yield lower delivery ratios than previously reported. Packets are often dropped at the heavily congested bridges. Packets that miss the bridge tend to wander in the network. This observation is especially true for GPSR in perimeter mode. Thus, the performance for a static environment is highly dependent on the network topology.

For non-zero speed settings, we let nodes move for 1000s before sending the first data packet.

EFR yields the highest delivery ratio in all but the static mobility settings. In fact, EFR's delivery ratio degrades rather slowly as the node speed increases in this environment. At speed 0, however, EFR's performance is highly dependent on the topology, and is not always optimal.

Although AOMDV and DREAM have similar delivery ratios, they pay a very high cost in overhead packets; this will be discussed later.

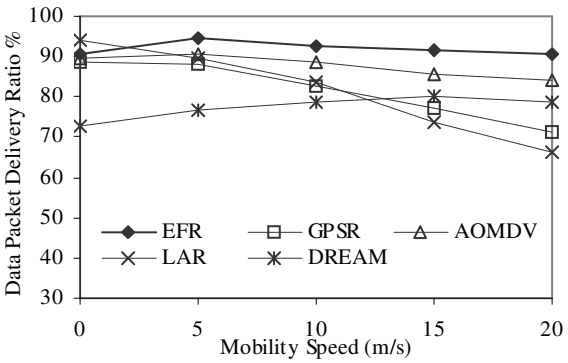

Fig. 3a – Data Packet Delivery Ratio
(confidence intervals omitted for readability)

As speed increases, LAR's delivery ratio degrades rapidly. Even though LAR uses location information to reduce the flooding overhead, it still relies on precomputed hop-by-hop routes that break more frequently as mobility increases. AOMDV performed better with multiple paths because it can switch to a backup path when the current path is broken, thus reducing flooding.

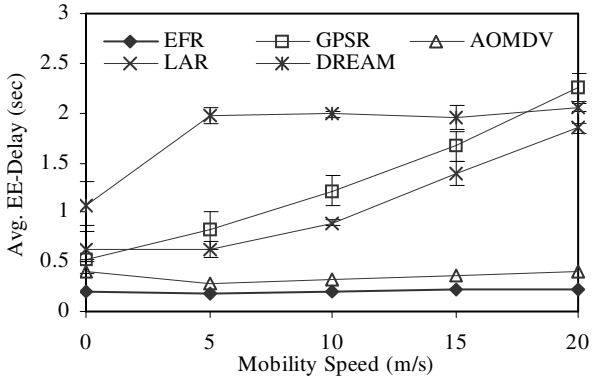

Fig. 3b – Avg. End-to-End Delay

GPSR performed better than LAR for being a pure location-based approach with guaranteed delivery. However, GPSR performed worse than AOMDV for several reasons. First, GPSR produces only a single route as opposed to three routes under AOMDV. Second, sparse topologies force GPSR to trigger the perimeter mode more often, and bridges in those topologies make GPSR break more often. Third, AOMDV uses a HELLO-message technique for early detection of stale routes. Thus, AOMDV can quickly perform recovery procedures if all routes are broken. However, AOMDV pays a high cost in control overhead to achieve early detection (as shown later in Fig. 3c).

Finally, DREAM maintains an almost constant (but much lower) data delivery ratio because of contention and congestion (as explained in [6]).

Fig. 3b shows end-to-end delay versus speed. EFR offers the lowest end-to-end delay because of its metric for selecting the best path. AOMDV's delay is almost 1.5 to 2 times longer than that of EFR. All other protocols degrade rapidly as speed increases.

GPSR's greedy mode helps it find the shortest path regardless of network congestion. Given the random distribution of nodes and communication pairs, nodes in the middle of the simulation area are more likely to be selected, resulting in a congested central network area that adversely affects GPSR's end-to-end delay.

There are several reasons why AOMDV has a lower end-to-end delay than GPSR and LAR. First, AOMDV actively maintains the freshness of multiple paths to the destination at the cost of high control

overhead; data packets do not often stay in the buffer queue for a long period. The packet will instead be sent immediately using other routes if the current path is down. Second, the current MAC-layer implementation in ns2 gives a higher transmission priority for control packets than data packets for AOMDV. Third, greedy approaches like GPSR often try to forward data packets to a neighbor that makes the most progress toward the destination. These neighbor nodes are likely to be near the maximum transmission range, and so could move outside that range soon, making the greedy approach counterproductive.

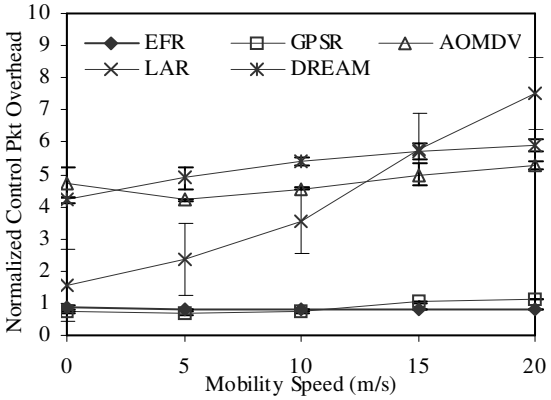

Fig. 3c – Normalized Control Overhead

Fig. 3c shows the normalized control overhead as speed increases. GPSR and EFR have the smallest overhead, since both perform stateless forwarding. Other protocols pay higher overhead for route discovery and maintenance: AOMDV and DREAM have 5x overhead of GPSR and EFR.

Fig. 3d shows average hop counts versus speed. EFR has a lower hop count than all the other protocols except GPSR, although all are very close. Recall that EFR chooses the route with the minimum end-to-end delay, while GPSR uses a greedy approach as the default routing mode. Therefore, GPSR always gives the shortest path, regardless of the traffic congestion. Unsurprisingly, EFR's end-to-end delay metric produces small hop counts as a side effect.

In this scenario, EFR still was able to find multiple paths and performed better than the other protocols, considering the density of nodes in this experiment is rather sparse compared to many existing studies. For a sparser network, EFR may encounter difficulties in finding multiple paths. We will discuss this issue further in Section VII.

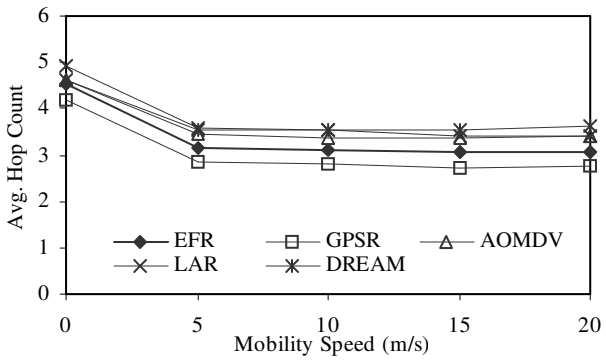

Fig. 3d – Avg. Hop Count

Scenario 2: (100 nodes – 1000x1000m – large size and dense topology – highest mobility – high network load distributed equally)

In this scenario, we wanted to see the protocols' performance in a dense and large topology under high load and mobility. In this topology, network load is spread evenly as it increases.

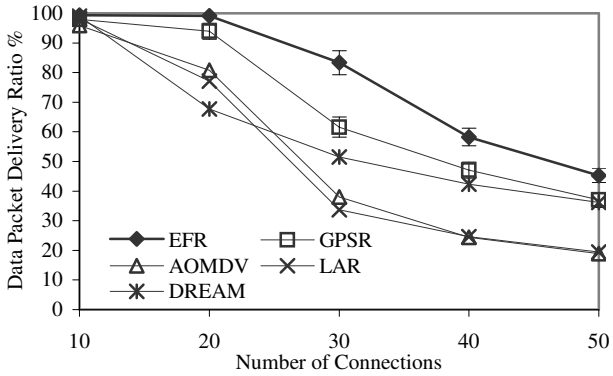

Fig. 4a – Data Packet Delivery Ratio

Fig. 4a shows the delivery ratio. EFR offers the highest delivery ratio at high load. When the number of connections reaches its peak of 50, the network is extremely congested almost everywhere. EFR is better than the other protocols here, but even its delivery ratio is too low for it to be useful. We did not simulate beyond 50 connections; at this point, the end-to-end delay reaches a totally unacceptable level of 3 to 7 seconds for all protocols. Beyond 50 connections, all protocols might converge to the same point, but the number would be meaningless because the network would have become unusable.

The performance of AOMDV and LAR suffers due to frequently broken hop-by-hop routes that are

predefined. Recall that EFR and GPSR do not rely on pre-computed hop-by-hop routes.

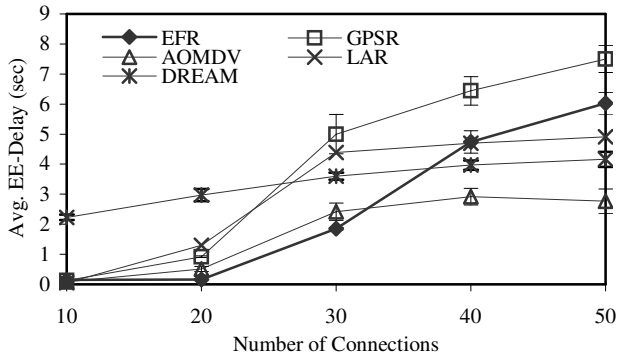

Fig. 4b – Avg. End-to-End Delay

As Fig. 4b shows, EFR and GPSR start to have high end-to-end delay at high connection counts. However, they are still delivering many more data packets than the other protocols. DREAM achieves a delivery ratio similar to GPSR with a much lower latency than either EFR or GPSR because it is delivering packets by flooding.

By flooding, DREAM offers a moderate level of data delivery at all connection counts. However, because of this flooding, its data overhead is 30 times larger than other protocols (not shown here due to space limitations). This observation is consistent with results described in [6].

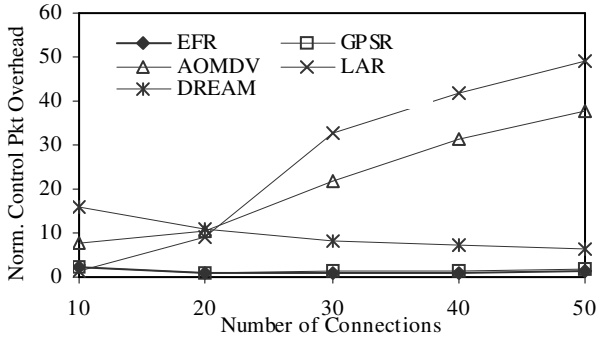

Fig. 4c – Normalized Control Overhead

As in the first scenario, Fig. 4c shows that EFR and GPSR have the lowest control overhead.

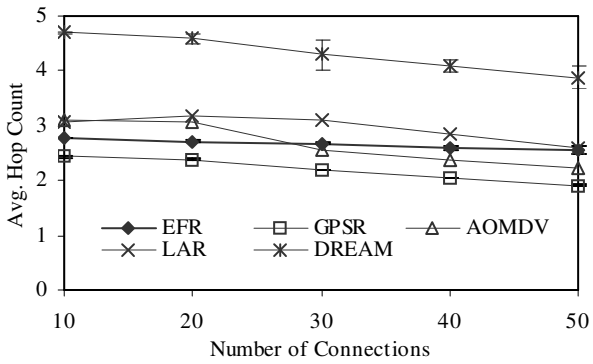

Fig. 4d – Avg. Hop Count

As Fig. 4d shows, GPSR has the lowest hop count and is slightly better than EFR, similar to the previous scenario. However, DREAM is significantly worse in this case.

Scenario 3: (100 nodes – 1000x1000m – large size and dense topology – highest mobility – high network load concentrated in some areas)

Real networks often face unevenly distributed loads through different parts of the networks. This scenario is designed to investigate that situation by keeping the number of connections constant at 20 and varying the packet sending rates.

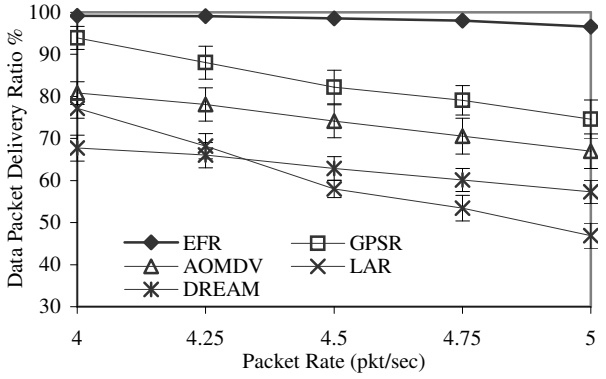

Fig. 5a – Data Packet Delivery Ratio

Figures 5a to 5c show the performance of the five protocols for scenario 3 (the graph for the average hop count is omitted since it is similar with previous scenario). As the load increases, EFR still achieves a data packet delivery ratio of up to 95%. All the other protocols degraded rapidly under high load. Since EFR chooses the angle route with smallest end-to-end delay, it can minimize delay, hop count, and control overhead while avoiding highly congested paths.

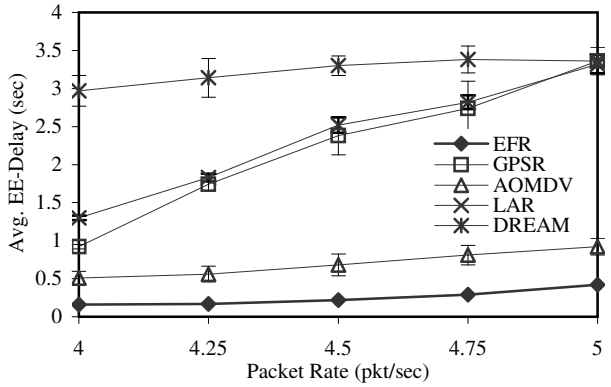

Fig. 5b – Avg. End-to-End Delay

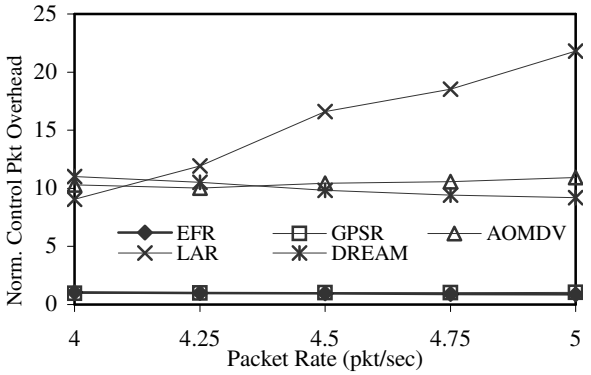

Fig. 5c – Normalized Control Overhead

V. DENIAL-OF-SERVICE ATTACKS

As mentioned earlier, the EFR framework can offer features such as load-balancing, bandwidth aggregation, power management and resiliency. In this section we show how EFR can resist problems caused by network failures or DOS attacks from misbehaving nodes.

A. Problem Statement and Related Work

We focus on the problem of misbehaving nodes that agree to participate in forwarding but then indiscriminately drop all data packets. This problem may happen when a node is overloaded, selfish, malicious, or broken, as discussed in [27]. By not forwarding data packets, misbehaving nodes can cause a DOS attack since the destination can no longer receive any data packets.

In [27], the authors proposed a solution using *watchdog* and *pathrater*. When a node forwards a packet, the node's watchdog verifies this by eavesdropping to confirm that the next node in the path also forwards the packet. The *pathrater* uses this knowledge to choose the path that is most likely to deliver packets.

The problem with this approach is the need to buffer recently sent packets at each node for comparison with overheard ones to make sure the next node is forwarding correctly. For mobile nodes, the memory and processing cost of these comparisons can be high. Also, the approach relies on a trust relationship among nodes. To choose a reliable path, the *pathrater* at the source has to rely on reports from intermediate, possibly malicious, nodes. Finally, for the watchdog to work properly, it must know where a packet should be two hops later, so it must be built on top of a source routing protocol such as DSR. As we have seen, source routing protocols have high control overhead when mobility is high.

In [30], the authors suggest building node-disjoint routes. Since their approach relies on source routing algorithms and on building hop-by-hop routes, issues similar to the above arise.

B. How EFR Defends Against DOS Attacks

EFR inherently resists this type of DOS attack. A misbehaving node can drop: (1) route requests corresponding to a given angle; (2) ACKs from destination nodes for a given angle (to refresh the route status); (3) data packets. (Note that we omit security concerns related to location-discovery since EFR is independent of the location service.)

If the route request is dropped, the destination will never receive the request for that angle, and thus the source will never receive the corresponding ACK. Therefore, the route containing misbehaving nodes is not used. The same happens if the ACK packet is dropped. We assume that ACKs from the destination can be cryptographically authenticated by the source so that other nodes cannot forge ACKs. We now only need to consider the third case in which the data packets are dropped.

Misbehaving nodes can either drop all data packets or only a percentage of them.

In the former scenario, the destination will not receive any packets and thus will not send back any ACKs to refresh the route. As a result, the route will not be used.

To avoid detection, misbehaving nodes might drop only a certain percentage of data packets. If only some packets are dropped, the attack is also only partial.

Our simulation results (not presented here) show that when the misbehaving nodes reduce their dropping rate from 100% to 25%, EFR's packet delivery ratio increases from 80% to 90%, which is higher than other compared protocols. So if the attacker's goal is to maximize the packet loss rate by dropping most or all data packets, EFR will offer the most resilience to the attack.

In addition, the source can randomly include a request for an ACK embedded in the data packet. If no ACK arrives, the source can determine that either the message or its ACK was dropped somewhere. Finally, the destination can measure the throughput of an angle from the received data packets and return that information in the ACK. The source can use that information to decide the best angle to use. Note that the congestion-control feature of the upper protocol layers cannot solve this problem by itself, since it does not have the ability to switch among different routes (as in EFR).

In some cases, certain types of packets are crucial to the application service. If the attacker drops them, remaining data packets become useless to the destination. To combat such an attack, encryption could be applied so that intermediate nodes cannot differentiate between crucial packets and normal packets, making it impossible for an attacker to preferentially drop only crucial packets.

If the misbehaving nodes can interfere with all chosen angle routes, the source cannot send data. One solution is to increase the number of probing angles in response. The attacker will have to compromise a large percentage of nodes to stop all the possible angles. This is not a trivial task for the attacker, since our simulation results show that EFR can still achieve good performance when up to 30% of the nodes are compromised.

C. Simulation

Our simulation compares EFR with GPSR and AOMDV under DOS attack. A more comprehensive analysis would include protocols using a watchdog mechanism [27].

Our simulation area was 1000x1000m for 100 nodes with radio range of 250m. The pause time was 10s, and mobility speed was 10m/s. The packet rate was 4.75pkt/sec for 15 CBR pairs. This moderate network load isolated the effect of misbehaving nodes from network congestion. We also tried a high load setting (20 CBR pair). Since the results are similar, they are not shown.

All configurations for all protocols were the same as in the earlier simulations. Similar to [27], we varied the percentage of misbehaving nodes from 0% to 30%, each time adding new malicious nodes to the existing set. This ensures that obstacles present in lower-percentage runs are also present in higher-percentage runs.

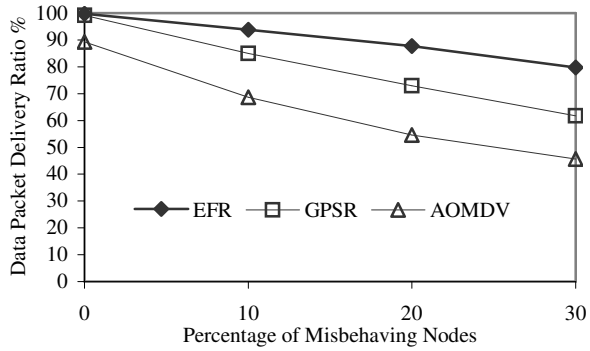

Fig. 6a – Data Packet Delivery Ratio

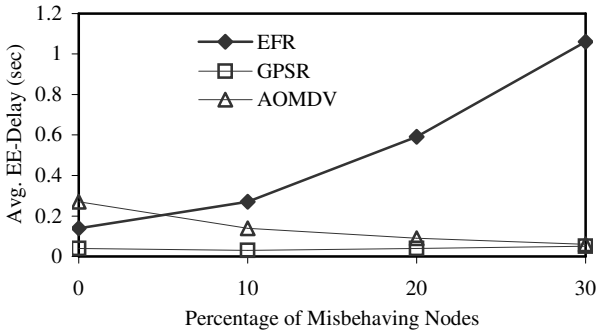

Fig. 6b – Avg. End-to-End Delay

Fig. 6a shows the delivery ratio of each protocol for different percentages of misbehaving nodes. When there are no misbehaving nodes, GPSR and EFR achieve an almost perfect data delivery ratio, which is consistent with the behavior described in Section IV.

As the number of misbehaving nodes increases, EFR can still deliver up to 15% more packets. Of course, to one extreme, all protocols should converge when all intermediate nodes are malicious and no transmissions are possible for paths longer than 1 hop. Figure 6a demonstrates that EFR significantly outperforms other protocols with 30% of misbehaving nodes.

Fig. 6b shows the end-to-end delay of all protocols. As the number of misbehaving nodes increases, EFR's end-to-end delay starts to increase. This is not

surprising since there are fewer routes from which to choose from, especially for long-distance CBR pairs. Therefore, packets have to wait longer for feasible paths. In contrast, GPSR and AOMDV drop most data packets on long paths and only deliver along the shorter paths. Since we do not penalize dropped packets in the end-to-end calculation, the delay for GPSR and AOMDV is artificially understated.

In addition, the packet dropping reduced the GPSR and AOMDV total network load, again reducing the end-to-end delay for the remaining packets. In contrast, EFR delivers 20% more of the data packets, putting a greater burden on the remaining 70% of well-behaving nodes.

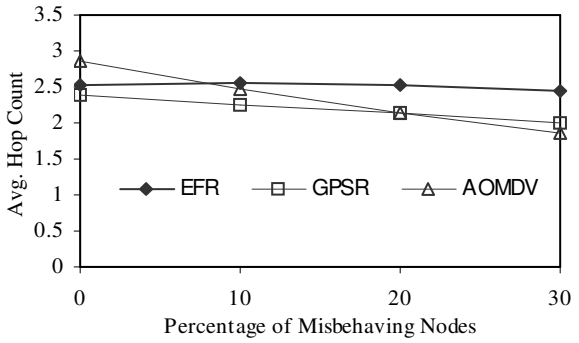

Fig. 6c – Avg. Hop Count

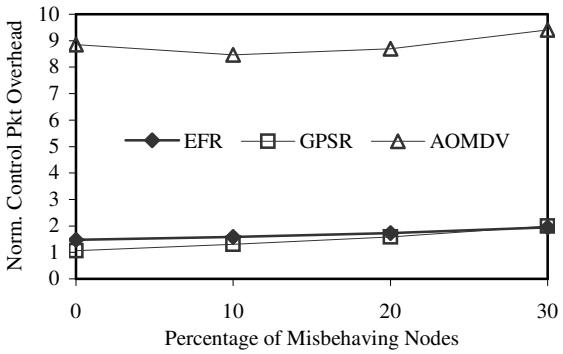

Fig. 6d – Normalized Control Overheads

Fig. 6c indicates that EFR is still able to deliver packets to distant nodes when other protocols can only deliver packets between closer ones. Unlike the end-to-end delay, the hop count for EFR does not increase, since longer routes have a higher chance of being corrupted by misbehaving nodes, causing packets that use those routes to be dropped.

Finally Fig. 6d shows that the low control overheads of EFR and GPSR are not affected by malicious nodes. AOMDV's high overhead is consistent with our earlier results in Section IV.E.

Even though AOMDV supports multiple routes, it does not detect misbehaving nodes. However, we believe that if a mechanism like [27] was added, the overhead would be increased. Also, since routes will be broken more often due to misbehaving nodes, route discovery will be exercised more often, also increasing overhead.

DSR [16] and AODV [31] are the most popular on-demand routing protocols for ad hoc wireless networks. DSR is a source-routing protocol, and relies on fixed per-session routes. Extensive caching helps to reduce the number of flooding requests. However, increased mobility tends to increase the chance of caching invalid entries, thereby reducing performance. Stale routes, if used, may start polluting other caches [25].

VI. RELATED WORK

AODV uses a traditional routing table. Since it keeps less routing information, AODV relies on a route discovery method that floods more often. Like DSR, it is susceptible to broken routes under high-mobility conditions.

Location-based routing protocols, including EFR, assume that each node knows its own approximate geographic position, from a GPS device, or by other means [7, 18]. In DREAM [1], each node also tracks the location of all other nodes. Each node propagates location packets to the whole network. Data packets are sent by *flooding* in a forwarding zone, calculated by the source.

LAR [20] is an enhanced version of DSR, where location information is stored in all packets to decrease the overhead of route discovery. When route discovery occurs, the route requests are flooded within a forwarding zone. This approach reduces the overhead when the destination node happens to be inside the search zone. LAR inherits characteristics of source-routing protocols.

Stateless location-based protocols avoid using a precomputed hop-by-hop route. Thus, route discovery is less expensive. They also reduce the chance of route failure under a high density of nodes, because any nearby node can substitute for a failed neighbor node. One example of this is greedy packet forwarding, known as the most-forward-within-r

protocol [32]. Each node forwards packets to a node that makes the most progress toward a destination. A similar approach, Compass routing [21], forwards packets along a straight line between the source and destination nodes. These greedy approaches can be suboptimal when backtracking is required. A particularly pronounced case is network holes, or regions with no network nodes or services.

Intermediate node forwarding (INF) [11] is proposed to partially solve this problem. INF randomly chooses a point between the source and destination and routes packets to that point. The packets then travel from that intermediate point to the destination. If the packet still cannot be delivered, another intermediate node will be picked. Similar to EFR, INF relies on different routes to probabilistically avoid holes. However, INF does not utilize different routes to select the route with the best metrics. A route in INF is used until it cannot reach the destination. Routing to and from the intermediate node uses a greedy algorithm, so different routes may partially overlap if the alternate intermediate nodes reside in the same direction as the previous nodes.

GPSR [19] and GFG [9] provide guarantees for routing around network holes by using planar graph traversals [2]. When no holes are encountered, both protocols build single-path routes via greedy routing. Both protocols guarantee delivery if a route exists, although finding such a path or determining non-reachability can cause long delays. Currently, they do not avoid congested paths.

Terminode routing [3, 4] combines hierarchical and position-based protocols. If the destination is near the source, a proactive distance-vector approach is used, while a greedy position-based approach handles long-distance routing. In this approach, a path is defined by multiple anchor positions rather than the node ID. Data packets are routed along these anchor positions to reach the destination, assuming that geographical points are more stable than a node ID. Mechanisms to find anchor points are currently under development. All intermediate anchor positions are required to be stored in the packet header (as coordinates and timestamps), and this occupies more space than storing the node ID in other schemes.

Trajectory-based forwarding (TBF) (currently under development) [29] is a generalization of the source-based protocol [16]. Similar to EFR, routing between nodes is performed along a trajectory or a curve. TBF provides a flexible and general framework for curve-based routes, by approximating curves with leading Fourier coefficients. However, since the source is responsible for defining the trajectory equations in advance for every route, each packet needs to carry all coefficients. If the destination moves away from the curves specified at the source, the route will not bend to follow it. In EFR, if an intermediate node is aware of an updated destination position, it automatically adapts since the calculation is based on the last known positions of the source and destination nodes.

Several multipath protocols have been proposed as variants of the DSR and AODV protocols [22, 26, 28, 34]. By deploying multiple routes, a node can switch from one path to another if failure occurs. The use of multiple paths helps to reduce the occurrences of expensive route discovery. In these protocols, the paths are not guaranteed to be spatially disjoint. These protocols also inherit the limitations of source-routing protocols.

Lin [24] proposes a location-based framework for disjoint multipath routing. Unlike EFR, the algorithm does not build spatially disjoint routes. Also, the source broadcasts the same packet to several neighbors, each of whom propagates it in duplication using a greedy algorithm.

VII. FUTURE WORK

A. *Guaranteed Delivery*

As a packet is forwarded along a requested electric field line, it might not arrive at the destination if the available routes are very different from the shape of the line. In particular, like greedy forwarding, EFR does not backtrack well. Instead, EFR relies on a high node density to reduce the probability of pathological topologies and uses redundant routes to increase the probability of delivery. In a high-mobility environment, pathological topologies are likely to be relatively short-lived. However, EFR does not guarantee 100% delivery even if some feasible route exists (for example, in a sparse network with many holes). We plan to investigate algorithms to guarantee delivery when the usual approach has failed. It would be acceptable for such an algorithm to be expensive, provided it was not exercised frequently.

B. *Security*

In Section V we discussed DOS attacks on data and control packets. In the worst situation, an attacker can

interfere with all chosen angle paths. One remedy is to increase the number of probing angles at the cost of maintaining more routes. Another solution is to revert to a guaranteed delivery method as discussed in Section VII.A.

We still need to expand our design to handle other attacks and to perform further work in secure location-discovery. We also plan to investigate the risk of common attacks (e.g., man-in-the-middle and replay attacks) and defenses against them.

C. Non-Symmetric Paths

Since a route between a source and a destination is not a perfect electric field line, forward and reverse paths in EFR are not necessarily symmetric. An available path with a certain angle at the source might not be available at the destination. This characteristic poses a problem in sparse topologies since some control packets in EFR require ACK messages to come back along the same angles. We are investigating the possibility of encoding the source route inside the control packet. The destination could then use the recorded routes to return the ACK. This design has little effect on EFR's statelessness, since the recorded route is used only once for an ACK.

At the application level, data communication between two nodes can traverse paths with different angles in each direction. Such behavior is unavoidable in a mobile environment for all known routing protocols. It is possible that we can take advantage of these asymmetries to achieve additional resiliency or to route around holes.

D. Other Issues

Theoretically, by controlling the initial angle of routes, the source can control the spatial disjointness between routes. Currently, we have not explored in detail the tuning of spatial disjointness in EFR. One possible plan is to simulate regional failures of nodes to understand how to tune the disjointness dial of EFR.

Currently, our implementation sends packets along only one path at a time, so out-of-order packets should not be a major problem except for short intervals when switching from one route to another. In the future, we would like to use EFR for load-balancing by switching between paths. EFR could also be used for power-aware routing by using power consumption as the routing metric.

The current implementation of EFR uses electric field lines with only three fixed initial angles. We have not explored the effect of adjusting the number of paths. More routes will increase both throughput and the cost of maintaining them.

Currently, end-to-end delay is the only metric for selecting a path. We plan to add parameters to control dynamically the redundancy, disjointness, and reliability of routes.

We have not measured the computational cost of solving EFR equations at each node. Since mobile nodes are bandwidth-limited, the small CPU cost of solving the equations will not have a significant effect on throughput. We will analyze the equations and possibly optimize them to reduce the cost in latency and power consumption.

The current location-discovery technique based on flooding is quite expensive. We will try other approaches such as Gossip [15], GLS [23], and DLM [33] to improve EFR's performance.

VIII. CONCLUSION

This paper presents the electric-field-based multipath routing protocol for MANETs. Our on-demand scheme does not use explicit hop-by-hop routes. Each hop is selected dynamically, allowing the node membership of a route to change constantly without triggering route recovery.

EFR can be extended to achieve a higher packet delivery ratio by sending multiple copies of critical packets over different paths. The properties of EFR make it easy to find varying numbers of spatially disjoint routes by simply choosing the initial angles used for transmissions.

Our results show that EFR can deliver packets much more reliably than other existing protocols, particularly with nodes moving at high speeds and high network load. Moreover, it achieves these results with very few control messages. Further, EFR is more resilient to denial-of-service attacks where malicious nodes drop packets that they are supposed to forward. These results and the theoretical simplicity of the EFR algorithm suggest its high potential for practical use.

IX. ACKNOWLEDGEMENTS

We are grateful to the authors of [6, 19, and 26] for providing their implementations of DREAM, LAR, GPSR and AOMDV protocols.

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