Magnetic Field Routing for Ad Hoc Networks

Nam Nguyen, An-I A. Wang, and Peter Reiher
Computer Science Department
University of California, Los Angeles
{songuku, awang, reiher}@cs.ucla.edu

Geoffrey H. Kuenning
Computer Science Department
Harvey Mudd College
geoff@cs.hmc.edu

Abstract - Ad hoc multipath routing provides reliable delivery, load balancing, and bandwidth aggregation in wireless networks without fixed infrastructures. Existing approaches for producing single routes in ad hoc networks do not easily generalize to producing multiple disjoint routes. Popular multipath routing approaches also fail to produce spatially disjoint routes in a simple and cost-effective manner. In this paper we propose a magnetic-field-based routing (MFR) protocol to build multipath routes in mobile networks. Our protocol is simple, yet naturally provides spatially disjoint routes based on the shapes of magnetic field lines. The computation is highly localized and requires no explicit coordination among the nodes. In simulations, MFR demonstrates a higher delivery ratio and lower overhead than popular multipath and location-based schemes in high mobility and heavily loaded networks.

I. INTRODUCTION

Mobile users must communicate when no wired infrastructure is available, either because it may not be economically practical or physically possible to provide the necessary infrastructure, or because the dynamics of the situation do not permit its installation. In such situations, a collection of mobile hosts with wireless network interfaces may form a temporary *ad hoc network* without the aid of any established infrastructure or centralized administration.

In an ad hoc network, each node communicates with the other nodes via radio. These radio packets have a short propagation range (100 to 250 meters in an open field), so the route must be multi-hop when the destination node is not within the source's transmission range. Participating nodes usually have limited power and bandwidth. Moreover, they are mobile, so the topology often changes.

Under high mobility and heavy traffic load, ad hoc multipath routing provides reliable delivery, load balancing, and bandwidth aggregation in wireless networks without fixed infrastructure. Multipath algorithms for wired networks are not readily adaptable to wireless ad hoc networks due to the lack of infrastructures. Moreover, mobile nodes in an ad hoc environment do not have enough power to afford costly multipath algorithms for disjoint routes. Spatially disjoint routes are important in ad hoc networks to avoid collisions, since nodes that are close to each other experience similar transmission conditions.

Some multipath on-demand routing protocols, which are variants of DSR [15] and AODV [29], have been proposed. In these protocols, routes are built whenever the source needs to communicate with the destination. The source sends out the route request, which is flooded throughout the entire 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 between the communication pairs. The data packets are transmitted using this pre-built route, which remains active until the end of the data session. In these protocols, a node can find multiple disjoint (link/node) routes to the destination and switch between them if one is broken. These approaches rely on precomputed hop-by-hop routes. However as mobility increases, precomputed hop-by-hop routes break easily. Thus, the performance of these protocols degrades badly as mobility increases. Moreover, recovery from route failure leads to high overhead.

Some location-based approaches, such as GPSR [18], INF [11] and GFG [10], have been proposed to avoid hop-by-hop routing. In these protocols, packet-forwarding decisions are based on the locations of the current node and the destination. However, 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 for high mobility or traffic load.

Some location-based multipath routing approaches [23] have been proposed, but they do not provide spatially disjoint routes in a simple and cost-effective manner.

As our experimental results show, current protocols experience bad performance in high mobility settings or heavily loaded networks. Specifically, when the network communication is highly concentrated in a group of nodes, current protocols degrade badly because they do not offer spatially disjoint routes to avoid the congested path.

In this paper we propose a magnetic-field-based multipath routing (MFR) protocol. MFR is the first protocol that provides:

(1) Spatially disjoint paths without explicit coordination
(2) Simplicity

(3) Stateless forwarding with localized information
(4) Low overhead and high performance
(5) No need for recovery mechanisms for changing node membership for a given route
(6) Scaling in high mobility and heavy load environments
(7) Ability to relieve and avoid congested paths for faster delivery.

II. RELATED WORK

DSR [15] and AODV [29] are the most popular on-demand routing protocols for ad hoc wireless networks. Both establish routes as needed. DSR is a source routing protocol, and relies on precomputed routes. The use of extensive caching and the promiscuous mode helps to reduce the number of flooding requests. However, when mobility increases, caching contributes negatively because cache entries are often invalid. Stale routes, if used, may start polluting other caches [24].

AODV uses a traditional routing table. Since it keeps less routing information, AODV relies on a route discovery method that floods more often.

These two protocols have two main disadvantages. First, both DSR and AODV rely on precomputed routes with a fixed set of nodes to forward data packets, so the chances of broken routes increase as nodes become more mobile. Precomputed routes reduce the delivery ratio for data packets in the presence of mobility. Second, because they use flooding to recover from broken routes, both DSR and AODV have a high control packet overhead.

LANMAR routing [28] with dynamic group support assumes that network nodes move in groups and a leader is elected within each group. Routing within a group uses local proactive approaches, while routing across groups uses the DSDV protocol. MFR does not assume that nodes move as a group.

Some location-based routing protocols have been proposed to improve the delivery ratio of data packets. In these protocols, each node is assumed to know its own approximated location (either from a GPS device, or by other means [7, 17]). DREAM [1] is a location-based proactive protocol where each node maintains a location table for all other nodes in the ad hoc network. To maintain the table, each node transmits location packets and propagates them to the whole network using a frequency threshold for separating nearby and far away nodes. To send data packets, a source node S calculates a circle around the destination node D based on the most recent location information. Data packets are sent by flooding in a forwarding zone, bounded by the region enclosed by an angle whose vertex is at S and whose sides are tangent to the circle calculated for D. While the flooding is limited, the protocol still suffers from high overheads.

LAR [19] is an enhanced version of DSR, where location information is stored in all packets to decrease the overhead of any future route discovery. When route discovery occurs, a forwarding zone is calculated and all flooded route requests are limited to this zone. By limiting the flooding zone, LAR reduces the overhead when the destination node happens to be inside the forwarding zone. However, it still inherits the disadvantages of traditional source routing DSR as discussed above.

Stateless location-based protocols avoid using a precomputed hop-by-hop route, so they need not store or find hop-by-hop routes to forward packets. Another advantage is that a higher density of nodes can greatly reduce the chance of route failure. If a neighbor node is no longer available, any nearby node can serve as a substitute. One example is greedy packet forwarding, known as the most-forward-within-r protocol [30]. An intermediate node forwards a packet to the node that most reduces the distance to the destination. This approach encounters problems when the route requires backtracking. In compass routing [20], packets are forwarded along a straight line between source and destination nodes. Intermediate Node Forwarding (INF) [11] is used when simple greedy geo-routing fails. INF randomly chooses a point between the source and destination and geo-routes packets to that point. The packets then travel from that intermediate point to the destination using further geo-routing.

Greedy algorithms encounter problems when a packet reaches a node that does not have any neighbors closer than itself to the destination. The situation occurs when there exists a *hole* in the network, or a geographical area with the absence of network nodes. GPSR [18] and GFG [10] have provided guarantees to route around network holes through the use of planar graph traversals [2]. When no holes are encountered, both protocols build single-path routes via greedy routing. They do not detect heavily congested paths. Also, since both protocols guarantee delivery with the presence of network *holes*, data packets can easily take long winding paths in the perimeter mode.

Terminodes routing [3, 4] combines hierarchical and position-based routing. If the destination is near the source, a proactive distance-vector approach is used. For long-distance routing, a greedy position-based approach is used. In this approach, a path is defined as multiple anchor positions rather than the node ID. Data packets are routed along these anchor positions to reach the destination, working on the assumption that geographical points are more stable than a node ID.

However, the protocol currently does not provide a mature mechanism to build or find these anchor positions and the current implementation requires periodic updates to be propagated within an area. The simulated results in [3, 4] further assumed a high-level geo-view of network, which may not be available in an ad hoc environment. Another disadvantage of this approach is the overhead in the packet header. Since all anchor positions (besides the source and the destination) along the path need to be stored in the packet, the size of one position field (x,y,z coordinates and a timestamp) is much larger than the node ID in the traditional source routing.

Trajectory based forwarding (TBF) [27] is a generalization of source-based routing [15] and Cartesian routing (location awareness). In this approach, routing between nodes is performed along a trajectory or a curve. However, this work is still in an "idea form" and no implementation is available. The work also relied on the assumption that the source knows the trajectory a priori.

Several multipath protocols have been proposed as variants of the DSR and AODV protocols [21, 25, 26, 32]. By deploying multiple routes, a node can switch from one path to another if failure occurs. However, they inherit the disadvantages of precomputed routes, which are easily broken under high mobility. Choosing a disjoint path is complex, as a node needs to consider all routes. Without location information, these protocols cannot easily provide spatially disjoint routes.

Lin [23] proposes a location-based framework for disjoint multipath routing. In multipath mode, the source broadcasts a packet to several neighbors, and each neighbor propagates the data packet using a greedy algorithm. Lin does not use the available location information to build spatial disjoint routes.

III. MAGNETIC FIELD ROUTING

The idea of MFR is inspired by the characteristics of the force field lines for a magnetic dipole. We will briefly review the physical aspects of magnetic fields, and demonstrate how to apply the concept of a magnetic field for finding reliable, spatially disjoint, and redundant routes. Finally, we will point out some of the major benefits of the MFR approach.

A Brief Review of Magnetic Fields: With a given pair of magnetic poles with opposite charges, any point in the space would experience two sets of forces: one attractive force emanating from the negative pole and one repulsive force emanating from the positive pole.

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 pole, and the direction of the force is either directly away from or toward a pole, depending on the pole's charge.

With a pair of magnetic poles, the net force for a given point in space is a vector sum of the forces exerted by both poles. A straight line between any two adjacent points in a magnetic field line is always parallel to the direction of force.

Using Magnetic Field Principles for Routing: Magnetic field lines have several intriguing characteristics. First, magnetic field lines are naturally disjoint, even when close to magnetic poles. Second, coordination is achieved entirely by applying the equations of magnetic 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 negative pole from the positive pole by following any one of the field lines.

In MFR, the positive pole is replaced by a source node, and the negative pole is replaced by a destination node. 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. 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 [20]. Figure 1 shows a pair of communicating nodes using MFR. The five routes shown are based on magnetic field lines with initial angles of 90, 45, 0, -45, and -90 degrees.

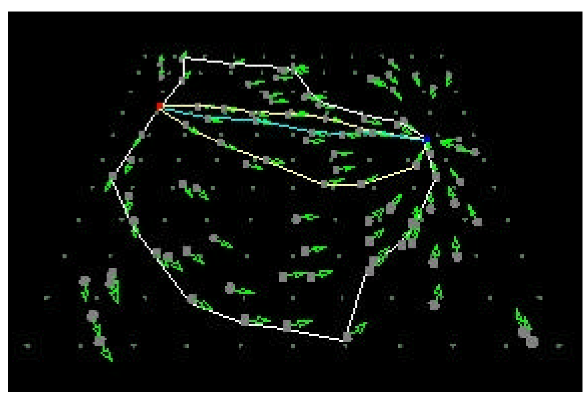

Fig. 1 - MFR with five paths.

Route forwarding is based on choosing a neighboring node that is close to the current field line and near maximum transmission range. For the source node to calculate the magnetic field line, the physical locations of the source and the destination have to be known in advance. GPS coordinates are a natural and readily available means to obtain those locations.

Benefits of MFR:

1. Construction of disjoint routes requires no explicit communication for 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 for any route. A node participates in a route when a packet arrives there. Mobility and changing node membership are thus readily handled without explicit route reestablishment.
3. Since each forwarding node only keeps track of its neighbors, MFR scales well. The size of the neighboring-node table grows in proportion to the density of nodes in an area, which grows as the square root (or cube root for 3D) of the number of nodes.
4. The quality or the disjointness of routes under MFR can improve as the number of nodes increases, while existing routing approaches are likely to encounter scaling problems due to the number of control messages needed for coordination.
5. MFR allows flexible control over the number of redundant routes, the disjointness of routes, and the reliability of data transmission, thus providing a continuum of solutions for various cost constraints.
6. Given that any packet can follow any field line to reach its destination, misrouted packets still have a high probability of delivery.
7. Spatially disjoint paths can be used for reliable delivery, load-balancing and bandwidth aggregation.
8. MFR also works for 3D environments, since magnetic field equations are inherently 3D.

Drawbacks of MFR: While MFR has many advantages over existing ad hoc routing solutions, it is not uniformly better. The following are a few drawbacks of MFR that do not apply to all the other protocols:

1. MFR requires an ability to determine the physical location of source and destination nodes, which some other ad hoc routing protocols do not need.
2. MFR does not absolutely guarantee delivery of all packets when some feasible path exists. Some other ad hoc protocols do.
3. MFR does not perform as well as some other protocols in a few situations, such as when no nodes are moving.

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

IV. MFR IMPLEMENTATION

Location Discovery: In our implementation, each node determines its own geographic position via GPS or some other method [7, 17]. To compute the magnetic field line, the source needs to be able to obtain the destination's position. To avoid relying on centralized location servers, we use a protocol with on-demand location discovery.

There are several approaches to location discovery [8, 22, 31]. For simplicity and completeness, we currently implement a very basic location discovery mechanism based on flooding. Location discovery does not change the statelessness of the MFR protocol itself. Any location services can be adopted without affecting the MFR protocol. We chose to use a basic location service for a fair comparison with other protocols.

In our basic location discovery service, the location request floods the entire network. However, this flooding needs to be done only once, at the beginning of the data session. The destination will periodically send back its new location as it moves.

Each location request contains the source coordinates, the position request sequence number, and the old destination timestamp (if available). On receiving a request, an intermediate node will return an up-to-date location for the destination, if the destination location is in the cache. We will discuss cache management at the end of this section. Otherwise the node will forward the request to all its neighboring nodes. By allowing the intermediate node to answer the location request, the source node will receive an early response, at the cost of multiple responses. Once the request reaches the destination node, the destination will send back its coordinates directly to the source.

Routing Data Packets: After discovering the destination position, the source node can select routes by picking the initial angles of the magnetic field lines. For intermediate nodes, the ideal choice of the next hop is the node that is closest to the existing field line (to ensure the quality of disjoint routes) while being the most distant in terms of transmission range (to minimize hop counts).

As shown in Figure 2, we want to minimize a, the angle between the current field line and the direction of the next node. Also, we want to minimize d, to make sure that the chosen node is close to the ideal next hop, with near-maximum transmission range.

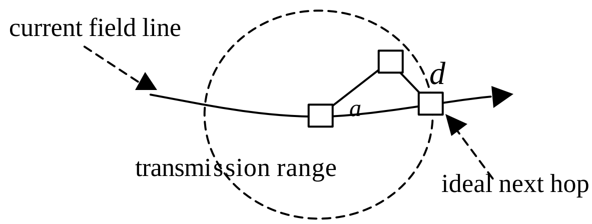

Fig. 2 - Finding the ideal next hop.

Considering mobility, locating a node with the maximum transmission range can be suboptimal, since the node may quickly move out of range before the next location update arrives. We can avoid this problem by choosing nodes at a slightly shorter range, obtained by multiplying the maximum node speed by the inter-update interval.

Initially the source node probes the destination by sending data packets using different angles. On receiving the packets, the destination will send back a reply (if the source requested an ACK). After receiving the first ACK for a specific angle, the source starts to send all subsequent messages using that angle. If multiple replies are received for different angles, the source will choose the angle with smallest end-to-end delay. Valuing minimum end-to-end delay over hop count avoids congested paths. Periodically, the source will request an ACK from the destination to refresh the current active route.

Heartbeats: Each node maintains a location cache to track neighboring nodes. This cache is maintained by periodic location updates (heartbeats) that each node broadcasts to its neighbors. If a cache entry is not refreshed by these heartbeats within a timeout period, the entry is removed on the assumption that the node is out of service or out of transmission range.

A high broadcast frequency causes collisions, which can be reduced by eavesdropping on regular messages, since MFR requires location information in each message. This optimization reduces the number of heartbeat control messages dramatically, especially for heavily loaded networks.

A failed neighbor can be detected by the time-out of heartbeat messages or by explicit notification of delivery failures. The MAC layer notifies the routing protocol if it fails to deliver a data or control packet to the next-hop neighbor. This failure condition can be detected by receiving link-layer feedback from IEEE 802.11 [13] or by not receiving a passive acknowledgement [16].

Each MFR node also maintains a cache of recently overheard location messages. The cache is used to reduce the amount of location request flooding and to update the correct coordinates in packets that pass through the node. If an in-transit packet contains newer location information, it will update the local location cache. On the other hand, if the local cache table is more up-to-date, the location in the packet will be updated. These on-the-fly updates improve the accuracy of routing. The security implications of allowing such updates will be addressed in the future, as will other security issues for MFR. The timeout for location information is currently set to 30 seconds.

V. PERFORMANCE

A. *Tested Protocols*

To show the effectiveness of MFR, we compared it with some popular protocols. Our results are limited in the following ways. First, due to the large number of existing protocols and their variants, 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 available and could be ported to ns-2 (version 2.1b9), which we used for our implementation. 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 MFR with LAR, DREAM, GPSR, and AOMDV. DREAM is a flooding location-based approached [1]. LAR is a source routing location-based approached [19]. GPSR is a guaranteed delivery location-based approach [18]. AOMDV [25] is a multipath variant of the on-demand AODV [29] protocols.

[6] is the first attempt to implement and compare the performance of the location-based DREAM and LAR protocols. We are grateful to the authors of [6] for providing us their implementations of these protocols. We made minor modifications to port their implementations to the latest stable version of ns-2.

GPSR [18] is a popular guaranteed-delivery protocol using a planar subgraph traversal algorithm [2]. The original code assumed the existence of an ideal location management database that allows the source node to always know the precise location of the destination without cost. For a fair comparison with LAR and DREAM, we used the same location discovery mechanism for GPSR as for MFR.

Existing multipath routing protocols [21, 25, 26, 32] are largely variants of AODV and DSR. We selected a variant of AODV, as opposed to a variant of DSR for comparing multipath results, since AODV performs better than DSR in a more stressful environment [9].

The protocol we chose was AOMDV [25], configured to use three disjoint link routes as in [25].

B. Simulation Model

We evaluated these five protocols using the ns-2 simulator [12]. The distributed coordination function (DCF) of IEEE 802.11[13] for wireless LANs is used as the MAC layer. The 802.11 DCF uses Request-to-send (RTS) and Clear-to-send (CTS) control packets to perform unicast data transmissions to a neighboring node. The CSMA/CA protocol was used to transmit packets. The radio model we used was characteristically similar to a commercial radio interface, Lucent's WaveLAN. WaveLAN is a shared-media radio with a nominal bit-rate of 2Mb/sec and a nominal radio range of 250 meters. (We did, however, try a radio range of 100 meters in one scenario for a small-size network).

All protocols maintain a send buffer of 64 packets for data packets waiting for a route. To prevent unbounded queueing of packets in the buffer, packets are dropped if they wait in the buffer for more than 30 seconds. All packets sent by the routing layer are kept in the interface queue until the MAC layer can transmit them. To keep packets from unnecessarily wandering in the network, the maximum hop count was set to 32 for all protocols.

Mobility and traffic models were similar to those in prior studies [6, 25]. The *random waypoint* model [5] was used to model mobility. Each node started its journey from a random location to a random destination with a randomly chosen speed (uniformly distributed between 0 to 20 m/sec). Once the destination was reached, another random destination was targeted after a pause. As in [6], we fixed the pause time at 10 sec and varied the maximum speed of the nodes to stress various protocols.

The traffic sources were CBR (continuous bit rate). As in [6], we used 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 unnecessary contention, we padded the transmission of data packets by 0.0001 seconds 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 they started to send their first packet.

Each data point represents the average of 10 simulation trials for each speed setting and CBR load. Confidence intervals at the 90% level are shown when they are not insignificantly small.

C. Simulation Scenarios

We evaluated the protocols in both small and large networks, and both rectangular and square simulation areas. We tested various protocols for high mobility and heavily loaded traffic by varying mobility speeds and the sources' CBR. We tested these protocols for both high-concentrated traffic loads and equally distributed loads.

Scenario 1:
This scenario was used to compare DREAM and LAR in [6]. The simulation involved 50 nodes in a 600m-by-300m rectangular area. The use of a rectangular area resulted in a larger hop count than that of a square with the same area. The radio range was 100m. Each node had an average of eight neighbors. There were 20 CBR sources sending data to 20 receivers. The maximum mobility speed was varied between 0 and 20 m/s. The total simulation time was 2000 seconds, which included 1000 seconds of warm-up time. Each routing protocol was simulated 50 simulation times (5 speed settings x 10 topologies).

This scenario is designed to test the performance of the protocols in a small and sparse network with respect to mobility and a rectangular simulation area.

Scenario 2:
This scenario was used in [6]. The simulation involved 100 nodes in a 1000m-by-1000m square area. The use of a square area allows nodes to move more freely and maximizes the benefit of spatially disjoint routes. All settings were the same as in Scenario 1, except that the transmission range was 250m. Each node had an average of 20 neighbors, which is considered a dense topology. The maximum mobility speed was fixed at 20m/s. The number of CBR sources was varied between 10 to 50 pairs. The total simulation time was 1000 seconds, which included 250 seconds of warm-up time. Each protocol was simulated for 50 times (5 load settings x 10 topologies).

This scenario was designed to test the performance of the protocols in a large and dense network with high network load. Specially, as the load increases with the number of CBR connections, the traffic is distributed more equally in the network.

Scenario 3:
In this scenario, we wanted to show the advantages of MFR under heavily loaded traffic generated by a concentrated group of nodes. The settings were similar to those in Scenario 2, except that we fixed the number of CBR sources to be 20. We increased the traffic load by varying the data-sending rate of each CBR connection from 4 to 5 pkt/sec.

This scenario was designed to test the performance of the protocols in a large and dense network with a high network load. In contrast to Scenario 2, the traffic was more concentrated in a group of network nodes.

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 the 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. All control packets, including those required to find locations, are included.

E. Simulation Results

Scenario 1: (50 nodes – 600m-by-300m – small-size and sparse topology)

Figure 3a illustrates the data packet delivery ratio versus speed (since the confidence intervals are small, for readability we do not show them). Surprisingly, no protocol achieves a 100% delivery ratio at speed 0, even though the network is not partitioned. The node positions were generated randomly at speed 0 (using the setdest utility in ns-2), and we selected unpartitioned topologies. We found that when a network topology contains 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 aimlessly in the network. This observation is especially true for GPSR in perimeter mode. Therefore, the performance for a static environment is highly dependent on the network topology.

For speed settings of 5 to 20m/s, we followed the same experimental setup as in [6]; that is to let nodes move for 1000s before the first data packet is sent.

The MFR protocol yields the highest delivery ratio in all mobility settings (except for the static case). In fact, MFR's delivery ratio degrades rather slowly as the node speed increases in this environment. At speed 0, MFR's performance is highly dependent on the topology, and may not always yield optimal performance.

Even though other protocols like AOMDV or DREAM have a competitive delivery ratio, they pay an unreasonably high cost in overhead packets, which will be discussed later.

As speed increases, LAR delivery ratio degrades rapidly. Even though LAR uses location information to reduce the flooding overhead, like DSR, LAR is a source routing protocol relying on a precomputed hop-by-hop route. Therefore, routes are broken more often due to high mobility.

GPSR performed better than LAR, as it is a pure location-based approach with guaranteed delivery. However, in this scenario, GPSR performed poorly compared to AOMDV, a multipath approach that relies on a precomputed hop-by-hop route. There are several explanations. First, GPSR produces only a single route, but AOMDV supports three different routes. Second, sparse topologies force GPSR to be in 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 very high cost in control overhead for maintaining these multipath routes (as discussed later). DREAM maintains an almost constant data delivery ratio due to contention and congestion (as explained in [6]).

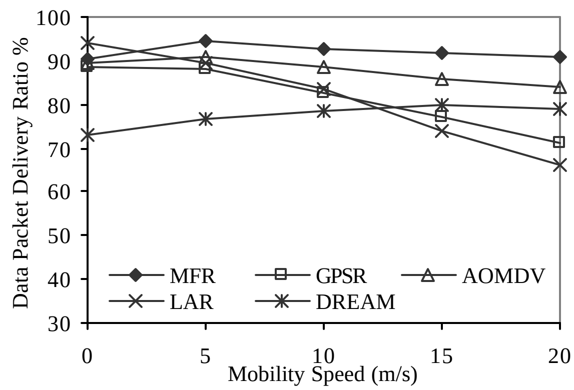

Fig. 3a – Data Packet Delivery Ratio
(confidence intervals omitted for readability)

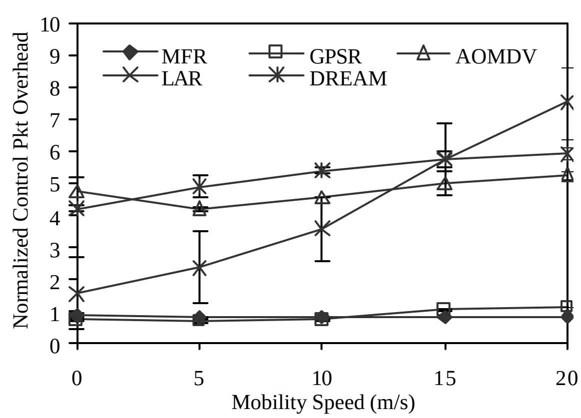

Fig. 3b – Normalized Control Overhead

Figures 3b shows the control overhead transmission for each data packet delivered as speed increases. GPSR and MFR have the smallest overhead since both protocols perform stateless forwarding. Other protocols suffer high overhead for route discovery and maintenance. AOMDV pays around five times the overhead of GPSR and MFR.

Figure 3c shows the end-to-end delay versus speed. MFR offers the lowest end-to-end delay because it uses end-to-end delay as the metric to select the best path. AOMDV's delay is almost 1.5 to 2 times larger than that of MFR. All others protocols degrade rapidly as speed increases. By using a greedy algorithm, GPSR obtains 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 network area that adversely affects the end-to-end delay.

There are some other reasons that AOMDV has a lower end-to-end delay compared to GPSR and LAR. 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. The current MAC-layer implementation in ns2 gives a higher transmission priority for control packets than data packets for AOMDV. Finally, 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.

Figures 3d shows the average hop counts versus speed. MFR has a lower hop count than the other protocols, with the exception of GPSR. Recall that MFR 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.

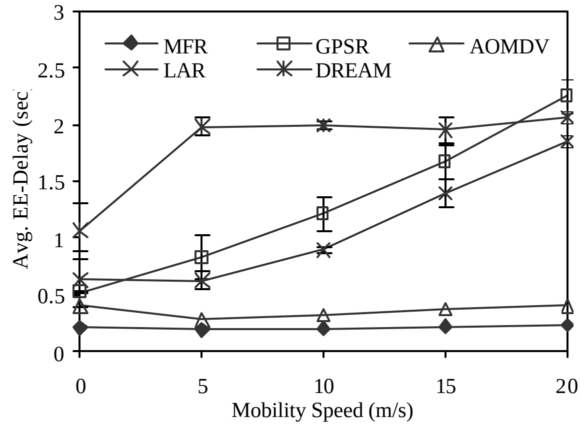

Fig. 3c – Avg. End-to-End Delay

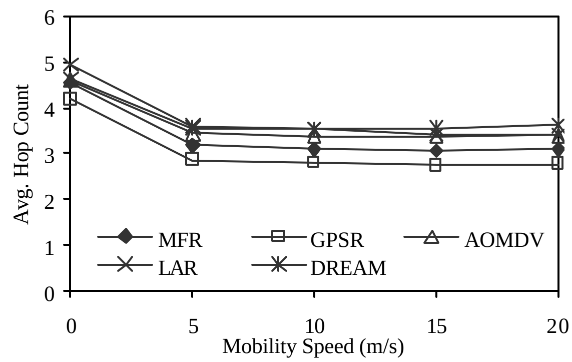

Fig. 3d – Avg. Hop Count

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 everywhere equally as it increases.

Figure 4a shows the delivery ratio of all protocols for this scenario. MFR 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. MFR is better than the other protocols here, but even its delivery ratio is too low for real utility. 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 stopped being useful.

As Figure 4b shows, GPSR has the lowest hop count and MFR has a slightly larger hop count, similar to the previous scenario.

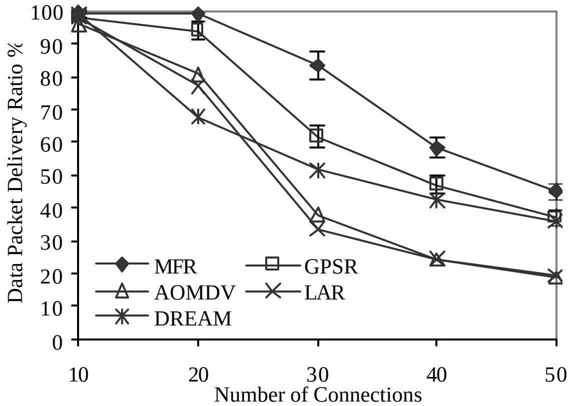

Fig. 4a – Data Packet Delivery Ratio

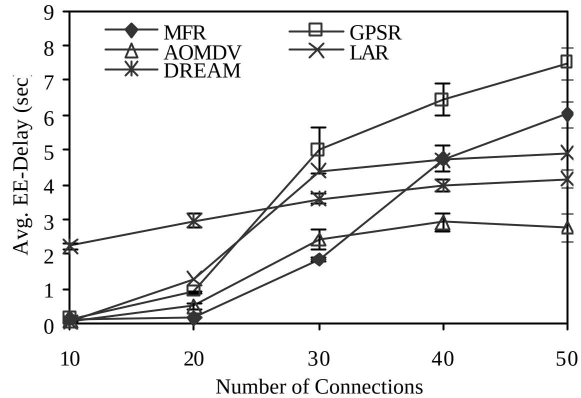

Fig. 4c – Avg. End-to-End Delay

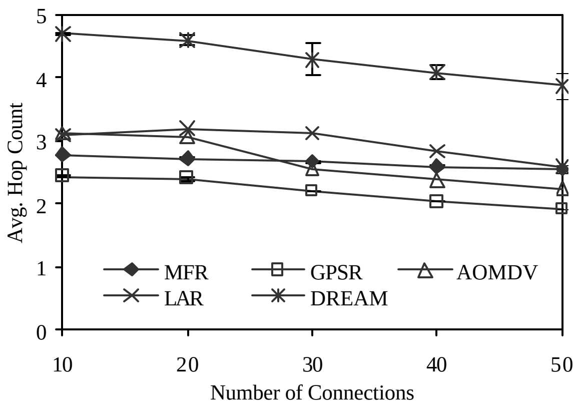

Fig. 4b – Avg. Hop Count

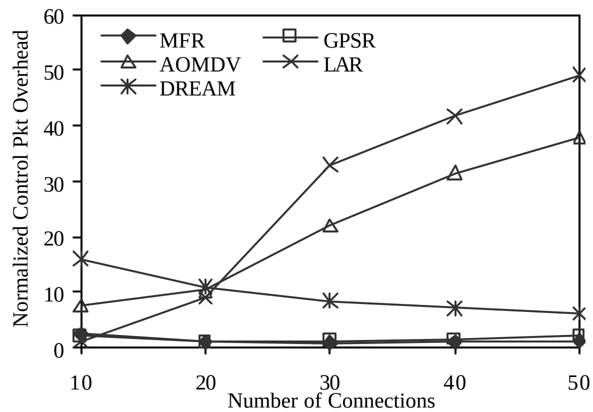

Fig. 4d – Normalized Control Overhead

As Figure 4c shows, MFR and GPSR start to have high end-to-end delay at high numbers of connections. While this may seem bad, they are actually still effectively delivering many more data packets than the other protocols, albeit slowly and with great effort. DREAM achieves a packet delivery ratio similar to GPSR while having a much lower delivery latency than either MFR or GPSR because it is delivering data packets by flooding, which has other undesirable results that will be discussed later.

Similarly to the first scenario, Figure 4d shows that MFR and GPSR have the lowest control overhead.

By flooding, DREAM offers a moderate level of data delivery at all numbers of connections. However, its data overhead is 30 times larger than all other protocols, also because of flooding. (Due to space limitations, we do not show the graph here.) This observation is consistent with results described in [6].

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

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

Figures 5a to 5d shows the performance of the five protocols for scenario 3. As the load increases, MFR still achieves a data packet delivery ratio of up to 95%. (As the confidence intervals of MFR are small, for readability we do not show them). All the other protocols degraded drastically. Since MFR chooses the angle route with smallest end-to-end delay, it minimizes delay and can avoid highly congested paths. With the lowest control overhead among the tested protocols, MFR shows its advantages in this scenario.

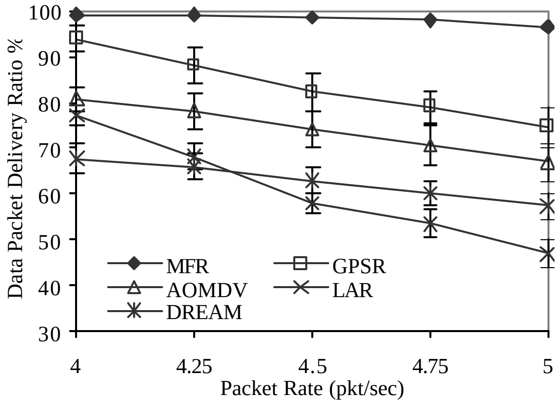

Fig. 5a – Data Packet Delivery Ratio

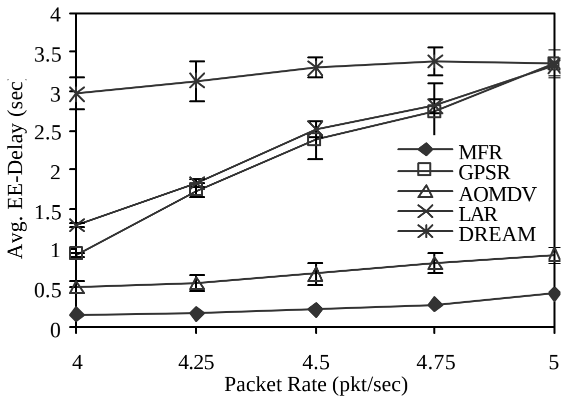

Fig. 5b – Avg. End-to-End Delay

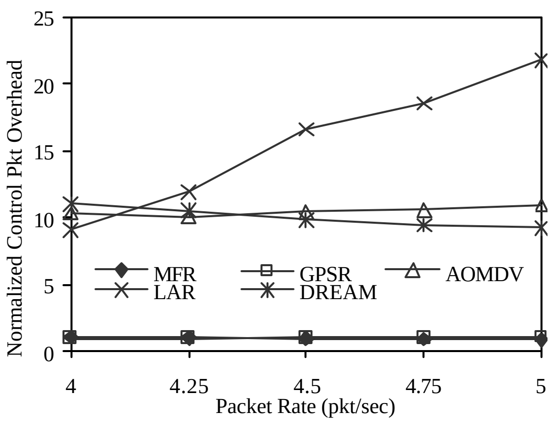

Fig. 5d – Normalized Control Overhead

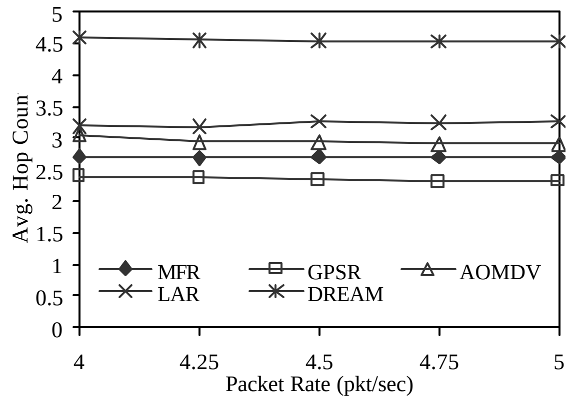

Fig. 5d – Avg. Hop Count

VI. FUTURE WORK

A. Guaranteed Delivery

As a packet is forwarded along the requested magnetic field line, it might not arrive at the destination if the actual available routes are very different from the shapes of magnetic field lines. MFR currently relies on a high density of nodes to reduce the probability of such pathological topologies. MFR also relies on different route angles, so that data packets have a high probability of finding a route. Further, mobility is likely to make pathological topologies relatively short-lived. However, MFR does not guarantee 100% delivery even if some feasible route exists. We will investigate a simple (perhaps expensive) algorithm to guarantee delivery in pathological cases when the usual approach has failed. Such an algorithm would be acceptable, provided it was not exercised frequently.

B. Non-Symmetric Paths

Since a route between the source and destination is not a perfect magnetic field line, forward and reverse paths in MFR are not necessarily symmetric. An available path with an angle *a* at the source might not be available at the destination. This characteristic poses a problem in sparse topologies since some control packets in MFR require ACK messages to come back along the same angles. We are investigating solving this problem by encoding the source route inside the control packet. The destination can use the recorded routes to return the acknowledgement. This design has little affect on the stateless characteristic of the MFR protocol, since the recorded route is used only once for the ACK.

At the application level, data communication between two nodes can traverse paths with different angles for each direction. Such behavior is unavoidable in a mobile environment for all known routing protocols.

C. Other Issues

Currently our implementation sends packets using one path at a time, so out-of-order packets should not be a problem. There may be some short interval when messages might be delivered out of order when we switch from one path to another. In the future, we may want to use MFR for load balancing by switching between paths. More work needs to be done in exploring the behavior of MFR when using this technique. Besides load balancing, paths in MFR can be used for power-aware routing.

The current implementation of MFR uses magnetic field lines with only three fixed initial angles. We have not explored the effect of the number of paths in MFR. More routes will increase both throughput and the cost for maintaining them. End-to-end delay is the current metric for selecting the best path. We plan to add parameters to control the redundancy, disjointness, and reliability of routes dynamically.

The current location discovery technique based on flooding is quite expensive. We will try other approaches such as GLS [22], DLM [31] or gossip-based approach [14] to improve MFR's performance.

VII. CONCLUSION

This paper presents the magnetic-field-based multipath routing protocol for ad hoc networks, an on-demand routing scheme that does not rely on an explicit hop-by-hop route. The next hop is calculated dynamically at each intermediate node; therefore the node membership of a route can change constantly without triggering route recovery.

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

Our results show that MFR 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 fewer control messages. These results and the theoretical simplicity of the MFR algorithm suggest that it may be adopted for practical use in existing ad hoc routing algorithms.

VIII. REFERENCES

[1] S. Basagni, I. Chlamatac, V. Syrotiuk, B. Woodward. A distance routing effect algorithm for mobility (DREAM). *Proceedings of the 4th Annual ACM/IEEE International Conference On Mobile Computing and Networking (MOBICOM)* '98, pp. 76-84, 1998.

[2] P. Bose, P. Morin, I. Stojmenovic, and J. Urrutia. Routing with guaranteed delivery in ad hoc wireless networks. *Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications (DialM)*, 1999.

[3] L. Blazevic, L. Buttyan, S. Capkun, S. Giordano, JP. Hubaux, J. Le Boudec. Self-organization in mobile ad-hoc networks: the approach of terminodes. *IEEE Communication Magazine*, 2001.

[4] L. Blazevic, S. Giordano, J. Le Boudec. Self-organized terminode routing. Technical Report DSC/2000/040, Swiss Federal Institute of Technology, Lausanne, 2000.

[5] J. Broch, D. Maltz, D. Johnson, Y. Hu, and J. Jetcheva. Multihop wireless ad hoc network routing protocols. In *Proceedings of the ACM/IEEE Int. Conf. On Mobile Computing and Networking MOBICOM, pp. 85-97, 1998*.

[6] T. Camp, J. Boleng, B. Williams, L. Wilcox, and W. Navidi. Performance comparison of two location based routing protocols for ad hoc networks. In *Proceedings of the IEEE INFOCOM 2002*, New York, NY, USA. June 2002.

[7] S. Capkun, M. Hamdi, and J. Hubaux. Gps-free positioning in mobile ad hoc networks. In *Proceedings of Hawaii Int. Conf. on System Sciences, Jan 2001*.

[8] C. Cheng, H. Lemberg, S. Philip, E. Berg, and T. Zhang. SLALoM: a scalable location management scheme for large mobile ad hoc networks. In *Proceedings of the IEEE WCNC 2002, FL, USA, Mar 2002*.

[9] S. Das, C. Perkins, E. Royer. Performance comparison of two on-demand routing protocols for ad hoc networks. *Proceedings of IEEE INFOCOM 2000*, March 2000.

[10] S. Datta, I. Stojmenovic and J. Wu. Internal node and shortcut based routing with guaranteed delivery in wireless networks. *Proceedings of IEEE Int. Conf. On Distributed Computing and Systems (Wireless Networks and Mobile Computing Workshop)*, Phoenix, AR, April, 2001.

[11] D. De Couto, R. Morris. Location proxies and intermediate node forwarding for practical geographic forwarding. Technical Report MIT, MIT Laboratory for Computer Science, June 2001.

[12] K. Fall, and K. Varadham, The ns Manual, http://www.isi.edu/nsnam/ns/ns-documentation.html/

[13] IEEE Computer Society LAN MAN Standards Committee, *Wireless LAN Medium Access Protocol (MAC) and Physical Layer (PHY) Specification*, IEEE Std 802.11 – 1997. The Institute of Electrical and Electronics Engineers, New York, NY, 1997.

[14] Z. Haas, J. Halpern, and L. Li. Gossip-based ad hoc routing. In *Proceedings of the IEEE INFOCOM 2002*, New York, NY, USA. June 2002.

[15] D. Johnson and D. Maltz. Dynamic Source Routing in Ad Hoc Wireless Networks. *Mobile Computing*, edited by Tomasz Imielinski and Hank Korth, Chapter 5, pp. 153-181, Kluwer Academic Publishers, 1996.

[16] J. Jubin, J. Tornow. The DARPA Packet Radio Network Protocols. *Proceedings of the IEEE*, 75(1), pp. 21-32, January 1987.

[17] E. Kaplan. *Understanding GPS*. Artech House, 1996.

[18] B. Karp, H. Kung. GPSR: Greedy Perimeter Stateless Routing for Wireless Networks. In *Proceedings 6th Annual Int. Conf. On Mobile Computing and Networking (MobiCom)*, pp. 243-254, 2000.

[19] Y. Ko and N. Vaidya. Location aided routing (LAR) in mobile ad hoc networks. In *Proceedings of the IEEE/ACM Mobicom '98*, Dallas, TX, USA, Oct 1998.

[20] E. Kranakis, H. Singh, and J. Urrutia. Compass routing on geometric networks. In *Proceedings of 11th Canadian Conf. On Computational Geometry, Vancouver, August 1999*.

[21] S. Lee, M. Gerla. Split Multipath Routing with Maximally Disjoint Paths in Ad Hoc Networks. *IEEE International Conference on Communications*, 2001.

[22] J. Li, J. Jannotti, D. De Couto, D. Karger, R. Morris. A scalable location service for geographic ad hoc routing. *Proceedings of ACM MOBICOM*. ACM, August 2000.

[23] X. Lin, M. Lakshdisi, and I. Stojmenovic. Location based localized alternate, disjoint, multi-path, and component routing

algorithms for wireless networks. *Proceedings of ACM Symposium on Mobile Ad Hoc Networking & Computing MobiHoc*. Long Beach, California, USA, Oct 2001.

[24] D. Maltz, J. Broch, J. Jetcheva, D. Johnson. The effects of on-demand behavior in routing protocols for multi-hop wireless ad hoc networks. *IEEE Journal on Selected Areas in Communication*, 1999.

[25]M. Marina, S. Das. Ad hoc on-demand multipath distance vector routing. *Proceedings of the International Conference for Network Protocols (ICNP)*, pp. 14-23, Nov 2001.

[26]A.Nasipuri and S.R. Das. On-demand multi-path routing for mobile ad hoc networks. In *IEEE ICCCN'*99, 1999, pp. 64–70.

[27]B. Nath, D. Niculescu. Routing on a curve. *HotNets-I*, Princeton, NJ, October, 2002.

[28] G. Pei, M. Gerla, X. Hong, LANMAR: Landmark routing for large scale wireless ad hoc networks with group mobility. *Proceedings of IEEE/ACM MobiHOC 2000*, pp. 11-18, August 2000.

[29] C. Perkins, E. Royer. Ad hoc on-demand distance vector routing. *Proceedings of IEEE WMCSA'99*, pp. 90-100, February 1999.

[30]H. Takagi and L. Kleinrock. Optimal transmission ranges for randomly distributed packet radio terminals. *IEEE Trans. On Communications*, March 1984.

[31]Y. Xue, B. Li, and K. Nahrstedt. A scalable location management scheme in mobile ad hoc networks. In *Proceeding of the IEEE Conference on Local Computer Networks – LCN 2001, FL, USA, Nov 2001*.

[32]Z. Ye, S. Krishnamurthy, S. Tripathi. A framework for reliable routing in mobile ad hoc networks. In *Proceedings of IEEE INFOCOM 200*3.