

UC Santa Cruz

UC Santa Cruz Previously Published Works

Title

Automatic Incremental Routing Using Multiple Roots

Permalink

<https://escholarship.org/uc/item/8dg5160g>

Authors

Ghosh, Rumi
Garcia-Luna-Aceves, J.J.

Publication Date

2013-10-01

Peer reviewed

Automatic Incremental Routing Using Multiple Roots

Rumi Ghosh
Computer Engineering Department
University of California
Santa Cruz, CA 95064, USA
Email: rumi@soe.ucsc.edu

J.J. Garcia-Luna-Aceves
Computer Engineering Department
University of California
Santa Cruz, CA 95064, USA
Email: jj@soe.ucsc.edu

Abstract—We present Multi-root Automatic Incremental Routing (MAIR), an efficient routing approach for mobile ad hoc networks (MANET). MAIR has a low routing stretch (ratio of selected path to shortest path length) and provides multiple paths to each destination. Every node is assigned multiple prefix labels with respect to multiple roots in the network. The roots are distributed in the network such that the paths calculated from each of the root labels are as disjoint as possible from each other. The labels of a node are stored distributively in hash tables at “anchor nodes” across the network. Data packets are routed using the distributed hash table (DHT) lookup and longest prefix match with neighbor labels. This eliminates the need to maintain large routing tables in the nodes, which substantially reduces the routing state at each node. A region of interest (ROI) is formed around each active source-destination pair using the node labels. The nodes in the ROI maintain the most recent mapping of the node identifier of a destination to its labels. This reduces the route establishment delay for the nodes inside ROI as the need for DHT lookup is reduced.

I. INTRODUCTION

Traditional routing protocols for MANETs are based on destination-based routing tables obtained by means of protocols based on the exchange of topology information (e.g., [8]), or distances or path information for destinations (e.g., [13], [16]).

Maintaining destination-based routing tables in large MANETs incurs substantial overhead, because the control signaling required to update destination-based routing tables spans the entire topology. As a result, many approaches have been proposed to reduce the size and overhead in current in the computation of routing tables. The basic objective of all these approaches, which we discuss in Section II, consists of reducing the amount of broadcast traffic that is disseminated in a MANET, which is necessary to make MANETs scale [22].

This paper introduces a new routing approach for MANETs called *Multi-root Automatic Incremental Routing* (MAIR) that eliminates the need to maintain destination-based routing tables at each node based on the prefix-labeling approach introduced in [6].

Section III describes the details of how MAIR operates, and Section IV presents examples of this operation. MAIR consists of three components: (a) assigning prefix labels to nodes with respect to multiple labeling roots; (b) using a distributed hash table (DHT) to provide the mappings of

node identifiers to their labels; and (c) establishing regions of interest (ROI) between sources and destinations to expedite the task of obtaining routes to destinations as they move.

MAIR augments the prefix labeling used in Automatic Incremental Routing (AIR) [6] by electing multiple labeling roots instead of one in order to make the automatic routes induced by the prefix labels closer to shortest paths. The multiple labeling roots used in MAIR are elected by nodes dynamically starting from an initial root, such that they are as far away from each other as possible. This leads to assigning nodes multiple labels that correspond to disjoint routes to the labeling roots.

The labels of a node are stored distributively using the distributed hash table (DHT). Each destination publishes its labels at its anchor in the DHT, which is the node whose own first label is the best match to the label obtained by hashing the identifier of the destination using a common hashing function. A source uses the same common hash function to contact the anchor of the destination with a subscription request.

Once the source receives the labels from the anchor of the destination it can send data packets to the nearest label for the destination using a longest prefix match with neighbor labels. This eliminates the need to maintain large routing tables in the nodes, which substantially reduces the routing state at each node. In addition, a region of interest (ROI) is formed around each active source-destination pair using the node labels. The nodes in the ROI maintain the most recent mapping of the node identifier of a destination to its labels. This reduces the route establishment delay for the nodes inside ROI as the need for DHT lookup is eliminated. The availability of multiple routes leads to easy local repair.

Section V demonstrates that MAIR terminates and provides loop-free routes.

Section VI presents the results of simulation experiments comparing MAIR with AODV, OLSR, and the original AIR protocol [6] operating over IEEE 802.11 as the medium access control (MAC) protocol. The results clearly show that MAIR incurs much less overhead while attaining similar or better end-to-end delays and delivery ratios than the other three protocols.

II. RELATED WORK

Hierarchical routing schemes organize nodes into clusters (e.g., [1], [10], [17]) and some reduce signaling of clustering schemes by limiting propagation of control messages based on their distance from an originating point (e.g., HSLs [15] and FSR [12]). The key limitation of prior clustering schemes is that the affiliation of nodes to clusters is easily broken when nodes move, and re-establishing such affiliations involves flooding. On the other hand, routing schemes in which signaling decays based on the distance to links or destinations have not been properly tested under major disruptions.

Several schemes have been proposed based on establishing a distributed hash table (DHT) over a virtual topology defined on top of the physical network (e.g., [23], [2]). The advantage of this approach is that the DHT size grows only logarithmically with the number of intended destinations. However, a virtual link in the virtual topology can correspond to a multi-hop path in the physical network topology, and signaling overhead must be incurred to maintain such links, which becomes excessive in large MANETs.

Approaches based on Bloom filters to reduce the overhead of routing updates (e.g., [14]) suffer from the existence of false positives, which forces nodes to use flooding in the case of MANETs. Many proposals attempt to reduce the number of relays that need to forward signaling messages for a given number of destinations (e.g., OLSR [8]). However, they require maintaining connected dominating sets involving a large subset of the nodes in dynamic topologies.

Routing protocols based on geographical coordinates (e.g., GPSR [9] and XYLS [3]) are limited by the requirement of line-of-sight to satellites (for GPS based devices) and the overhead of discovering nodes and their corresponding locations. A number of schemes use virtual coordinates consisting of the distances of nodes to a few reference nodes (e.g., BVR [5] and Hop ID [24]). The main limitation of this approach is that multiple nodes may be assigned the same virtual coordinates, which results in the use of flooding to resolve false positives.

Tribe [18] uses a depth-first approach and partitions the address space into control regions based on intervals of addresses. Tribe incurs a lot of re-labeling of nodes for node mobility. DART [4] uses prefix labels to generate clusters of nodes based on prefix address trees. However, it has the same node-to-cluster affiliation problem of hierarchical routing and therefore DART must re-label nodes after node or link failures.

Small State and Small Stretch (S4) [19] is a routing protocol for large-scale sensor networks that achieves low path stretch, low routing state at each node and high failure resilience. S4 maintains shortest paths for nodes inside the cluster for each source. For destinations outside the cluster, the source routes the packet to the beacon closest to the destination. The beacon node routes the packet to the destination. The signaling of S4 is not well suited for mobile networks.

AIR [6] uses a DHT based on prefix labels of nodes that runs directly on the physical topology, rather than a virtual topology as in prior DHT-based schemes, and supports routing

to content by name. The limitation of AIR is that the routes to content or destinations can be much longer than shortest paths, and variable-length prefix labels are needed for routing.

III. MAIR

Every node in MAIR routes packets based on the routing labels assigned to itself and the labels of its immediate neighborhood, without the need of destination-based routing tables at each node. The storage and communication complexities in MAIR grow sub-linearly with the number of nodes or links in the network.

The use of multiple roots leads to assignment of routing labels in multiple dimensions. The routing overhead is controlled by the number of roots in the network. In this paper we assume the number of roots to be three. There is a Labeled Directed Acyclic Graph (LDAG) from each of the three elected root nodes in the network and each node has one prefix label from each root. The three labels enable the nodes to have multiple paths to each destination. The multiple paths reduce the path stretch of a route. It also facilitates local repair for node and link failures. The use of multiple labels per node for MAIR also reduces control traffic around the nodes higher up in each LDAG by finding shorter paths across the LDAG.

Typically MANET nodes have some preferred destinations to which most of their data flow. The Region of Interest (ROI) for a preferred destination is a connected component of the network which includes the preferred destination, the sources that intend to send data packets to the destination and the relay nodes. The nodes within the ROI maintain multiple paths to the destination and each other through proactive signaling. These paths usually include the shortest path between the source and the destination. All the sources that want to send data to destination D , join the ROI for D . Once the source S does not have any more data for D , S leaves the ROI.

A. Root Election

The election of a labeling root is a three-step process. The nodes first distributively choose the first root. When a node comes up, it assigns itself as the root. It communicates its root identifier (ID) with the neighbors through the Hello message and selects a lower root if available from the Hellos it receives. Eventually, the node with the lowest ID is elected the first root. The first root is the root with label "0". Once a node is elected as a root, the nodes assign labels to their children according to their position in the LDAG with respect to the common root. Hence all the nodes are ordered with respect to the first root.

Once all the nodes converge to the root "0", the election for additional roots is done. If a node detects that it has a longer label with respect to root "0" than all of its one-hop neighbors, it elects itself as the second root, with label "1". If multiple nodes contend for the second root, the node with the lowest ID wins. A node uses its one-hop neighborhood information to decide if all nodes have converged to a root node. After the second root election all nodes in the network receive two labels with respect to the two roots. Once all the nodes converge to the same second root, the third root is selected in the same

way as the second root when a node has both labels longer than its one-hop neighbors. The third root has the label “2”.

B. Labeling of nodes

A node in MAIR has a location-independent node identifier (ID) and three topology dependent labels. Starting from each of the three roots, the network is visualized as a k -ary LDAG, where k is the degree of the LDAG. A node in the LDAG is labeled in a breadth-first manner by the Hello message. A link between two nodes in the LDAG exists if the nodes are neighbors in the actual topology. If Σ is the finite set of symbols, then the prefix label of a node with respect to root r , l_r , is a string with symbols from Σ such that $|l_r| \geq 1$. For each LDAG, the root node has the smallest label. When a node has a prefix label l_r from a root r , it assigns a unique suffix s_i^r to each child i in the LDAG. The child then assigns itself the label, $l_r \odot s_i^r$, where \odot is the concatenation operator. Each node has the set of labels $\langle l_{r_1}, l_{r_2}, l_{r_3} \rangle$ corresponding to the three roots.

C. Publish and Subscribe Operations

The *anchor* A of a node D is the node that stores the node ID to label mapping of D . D publishes itself to A by sending an Anchor Update. A globally-known hash function takes the node ID of D as an argument and returns an anchor label. As the anchor update travels through the network towards the anchor label, the nodes that do not match the anchor label just forward the update. Only the node that best matches the anchor label stores the mapping and becomes the anchor node of D . The collection of anchor tables distributed in all the anchor nodes of the network forms the distributed hash table (DHT) that stores the node ID to prefix labels mappings of all nodes. The *Publish* operation takes place on the expiry of a timer.

A node S subscribes to D if it has data to send to that destination. S hashes the node ID of D using the globally known hash function to get the anchor label. Then S embeds the Mesh Request(MR) message in the first data packet and sends to the anchor label. The data packet with the MR reaches A by selecting the next hop at each node through longest prefix match with the anchor label. A on receiving the message, retrieves the destination label from its anchor table and forwards the data and the MR to D .

D. Establishment and Maintenance of the Region of Interest

The anchor routes the MR with the data packet by longest prefix match with the neighbors to D . When the MR reaches the D , the shortest path of the three available paths is chosen by comparing the S and D label lengths. The length of the unmatched portion of S and D labels indicate the number of hops the packet has to traverse up the prefix tree from S and then down to D and hence gives the path length along that prefix tree. The label corresponding to the shortest path is called the preferred label. The *existence bound*(EB) is calculated as longest matching prefix between the preferred label of D and the corresponding label of S . The EB determines

TABLE I
MAIR NOTATION

L_D^r	The prefix label of dest D for root r
L_A^r	The prefix label of anchor A for root r
L_D^*	The preferred label of dest D
L_S^r	The prefix label of src S for root r
L_S^*	The preferred label of src S
L_x^r	The prefix label of of any node x for root r
L_x^*	The preferred label of any node x
$len(L_x^r)$	The length of the label of of any node x for root r
$PL(L_x^r, L_y^r)$	The path length between any two nodes x, y for root r
$LPM(L_x^r, L_y^r)$	The longest prefix match of the label of any two nodes x, y for root r

which nodes lie within the ROI. Now if the MR indicates the data packet to be a single packet with no subsequent interest in the destination, the ROI is not established and the MA is not sent.

If the MR indicates more than one data packets for D , Mesh Announcement (MA) is sent from node D on receiving the MR and is limited broadcast inside the ROI. The MA message sent by D has all the labels of D . Each node intermediate node I that receives the MA, stores the destination node ID to label mappings. The node I compares its label with the EB to determine if it lies in its sub-tree. If it does, node I is a relay node. The source, destination and relay nodes all lie in the sub-tree of the EB and constitute the ROI. If I lies in the ROI, it re-broadcasts the MA to its one-hop neighbors. All the nodes in the ROI have multiple paths to the destination as they store the latest destination labels. The node S then sends the rest of the data directly to D .

The nodes that are one-hop away from the ROI would be able to receive the MA and get additional labels but do not re-broadcast the MA. These nodes constitute a *hysteresis zone*. The nodes in the hysteresis zone maintain multiple paths to the destination of ROI and the latest destination labels.

E. Routing of Data Packets

In MAIR the packets are routed by *longest prefix match* of the preferred destination label and the labels of the one-hop neighbors. For prefix matches of same length, a next hop is randomly chosen from the matches. The use of three labels per node enables the nodes to find multiple paths of same or different length to the destination. The paths other than the preferred path are used as backup paths for local repair.

For source nodes inside the ROI, the route establishment to the known destination does not involve a request to the anchor node. For all other sources, the routing of data packets is preceded by the DHT lookup at the anchor.

F. Information stored and exchanged

The information stored at each node is shown in Table I. The message formats are shown below:

- Hello, which consists of $\{root_id, root_seq, node_id, node_seq, < L_x^{r_i}, i = 1, \dots, 3 >, < AU >\}$.
- Mesh Request, MR which consists of $\{dst, src, req_id, < L_S^{r_i}, i = 1, \dots, 3 >\}$.
- Mesh Announcement, MA which consists of $\{dst, src, < L_D^{r_i}, i = 1, \dots, 3 >, < L_S^*, i = 1, \dots, 3 >, EB\}$.
- Anchor Update, AU, which consists of $\{dst, L_A^r, < L_D^{r_i}, i = 1, \dots, 3 >\}$.

The Hello packet is a neighbor to neighbor broadcast message that originates in the root with a new sequence number periodically and propagates in a breadth-first manner. All nodes send periodic AU messages to their anchors with their prefix labels to refresh the mapping of the node ID to the prefix labels. The MR is sent on-demand for a flow to the anchor of a destination for lookup of the destination's prefix labels. The MA is initially sent in response to MR and then sent periodically as updates inside the ROI.

G. Enclave Condition

If L_S^* and L_D^* are the preferred source and destination labels of a $< S, D >$ pair if

$$PL(L_S^*, L_D^*) = \min(PL(L_S^{r_i}, L_D^{r_i})), i = 1, \dots, 3$$

The EB is calculated as

$$EB = LPM(L_S^*, L_D^*)$$

L_x^* is the corresponding label for node x for the same root node. Node x is a member of an ROI Enclave of $< S, D >$ if it satisfies either of the conditions:

if $(len(L_S^*) > len(L_D^*))$

$$len(L_D^*) \leq len(L_x^*) \leq len(L_S^*)$$

else if $(len(L_D^*) > len(L_S^*))$

$$len(L_S^*) \leq len(L_x^*) \leq len(L_D^*)$$

IV. EXAMPLES

A. Labeling of Nodes

Figure 1(a) shows an ad hoc network of 14 nodes. Node A has been elected the first root as per the root election algorithm and is assigned the label "0". Figure 1(a) shows the prefix tree labels with respect to the root A . Each node selects the lexicographically smallest label advertised by its neighbors and adds a unique prefix to it to generate its label. This neighbor is called a parent of the node. The LDAG edge points from the parent to the child. Figure 1(a) shows the LDAG for the first root.

Node L has been elected the second root as it has a longer first root label than its neighbors E and K . L is assigned the label "1". Figure 1(b) shows the label assignment and LDAG with respect to the second root. Node F has been elected the third root as it has a longer first and second root label than its neighbor B . The two root labels of F and G are the same

length. But F is chosen as the third root because it has a lower node ID and is assigned the label "2". Figure 1(c) shows the label assignment and LDAG with respect to the third root.

At this point every node in the network has three prefix labels. The advantage of prefix diversity is the nodes can select paths that are closer in length to the shortest path. For example in Fig. 1(d) the path from H to G through the prefix tree of the first root is $H \rightarrow X \rightarrow A \rightarrow B \rightarrow G$. When used multiple roots and multiple labels, the path reduces to $H \rightarrow D \rightarrow I \rightarrow G$, which is the shortest path. This path is shown in figure 1(e).

B. Region of Interest

In the above example, assume that node H initiates a flow to node G . Assume also that the anchor label of G is node "054" and therefore the anchor node is A . Node G sends AUs periodically to A with the label "111121" as this has the longest prefix match with the anchor label. Assume H does not have the labels of G in its cache. The path from node H through the anchor to G is $H \rightarrow X \rightarrow A \rightarrow B \rightarrow G$. So node H sends an MR along with the first data packet along this path. The hop count along this path is 4. Fig. 2(a) shows the propagation of MR from node H to node G . As G receives the MR, it compares its three labels with the three labels of H . In this case the shortest path is of length 3 and along the subtree of "22". Node G sets the EB to "22" and sends out an MA with the labels of H , G and the EB.

The nodes that fall in the sub-tree of the EB are part of the ROI. These nodes re-transmit the MA after receiving it, till the MA reaches node H . The MA from G reaches H through the path $G \rightarrow I \rightarrow D \rightarrow H$ which has a hop count 3. On all other paths, the MA gets dropped as EC does not hold for these. The path of the MA is shown in Fig. 2(b).

The ROI in this example, as shown in Figure 2(c), constitutes of the nodes G , I , D , and H . The nodes X , A , B and F receive the MA from node H , D and G , but do not re-transmit it. These nodes maintain the recent labels of destination G and constitute the hysteresis zone.

The nodes in the ROI have the most recent labels of destination G at all times. Now the data packets from H follow the path $H \rightarrow D \rightarrow I \rightarrow G$ by longest prefix match of the preferred label at each node. This path is 3 hops and is the shortest path between H and G . The path $H \rightarrow X \rightarrow A \rightarrow B \rightarrow G$ is a backup path that can be taken in case of a link failure on the primary path.

V. MAIR CORRECTNESS

Let us assume there has been a finite number of network changes due to network conditions and traffic flows till time t_0 . The nodes can determine which label updates are more recent based on the sequence numbers of the Hello that carries it.

Theorem 1: MAIR terminates within a finite time. \square

Proof: We have to show that in MAIR all nodes stop updating their labels a finite time after t_0 .

We have a finite network with a finite number of nodes. For a change in label of a neighbor, n_0 , the node x_0 gets a Hello from the neighbor and updates its label. Then it sends the new

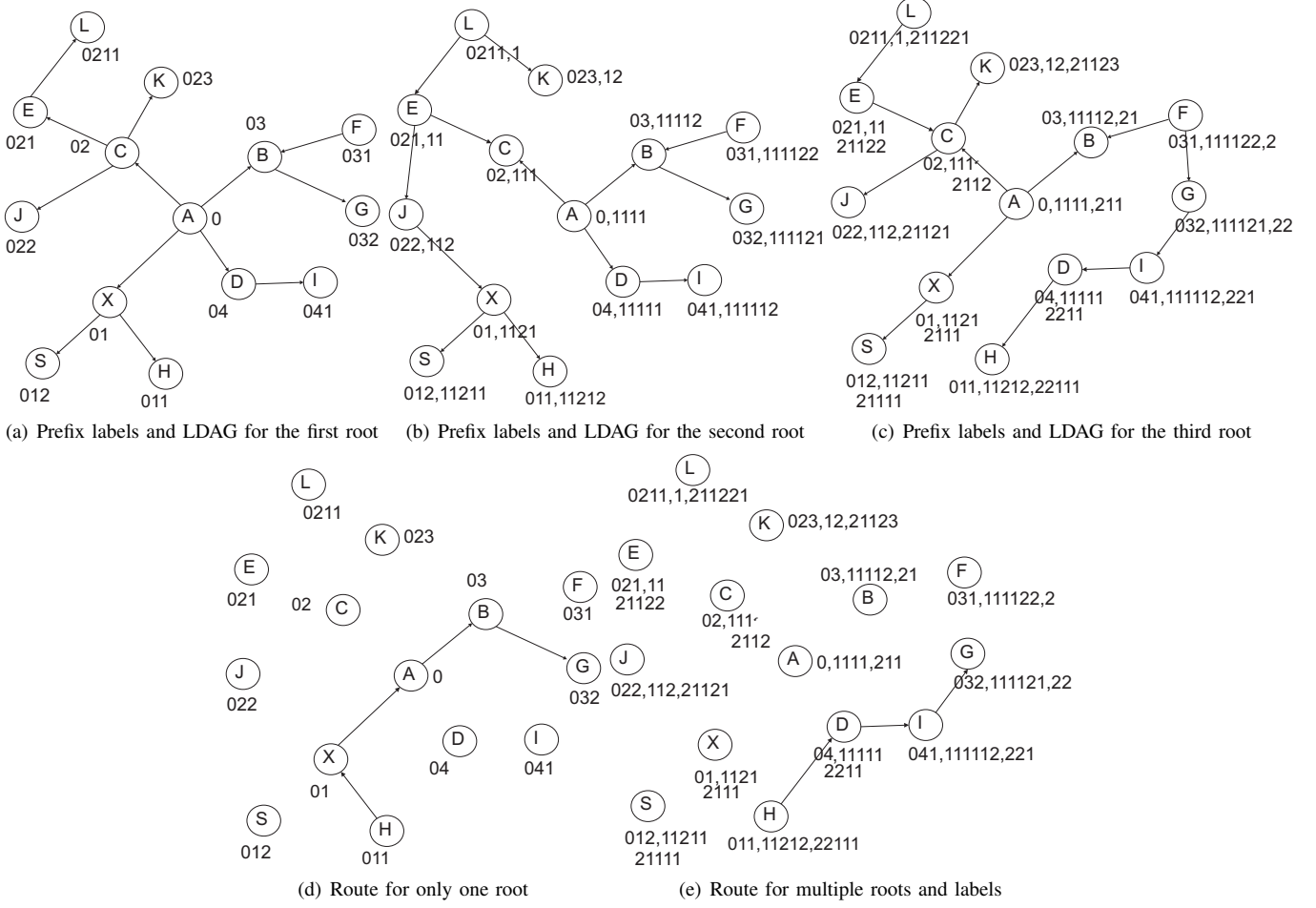


Fig. 1. Example showing set up of labels in MAIR

label in the next Hello. So there can be no infinite updates for n_0 in this case.

Given that there are no network changes after t_0 , for a node x_0 to generate infinite updates it has to generate infinite updates for at least one node n_1 which is not a direct neighbor. This can happen when one of x_0 's neighbors, x_1 sends an infinite number of label updates for n_1 or some other neighbor n_2 which caused x_1 to send update for n_1 . Since the network is finite, continuing the same argument we find that there has to be some node x_i which has a direct neighbor n_i which has created the infinite label updates. But that is a contradiction since we know no node can generate infinite updates for a direct neighbor. ■

Theorem 2: MAIR is loop-free. □

Proof: MAIR generates an LDAG of all the nodes with respect to each of the three roots. From Theorem 1 we know that the labels at all the nodes are consistent a finite time after t_0 . A source node sends data along one of these LDAG paths to the destination. Hence, the union of the paths at all the nodes is also a DAG. So there are no loops if the data follows the LDAG.

If a node i sees that the neighbor n has a label that has a longer prefix match with destination j than its LDAG

predecessor p , i would choose n as its next hop. We will prove by contradiction that loops can not form in MAIR in this case. Let us assume that at time t , a, b, c, \dots, x is the path chosen to destination j . Therefore, $LPM(L_a^r(t), L_j^r(t)) < LPM(L_x^r(t), L_j^r(t))$. The last change of successor was at time $t' < t$, x chose a as the next hop forming the loop. So, $LPM(L_x^r(t), L_j^r(t)) = LPM(L_x^r(t'), L_j^r(t')) < LPM(L_a^r(t''), L_j^r(t''))$, where t'' is the time when a sent its last Hello with label L_a^r and $t_0 < t'' < t' < t$. It follows that node x obtained a new label with a longer prefix match to j than a in the time $(t'', t]$, which is a contradiction because we can have no label changes. ■

VI. PERFORMANCE EVALUATION

We present simulation results comparing MAIR with AODV, OLSR, AIR and MAR. AODV and OLSR are the widely used standard baselines for performance comparisons. We selected AIR and MAR because they are predecessors of MAIR that use a single labeling root. AIR has one label per node and hence doesn't have multiple paths. MAR [7] has multiple paths to destination through the multiple labels it acquires from each of its neighbors.

The Qualnet simulator [20] has been used with IEEE 802.11

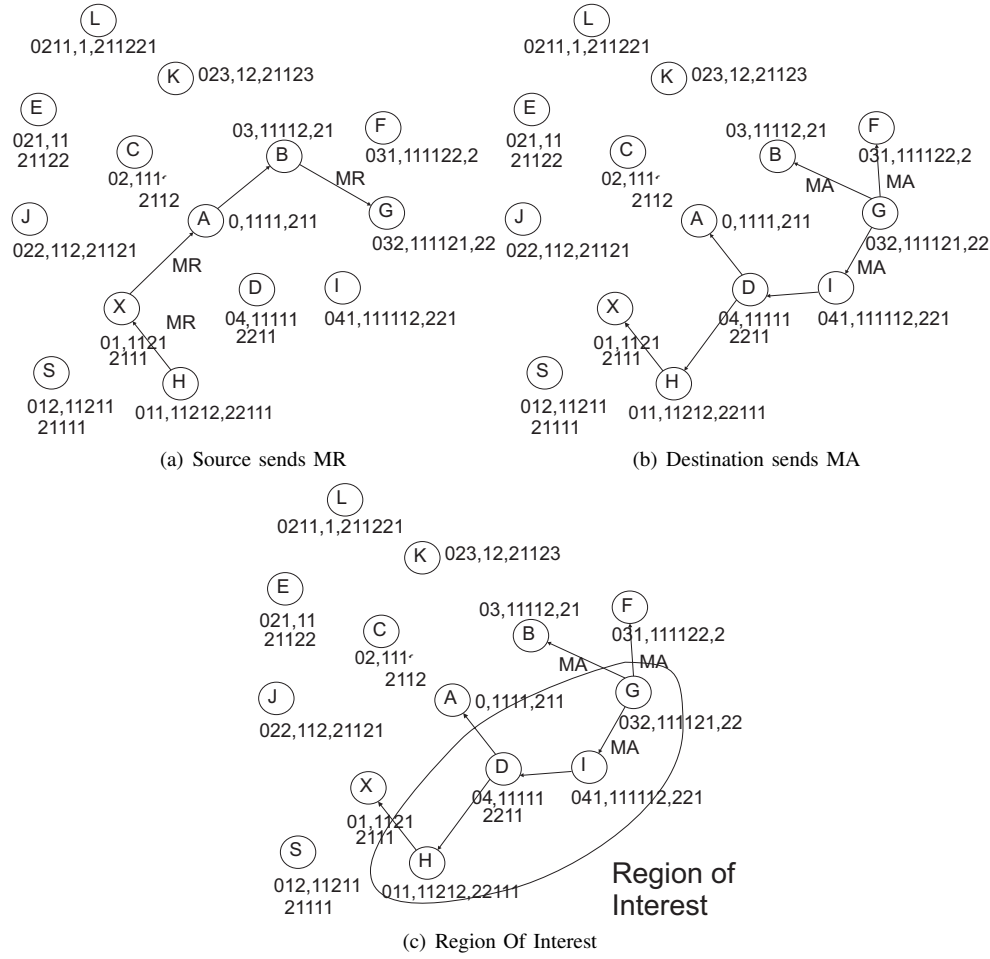


Fig. 2. Example showing ROI in MAIR

DCF as the MAC protocol at 2 Mbps bandwidth. The performance of all protocols is affected negatively by the multiple access interference at the MAC layer [21]. Nodes are simulated in an area of 900m x 900m. Several simulations with random seeds were run. The traffic generated is CBR. The metrics used are end to end delay, delivery ratio, network load and path length. End to end delay is the one-way delay between a source sending the packet and the destination receiving it. The delivery ratio is the ratio of number of packets received by the destinations to the number of packets sent by the sources. Network load is the control overhead per node. For the third scenario we have also reported path length. The path length is the average number of hops between the source and the destination.

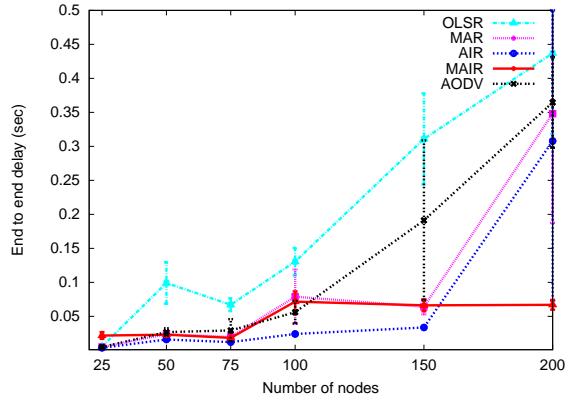
A. Static configuration with increasing number of nodes and flows

This scenario simulates realistic MANET traffic. The CBR flows have exponential arrival times. The mean inter-arrival time for flows is 10 sec and mean flow duration is 200 sec which one-third of the simulation duration of 600 sec. At any instant we have about 20 CBR flows. Each CBR flow generates 256 byte packets at 5 packets/sec. The network size is varied

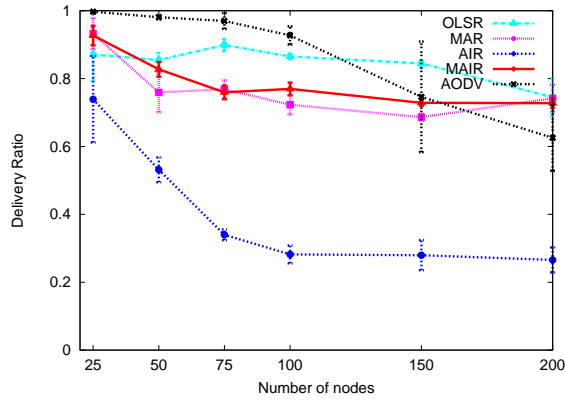
from 25 to 200 nodes while the concurrent load is kept more or less constant. The mean performance of several runs with 95% confidence interval, assuming a normal distribution, has been reported.

Figures 3(a)- 3(c) show the results for delay, delivery ratio and network load. At low node densities the delay of MAIR is lower than OLSR and similar to AODV, MAR and AIR. At node densities higher than 150 nodes, MAIR has the delay lowest of all protocols. It is less than 1/5th of OLSR, less than 1/3rd of MAR and AODV and almost half of AIR. MAIR has a low delay because the ROI ensures a lot of nodes in the network maintain the latest label of the destination nodes. Hence the need for anchor lookup is eliminated for new flows. Choosing the shortest path for the ROI also ensures a lower end to end delay.

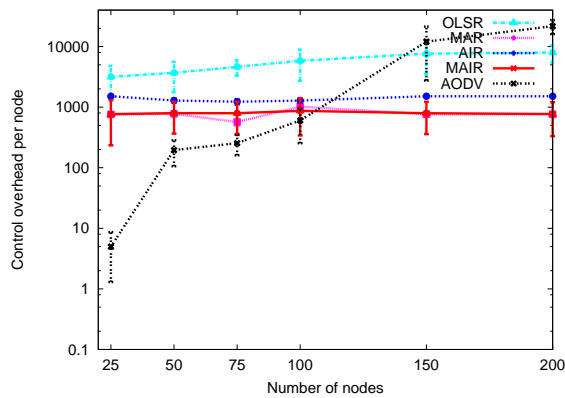
The delay of OLSR increases significantly with number of nodes in the network as more control overhead is incurred to maintain the link states. At 150 nodes the delivery ratio of AODV also falls sharply due to increased contention as is evident from the network load graph. AIR has similar network load to MAR. But for higher network sizes, it generates congestion around the nodes higher up in the LDAG, who drop the packets. As a consequence, the delivery ratio of AIR



(a) Increasing network density vs. end-to-end delay



(b) Increasing network density vs. delivery ratio



(c) Increasing network density vs. network load

Fig. 3. Performance with increasing network density and exponential flows in static topology network

falls. MAIR uses shorter paths using the multiple labels and does not have the same problem as AIR; however, it has a higher delay than MAIR.

MAIR chooses the shortest path from the three available paths along the three root LDAGs. So the control traffic is more distributed in the network and there is less congestion around the top level nodes of any one LDAG. So MAIR delivers far more packets than AIR. For 200 nodes the delivery ratio of MAIR is almost double of AODV and four times of AIR. The network load of MAIR is lower than OLSR for all network sizes. For lower network density AODV has a low network load because it discovers routes on demand. AIR, MAR and MAIR on the other hand have to maintain the DHT mappings and exchange the Hellos even if there is no traffic. After 100 nodes, the network load of AODV is more than AIR, MAR and MAIR as AODV interprets congestion as link failures and has to rediscover routes. The network load for AIR, MAR and MAIR do not increase much with node density unlike AODV and OLSR.

B. Mobile configuration with increasing number of nodes and high data load

This is a high-traffic scenario with high mobility and tests the scalability of MAIR. In this test, the number of nodes is constant at 50. The flows are on-off and uniformly distributed. Each node has a round-robin schedule of flows to every other node. From node n_1 , the flows look like: off, on to n_2 , off on to n_3 , off, ..., off, on to n_N , with N being the number of nodes in the network. In a network of N nodes, the number of concurrent flows is N and the total number of flows is N^2 . Each source sends 512 byte packets for 50 secs. The rate is 4 packets/sec. The nodes move at 10 m/s rate. The pause time has been varied from 0(always mobile) to 300s. The mean performance of several runs with 95% confidence interval, assuming a normal distribution, has been reported.

Figures 4(a)- 4(c) show the results for delay, delivery ratio and network load. The delay of MAIR is the lowest, even lower than single label AIR. For 300s pause time, the delay for OLSR and AODV is roughly 15 times that of MAIR. The delay of MAIR is one third of AIR at 300s pause time. All the protocols have low delivery ratio due to the high data traffic. The delivery ratio of MAIR is the same as OLSR and is about 10 times higher than AODV. It is also slightly higher than AIR. The network load of MAIR is also the lowest. It is almost 100 times less than AODV, 10 times less than OLSR and about half of that of AIR. MAR performs similar to MAIR in this scenario.

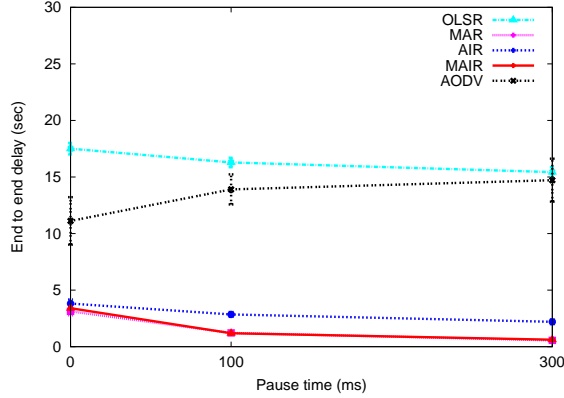
C. Routing beyond two hop neighborhood

This scenario shows that MAIR routes packets efficiently beyond two hops and the path lengths of the routes are similar to those achieved by shortest path protocols such as AODV and OLSR. For this scenario we selected flows that are longer than two hops in a 25-node static topology.

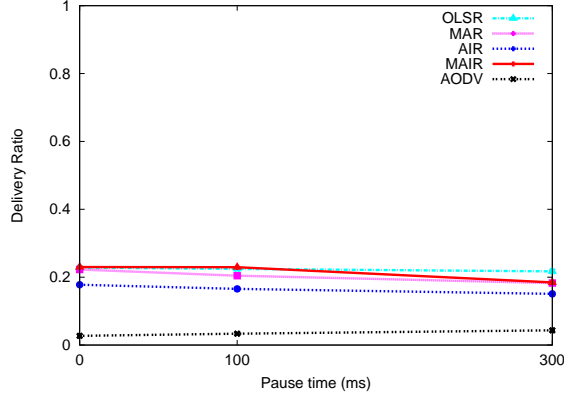
Figures 5(a)- 5(d) show the delay, delivery ratio, network load and path length for 2, 5, 7 and 10 flows. The results

TABLE II
PERFORMANCE COMPARISON

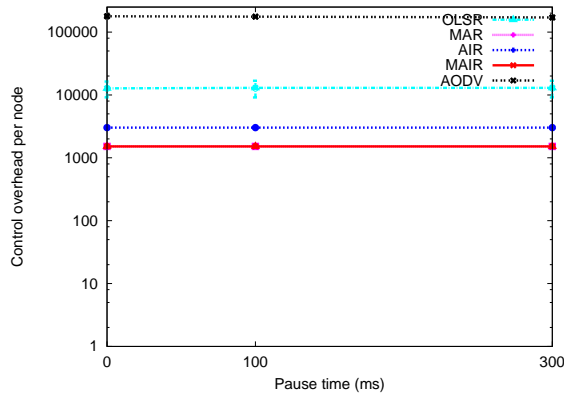
Flows	Metric	MAIR	AODV	OLSR
2	Delay	0.005512	0.005499	0.004982
	Delivery Ratio	1.0	1.0	1.0
5	Delay	0.006265	0.006229	0.005031
	Delivery Ratio	1.0	1.0	1.0
7	Delay	0.006991	0.007698	0.005545
	Delivery Ratio	1.0	1.0	1.0
10	Delay	0.006261	0.007664	0.005153
	Delivery Ratio	1.0	1.0	1.0



(a) Increasing pause time vs. end-to-end delay



(b) Increasing pause time vs. delivery ratio



(c) Increasing pause time vs. network load

Fig. 4. Performance with increasing pause time and high mobility

clearly demonstrate that MAIR finds shortest paths to destinations and delivers more packets while maintaining lower delay and network load compared to OLSR. The network load of AODV is lower than MAIR because of the small size of the network. We have already shown that for larger networks and more flows the network load of AODV drastically increases and MAIR scales much better than AODV. The delivery ratio and path lengths of MAIR is comparable to AODV in this scenario.

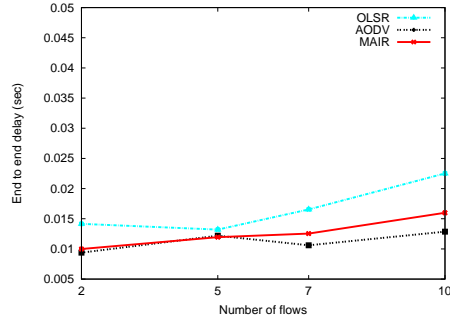
D. Routing with No-collision PHY

For this scenario we used the topology in the previous 25-node static scenario with paths longer than two hops. Then we made changes in Qualnet PHY code so that there are no collisions. The purpose of this scenario is to show MAIR behaves as well as AODV and OLSR in terms of end-to-end delay and delivers all the packets in the absence of MAI.

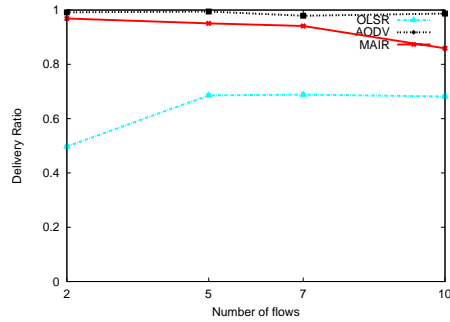
Table II shows the delay and delivery ratio for this scenario for 2, 5, 7 and 10 flows. All the protocols deliver all packets even with the increase of flows. OLSR benefits most from the no collision PHY as it has a high control overhead which causes significant collisions and drops the delivery ratio in the previous scenario. OLSR also has a slightly lower delay than MAIR and AODV since it maintains routes at all times and does not have a route establishment delay. MAIR has a low route establishment delay due to its ROIs. So the end to end delay is lower than AODV.

VII. CONCLUSION

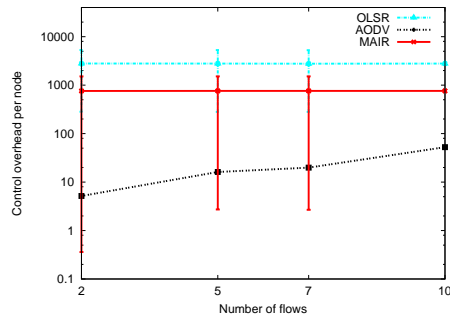
We presented MAIR, an efficient routing protocol that works in mobility scenarios and attains a low delay and low path stretch. In MAIR each node is assigned three labels from three distributively elected labeling root nodes. Each label is based on the location of the node with respect to the corresponding root in the network. Then each node communicates its labels to its neighbors and publishes the labels to an anchor node using a common hash function. The use of the three labels allows the node to have multiple paths to each destination. The destination node then chooses the shortest of the multiple paths and builds a region of interest around that path. The nodes in the region of interest maintain the latest labels of the destination. This enables new route discovery without the expensive anchor lookup. Hence MAIR has much lower route



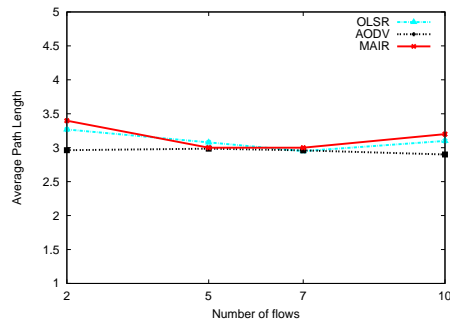
(a) Increasing flows vs. end-to-end delay



(b) Increasing flows vs. delivery ratio



(c) Increasing flows vs. network load



(d) Increasing flows vs. path length

Fig. 5. Performance with increasing number of flows and path lengths being more than two hops

establishment delay. The multiple paths can also be used for local repair. Qualnet simulations show that MAIR performs much better than AODV and OLSR in terms of end-to-end delay and control overhead. The path stretch and delivery ratio of MAIR is similar to AODV and OLSR.

VIII. ACKNOWLEDGMENTS

This work was supported in part by the Baskin Chair of Computer Engineering at UCSC.

REFERENCES

- [1] J. Behrens and J.J. Garcia-Luna-Aceves, "Hierarchical Routing Using Link Vectors," *IEEE Infocom 98*, 1998.
- [2] M. Caesar et al., "Virtual ring routing: network routing inspired by DHTs," *SIGCOMM '06*, 2006.
- [3] S. Das, H. Pucha, and Y. Hu, "Performance comparison of scalable location services for geographic ad hoc routing," *IEEE Infocom '05*, March 2005.
- [4] J. Eriksson, M. Faloutsos and S. V. Krishnamurthy, "Dart: dynamic address routing for scalable ad hoc and mesh networks," *IEEE/ACM Trans. Netw.*, Vol. 15, No. 1, 2007.
- [5] R. Fonseca et al., "Beacon vector routing: scalable point-to-point routing in wireless sensor networks," *Proc. NSDI '05*, Berkeley, CA, USA, 2005.
- [6] J.J. Garcia-Luna-Aceves and D. Sampath, "Scalable Integrated Routing Using Prefix Labels and Distributed Hash Tables for MANETs," *Proc. IEEE MASS 2009*, Oct. 2009.
- [7] R. Ghosh and J. J. Garcia-Luna-Aceves, "Automatic Routing Using Multiple Prefix Labels," *Proc. IEEE Globecom 2012*, Dec. 3-7, 2012.
- [8] P. Jacquet et al., "Optimized Link State Routing Protocol for Ad Hoc Networks," *Optimized Link State Routing Protocol*, *Proc. IEEE INMIC '01*, Dec. 2001.
- [9] B. Karp and H. T. Kung, "GPSR: Greedy Perimeter Stateless Routing for Wireless Networks," *Proc. ACM MobiCom 2000*, New York, NY, 2000.
- [10] L. Kleinrock and F. Kamoun, "Hierarchical Routing for Large Networks, Performance Evaluation and Optimization", *Computer Networks*, Vol. 1, No. 3, pp. 155-174, January 1977.
- [11] L. Li and L. Lamont, "A Lightweight Service Discovery Mechanism for Mobile Ad Hoc Pervasive Environment Using Cross-layer Design," *Proc. IEEE PerCom '05 Workshops*, 2005.
- [12] G. Pei, M. Gerla, and T.-W. Chen, "Fisheye state routing: a routing scheme for ad hoc wireless networks," *Proc. IEEE ICC 2000*, 2000.
- [13] C.E. Perkins and E.M. Royer, "Ad-hoc On-Demand Distance Vector Routing," *Proc. 2nd IEEE WMCSA*, pp. 90-100, Feb.1999.
- [14] S.C. Rhea, J. Kubiawicz, "Probabilistic Location and Routing," *Proc. IEEE Infocom 2002*, 2002.
- [15] C. A. Santiv  ez et al., "Making link-state routing scale for ad hoc networks," *Proc. ACM MobiHoc 2001*, 2001.
- [16] M. Spohn and J.J. Garcia-Luna-Aceves, "Neighborhood Aware Source Routing," *Proc. ACM MobiHoc 01*, 2001.
- [17] P. F. Tsuchiya, "The landmark hierarchy: a new hierarchy for routing in very large networks," *Proc. SIGCOMM '88*, Stanford, CA, 1988.
- [18] A. C. Viana et al., "An underlay strategy for indirect routing," *Wireless Networks*, Vol. 10, No. 6, 2004.
- [19] Y. Mao et al., "S4: Small State and Small Stretch Compact Routing Protocol for Large Static Wireless Networks," *IEEE/ACM Trans. on Networking*, Vol. 18, No. 3, June 2010.
- [20] Scalable Network Technologies, *Qualnet*, <http://web.scalable-networks.com/content/qualnet>.
- [21] Y. Wang and J.J. Garcia-Luna-Aceves, "Collision Avoidance in Multi-hop Ad Hoc Networks," *Proc. IEEE MASCOTS 2002*, 2002.
- [22] Z. Wang, H.R. Sadjadpour, and J.J. Garcia-Luna-Aceves, "A Unifying Perspective on The Capacity of Wireless Ad Hoc Networks," *Proc. IEEE INFOCOM 2008*, 2008.
- [23] B. Zhao et al., "Tapestry: An infrastructure for fault-tolerant wide-area location and routing," Report No. UCB/CSD-01-1141, University of California, Berkeley, April 2001.
- [24] Y. Zhao et al., "Hop ID: A Virtual Coordinate-Based Routing for Sparse Mobile Ad Hoc Networks," *IEEE Trans. Mobile Comp.* Vol. 8, No. 9, 2007.