Wireless, mobile ad-hoc network routing

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Abstract

In this paper we survey various types of routing strategies proposed for wireless ad hoc networks. An ad hoc network operates without a fixed infrastructure, and consists of a multitude of devices - hosts, repeaters or both. In this environment, as network size grows, multihopping over several intermediate devices to reach the final destination becomes prevalent, because of obstacles, spatial spectrum reuse and power saving considerations. Mobility is also common in ad-hoc networks, because of the nature of the applications they are designed ot support (eg, disaster recovery, battlefield, search and rescue, sensor nets, etc). Multihopping, mobility, large network size combined with device heterogeneity and bandwidth and battery power limitations make the design of adequate routing protocols a major challenge. In recent years, various different routing protocol "styles" have been proposed for wireless ad-hoc networks. In the presentation, we will review a representative subset including traditional table-driven (distance vector, link state) protocols, reactive on-demand protocols, and location based protocols that use position information provided by GPS. Using simulation results from the simulation platform using the PARSEC we will compare the protocols in different traffic and speed scenarios and under different performance criteria.

1 Introduction

In this paper we survey various types of routing strategies proposed for wireless ad-hoc network. A key feature which sets multihop wireless networks apart from the more traditional cellular radio systems is the ability to operate without a fixed, wired communications infrastructure, and to be rapidly deployed to support emergency requirements, short term needs and coverage in undeveloped areas. The applications of this wireless infrastructure range from civilian (e.g., ad hoc networking for collaborative, distributed computing) to disaster recovery (e.g., fire, flood, earthquake), law enforcement (e.g., crowd control, search-and-rescue) and military (automated battlefield).

A key protocol in ad hoc networks is routing. Multihopping, mobility, large network size combined with device heterogeneity and bandwidth and battery power limitations make the design of adequate routing protocols a major challenge. In recent years, various different routing protocol "styles" have been proposed for wireless ad-hoc networks.

In section 2 we review existing routing protocols for wireless ad-hoc networks, focusing mostly on hierarchical routing, on-demand and location based schemes. In section 3 we present simulation results. Section 4 concludes the paper.

2 Existing routing protocols for ad-hoc wireless networks

Existing wireless routing schemes can be classified into four broad categories:

- **(a) global, precomputed routing:** routes to **all** destinations are computed a priori and are maintained in the background via a periodic update process. Most of the conventional routing schemes, including Distance Vector and Link State (LS), fall in this category.
- **(b) on-demand routing:** the route to a specific destination is computed only when needed.
- **(c) location based routing:** route computation is assisted by the knowledge of geographical location of the destination, usually provided by GPS.
- **(d) flooding:** minimal or no priori knowledge of network structure is assumed. No routes are computed on demand. A packet is simply broadcast to all destinations, with the

expectation that at least one copy of the packet will reach the intended destination. Scoping may be used to limit the overhead of flooding.

In the sequel we focus in more detail on the three two categories, by using some typical examples recently proposed in the literature.

2.1 Global, precomputed routing schemes

Global, precomputed routing schemes can be subdivided into two further categories: flat and hierarchical. In the "flat routing"category, many protocols have been proposed to support mobile ad-hoc wireless routing. Some proposals are extensions of schemes previously developed for traditional wired networks. For example, Perkins' Destination-Sequenced Distance Vector (DSDV) [18] is based on Distributed Bellman-Ford (DBF), Garcia's Wireless Routing Protocol (WRP) [14] [15] is based on a loop-free path-finding algorithm, etc. In flat routing schemes each node maintains a routing table with entries for all the nodes in the network. This is acceptable if the user population is small. However, as the number of mobile hosts increases, so does the overhead. Thus, flat routing algorithms do not scale well to large networks.

To permit scaling, hierarchical techniques can be used. In the following sections, we describe two hierarchical (implicit or explicit) schemes recently proposed for wireless networks [23].

2.1.1 Fisheye State Routing (FSR) scheme

FSR is an implicit hierarchical routing protocol. It uses the "fisheye" technique proposed by Kleinrock and Stevens [11], where the technique was used to reduce the size of information required to represent graphical data. The eye of a fish captures with high detail the pixels near the focal point. The detail decreases as the distance from the focal point increases. In routing, the fisheye approach translates to maintaining accurate distance and path quality information about the immediate neighborhood of a node, with progressively less detail as the distance increases.

FSR is functionally similar to LS Routing in that it maintains a topology map at each node. The key difference is the way in which routing information is disseminated. In LS, link state packets are generated and flooded into the network whenever a node detects a topology change. In FSR, link state packets are not flooded. Instead, nodes maintain a link state table based on the up-to-date information received from neighboring nodes, and periodically exchange it with their local neighbors only (no flooding). Through this exchange process, the table entries with larger sequence numbers replace the ones with smaller sequence numbers. The FSR periodic table exchange resembles the vector exchange in DBF (or more precisely, DSDV [18]) where the distances are updated according to the time stamp or sequence number assigned by the node originating the update. In FSR (like in LS) link states are propagated, a full topology map is kept at each node, and shortest paths are computed using this map.

In a wireless environment, a radio link between mobile nodes may experience frequent disconnects and reconnects. The LS protocol releases a link state update for each such change, which floods the network and causes excessive overhead. FSR avoids this problem by using periodic exchange of the entire topology map, greatly reducing the control message overhead.

When network size grows large, the update message could consume considerable amount of bandwidth, which depends on the update period. In order to reduce the size of update messages without seriously affecting routing accuracy, FSR uses the Fisheye technique. Figure 1 illustrates the application of fisheye in a mobile, wireless network. The circles with different shades of grey define the fisheye scopes with respect to the center node (node 11). The scope is defined as the set of nodes that can be reached within a given number of hops. In our case, three scopes are shown for 1, 2 and 3 hops respectively. Nodes are color coded as black, grey and white accordingly.

The reduction of update message size is obtained by using different exchange periods for different entries in the table. More precisely, entries corresponding to nodes within the smaller scope are propagated to the neighbors with the highest frequency. Referring to Figure 2, entries in bold are exchanged most frequently. The rest of the entries are sent out at a lower frequency. As a result, a considerable fraction of link state entries are suppressed, thus reducing the message size. This strategy produces timely updates from near stations, but creates large latencies that from stations afar. However the imprecise knowledge of the best path to a distant destination is compensated by the fact that the route becomes progressively more accurate as the packet gets closer to destination.

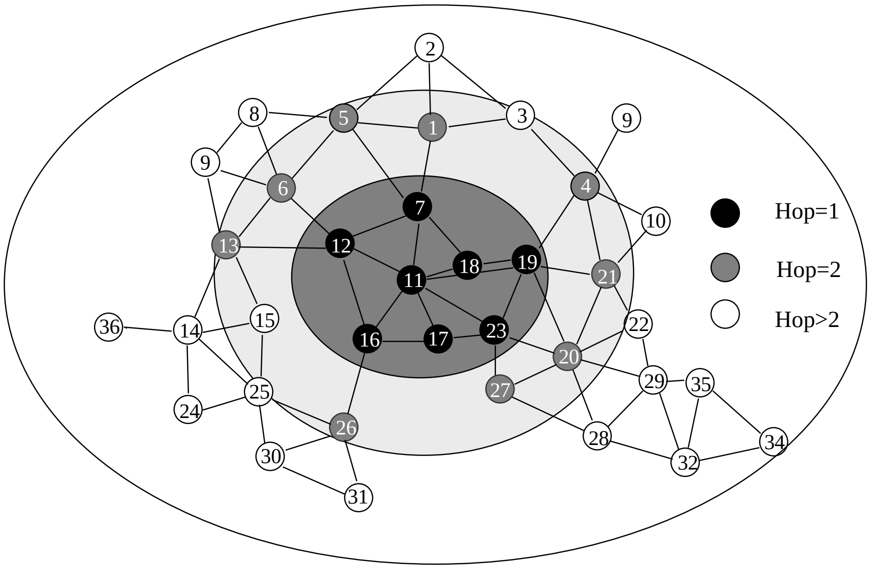

Figure 1: Scope of fisheye

FSR scales well to large networks, by keeping link state exchange O/H low without compromising route computation accuracy when the destination is near. By retaining a routing entry for each destination, FSR avoids the extra work of "finding" the destination (as in on-demand routing) and thus maintains low single packet transmission latency. As mobility increases, routes to remote destinations become less accurate. However, when a packet approaches its destination, it finds increasingly accurate routing instructions as it enters sectors with a higher refresh rate.

2.1.2 Hierarchical State Routing (HSR) scheme

Partitioning and clustering is common practice in multihop wireless networks both at the MAC layer and at the network layer [6] [4]. Clustering can enhance network performance. For example, at the MAC layer, by using different spreading codes across clusters the interference is reduced and the spatial reuse is enhanced. As the number of nodes grows, there is further incentive to exploit partitions at the network layer in order to implement hierarchical routing and thus reduce routing overhead. In a mobile network, the main drawback of hierarchical routing is mobility and location management. To overcome this problem, in this section, we describe the Hierarchical State Routing (HSR) scheme proposed in [23], which combines dynamic, distributed multi-level hierarchical clustering with an efficient location (membership)

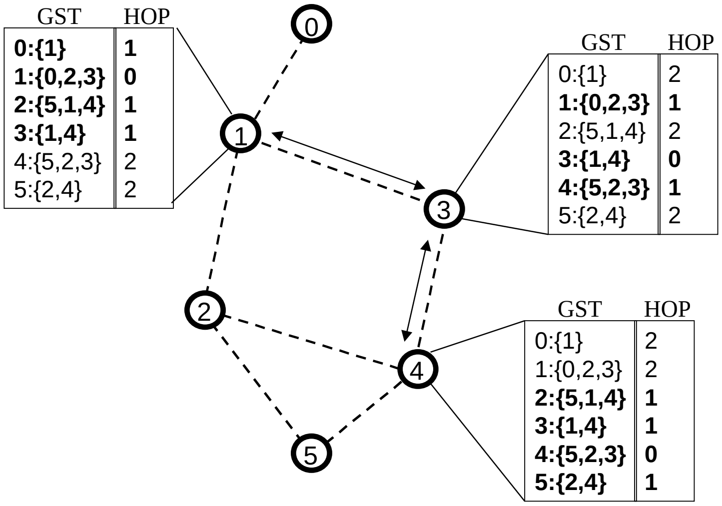

Figure 2: Message reduction using fisheye

management.

HSR maintains a hierarchical topology, where elected cluster heads at the lowest level become members of the next higher level. These new members in turn organize themselves in clusters, and so on. The goals of clustering are the efficient utilization of radio channel resources and the reduction of network-layer routing overhead (i.e., routing table storage, processing and transmission).

Figure 3 shows an example of physical clustering. At $Level = 0$ we have 4 physical level clusters C0-1, C0-2, C0-3, and C0-4. Level 1 and level 2 clusters are generated by recursively selecting cluster heads. Different clustering algorithms can be used for the dynamic creation of clusters and the election of cluster heads [6] [4]. At level 0 clustering, spread-spectrum radios and code division multiple access (CDMA) can be introduced for spatial reuse across clusters. Within a level 0 cluster, the Medium Access Control (MAC) layer can be implemented by using a variety of different schemes (polling, MACA, CSMA, TDMA etc) [9]. Generally, there are three kinds of nodes in a cluster, namely, cluster-head node (e.g., Node 1, 2, 3, and 4), gateway node (e.g., Node 6, 7, 8, and 11), and internal node (e.g., 5, 9, and 10). The cluster-head node acts as a local coordinator of transmissions within the cluster. The node IDs shown in Figure 3 (at level = 0) are physical (e.g., MAC layer) addresses. They are hardwired and are unique to each node. In HSR, the hierarchical address HID (Hierarchical ID) of a node

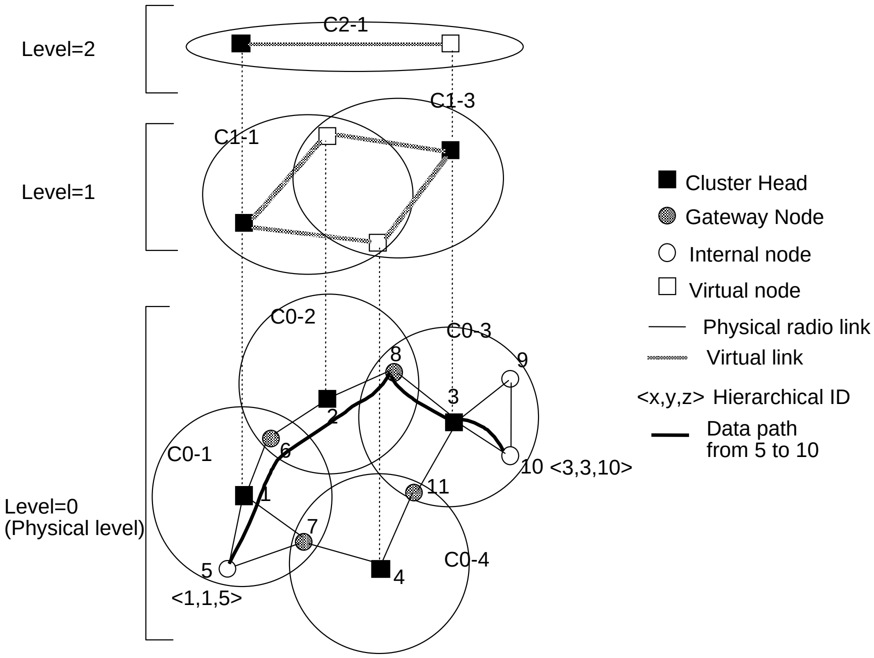

Figure 3: An example of physical/virtual clustering

is defined as the sequence of the MAC addresses of the nodes on path from the top hierarchy to the node itself. For example, in Figure 3 the hierarchical address of node 6, HID(6), is $< 3, 2, 6 >$. In this example, node 3 is a member of the top hierarchical cluster (level 2). It is also the cluster head of C1-3. Node 2 is member of C1-3 and is the cluster head of C0-2. Node 6 is a member of C0-2 and can be reached directly from node 2. The advantage of this hierarchical address scheme is that each node can dynamically and locally update its own HID upon receiving the routing updates from the nodes higher up in the hierarchy. The hierarchical address is sufficient to deliver a packet to its destination from anywhere in the network using HSR tables. Referring to Figure 3, consider for example the delivery of a packet from node 5 to node 10. Note that HID(5)=$< 1, 1, 5 >$ and HID(10)= $< 3, 3, 10 >$. The packet is forward upwards to the top hierarchy by node 5 (i.e., to node 1). Node 1 delivers the packet to node 3, which is the top hierarchy node for destination 10. Node 1 has a “virtual link”, i.e. a tunnel, to node 3, namely, the path (1,6,2,8,3). It thus delivers the packet to node 3 along this path. Finally, node 3 delivers the packet to node 10 along the downwards hierarchical path, which in this case reduces to a single hop.

In addition to multilevel clustering, HSR also provides multilevel logical partitioning. While clustering is based on geographical (i.e., physical) relationship between nodes, (hence, it will be referred to as **physical** clustering), logical partitioning is based on logical, functional affinity between nodes (e.g., employees of the same company, members of the same family, etc). **Logical** partitions play a key role in location management. Besides MAC addresses, nodes are assigned logical addresses of the type $< subnet,\ host >$. These addresses have format similar to IP, and can in fact be viewed as private IP addresses for the wireless network. Each subnet corresponds to a particular user group (e.g., tank battalion in the battlefield, search team in a search and rescue operation, etc). The notion of a subnet is important because each subnet is associated with a home agent, as explained later. Also, a different mobility pattern can be defined independently for each subnet. This allows us to independently define the mobility models for different formations (e.g., members of a police patrol). The transport layer delivers to the network a packet with the private IP address. The network must resolve the IP address into a hierarchical (physical) address which is based on MAC addresses. Nodes in the same IP subnetwork have common characteristics (e.g., tanks in the same battalion, professionals on the move belonging to the same company, students within the same class, etc). Note that the IP subnetwork is a "virtual" subnetwork which spans several physical clusters. Moreover, the subnet address is totally distinct from the MAC address. Each virtual subnetwork has at least one home agent (which is also a member of the subnet) to manage membership. For simplicity, we assumes that all home agents advertise their HIDs to the top hierarchy. The home agent HIDs are appended to the top level routing tables. Optionally, the home agent HIDs can be propagated downwards to all nodes together with such routing tables.

Each member of a logical subnetwork knows the HID of its home agent (it is listed in the routing table). It registers its own current hierarchical address with the home agent. Registration is both periodic and event driven (e.g., whenever the member moves to a new cluster). At the home agent, the registered address is timed out and erased if not refreshed. Since in most applications, the members of the same subnet move as a group (e.g., tanks in a battalion), they tend to reside in neighboring clusters. Thus, registration overhead is modest.

When a source wants to send a packet to a destination of which it knows the IP address, it first extracts the subnet address field from it. From its internal list (or from the top hierarchy) it obtains the hierarchical address of the corresponding home agent (recall that all home agents advertise their HIDs to the top level hierarchy). It then sends the packet to the home agent using such hierarchical address. The home agent finds the registered address from the host ID (in the IP address) and delivers the packet to destination. Once source and destination have learned each other hierarchical addresses, packets can be delivered directly without involving the home agent.

2.2 On-demand routing schemes

On-demand routing is the most recent entry in the class of scalable wireless routing schemes. It is based on a query-reply approach. Examples include Lightweight Mobile Routing (LMR) protocol [5], Ad-hoc On Demand Distance Vector Routing (AODV) [20], Temporally-Ordered Routing Algorithms (TORA) [16] [17], Dynamic Source Routing Protocol (DSR) [2] and ABR [21]. Most of the routing proposals currently evaluated by the IETF's MANET working group for an Ad Hoc Network Standard [20] [17] [2] fall in on-demand routing category.

There are different approaches for discovering routes in on-demand algorithms. Most algorithms employ a scheme derived from LAN bridge routing, i.e. route discovery via backward learning. The source in search of a path floods a query into the network. The transit nodes upon receiving the query "learn" the path to the source (**backward learning**) and enter the route in the forwarding table. The intended destination eventually receives the query and can thus respond using the path traced by the query. This permits establishment of a full duplex path. To reduce new path search overhead, the query packet is dropped on its way to a destination if it encounters a node which already has a route to such destination. After the path has been computed, it is maintained up to date as long as the source uses it. For example, a link failure may trigger another query/response so that the route is always kept up to date.

An alternate scheme for tracing on demand paths (also inspired by LAN bridge routing) is **source routing**. Dynamic Source Routing (DSR) proposed in [25] is such a protocol. A source floods a ROUTE REQUEST if data to send exists but no route to its destination is known. When this packet is received by the destination or a node that knows a route to the destination, a ROUTE REPLY is sent to the source via selected route. Each node in the network maintains a route cache storing routes it has learned over time. Aggressive caching helps minimizing the cost incurred by the route discovery process. DSR uses source routing instead of hop-by-hop routing; the source node appends the list of nodes that comprise the route in the data header. Route breaks are detected when *passive acknowledgments* cannot be heard from the next hop. If a node learns the route is obsolete due to topology changes, it builds and sends a ROUTE ERROR to the source. The source then invokes a route discovery process to construct a new route. No periodic message of any kind are required in DSR.

On-demand routing introduces the initial search latency which may degrade the performance of interactive applications (e.g., distributed database queries). Moreover, it is impossible to know in advance the quality of the path (e.g., bandwidth, delay etc) prior to call setup. Such a priori knowledge is very desirable in multimedia applications, since it enables call acceptance control and bandwidth renegotiation.

A recent proposal which combines on-demand routing and conventional routing is Zone Routing [7] [8]. For routing operation inside the local zone, any routing scheme, including DBF routing or LS routing, can be applied. For interzone routing, on-demand routing is used. The advantage of zone routing is its scalability, as "global" routing table overhead is limited by zone size. Yet, the benefits of global routing are preserved within each zone.

2.3 Location Assisted Routing

In this section we review two location assisted schemes. The first (LAR) is of the on-demand type. The second (DREAM) is of the precomputed type. We discribe LAR and DREAM next.

2.3.1 Location-Aided Routing (LAR)

Location-Aided Routing (LAR) [26] is a location based on-demand routing protocol. In fact, LAR operates very similarly to DSR. The major difference between the two protocols is that LAR uses location information obtained from GPS to restrict the flooded area of ROUTE REQUEST packets. There are two schemes to determine which nodes propagate ROUTE REQUESTS. In scheme 1, the source defines a circular area in which the destination may be located. The position and size of the circle is decided with the following information: (a) the destination location known to the source; (b) the time instant when the destination was located at that position; and (c) the average moving speed of the destination. The smallest rectangular area that includes this circle and the source is the *request zone.* This information is attached to a Route Request by the source and only nodes inside the request zone propagate the packet. In scheme 2, the source calculates the distance between the destination and itself. This distance, along with the destination location known to the source, is included in a Route Request and sent to neighbors. When nodes receive this packet, they compute their distance to the destination, and continue to relay the packet only if their distance to destination is less than or equal to the distance indicated by the packet. When forwarding the packet, the node updates the distance field with its distance to the destination. In both schemes, if no Route Reply is received within the timeout period, the source retransmits a Route Request via pure flooding.

2.3.2 Distance Routing Effect Algorithm for Mobility (DREAM)

Distance Routing Effect Algorithm for Mobility (DREAM) [24] is another location based routing protocol. In contrast to LAR, DREAM is a proactive scheme and partially floods data to nodes in the direction of the destination. In the route table, coordinates of each node are recorded instead of route vectors. Each node in the network periodically exchanges control messages to inform of all other nodes its location. *Distance effect* is taken into account by sending location control messages more frequently to nodes that are more closely positioned. In addition, DREAM adjusts to network dynamics by controlling update frequency based on movement speed. When sending data, if the source has “fresh enough” location information of the destination, it selects a set of one hop neighbors that are located in the direction from source to destination. If no such nodes are found, the data is flooded to the entire network. If such nodes exist, the list is enclosed in the data header and transmitted. Only nodes specified in the header are qualified to process the packet. Once those nodes receive the packet, they select their own list of possible next hops and forward the data with the updated list. If no neighbors are located in the direction of the destination, the packet is simply dropped. When the destination receives data, it sends ACKs back to the source in a similar fashion. However, ACKs are not transmitted when data was received via flooding. When the source sends data with designated next hops, (i.e., not by pure flooding), it starts a timer for receiving ACKs. If no ACK is accepted before the timer expires, the data is retransmitted by ordinary flooding.

3 Performance evaluation

3.1 Simulation environment

The multihop, mobile wireless network simulator was developed on a simulation platform built upon the language Maisie/PARSEC [22]. The simulator is very detailed. It models all the control message exchanges at the MAC layer (e.g., polling) and the network layer (e.g., HSR Protocol control messages). This is critical in order to monitor and compare the traffic overhead (O/H) of the various protocols. In most experiments, the network consists of 100 mobile hosts roaming randomly in all directions at a predefined average speed in a 1000x1000 meter square (i.e., no group mobility models are used). A reflecting boundary is assumed. Radio transmission range is 120 meters. A free space propagation channel model is assumed. Data rate is 2Mb/s. Packet length is 10 kbit for data, 2 kbit for cluster head neighbor list broadcast, and 500 bits for MAC control packets. Transmission time is 5 ms for data packet, 1 ms for neighboring list and 0.25 ms for control packet. The buffer size at each node is 15 packets.

3.2 System and protocol parameters

The performance measures monitored in this study are: (a) control O/H generated by the routing update mechanisms; (b) average delay for data packets; (c) average number of hops for data packets. The variables are: number of pairs communicating with each other (this is a good indication of the "sparseness" in the traffic pattern), node mobility, and; number of nodes. Most of our results are for 100 nodes except for the experiment reported in Figure 7 where we study the scalability of the protocols and thus consider various network sizes up to 400 nodes. For FSR, we use a 2-level fisheye scoping in our experiments. The scope radius is 2 hops i.e. nodes within 2 hops are in-scope. The refresh rate ratio is 1:3 between in-scope nodes and out-scope nodes. This is quite conservative for network sizes larger than 200, leaving room for improvement. For example, we could use multiple level fisheye scoping and refresh the table entries corresponding to nodes in the outmost scope with even lower frequency. Similarly, in HSR we assume only 2 levels. The number of logical partitions (i.e., IP subnets) in HSR varies depending on network size. Namely, it is 1, 2, 4, 8, 12, 16 for 25, 49, 100, 225, 324 and 400 nodes respectively.

The traffic load corresponds to an interactive environment. Several sessions are established (in most cases, 100 sessions) between different source/destination pairs. Within each session, data packets are generated following a Poisson process with an average interval of 2.5 s. This amounts to a traffic volume of 4 Kbps per source/destination pair, recalling that data packet length is 10 kbits. In all, this load (even with 500 pairs, which is the maximum we considered in our experiments) could be comfortably managed by the network in a static configuration, using any of the routing schemes so far described. With mobility, however, routes may become invalid, causing packets to be dropped and leading to throughput degradation.

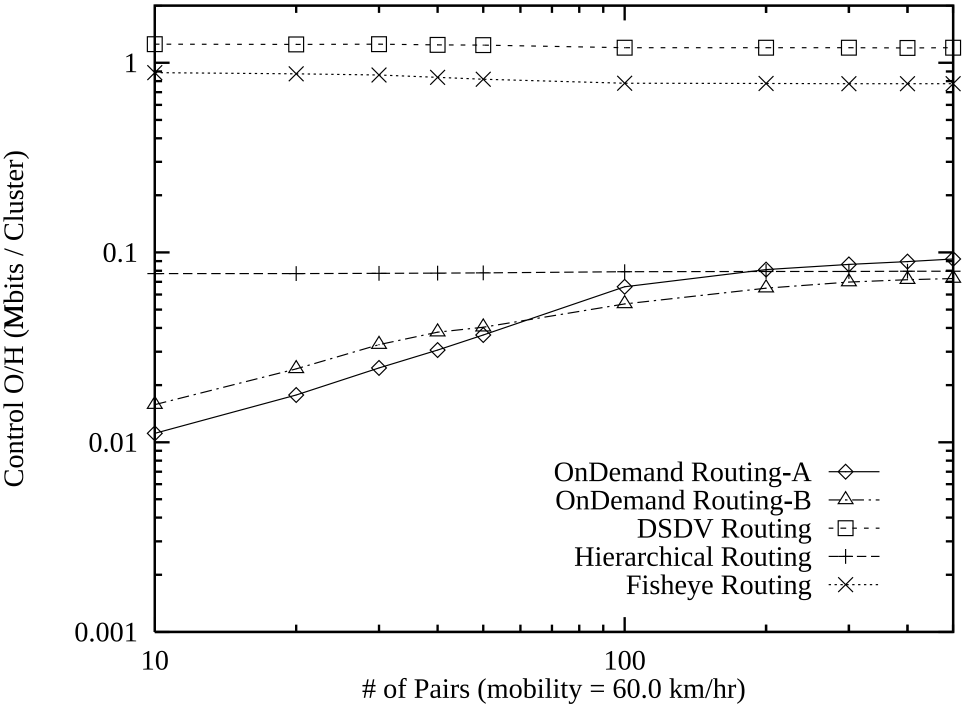

Figure 4: Control O/H vs. Traffic Pairs

3.3 Experiment results

3.3.1 Overhead measurements

The first experiment reports the control O/H caused by routing update messages in the various schemes (see Figure 4 and Figure 5). In Figure 4 we show the O/H as a function of number of communicating pairs, for a node speed of 60 Km/hr. Tables are refreshed every 2 seconds for DSDV and HSR. The refresh rate of FSR is 2 seconds for in-scope and 6 seconds for out-scope nodes. There are 2 types of on-demand routing experiments, type-A and type-B depending

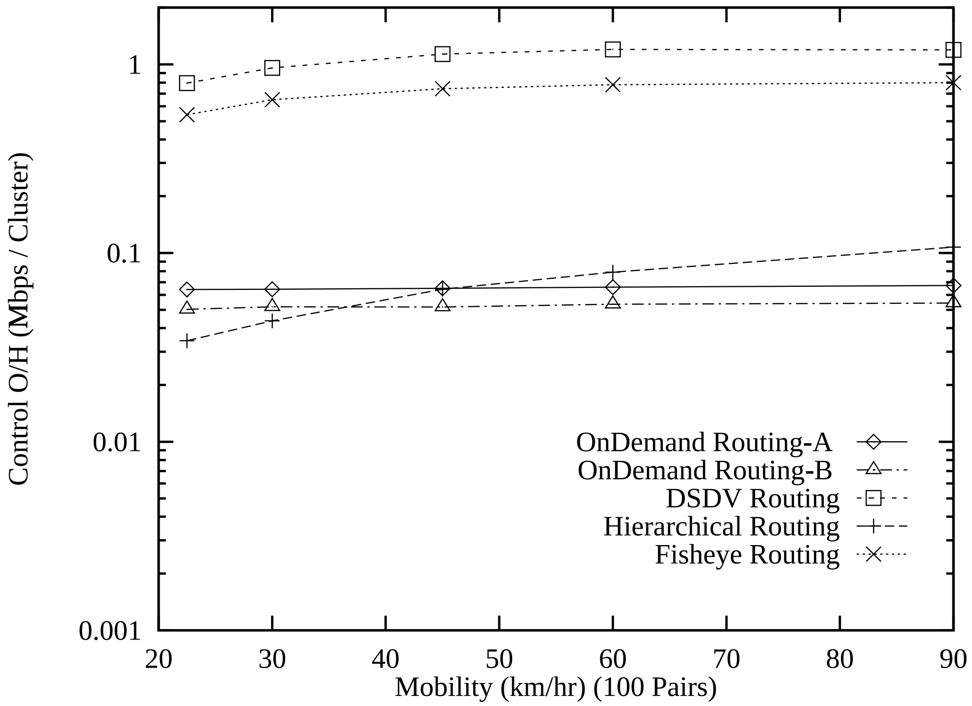

Figure 5: Control O/H vs. Mobility (100 Pairs)

on routing entry timeouts. The entries for active routes are timed out 3 seconds for type-A and 6 seconds for type-B. The O/H is measured in Mbits/cluster. From Figure 4 we note that the O/H in DSDV, FSR and HSR is constant with the number of pairs, as expected, since background routing updates are independent of user traffic. On-demand routing O/H, on the other hand, increases almost linearly with the number of pairs, up to 100 pairs (these pairs have distinct destinations). Beyond 100 pairs, destinations are repeated and therefore a previously cached route may be used over again. Thus, the O/H increases with a lesser rate beyond 100 pairs since some paths have already been discovered. Recalling that the maximum throughput achievable in a single cluster is 2 Mbps (ignoring MAC layer O/H), we note that both HSR and on-demand routing have acceptable O/H (< 10% in the entire range between 10 and 100 nodes). Although the active route timeout period in on-demand routing for type-B is much longer than that for type-A, the O/H for type-A and type-B are fairly close. The reason why in on-demand routing the O/H is not reduced more dramatically by increasing the timeout period is that the next hop pointed to by the cached routing entry is no longer available due to mobility. A patch request must be issued again. As for the remaining schemes, DSDV, is quite "heavy", introducing more than 50% of line overhead! This is because DSDV propagates full routing tables (with 100 entries). FSR O/H is also quite heavy, albeit not as bad as DSDV. HSR uses much smaller tables (10 entries on average), while on-demand routing propagates only single entry tables whenever needed. It is clear that already for 100 nodes a flat routing scheme such as DSDV is untenable if the network is mobile and therefore requires rapid refresh.

In Figure 5 we report the control O/H as a function of node speed. On-demand routing O/H is constant since the updates are independent of speed. Again, type-A O/H is higher than type-B. HSR, FSR and DSDV all exhibit increasing O/H with speed - the update rate must be increased with speed to keep accurate routes. Again, DSDV O/H is prohibitive over the entire range between 20 and 90 Km/hr. FSR O/H is also quite high. While for On-demand and HSR, the penalty is quite reasonable ($< 5\%$).

3.3.2 Delay measurements

The next experiment reports average packet delay as a function of mobility. In Figure 6 we note that for DSDV, FSR and HSR the delay is almost constant (less than 100 ms). As speed increases, DSDV, FSR and HSR progressively lose track of routes and thus drop packets. However, the dropped packets are not accounted for in the delay computation. Moreover, packets to remote destinations are the most likely do be dropped. This is particularly true for HSR which experiences long paths due to home agent redirection and thus shows a "misleading" overall decrease of average delay with mobility. Note FSR routing has overall shorter delay than HSR because FSR uses shortest path routing; FSR routing has also shorter delay than DSDV because FSR has less control O/H than DSDV and data packets experience less queueing delay (control packets have higher priority than data packets). For on-demand routing, on the other hand, packets are not dropped, but delay becomes larger as the speed increases from 20 to 90 Km/hr. This is due to the fact that if the path to destination is lost (because of mobility, in this case), On-demand routing will not drop the packet, rather it will initiate a search to find a new path at the cost of additional delay. Note that the delay in on-demand routing for type-B is much larger than that of type-A when the mobility is high since the stale entries in type-B will make the route less optimal.

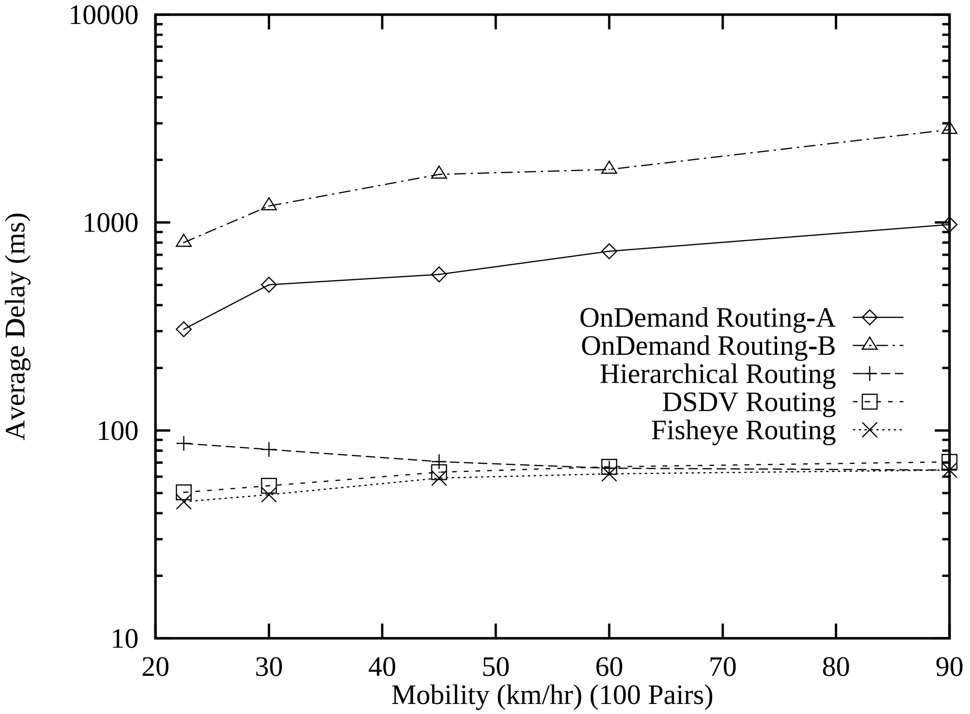

Figure 6: Average Delay vs. Mobility (100 Pairs)

3.3.3 Scalability performance

Figure 7 shows the increase of the control O/H as function of number of nodes. Geographical node density is kept the same for all runs as shown in Table 1. When the network size is small (say less than 50 nodes), 2-level fisheye scoping does not significantly reduce O/H with respect to DSDV. However, as network size grows larger, the fisheye technique aggressively reduces the O/H. In fact, O/H is almost independent of size beyond 100 nodes. For larger network sizes, further improvements in performance may be achieved by using more than 2 levels of scoping. On-demand routing performs well in a small network since most routes are reusable (we assume up to 100 active node pairs). For large networks, however, on-demand routing generates considerable O/H. This is because the chance of finding precomputed (and thus reusable) routes decreases. Note that the control O/H of on-demand routing increases linearly as the number of nodes increases. For HSR as the network size grows, the control O/H also increases due to the growth in number of clusters and logical subnets. However the growth slope is less than in DSDV because the routing information exchange is done in a hierarchical fashion (i.e., only cluster heads exchange the routing information). As for FSR, also in HSR

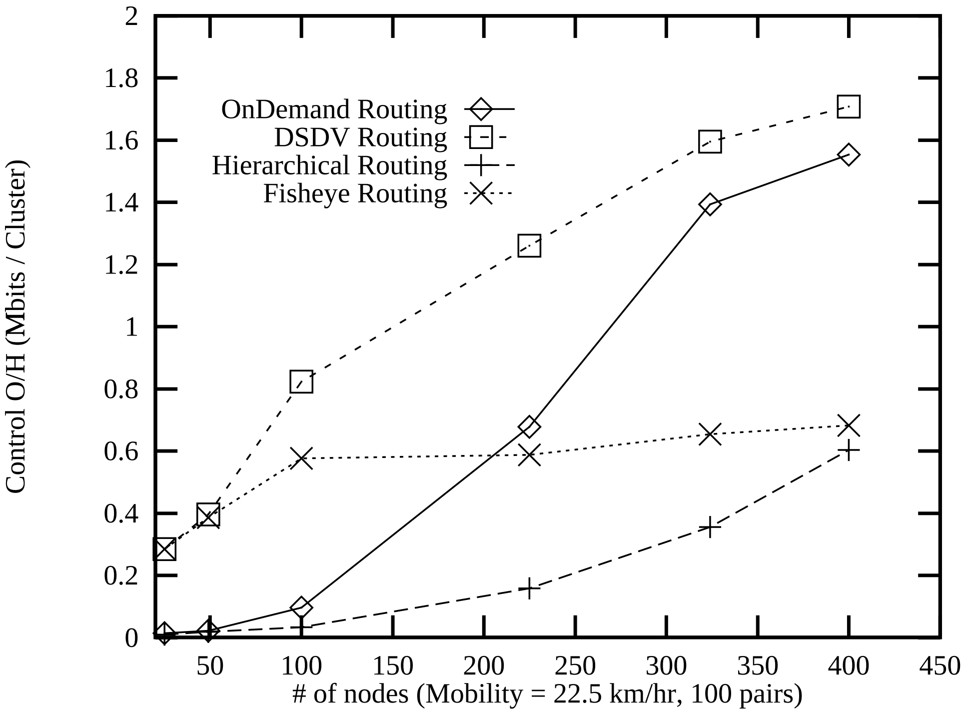

Figure 7: Control O/H vs. number of nodes

multiple hierarchical levels should be considered for network size larger than 400.

Table 1: Node density (nodes vs. area)

Number of nodes	25	49	100	225	324	400
Simulation area	500x500	700x700	1000x1000	1500x1500	1800x1800	2000x2000

3.4 Location based routing experiements

In a separate experiment with 50 network hosts, we evaluated LAR and DREAM. The metrics are: (a) the average number of data packets transmitted per data packet delivered; and (b) the average number of control bytes transmitted per data bytes delivered.

The average number of data transmissions per data packet delivery for each protocol is shown in Figure 8. As expected, DREAM has a higher measure since it partially floods data while LAR unicasts data. The value increases with mobility because sources are more likely to send data by pure flooding.

Figure 9 shows the efficiency of control overhead utilized in data delivery. DREAM shows

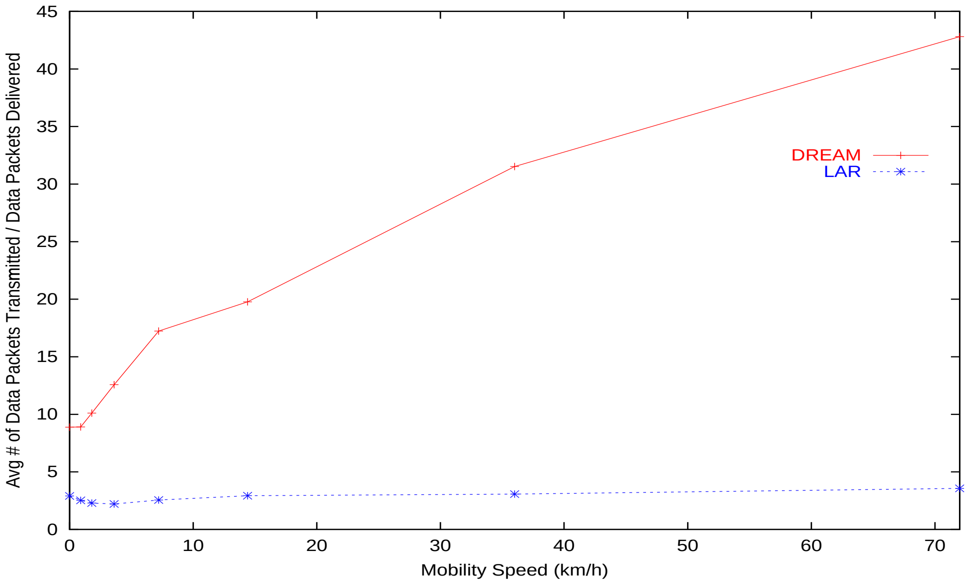

Figure 8: Avg # of Data Pkts Txed / Data Pkt Delivered

a higher control overhead because of its periodic transmission of location messages. If our implementation used ACK procedure, where ACKs are partially flooded in a manner similar to data, the value would be much higher. LAR has lower control traffic because it has no periodic messages and sends control packets only when necessary. Link changes that are not part of existing data session routes are not updated in LAR. In other words, control packets in LAR are used efficiently.

Figure 10 highlights the packet delivery ratio. Both protocols perform well under low mobility rates, but they become less effective as the mobility speed increases. DREAM is the most robust to mobility. This robustness is due to the partial flooding of data. With this flooding, multiple packets can reach the destination via different paths. Utilizing location information, this flooded area is confined to reduce network congestion. However, flooding did induce increased congestion, contention, and collisions, causing DREAM to be the only protocol that did not successfully deliver all packets in the absence of mobility.

LAR has very high packet delivery ratio overall, especially when subject to relatively low mobility. We observe only a slight performance degradation with mobility. In highly mobile situations, routes taken by Route Requests may already be broken when the source sends data or even when Route Replies are being returned back to the source. Thus, we find that the delay resulting from discovering routes plays an important role in the performance

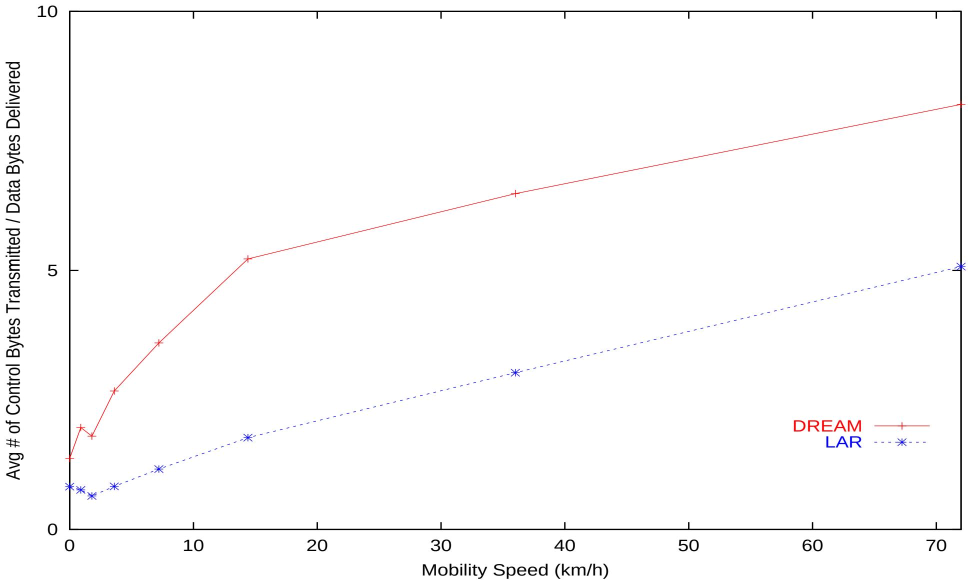

Figure 9: Avg # of Ctl Bytes Txed / Data Byte Delivered

degradation at high mobility speed.

4 Conclusions

We discribe several existing routing schemes proposed for mobile wireless networks and evaluate subset of proporties of these protocols. FSR and HSR schemes are extensions of conventional link state routing schemes, but improve scalability by reducing update traffic O/H. FSR achieves control traffic reduction by selectively adjusting routing update frequencies, while HSR reduces the size of update messages by using a hierarchical addressing approach. FSR maintains a flat addressing scheme and topology map. This makes it easy to locate destinations, but limits scalability because of routing table storage and processing O/H. HSR, in contrast, resolves the routing table scalability problem by using the hierarchical approach. However, it must face the difficult problem of “finding” the destination. HSR resolves this problem with a Home Agent technique which extends the Mobile IP concept to the multihop, mobile environment (no fixed base stations).

When compared with flat, table driven routing schemes (such as DSDV) these proposed solutions exhibit a much better scalability, at the cost of routing inaccuracy and increased complexity (e.g., home agent). The scalability advantage is clearly shown by the simulation results.

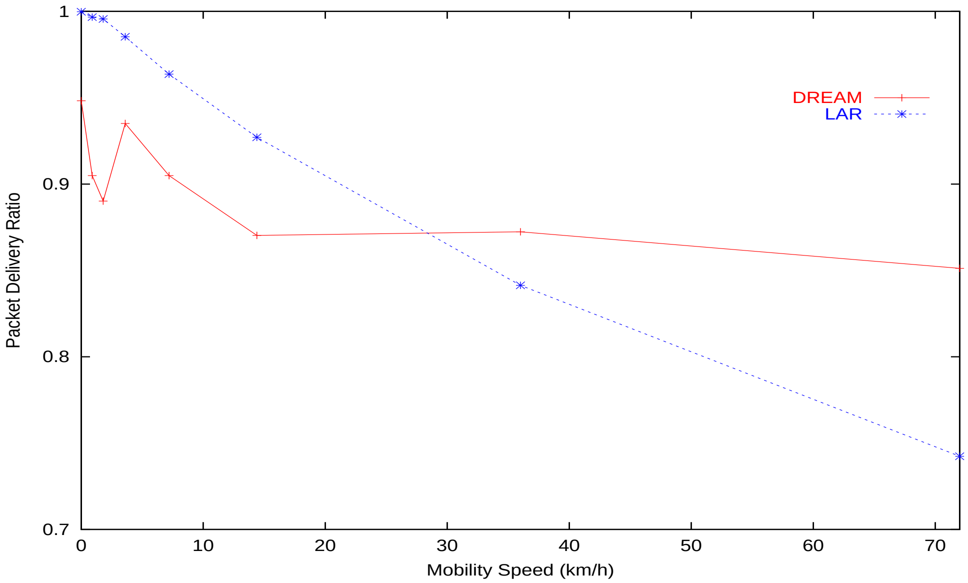

Figure 10: Pkt Delivery Ratio

We have also compared HSR and FSR with recently proposed on-demand routing schemes. HSR and FSR suffer of some disadvantages with respect to on-demand routing, most notably: (a) if a route becomes invalid because of mobility, packets are dropped until the new route is establish via the background routing update process (in contrast, in on-demand, the packet is buffered until the new route is discovered); (b) routing table storage O/H is higher (FSR); (c) protocol complexity is higher (e.g., home agent in HSR). On the other hand, HSR and FSR provide the following advantages: (a) lower latency for access to non frequently used destinations; (b) lower control traffic O/H in dense traffic situations (avoiding the flood type search for each destination); (c) QoS advertising prior to connection establishment (this is particularly useful for acceptance control in real time traffic environments).

Via simulation, we have compared HSR, FSR DSDV and on-demand routing. We have explored only a small set of the properties and tradeoffs. Yet, the simulation results clearly indicate the inadequacy of flat, table driven routing as the number of nodes grows. Also, clear is the increase of on-demand control overhead as the number of connections grows (i.e., the traffic pattern becomes dense). When the network grows large, the query on-demand flood will generate considerable control O/H. Higher delays are noticed in on-demand, while higher packet loss rates are observed in HSR, as expected.

Both global routing and on-demand routing schemes can be aided by location knowledge, as expected. Two location assisted schemes (LAR and DREAM) are evaluated. The results show that DREAM has more control O/H, because of the underlying flooding mechanism; but it is more robust in high mobility situations.

The main conclusion that can be drawn from these studies and experiments is that all the above schemes offer different, competitive and complementary advantages and are thus suited for different applications. A promising direction of future research is the integration of hierarchical, table driven (perhaps Fisheye) concepts with on demand routing concepts to generate routing strategies that can perform consistently well across various application domains.

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