A Wireless Hierarchical Routing Protocol with Group Mobility

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Abstract *– In this paper we present a hierarchical routing protocol in a large wireless, mobile network such as found in the automated battle field or in extensive disaster recovery operations. Conventional routing does not scale well to network size. Likewise, conventional hierarchical routing cannot handle mobility efficiently. We propose a novel soft state wireless hierarchical routing protocol – Hierarchical State Routing (HSR). We distinguish between the "physical" routing hierarchy (dictated by geographical relationships between nodes) and "logical" hierarchy of subnets in which the members move as a group (e.g., company, brigade, battalion in the battlefield). HSR keeps track of logical subnet movements using Home Agent concepts akin to Mobile IP. A group mobility model is introduced and the performance of the HSR is evaluated through a detailed wireless simulation model.*

I. INTRODUCTION

Wireless, multihop, ad hoc networks are expected to play an increasingly important role in future civilian and military environments where wireless access to a wired backbone is either ineffective or impossible. The applications range from collaborative, distributed mobile computing to disaster recovery (fire, flood, earthquake), law enforcement (crowd control, search and rescue) and digital battle field communication. Some key characteristics of these systems are team collaboration of large number of mobile units, limited bandwidth, the need for supporting multimedia real time traffic and low latency access to distributed resources(e.g., distributed database access for situation awareness in the battlefield).

Scalable and efficient routing scheme plays important role in ad-hoc networks. Existing wireless routing algorithms for ad-hoc networks can be classified into two general categories: precomputed global routing and on demand routing. In precomputed global routing schemes, routes to *all* destinations are periodically computed and maintained in the background. Precomputed global routing algorithms can be further divided into flat (e.g., DSDV [8] and WRP [6] etc) and and hierarchical (e.g., MMWN [11], [5]). The flat routing schemes can easily overload the channel capacity by sending nothing but large periodical routing updates among the nodes when the size of network becomes large. MMWN is a hierarchical routing scheme recently proposed for ad hoc networks to achieve scalability. This scheme, however, creates implementation problems which are potentially complex to resolve. The location management is closely tied with the network hierarchical topology. This feature makes the location updating and location finding quite complex. A location updating/finding has to travel along the hierarchical tree of the location managers. Furthermore, the changing in hierarchical cluster membership of an location manager will cause the reconstructing of the hierarchical location management tree and complex consistency management.

On demand routing is the most recent entry in the class of wireless routing schemes (e.g., LMR [3], AODV [9], TORA [7], DSR [4] and ABR [10] etc). It is based on a query-reply approach and a route to a destination is computed only when there is a need. On-demand routing does scale well to large population as it does not regularly maintain a routing table for all destinations. However, on-demand routing introduces the less desirable initial latency which makes it not very efficient for interactive traffic (e.g., distributed database query applications). It is also impossible to know in advance the quality of paths to all destinations (e.g., bandwidth, delay etc.) - a feature which can be very effective in call acceptance and path selection of QoS oriented connections.

In this paper, we will propose a noval wireless hierarchical routing protocol – Hierarchical State Routing (HSR). The key feature is the notion of logical subnets (e.g., brigade in the battlefield, colleagues in the same organization, or a group of students from same class) in order to handle mobility. A group mobility model is described in section II. In section III we explain the new hierarchical routing scheme in detail. The performance evaluation of our protocol is given in section IV. Section V concludes the paper.

II. GROUP MOBILITY MODEL

In an ad-hoc network, grouped motion behavior is very likely to occur. For example, in disaster recovery or military deployment, collaborative behavior among some nodes is quite common. In the paper, we introduce our new Reference Point Group Mobility model (Fig. 1). Nodes are partitioned into groups based on their logical relationship (e.g., logical subnets in our HSR). Each group has a conceptual center, the center's motion represents the group's motion, including location, speed, and direction and other facts such as acceleration. This model allows an independent motion behavior among groups, but each group moves as a whole. The trajectory of a group can be determined by providing a path for the center of the group. Many methods can be used to generate the path of a

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group, such as, digitizing a route from a map, outputs from a program, or a profile recorded from a battle field etc. Fig. 1 gives an example of a two-group model. Each group has a group motion of vector $\overrightarrow{V_{g_i}}$. Each node has its own random motion behavior, in addition to the group motion. The movement of a node in Group g_1 between time tick τ and $\tau + 1$ is computed as follows. First, the reference point of the node moves from $RP(\tau)$ to $RP(\tau + 1)$ with the group motion vector $\overrightarrow{GM}$ (here $\overrightarrow{GM} = \overrightarrow{V_{g_i}}$). Then the new node position is generated by adding a random motion vector $\overrightarrow{RM}$ to the new reference point $RP(\tau + 1)$. There are many ways to model the random motion vector $\overrightarrow{RM}$. In our experiments, we use a uniform random distribution, i.e., vector $\overrightarrow{RM}$ has its length uniformly distributed within a certain radius centered at the reference point and its direction uniformly distributed between 0 to 360 degree. This random vector is independent from node's previous location.

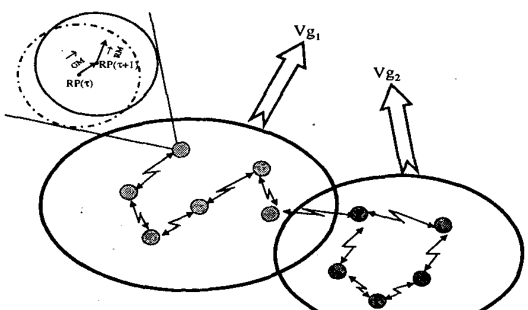

Fig. 1. Group Mobility Model

III. HIERARCHICAL STATE ROUTING PROTOCOL

HSR is a hierarchical link state based routing protocol. It 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). 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., tanks in the battlefield, or traveling salesman of the same company etc). **Logical** partitions play a key role in mobility management. The proposed mobility management scheme tracks mobile nodes, while keeping the control message overhead low. It is based on a distributed location server approach which exploits logical partitions. The following sections give more details on both physical and logical partitions.

A. Physical multilevel clustering

The physical clustering hierarchy used in HSR is illustrated in Fig. 2. Different clustering algorithms can be used for the dynamic creation of clusters and the election of cluster heads. At lowest level (level 1), we have 4 physical clusters. Level 2 and level 3 clusters are generated recursively, new cluster heads are elected at each level and become members of the higher level cluster. 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, 10, and 12). The cluster-head node acts as a local coordinator of transmissions within the cluster.

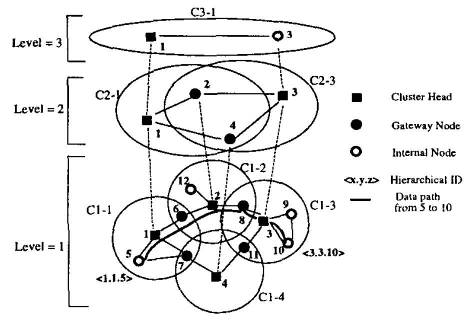

Fig. 2. An example of physical clustering

Each node has a unique identifier *NodeID*. NodeIDs are the physical hardwired addresses (i.e., MAC addresses). The NodeIDs shown in Fig. 2 are MAC addresses. In HSR, we define the HID (Hierarchical ID) of a node as the sequence of the MAC addresses of the nodes on the path from the top hierarchy to the node itself. For example, in Fig. 2 the hierarchical address of node 12, HID(12), is $< 3.2.12 >$. We use the dotted notation for the hierarchical address. In this example, node 3 is a member of the top hierarchical cluster (level 3). It is also the cluster head of C2-3. Node 2 is member of C2-3 and is the cluster head of C1-2. Node 12 is a member of C1-2 and can be reached directly from node 2. The HID address of node 12 is the concatenation of MAC addresses of the nodes along the path to reach node 12 from the top hierarchy. In other words, node 3 is the top hierarchy representative of node 12, node 2 is the next level hierarchy representative of node 12.

The hierarchical address is sufficient to deliver a packet to its destination from anywhere in the network using HSR tables. Referring to Fig. 2, 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. 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. No central control is required.

HSR reduces the routing table overhead by the aforementioned physical clustering. Let us assume that the average number of nodes in a cluster (at any level) is N, and the number of hierarchical levels is M. Then, the total number of nodes is N^M. A flat link state routing requires $O(N^M)$ entries. The proposed hierarchical routing requires only $O(N \times M)$ entries in the hierarchical map. This maximum occurs in the top hierarchy nodes which belong to M levels (i.e., clusters) simultaneously and thus must store N entries per cluster. Thus, routing table storage, processing and updating at each node is greatly reduced by introducing the hierarchical topology. The drawback of HSR with respect to flat link state routing is the need of continuously updating the cluster hierarchy and the hierarchical address as nodes move. In principle, a continuously changing hierarchical address makes it difficult to locate and keep track of nodes. Fortunately, logical partitioning comes to help, as discussed in the next section.

B. Logical partitions for HID mapping management

In addition to 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 IP subnet corresponds to a particular user group with common characteristics (e.g., tank battalion in the battlefield, search team in a search and rescue operation, professionals on the move belonging to the same company, students within the same class,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.

A node does not know which cluster a particular destination belongs to, except for those destinations within the same lowest level cluster. The distributed location server assists in finding the destination. The approach is similar to mobile IP, except that here the home agent may also move. Note that the IP subnetwork is a "logical" subnetwork which spans several physical clusters. Moreover, the subnet address is totally distinct from the MAC address. Each logical IP 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. As the number of logical subnets (and therefore Home Agents) grows, it may be desirable to define hierarchy also in the logical subnets. Only the top hierarchy Agent HIDs are then broadcast to all nodes via 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.

The advantages of this logical partition is the separation of mobility management from physical hierarchy. As mentioned earlier, it is very complex and expensive to couple location manager with physical clustering as in MMWN. The tree of location managers has to change upon the variations of physical clustering. The hand-off and consistency management of location database are formidable in the dynamic changing environment. HSR solves these problems by introducing the home agent for each IP subnet to manage the hierarchical address changes of its subnet members. Furthermore, logical IP subnets can take advantage of the "movement locality" since the nodes from same subnets tend to have common tasks and move as a group. The location of a home agent (physical hierarchical address) roughly represents the routing direction for the nodes in the subnet it represents.

IV. PERFORMANCE EVALUATION

A. Simulation Environment

The multihop, mobile wireless network simulator was developed using the parallel simulation language PARSEC [1] and the simulator [2] is very detailed. It models all the control message exchanges at the MAC layer and the network layer. Thus, the simulator enables us to monitor the traffic O/H of the protocols. The network consists of 100 mobile hosts roaming in a 1000x1000 meter square. Radio transmission range is 120 meters. Free space propagation channel model is assumed. Data rate is 2Mb/s. Data packet length is 10 kbit. Buffer size at each node is 15 packets.

B. Simulation Results

In this section we evaluate and compare the various routing schemes. The performance measures of interest in this study are: (a) impact of the group size in the group mobility model; (b) control O/H generated by the routing update mechanisms, and; (c) throughput. The variables are: number of pairs communicating with each other (the smaller the number, the more "sparse" the traffic pattern) and node mobility. 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 average interval of 2.5 s. This amounts to a traffic volume of 4Kbps 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) can 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.

In first experiment (Fig. 3), we would like to find out the impact of the node mobility to the performance of HSR. We keep the logical subnet size fixed, i.e., 25 members each subnet and total 4 subnets and we vary the group size in the group mobility model (note: the size of the group in the group mobility is independent from the logical subnets). The number of groups in group mobility model can at most be equal to the number of the nodes. In this case, the group mobility model becomes individual node mobility model. The performance of HSR will degrade when the number of the group size increases. When the number of the groups increases, so does the randomness of the nodes mobility. HSR has the highest performance when the logical subnets are identical to the group in the group mobility model. HSR has the worst performance in the case of group member size is equal to 1, i.e., each individual node has its own independent mobility pattern. In the rest of the experiments, we use same mobility model for all the protocols that are compared, i.e., the group size of the mobility model is 4 and the each group has 25 nodes.

In Fig. 4, the throughput results are reported. Under the group mobility pattern of the logical subnets, the performance of HSR is better than DSDV and on demand routing. DSDV's poor performance can be attributed to excessive channel usage

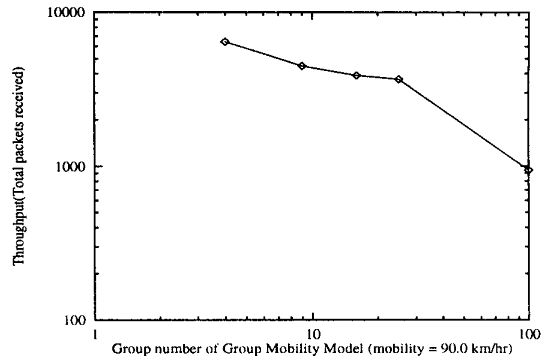

Fig. 3. Throughput vs group number (mobility = 90 km/hr)

by route control messages. Also, as mobility speed increases, more event-triggered updates are generated. In on demand, when the number of pairs increases , the overhead of path finding increases.

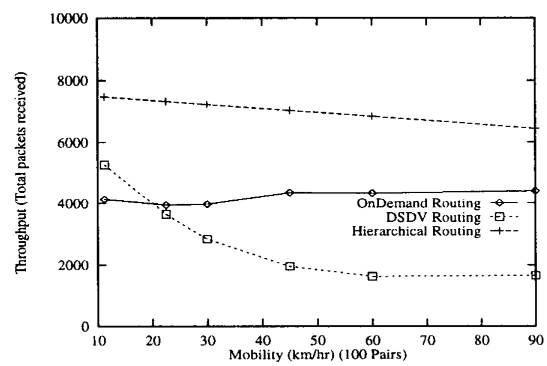

Fig. 4. Throughput vs. Mobility (100 Pairs)

The next experiment reports the control O/H caused by routing update messages in the various schemes (Fig. 5). In Fig. 5 we show the O/H as a function of number of communicating pairs, for a node speed of 60Km/hr. Tables are refreshed every 2 sec for DSDV and HSR, and are timed out after 6 sec for on demand. The O/H is measured in Mbps/cluster. The O/H in DSDV and HSR is constant with number of pairs, as expected, since background updating is independent of user traffic. On demand O/H, on the other hand, increases almost linearly with the number of pairs, up to 30 pairs (most of these pairs have distinct routes). Beyond 30 pairs, routes (or at least a large portion) are repeated and therefore the same route is reused by multiple sources to reach the same destination. Thus, the O/H increase is less than linear beyond 100 pairs since some paths have already been discovered. Recalling that the maximum throughput achievable in a single cluster is 2 Mbps, we note that both HSR and on demand have acceptable O/H (< 10% in the entire range between 10 and 100 pairs). DSDV, on the other hand, is quite "heavy", introducing more than 50% of line overhead! This is because DSDV propagates full routing tables (with 100 entries). HSR uses much smaller tables (10 entries on average for clusterheads), while On Demand propagates only single entry tables whenever needed. It is clear that already at 100 nodes a flat routing scheme such as DSDV is untenable if the network is mobile and therefore requires rapid refresh.

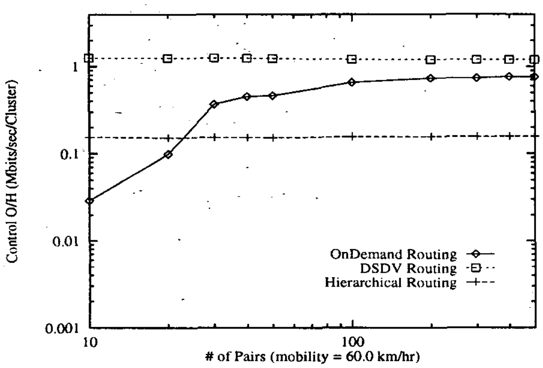

Fig. 5. Control O/H vs. Traffic Pairs

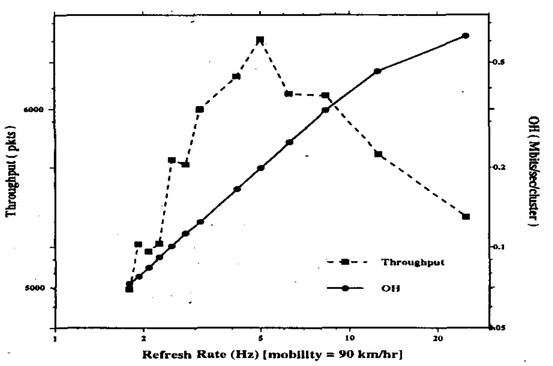

Fig. 6. Soft state evaluation (90 km/hr)

Fig. 6 illustrate the tradeoffs between throughput and control O/H in HSR when the route refresh rate is varied. In Fig. 6 (at 90 Km/hr) we note that the O/H increases linearly with refresh rate until the network becomes saturated with control packets, and starts dropping them. The throughput first increases rapidly with refresh rate, owing to more accurate routes and lower packet drops due to lack of route. Eventually, throughput peaks and then starts decreasing as the network becomes saturated and data packets are dropped because of buffer overflow. The optimum refresh rate is the rate yielding the max throughput value.

V. CONCLUSION

We have introduced the novel wireless hierarchical routing scheme HSR for large, mobile wireless networks with group mobility. The scheme is the extension of the conventional table driven routing schemes, but improves scalability by reducing update traffic O/H.

Compared with flat, table driven routing schemes (such as DSDV) HSR exhibits a much better scalability, at the cost of non-optimal routing and increased complexity (e.g., home agent). The scalability advantage is clearly shown by the simulation results. We have also compared HSR with recently proposed on demand routing schemes. HSR provides the following advantages over the on demand schemes: (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.

In summary, HSR is a scalable, low latency solution for the applications that have the group mobility. A promising direction of future research is the integration of hierarchical, table driven concepts with on demand routing concepts to generate routing strategies that can perform consistently well across various application domains.

References

[1] R. Bagrodia, R. Meyer, M. Takai, Y. Chen, X. Zeng, J. Martin, and H.Y. Song, "PARSEC: A Parallel Simulation Environment for Complex Systems," *IEEE Computer*, vol. 31, no. 10, Oct. 1998, pp.77-85..

[2] C.-C. Chiang and M. Gerla, "Routing and Multicast in Multihop, Mobile Wireless Networks," In *Proceedings of IEEE ICUPC'97*, San Diego, CA, Oct. 1997, pp. 546-551.

[3] M.S. Corson and A. Ephremides, "A Distributed Routing Algorithm for Mobile Wireless Networks," *ACM/Baltzer Wireless Networks*, vol. 1, no. 1, Feb. 1995, pp. 61-81.

[4] D.B. Johnson and D.A. Maltz, "Dynamic Source Routing in Ad Hoc Wireless Networks," In *Mobile Computing*, edited by T. Imielinski and H. Korth, Chapter 5, Kluwer Publishing Company, 1996, pp. 153-181.

[5] K. K. Kasera and R. Ramanathan, "A Location Management Protocol for Hierarchically Organized Multihop Mobile Wireless Networks," In *Proceedings of IEEE ICUPC'97*, San Diego, CA, Oct. 1997, pp. 158-162.

[6] S. Murthy and J.J. Garcia-Luna-Aceves, "An Efficient Routing Protocol for Wireless Networks," *ACM/Baltzer Mobile Networks and Applications*, vol. 1, no. 2, Oct. 1996, pp. 183-197.

[7] V.D. Park and M.S. Corson, "A Highly Adaptive Distributed Routing Algorithm for Mobile Wireless Networks," In *Proceedings of IEEE INFOCOM'97*, Kobe, Japan, Apr. 1997, pp. 1405-1413.

[8] C.E. Perkins and P. Bhagwat, "Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computers," In *Proceedings of ACM SIGCOMM'94*, London, UK, Sep. 1994, pp. 234-244.

[9] C.E. Perkins and E.M. Royer, "Ad-Hoc On-Demand Distance Vector Routing," In *Proceedings of IEEE WMCSA'99*, New Orleans, LA, Feb. 1999, pp. 90-100

[10] C.-K. Toh, "Associativity-Based Routing For Ad Hoc Mobile Networks," *Wireless Personal Communications Journal*, Special Issue on Mobile Networking and Computing Systems, Kluwer Academic Publishers, vol. 4, no. 2, Mar. 1997, pp. 103-139.

[11] R. Ramanathan and M. Steenstrup, "Hierarchically-Organized, Multihop Mobile Wireless Networks for Quality-of-Service Support," *ACM/Baltzer Mobile Networks and Applications*, vol. 3, no. 1, Jun. 1998, pp. 101-119.