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Hierarchical Routing For Multi-Layer Ad-Hoc Wireless Networks With Uavs

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ABSTRACT: *Routing scalabiliy in multi-hop wireless neworks faces many challenges. The spatial concurrency constraint on nearby nodes sharing the same channel is the fundamental limitation. A recent theoretical study shows that the through- put furnished to each user is rapidly reduced as neMork size is increased. In order to solve this pmblem, we extended the Hierarchical State Routing scheme to a hierarchical multi- layer environment. With the hieramhical approach, many pmblems caused by "flat" multi-hopping disappear. In the real battlefield, a maffi-level physical heterogeneous neMork with UAVs pmvides an ideal suppon for the multi area the- ater with large number of fighting units. Extended Hierarchical State Routing (EHSR) shows very promising results in this hierarchical infrastructure.*

I. INTRODUCTION AND BACKGROUND

Multi-hop wireless networks are an ideal technology to estab- lish an instant communication infrastrucmre for civilian and military applications. However, as ie size of an ad hoc multi- hop network grows (as in battlefield and ubiquitous comput- ing applications), the peJormance tends to decrease. Key causes of such a degradation include the resulting excessive control traffic overhead required to maintain accurate routing tables in ie presence of mobility, and the difficulty in guar- anteeing any kind of performance on a pal with many wire- less hops. The latter is of particular concern for ie support of real time applications.

Many routing protocols have been proposed for efficient ad hoc routing. Existing wireless routing protocols can be classified into four different types: (1) global, precomputed routing. (2) on-demand routing. (3) location based routing.

(4) flooding. All those approaches assume that the network is a homogeneous network in that all nodes have the same trans- mission capabilities and use ie same frequency and channel

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‘This work was supported in part by NSF under contract ANI-9814675, in part by DARPA under contract DAAB07-97-C-D32l and in part by In- tel. access scheme. On demand routing is the most recent entry in the class of scalable wireless routing schemes. It avoids ex- cessive routing overhead by simply relaxing ie requirement to maintain routes to all nodes. Namely, a route to a specific destination is constructed only when needed. However, on demand routing does scale well to large population only if the traffic pattern is sparse. As discussed in [2], routing over- head grows as the traffic load increases. In the case of 100 nodes and 40 sources, ie results in [2] show that on demand routing protocols will generate much higher routing overhead than actual throughput capacity. Furthermore, the maximum achievable throughput in the simulation scenarios is only 2-3% of total network capacity [2]. A recent theoretical smdy in[3] presents the throughput bounds of homogeneous wireless networks. Under uniform traffic pattern, the lroughput furnished to each user eventually reduces to zero as the number of users is progressively increased. The limitation is funda- mentally due to the spatial concuaency constraints on nearby nodes sharing the same channel. All these results strongly suggest that we should consider a "heterogeneous" hierar- chical strucmre to solve ie large ad hoc network problem. An Unmanned Aerial Vehicle (UAV) added to ie ground embedded mobile backbone can naturally form a multi-level physical heterogeneous multi-hop network, which is ie best infrastmcture for multi-area military environments.

In lis paper we address the problem of routing in het- erogeneous multi-hop networks. On top of ie multi-hop ground radio network, we propose to construct dynamically a point-to-point embedded mobile backbone network which connects (using directive antennas and separate frequencies from the ground radio network) properly elected backbone nodes. The mobile, embedded backbone network semes a single area (say, a few kilometers in diameter). Multiple UAVs form a Aerial Mobile Backbone to connect different ground mobile backbones. This multi-level physical hetero- geneous multi-hop network will provide communications on- the-move for all fighting units in the entire multi-area leater as both "ground backbone" and "aerial backbone" move. We extend a hierarchical routing protocol HSR [5] to this het- erogeneous, hierarchical strucmre, with physically different networks at various levels. The nodes in ie lower level par-tition commtlnicates wit each other and with the backbone nodes via multiple hops. The backbone nodes are point-to- point connected via the backbone network. Furthermore, backbone nodes are integrated with the Unmanned Aerial Vehicle (UAV) network. With this physical hierarchical ap- proach, it is easy to see fat many of the scaling problems disappear. In fact, in the extreme case, the path between any two arbitrary nodes may consist of just three hops.

The main challenge of this approach is to maintain hierar- chical addresses in the face of mobility. To this end, we use the scheme proposed in (7]. A further challenge, in a military environment, is ie need for coexistence of backbone routing and low level multi-hop routing. In fact high transmit power backbone nodes are susceptible to high probability of detec- tion by the enemy, and thus are likely targets for destruction.

In case the backbone topology is temporarily disconnected, because of enemy attack or mobility, one must fall back to the multi-hop strategy.

The rest of ie paper is organized as follows. In sec- tion 2, we introduce the infrastructure of the multi-level het- erogeneous ad hoc wireless network with UAVs. Section 3 describes the extended hierarchical state routing scheme for heterogeneous environments. Perfomance evaluation is pre- sented in section 4 and we conclude our paper in section 5.

2 Multi-level Heterogeneous Ad-Hoc Wireless Network with UAVs

The Tactical Environment

In lis section, we briefly describe the characteristics of the tactical environment.

1. Large number of highly mobile nodes in a single area: The Army’s vision of the 2lst century battle- field is that digital communication networks will make heavy use of wireless technology, with broadband links transporting high volumes of multimedia information to highly mobile fighting units as well as individual soldiers on the battlefield. The combination of Com- mand, Control, Communications, Computers, and In- telligence, which is known in the military as t7^{4}I, ad- dresses the systems and functfons used by the wartight- ers to transmit/receive, process/analyze, display/use in- formation [10].

The entire theater can be fu8her divided into many ar- eas [9]. Each area has a large number of highly mobile soldiers, fighting units, monitor sensors, and other com- munication facilities that suppoñ the baitlefield.

2. Each single area has a UAV stationed at 50-60kft high as a multi-functional gateway: An unmanned Aerial Vehicle (UAV) flies at relatively high elevations, us can be in sight of all the mobile hosts in ie single area. This enable two hop transmissions between any pair of ground mobile backbone nodes in the area using the UAV as a router, providing a backup path whenever ie wireless direct point-to-point link breaks up due to hills or high buildings.
3. Aerial Mobile Backbone: In the battlefield, warfight- ers mi$ht become separated and end up in areas which are geographically far away from each other. Multiple UAVs cover the entire area of operation and, by using Phased Array Antenna (PAA) technology, maintain line- of-sight connectivity with each others. Thus, multiple UAVs form a mobile backbone in the sky fat intercon- nects different areas in the theater.
4. Asymmetric Routing: In the tactical environment, in- fomation traffic is quite asymmetric. Fighting units are information consumers and receive far more data than they transmit. The up-link is used for sending requests for situation infomation and network configuration up- dates, while the down-link is used to return the data re- quested. For example, when soldiers get into a new area, they might send sho< requests (a few kilobits) for geo- graphic information, and the remrn data is most likely a megabits size multimedia file wit images and charts. So in our design, we can not assume a symmetric model.
5. Heterogeneous Nodes: In the tactical environment, mobile nodes could. be individual soldiers, artillery, SAM launchers, trucks, helicopters, suppo8 vehicles, UAVs in the sky and even satellites at higher eleva- tions. Each entity has different communication capa- bilities. So, it is reasonable to assume that the network is a heterogeneous environment.

Architecture of the Multi-level Heterogeneous Ad-Hoc Wireless Network with UAVs

Figure 1 shows ie architecture of a multi-level heteroge- neous ad hoc wireless network wit UAVs. The hierarchical infrastructure reflects the three layers previously described.

6. level 1: Ground Ad-Hoc Wireless Network: Based on the hop distance of packet transfer, wireless networks can be divided into two types: single-hop and multi- hop. The multi-hop wireless network, also called “ad hoc” wireless network , allows all mobile hosts to move

Figure 1: Multi-level UAV Heterogeneous Ad-Hoc Wireless

Network for Multi-area Theater freely without any constraints by fixed communication infrastruemre. Due to the ad hoc topology, maintaining eflicient routes become very challenging.

At this level, we have both regular ground mobile nodes and backbone nodes. A variety of clustering algorithms have been proposed for the dynamic creation of clusters and the election of cluster heads in ad hoc wireless net- works. The only modification needed here is, fat back- bone nodes have higher priority to be selected as cluster heads lan regular nodes. Spread-spectrum radios per- mit code division multiple access (CDMA) and spatial reuse across clusters. Within a cluster, we use 802.11 as the Medium Access Conaol (MAC) layer protocol.

7. level 2: Ground Embedded Mobile Backbone net- work: Due to the poor performance of ad hoc wire- less network where many hops are involved, an em- bedded mobile backbone was introduced. In the tacti- cal environment, special fighting units like trucks, tanks may carry a lot more equipment than individual soldiers, These mobile nodes , with the help of beam-forming an- tennas, can offer high-speed point-to-point direct wire- less links. So if we select those mobile nodes as back- bone nodes, we can establish a ground mobile backbone embedded within the ground ad hoc wireless network.

In %is level, we only have ground backbone nodes. Di- rect point-to-point wireless links are used for the com- munications among the neighboring backbone nodes.

8. level 3: Aerial Mobile Backbone Network: Each UAVcan maintain a station at an altimde of 50 to 60 You-sands feet by flying in a circle with a diameter of around 8 nautical miles. With the help of Phased Array Anten- nas, it can provide ie shared beam to the ground to keep line-of-sight connectivity for one area of operation down below. Multiple UAVs fly in the sky to form a mobile backbone with beam-forming technology to connect to each other. With the aerial mobile backbone, we can connect multiple areas of operations together to provid» theater-wide communication.

Hierarchical State Routing in the Het- erogeneous Environment

\Hierarchical State Routing Protocol

HSR [5] [7] [4J is a hierarchical link state routing protocol. It maintains a multi-level hierarchical topology, where ie cluster heads at the lower level become ie members of ie next higher level. These new members will organize them- selves in clusters on the new level and so on, recursively. The purpose of clustering is to reduce the routing overhead and to efficiently use the radio channel resources. HSR provides multilevel clustering as well as multilevel logical partition- ing. Clustering is based on geographical (physical) relation- ship among nodes, (so, it is also called physical clustering. See example in Figure 2). Logical partitioning, on the other hand, is based on logical relationship among nodes (e.g. sol- diers in the same company). Logical pa<itions play a major role in mobility management.

Extended HSR for Multi-area Theater

In this paper, we have extended Hierarchical State Routing to a multi-area theater. Extended HSR (EHSR) establishes multi-level communications with multiple interfaces at dif- ferent levels.

1, Physical multi-level clustering in heterogeneous en- vironment The physical multi level clustering hierar- chy used in ESHR is illustrated in Fig. 2. In level 1, we use an extended clustering algoriihm to dynamically create clusters and elect cluster heads. Only backbone nodes are selected as cluster heads. We have 4 physical clusters in each area at this level. Generally, there are two kinds of nodes in a cluster at any level: cluster-head node (e.g., Node 1, 2, 3, and 4), and internal node (e.g.,
5, 6, 7, 8, 9, 10, 11, and 12). The cluster-head node acts as a local coordinator of transmissions within ie cluster. Level 2 consists of all ground backbone nodes selected

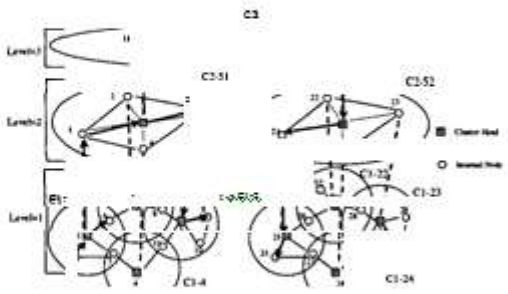

Figure 2: Multi-level Physical Hierarchical Clustering in Multi-area Theater

as cluster heads in the level 1. At level 2, each area will have only one cluster, UAV will by default declare itself as the cluster head. There are two kinds of nodes in a cluster at level 2 : cluster-head node (UAV), and inter- nal node (ground backbone nodes). Inside the cluster, internal nodes will communicate to each other via di- rect point-to-point wireless links. The cluster head will communicate wit the internal nodes through a multiple access channel. Level 3 is the UAV backbone.

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 EHSR, the HID (Hierarchical ID) of a node is defined as the sequence of the MAC addresses of the nodes on the pal from the top hierarchy to the node itself. The hierarchical address is sufficient to deliver a packet to its destination from anywhere in the theater using EHSR tables. Referring to Fig. 2, consider the following example: the delivery of a packet from node 5 to node 25. Since HO(5) (51.1.5) and HO(25)=(52.21.25)are located in ie different area, so the pal should go trough UAVs on the level 3, fat is (5,1,51,52,21,25).

2. Logical grouping _for HO mapping management in the heterogeneous environment In addition to MAC addresses, mobile fighting units can be assigned logi- cal addresses of the type (subnetID, hostID). These ad- dresses have a pattern similar to IP, and can be viewed as private IP addresses for the entire leater. Each IP subnet defines a particular user group with similar fea- tures (e.g., tank battalion in the battlefield, soldiers in the same company). The transpor layer delivers to the net- work a packet wit ie tactical private IP address. The network will resolve the IP address into a HO which is based on MAC addresses. The notion of subnet is im- portant because each subnet is associated with a home agent. All home agent will advertise leir HOsto the top hierarchy (UAV). Thus, the home agent H&s are appended to the top level routing tables in the UAVs. When a source node wants to deliver a packet to a desti- nation node of which it knows ie IP address, it first ex- tracts from it the subnet address field. From the subnet address, using internal list (or top hierarchy) it gets the hierarchical address of the coaesponding home agent. It then sends the packet to the home agent with this HID. The home agent will find ie registered physical address from the host ID in the IP address and forwards the packet to the destination. Once source node and des- tination node have discovered each other's HID, packets can be sent directly without involving the home agent.

4 Performance Evaluation

Our simulation environment is the GlomoSim library 1.2.3 [8] written in the parallel, discrete-event simulation lan- guage PARSEC [1]. The ground radio model reflects com- mercial radios such as the Lucent WaveLAN. The data rate is 2 Mbps. The transmission range is 150 meters. The MAC layer protocol used among grouad radios is IEEE802.11. Each ground backbone node has three different physical in- terfaces: (1) ground radio interface, which is used for com- munications among regular ground nodes and from regular ground nodes to backbone nodes; (2) directional point-to- point wireless links among backbone nodes and (3) radio in- terface for accessing UAV aerial backbone nodes.

In our simulation, we use a two level mobility model. The backbone nodes are moving at very slow speed while the ground mobile nodes move much faster. We use ran- dom waypoint mobility model [6] for individual nodes. The pause time is 30 seconds for ground mobile nodes and 20 minutes for backbone nodes. The speed for mobile nodes varies between 2 and 8 m/sec while the speed for backbone node is hXed at 2 m/sec. Traffic sources are CBR (constant bit rate). Thé size of the data payload is 512 bytes. The source-destination pairs are spread randomly over ie network. The number of source-destination pairs is varied to change the to- tal offered load in ie network. The interarrival time of the data packets is 0.5 second. The network consists of 100 mo- bile nodes in a l000x1000 meter square.

We have compared HSR with an ideal routing protocol in

[2] S.R. Das, C.E. Perkins and E. M. Royer, “Performance Comparison of Two On-demand Routing Protocols for Ad Hoc Networks”, In Proceedings ofIEEE INFOCOM 2000, Tel Aviv, Israel, Mar. 2000, pp. 3- 12

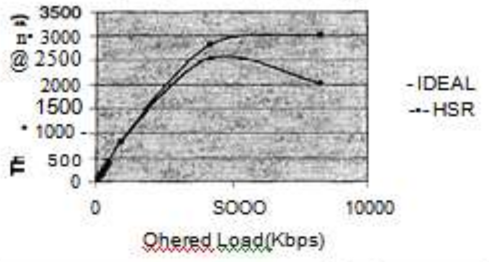

Figure 3: Throughput vs Offered Load

which routes are calculated based on the accurate topology provided by the simulator. Figure 3 shows average trough- put versus offered load for bo1 ideal routing protocol and HSR. Ideal routing has no overhead on routing message ex- change, and always has the most accurate knowledge of the entire network topology. This hypothetical protocol repre- sents the performance upper bound for all possible routing protocols. The simulation results show that HSR in a het- erogeneous environment can outperform ideal routing proto- col in a homogeneous environment. Therefore, the hierar- chical multi-layer approach is the most desirable approach to achieve routing scalability in multi-hop wireless networks.

II. CONCLUSION

We have introduced the Extended Hierarchical State Rout- ing (EHSR) in hierarchical, heterogeneous multi-layer ad hoc wireless networks. The EHSR is the extension of the pre- viously proposed HSR to multi-area theater environment. It improves scalability by reducing the number of transmissions with the help of hierarchical multi-layer infrastructure.

Compared with ie ideal routing protocol in a “flat” ad hoc wireless network, EHSR exhibits much better scalability, as clearly shown by simulation results.

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