A Multicast Protocol for Physically Hierarchical Ad Hoc Networks

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***Abstract*— Routing and multicasting in ad hoc networks is a matured research subject. Most of the proposed algorithms assume a physically flat network architecture with mobile hosts having homogeneous capability in terms of network resources and computing power. In practice however, this assumption often may not hold true since there exist various types of mobile hosts with different role, capacity, and mobility pattern. In the military scenarios for instance, the leader of the troop usually has more powerful networking equipment than the private soldiers. In this paper, we consider mobile ad hoc networks that have physically hierarchical architecture where different types of mobile hosts form an ad hoc network hierarchy. We present a novel and simple multicasting framework called PHAM (Physical Hierarchy-driven Ad hoc Multicast) for ad hoc networks with such an environment. PHAM builds a multicast structure at each level of the hierarchy for efficient and scalable multicast message delivery.**

I. Introduction

A key characteristic of ad hoc networks is their operation without infrastructure support or central administration. Because there is no base station, every node in ad hoc networks acts as a router, and hence, routes are multi-hop when nodes outside their transmission range communicate with each other. Having to build multi-hop routes is the main difference between ad hoc networks and cellular wireless networks. Recent research on ad hoc networks is focused naturally on routing and multicasting. Most of the proposed protocols such as AODV (Ad-hoc On-Demand Distance Vector) [14], LAR (Location-Aided Routing) [6], and ODMRP (On-Demand Multicast Routing Protocol) [7] assume a flat network architecture where all network hosts have the same or similar computing power and network resources. There are schemes that propose to utilize clustering to build hierarchical networks [2], [8], [12]. These protocols however, also assume a flat network structure and the hierarchies are merely *logical*, as opposed to physical.

In real ad hoc networks, this flat network architecture assumption will not hold true since there exist various types of mobile hosts with different role, capacity, and mobility pattern. In the military scenarios for instance, the leader of the troop usually has more capable networking equipment (e.g., has more powerful radio) than the private soldiers in the troop. Radios in the vehicles such as tanks and jeeps have more capabilities than radios the soldiers carry as vehicles do not have the same size or power restrictions as the soldiers. Another reason could be the financial cost. The state-of-the-art equipments are very expensive and hence only a small number of nodes could be supplied with such high-end radios [13]. Ad hoc networks with heterogeneous users are therefore quite common in practice.

We consider ad hoc networks to have *physically* hierarchical architecture where different types of mobile hosts form the network hierarchy. We present a simple multicast scheme for ad hoc networks with such an environment. We study multicasting as it is more applicable than unicasting in the likely scenarios (e.g., data dissemination, disaster recovery, crowd control, automated battlefields, search and rescue, etc.) where physically hierarchical ad hoc networks can be built. Our protocol, PHAM (Physical Hierarchy-driven Ad hoc Multicast), builds a multicast structure at each level of the hierarchy for efficient and scalable multicast message delivery. To our knowledge, PHAM is the first hierarchical multicast algorithm for ad hoc networks. Several hierarchical multicast protocols are proposed for wired networks [15], [16]. They also assume a physically flat network as most hosts on the fixed networks have similar networking and computing capabilities.

The rest of the paper is organized as follows. Section II introduces PHAM, followed by performance evaluation in Section III. Future directions and concluding remarks are made in Section IV.

II. Physical Hierarchy-driven Multicast

A. Network Model and Assumptions

Based on the nodes' network resources and roles, we categorize them into n-levels and build a hierarchy. For simplicity and ease of presentation, we use $n = 2$ in this paper. Let's use the above military scenario as an example. The commanders (i.e., troop leaders) have stronger radio transmission and more powerful computing/networking capabilities than the private soldiers. Let's say that the commanders are nodes in level-2 and the private soldiers are nodes in level-1. We assume that a level-2 node manages a group of level-1 nodes. For example, a commander leads a number of private soldiers for a given mission. We call a level-2 node a "super node." A super node and its level-1 nodes it manages form a *physical group*, as opposed to a logical group for multicast. We assume

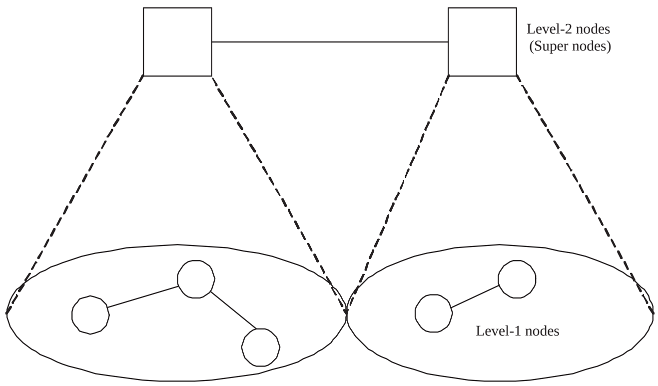

Fig. 1. A physically hierarchical ad hoc network.

nodes in the same physical group have similar mobility pattern. They are carrying out a mission together, so it is reasonable to assume they are taking a similar path. A group mobility model can be applied where nodes in the same physical group have the same "group mobility vector," but have different individual mobility vector.

We assume a node in level-1 is commanded by at least one super node. In other words, no level-1 node is isolated and each level-1 node can receive communication from at least one super node. Level-1 nodes have the knowledge of which super node they are managed by, and level-2 nodes have the information of all level-1 nodes they manage, including the multicast membership information. Since all nodes do not have the same radio transmission power, we do not assume bi-directional links or routes. Each super node has the capability to adjust its radio transmission power. We also assume that there exists a communication path (or a tunnel) between any two super nodes. They may have a direct path between each other (i.e., are within transmission range of each other), have multi-hop routes to each other with other super nodes and/or gateway nodes as intermediate hops, or communicate via satellite links. Figure 1 depicts our physically hierarchical ad hoc network architecture.

B. Protocol Operation

We propose PHAM (Physical Hierarchy-driven Ad hoc Multicast), an efficient multicast framework for physically hierarchical ad hoc networks. In our framework, communications between different physical groups always go through the super nodes. As mentioned, we assume there always exist a path between any two super nodes. The challenge lies on how each node in the same physical group communicate with each other and how level-1 nodes send and receive packets to/from the super node.

When all multicast group members are within the same physical group, message delivery is performed locally between a super node and its level-1 nodes. For this "local" multicast, there are two possible design choices. The first is to utilize any existing ad hoc multicast algorithm such as ODMRP [7], MAODV [14], or ADMR (Adaptive Demand-driven Multicast Routing) [4]. One disadvantage of this approach is the under-utilization of the super nodes and physical hierarchy because the existing ad hoc multicast protocols assume a flat architecture and treat the super nodes equally as level-1 nodes. The benefit of this approach is the flexibility of utilizing exiting protocols.

The other approach is somewhat similar to CBT (Core Based Trees) [1]. The multicast source (assuming it is a level-1 node) simply unicasts its announcement (and data packets) to its super node, and then the super node broadcasts it to the physical group as well as other super nodes. This scheme could be efficient, but it is more similar to a broadcast as level-1 nodes who are not interested in a particular multicast group will still receive packets from the super node.

This second approach requires all traffic from level-1 nodes to go through their super node. Therefore a question arises how each level-1 node maintains unicast routes to the super node. Any ad hoc routing algorithm can be adopted, whether it's proactive such as DSDV (Destination Sequenced Distance Vector) [11] or reactive such as DSR (Dynamic Source Routing) [5]. Utilizing source routes could be beneficial in this environment. A level-1 node floods a request packet within the physical group to locate the super node. When the super node receives the request, it directly sends a reply—possibly in one hop using it strong radio transmission—to the source with the reverse route attached. The intermediate nodes overhear the packet and realize they are part of the multicast forwarding group, as they are in the path from the multicast source to the receivers.

We select to use the first approach because we are presenting our algorithm as a framework run on top of existing protocols, instead of a replacement of them. We are proposing a framework to efficiently and effectively utilize the physical hierarchy of the network. We describe PHAM based on ADMR in this paper. We chose ADMR because it provides good throughput without generating excessive control overhead [4], but PHAM can work on top of any existing ad hoc multicast protocols. PHAM adopts the basic concept of ADMR, but several modifications are made to take advantage of powerful nodes (i.e., super nodes).

When a new source enters the multicast group, it must notify its super node of its information. It does so by flooding the registration packet to the physical group. When receiving this packet, the super node replies back with an acknowledgment via the reverse path. The multicast source now has a path to the super node, and the super node learns of a new source for a multicast group.

When a receiver wants to join a multicast group, it floods a join message to its physical group. If there are sources of this multicast group in the same physical group, the source replies with an ack packet using the reverse route. Hence the multicast structure within the same physical group may not include the super node. When receiving a join packet, the super node forwards the message to other super nodes in the network, so the multicast sources in the other physical group can reply. When other super nodes receive the packet, they relay the

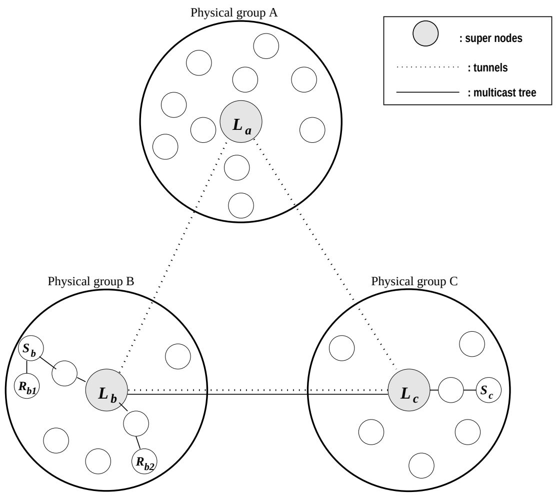

Fig. 2. Example.

packet to their level-1 nodes only when multicast sources exist in the physical group. The flooding of this join packet is hence localized and is not network-wide. The multicast source on a different physical group replies an ack through the reverse path that includes the super nodes. After receiving all the join acknowledgment packets from the multicast sources, the new receiver node sends a join tree packet to the sources to create the forwarding state for nodes in intermediate paths.

The multicast structure is formed by the above source registration and receiver join process. A subtree that consists only of super nodes and links that connect super nodes can be considered as an abstract 2nd-level tree. Note that level-1 nodes only maintain information of the nodes in the same physical group. Level-2 nodes have complete information of nodes in their physical group and information of other super nodes, but not level-1 nodes that belong to other super nodes.

Figure 2 shows an example with three physical groups A, B, and C, each with super node L_a, L_b, and L_c, respectively. There are two multicast sources; S_b in physical group B and S_c in group C, and two multicast receivers; R_{b1} and R_{b2}, both in group B. When two receivers join the multicast, they each send the join packet to the entire physical group B. L_b forwards this message to other super nodes using the tunnel. L_c sends this packet to S_c but L_a does not forward this packet as there is no multicast source in physical group A. Note that the path between S_b and R_{b1} does not include the super node.

III. Performance Evaluation

We evaluate the proposed PHAM protocol using an extended version of network simulator *ns-2* [10], implemented by the Monarch project [9]. Their extensions, including IEEE 802.11 MAC layer and radio propagation model implementations, enable it to simulate mobile nodes connected by wireless network interfaces and multi-hop ad hoc networks.

A. Simulation Environment

In our simulation model, 60 nodes form a mobile ad hoc network in a rectangular region of $1500m \times 300m$. The nodes in our simulations move around according to the *Reference Point Group Mobility (RPGM)* model [3], in which each group is assumed to have a 'logical reference point' whose movement determines the entire group member's motion behavior. Thus, group movements are based on the path traveled by a logical reference for the group. In our experiments, we use three groups in the RPGM model and each super node acts as a reference point for their own physical group.

Initially, nodes are uniformly distributed within the geographic scope of a physical group, and then follow the *random waypoint model* as their mobility model. After a three second pause time, each node randomly chooses its next position within the group scope and moves towards that position with three different average speeds of 5, 10, and 20m/sec. We use a relatively short pause time to simulate dynamic network topology. Two mobile nodes are considered disconnected if they are outside each other's transmission range, which is defined as $250m$ for all nodes. Note that the same transmission range is used for the super nodes in this paper, but the effects of adjusting their transmission range can be investigated in the future work. The wireless link bandwidth is 2 Mb/s.

There is one multicast source that generates four 64-byte data packets every second. In our simulations, the number of multicast receivers are varied: 1, 4, 7, 10, 15 and 19. Thus, we use six different combinations of multicast groups. For instance, the first combination of multicast group with two members consists of one multicast source and one multicast receiver, whereas the last combination with 20 multicast member nodes consists of one source and 19 receivers. However, one assumption applied for all those combinations is the fact that a multicast source and the corresponding receiver(s) are not located in the same physical group. This assumption was made to explore the behavior of multicasting protocol in the presence of longer route between the source and the receiver.

We evaluate the performance of PHAM that is run on top of ADMR and that of ADMR without applying our framework. The number of physical groups is three for PHAM. We use the following metrics:

- *Accuracy of multicast delivery*: We define the accuracy of multicast delivery as the ratio of the number of multicast group members that receive data packet, and the number of group members which were supposed to receive the packet. For example, in a multicast group with one source and four receivers, if only two receivers receive the packet from the source, accuracy of delivery for the multicast is 50%.
- *Normalized routing overhead*: We define the normalized routing overhead as the ratio between the total number of all data and control packets *transmitted* by the nodes and the total number of data packets *received* by all multicast receivers. This metric reflects the total routing load involved in delivering multicast data and hence protocol efficiency.
- *End-to-end latency*: The end-to-end latency is measured

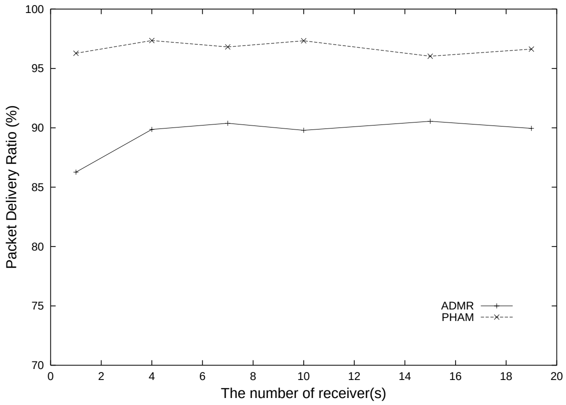

Fig. 3. Packet delivery ratio as a function of multicast size.

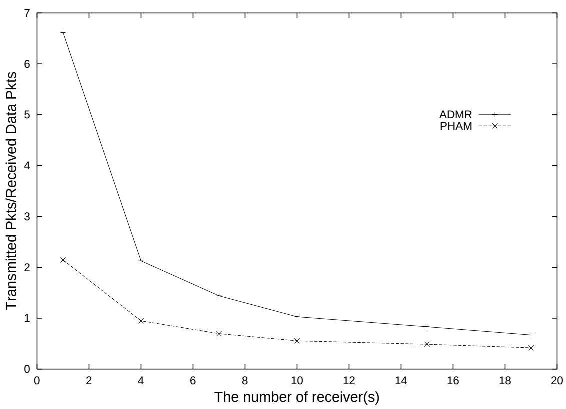

Fig. 4. Normalized routing overhead as a function of multicast size.

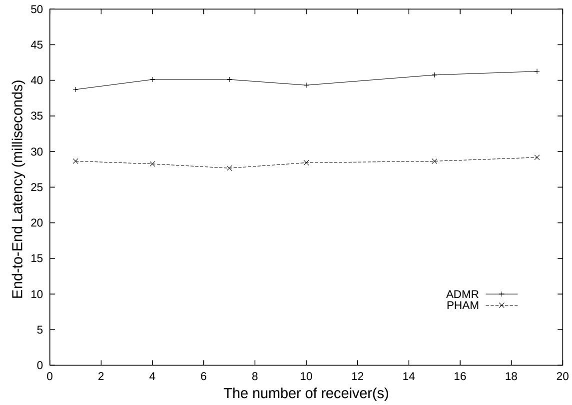

Fig. 5. End-to-end latency as a function of multicast size.

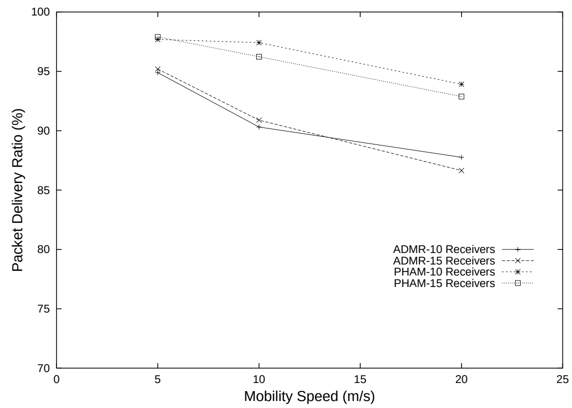

Fig. 6. Packet delivery ratio as a function of mobility speed.

in terms of the time from when the source generates a data packet to when a multicast group member receives it. In our simulation results, we report the average end-to-end delay over all the multicast source and receiver pairs.

B. Simulation Results

Figure 3 shows accuracy of multicast delivery for PHAM and ADMR as a function of the number of multicast receivers. While fixing the number of source at one and moving speed at 10m/s, the size of multicast group is varied to examine the scalability of the protocol. Having only one receiver corresponds to a unicast situation. Note that the y-axis scale in this figure and other figures for packet delivery ratio ranges from 70% to 100%. As seen in Figure 3, the delivery ratio is consistently higher for PHAM as compared to the ADMR (about 10% on average), even though both protocols deliver reasonably high portion of data packets and were not affected very much by the number of receivers. This improvement of PHAM is due to the relatively reliable link between the super nodes, which may exist in the multicast tree created by PHAM for the receivers and the distant source.

The normalized routing overhead as a function of the number of multicast receivers is shown in Figure 4. We observe that PHAM produces a much lower overhead than ADMR. This can be explained be the fact that PHAM limits the scope of control packet flooding to the nodes located in the same physical group. Thus, degree of flooding is smaller in PHAM, compared with the ADMR protocol or any other flooding-based multicasting protocols such as ODMRP. This limited flooding results in the lower overhead and better efficiency of PHAM.

Figure 5 presents the end-to-end packet delay as a function of the multicast size. Here again we see that the PHAM protocol yields a better performance (i.e., smaller latency) than ADMR. Such a significant latency improvement in PHAM is due to a corresponding decrease in the average path length. As PHAM builds paths through the super nodes, it produces shorter paths than.

The effect of varying the moving speed of nodes is shown in Figure 6. Packet delivery ratio with 10 and 15 receivers are presented. As expected, the delivery ratio of both protocols decreases with increasing node mobility. With low mobility rate, multicast trees are likely to be stable and, therefore, the delivery success rate is high. As mobility rate increases, the possibility of tree breaks, i.e., the delivery failure rate, also increases. Nevertheless, PHAM provides higher accuracy than ADMR for all moving speed.

Finally, in Figure 7 and Figure 8, we plot accuracy and overhead of multicast packet delivery with varying the number

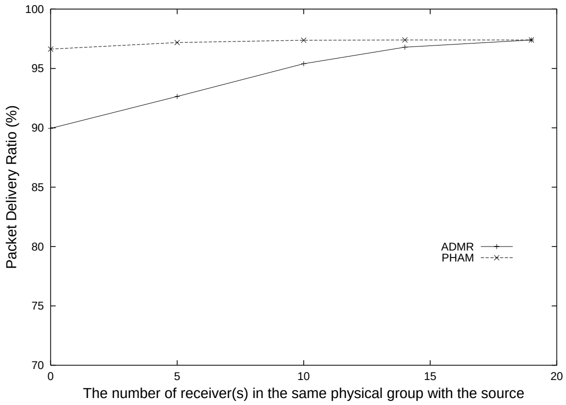

Fig. 7. Packet delivery ratio as a function of local receivers .

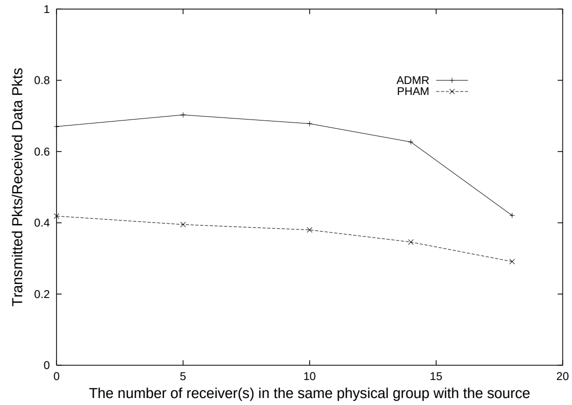

Fig. 8. Packet delivery ratio as a function of local receivers.

of receivers that are located in the same physical group with the source (namely, local receivers), while the total number of receivers (i.e., multicast size) is fixed at 19 nodes. For instance, five on the x-axis in the figures above means that five multicast receivers are physically near from a source and have the same super node with the source, but other 14 receivers are located in one of different groups from the source and therefore their path lengths towards the source are likely to be longer, resulting in a higher tree breakage.

The packet delivery ratio for PHAM seems robust to receiver locality distribution, although its normalized routing overhead slightly increases as the number of local receivers decreases. However, ADMR performance suffers when fewer number of receivers are local (i.e., in the same physical group). Figure 7 shows that ADMR has less accuracy at zero local receivers (90%), compared with at 19 local receivers (98%). The decrease of the number of local receivers increases the average path length of ADMR, resulting in smaller probability of data delivery success to multicast group members. It is interesting to observe that at 19 local receivers, ADMR's accuracy is approximately identical to that of PHAM. However, as Figure 8 shows, ADMR yields much higher overhead than PHAM to achieve such a packet delivery ratio. ADMR performs network-wide flooding for control packets such as MULTICAST SOLICITATION and that results in high overhead. Localized flooding of PHAM contributes to protocol efficiency.

IV. CONCLUSION

We proposed PHAM (Physical Hierarchy-driven Ad hoc Multicast), a simple framework designed for physically hierarchical ad hoc networks with heterogeneous nodes. Based on node capability, we categorize nodes into different roles and utilize the physical hierarchy of the network. PHAM is able to apply different multicast policies at each level of the hierarchy so that it achieves efficient and scalable multicast message delivery. We applied PHAM framework on top of ADMR and demonstrated the performance gain through simulation. PHAM showed higher throughput, more efficient use of control packets, and shorter latency.

Ongoing work includes addressing the single point of failure (at the super node) problem, exploring CBT-like scheme for local multicast, and applying our framework to other multicast protocols such as ODMRP and MAODV.

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