Improving Scalability of Heterogeneous Wireless Networks with Hierarchical OLSR

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Abstract—**Ad hoc routing protocols in general, including OLSR, are not specifically designed for heterogeneous networks, and thus they do not efficiently exploit the higher-capacity links found in such networks, where nodes are equipped with diverse communications capabilities. Although these protocols support nodes with multiple interfaces, scalability problems may arise when the protocols are applied to heterogeneous networks. Under OLSR, for example, control messages are sent to all the interfaces, generating a very high overhead.**

In this paper, we propose optimizations to OLSR in order to limit the amount of control traffic generated and to make more efficient use of the higher-capacity links in heterogeneous wireless networks such as military networks. Using OPNET simulations, we introduce a hierarchical mechanism to OLSR, and demonstrate that the Hierarchical OLSR (HOLSR) greatly reduces the required protocol overhead and thus improves protocol scalability in large size heterogeneous networks.

I. INTRODUCTION

HETEROGENEOUS wireless networks are characterized by mobile nodes outfitted with equipment having distinct communications capabilities with respect to data rate, radio range, frequency band, battery life, etc. Military communications networks are a case in point: ground units such as soldiers are commonly equipped with wireless communications equipment offering limited transmission coverage and communications bandwidth due to power limitations, while mobile units such as tanks or vehicles are equipped with more powerful communications equipment providing extended communications coverage with higher communications bandwidth capability.

Scalability is one of the most important factors governing the efficacy of ad hoc networks. Scalability can be defined as the ability of a network to adjust or maintain its performance as the size of the network increases (and the demands made upon it become greater and greater), yet the performance of an ad hoc network tends to degrade as the number of mobile nodes increases [1]. A non-hierarchical routing protocol cannot differentiate the capacities of member nodes, and does not scale well for heterogeneous networks such as military communications networks. When such a protocol is used, the resulting control overhead increases as the number of interfaces possessed by the nodes increase. More importantly, the high-capacity links are not efficiently exploited under such a routing strategy.

In this paper we present an approach specifically designed to improve the scalability of the Optimized Link State Routing protocol (OLSR) [2], rendering it more suitable as a routing protocol for large-scale heterogeneous wireless networks, including military communications networks. Our approach organizes the hierarchical structure dynamically while making full use of the various components in a military network (such as mobile units, command posts, and headquarters), and the hierarchical scheme here presented is fully integrated within the existing OLSR protocol (hereinafter designated as "flat" OLSR, in reference to its non-hierarchical mechanism). With this hierarchical structure we propose optimizations to OLSR which reduce the amount of control traffic generated and more efficient use is made of the higher-capacity links in the network. Furthermore, the hierarchical structure releases the OLSR from having to perform frequent routing computations, as the local movement of member nodes is now handled within the cluster, without affecting other parts of the network.

Using OPNET [3] simulations, we demonstrate that the Hierarchical OLSR (HOLSR) does scale more efficiently: the overhead is dramatically reduced, and protocol performance is greatly improved with respect to packet-delivery ratio and end-to-end delay of data packets. With the hierarchical approach, we not only retain the advantage of OLSR – the connection setup delay is minimized – but also improve two aspects of the protocol: 1) overhead is further reduced and 2) frequent route updates are avoided. Thus, for large heterogeneous ad hoc networks, HOLSR yields very promising results.

II. THE HOLSR

A. *Military Hierarchical Structure under HOLSR*

As a typical example of a heterogeneous network, the military communications network was selected as target study of this paper. Based on the different units in the military network, the mobile nodes are organized into multiple topology levels, creating a hierarchical architecture as

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illustrated in Figure 1.

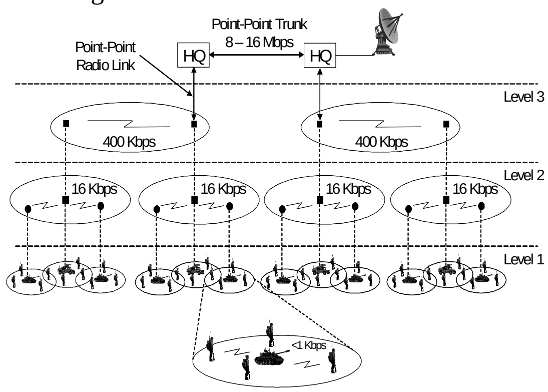

Fig. 1. Multilevel hierarchical ad hoc network

Topology Level 1 is composed mainly of ground units such as soldiers, and communication is constrained by the limitations of the communications equipment the soldiers can carry (such limitations may include short transmission-range and low data rate radios). For purposes of this study, these units are presumed to carry a single wireless interface. Topology Level 1 is composed also of mobile units, such as tanks and vehicles, which are capable of communicating with soldiers on the same frequency band.

Topology Level 2 nodes are composed of mobile units, such as tanks and vehicles, which are equipped with multiple wireless interfaces capable of communicating with Level 1 nodes. At the same time, these mobile nodes can relay messages at the logical topology Level 2 using a frequency-band or a medium-access control (MAC) protocol which differs from the one used for communication at the topology Level 1. The additional wireless interface carried by the Level 2 node offers a longer transmission range than that of the Level 1 node.

Topology Level 3 nodes are composed of nomadic command posts, which are equipped with multiple wireless interfaces capable of communicating with Level 2 and Level 1 nodes. Designated command posts are equipped also with a wired interface, allowing communication with headquarters.

Above the topology Level 3 are situated the nodes at the highest topology level: referred to as headquarters (HQ), these nodes are connected by high-capacity point-to-point trunks. In the network structure delineated above, it is assumed that communication can occur only between nodes equipped with the same type of wireless interface.

B. HOLSR

The HOLSR model is based on the protocol specifications for the OLSR algorithm. One of the main improvements realized by application of the HOLSR protocol is a reduction in the number of TC messages which need to be exchanged at the different levels of the hierarchical network topology. Another important benefit is the reduction in routing computational cost: if a link in one part of the network is broken, only those nodes within that cluster level need to re-calculate the routing table, while nodes in other clusters are not affected.

In the HOLSR protocol, the mobile nodes form different levels of clusters: a cluster is composed of a group of mobile nodes (at the same topology level) having selected a common cluster head, while TC messages generated by the mobile nodes are restricted to the local cluster and are transmitted at each hierarchical level independently. A hierarchical TC (HTC) message is used to transmit the membership information of a cluster to the higher hierarchical level nodes.

Three types of HTC messages are used: the *full membership* HTC message, the *update* HTC message and the *request* HTC message. The *full membership* HTC messages are periodically transmitted by a cluster head to provide information about its cluster members, including members of any lower-level clusters beneath it. The *update* HTC messages provide information with respect to cluster membership changes, that is, the *update* HTC messages are used when mobile nodes join or leave a cluster. As HTC messages carry a sequence number field, it is possible to determine whether any HTC packet loss has occurred, in which case a request for the re-transmission of a *full membership* HTC message is sent by the receiving node.

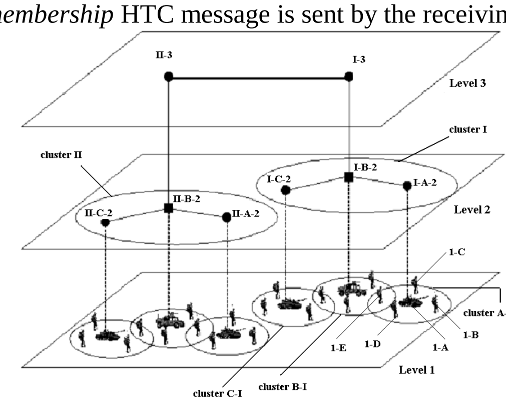

Fig. 2. Example of how HOLSR works

Cluster heads are configured during the start-up of the internal HOLSR process, whereby any node participating in multiple levels automatically becomes the cluster head of its lower-level nodes. In the example provided by Figure 2, vehicle 1-A, which participates in Level 2 as I-A-2, is the cluster head of the Level 1 soldiers, while Command Post I-B-2, which participates in Level 3 as I-3, is the cluster head of the Level 2 mobile units, and so on. These nodes thereafter declare their status as cluster heads of a certain topology level by periodically sending out Cluster ID Announcement (CIA) messages. To reduce the number of packet transmissions, the CIA and HELLO messages are sent together. CIA messages have two fields: *cluster head*, which identifies the cluster head selected by the message generator, and *distance* (in hops) to that cluster head. When a cluster head generates a CIA message, it identifies itself within the *cluster head* field, with *distance* being 0. The nodes near the cluster head receive the CIA messages, join the cluster, and begin generating CIA messages announcing their current membership in the cluster to neighboring nodes (whenever a node changes location and joins a new cluster, the updated membership information is incorporated into the CIA messages generated by that node). These CIA messages enable nodes further away from the cluster head to be notified of the existence and locations of the cluster heads and join the clusters. Any given node may receive two or more CIA messages, indicating that it is located in the overlapping regions of several clusters. In such cases, the node joins whichever cluster is closest in terms of the hop count. Continuing with the above example, soldiers 1-B, 1-C and 1-D join Cluster A-I, while soldier 1-E, being in the overlapping regions of Cluster A-I and Cluster B-I, chooses to join Cluster A-I. Similarly, Level 2 vehicles I-C-2 and I-A-2 join Cluster I, whose cluster head is I-3.

In HOLSR, a cluster head acts as *gateway* through which messages from cluster members are relayed to other parts of the network – therefore each cluster head needs to be aware of the membership information of its peer cluster heads. To this end, each cluster head uses the HTC messages (outlined at the beginning of this Section) to propagate the membership information of its lower-layer clusters to the higher-topology nodes. As per our example, node I-A-2, which is the cluster head of Cluster A-1, generates HTC messages informing other Level 2 nodes that soldiers 1-B, I-C, I-D, I-E and I-A (itself in Level 1) are members of its cluster. As with TC messages, HTC transmission is enabled by MPRs, and is restricted within a cluster. So I-A-2's HTC is relayed to other Level 2 nodes within Cluster I via the cluster MPRs.

Nodes at each hierarchical level independently select MPRs in their respective cluster level – in the above example, nodes in Cluster A-I select MPRs at Level 1, while nodes in Cluster I select MPRs at Level 2. At each hierarchical level, TC messages are generated and their propagation is restricted to that cluster level - for example, nodes in Cluster B-I do not accept or relay the TCs from Cluster A-I. Therefore, an HOLSR node's awareness of network topology is limited to its local cluster (obtained through TC messages) and the membership information of any lower hierarchical levels (obtained through HTC messages).

For data transmissions outside the local cluster, the gateway mechanism employed can be illustrated as follows: Node 1-E, a member of Cluster A-I, intends to send data to node II-C-2, which is in Cluster II. From HELLO and TC messages, 1-E knows that II-C-2 is not a member of its cluster, so it sends data to its cluster head I-A-2. I-A-2 in turn does not recognize II-C-2 as a member of its cluster, nor does it see II-C-2 from the TC or HTC messages (which convey only the topology or membership information within Cluster I), therefore it relays the data packet to its cluster head I-3. I-3 in turn knows from the HTC message originated by II-3 (which is within its Level 3 cluster) that II-C-2 is a member of II-3's cluster, therefore the data packet is relayed to II-3, and finally to its intended destination II-C-2. And so, in tracing the transmission route traveled by the data packet (1-E → I-A-2 → I-3 → II-3 → II-C-2), we see that the cluster head is always used by member nodes at lower hierarchical levels as the gateway for transmissions to destinations lying outside of the local cluster.

III. OPNET SIMULATION

A. Simulation Setup

The OPNET [3] simulation tool is used to evaluate and compare the performance of the HOLSR and the flat OLSR.

A general military layout in a battlefield is simulated: two subnets are connected to their headquarters via a point-to-point trunk. Each subnet occupies a 1200m x 1200m flat space, and contains several types of mobile nodes detailed as follows (802.11b is chosen as the physical layer used by all the mobile nodes): ***45 Soldiers*** – Soldiers are equipped with the least powerful equipment: a wireless card having a data rate of 1Mbps and a transmission range of 250m. ***15 Tanks*** – Each tank is fitted with two wireless cards: one card is identical to that carried by the soldiers; the other card supports a data rate of 5.5Mbps and a transmission range of 750m. ***5 Command Posts*** – The command posts are nomadic nodes which migrate occasionally and act as the backbone of the wireless subnet. In addition to the interfaces used by the tanks, command posts are equipped also with an interface card which supports the highest available data rate of 11Mbps. Because of this high data rate, the transmission range of the interface card is limited to 500m. One of the command posts also connects to headquarters via a point-to-point radio link.

The soldiers, tanks, and command posts each operate within a *maximum speed*, as follows: Soldiers = 3m/s (10.8km/h); Tanks = 10m/s (36km/h); Command Posts = 0m/s (the command posts are designated as fixed nodes in the 900s simulation time, and are strategically placed in the subnet so that they are inter-connected). Each mobile node changes its location within the subnet based on the "random waypoint" model [4], that is, the node randomly selects a destination, moves towards that destination at a speed not exceeding the *maximum speed* for that Level, and then pauses – this interval being known as *pause-time*. In order to calculate the effect of node movement on protocol overhead, pause-time is given five distinct values in the simulations: 0s, 150s, 300s, 600s, 900s.

B. Simulation Results

Protocol overhead and protocol performance of the flat OLSR and the HOLSR are compared and analyzed. Data was collected via multiple runs of OPNET simulation.

Protocol Overhead – a measure of the number of OLSR packets transmitted[1]. An individual OLSR packet may contain several OLSR messages – HELLO, TC, HTC (in HOLSR), etc.

Table 1 gives the average number of OLSR packets generated in the network. As demonstrated by the results, for all values of pause-time, HOLSR significantly reduces control

[1] Our OLSR OPNET model is based on version 3 of the OLSR Draft, which predates the introduction of the MID message. To adapt that model for use with multiple interfaces, we modified the TC message such that it includes all interfaces addresses of the nodes having selected the TC originator as MPR. As a result, the size of the TC message may be larger than the one based on OLSR RFC. However, we consider the performance obtained to be comparable to that of OLSR RFC: although the TC size is greater, fewer packets are transmitted as there is no MID message.

overhead in comparison with the flat OLSR. HOLSR can achieve this reduction because all nodes in the network are grouped into distinct hierarchical clusters, while the topology control messages in each cluster are propagated only within that cluster, which prevents these topology messages from flooding the entire network. Furthermore, because of the flat structure of the flat OLSR, when a TC message is transmitted by a multiple-interface node, it must be sent through all interfaces possessed by that node[2] - this mechanism greatly increases the number of packages sent in a network where many nodes have multiple interfaces. By contrast, a topology control message in HOLSR is sent through only that interface sharing the topology level of that message. Thus, message flooding through multiple interfaces is avoided.

TABLE 1.
COMPARISON OF NUMBER OF PACKET SENT (PACKETS/S)

Pause Time	0s	150s	300s	600s	900s
HOLSR	420	422	420	416	416
Flat OLSR	1940	1909	1853	1663	1664

Protocol Performance – this is evaluated using two metrics: *Packet-Delivery Ratio* and *End-to-End Delay* of data packets.

Packet Delivery Ratio: the percentage of data packets successfully delivered to the receiver nodes, against total number of data packets sent.

Figure 3 gives the packet-delivery ratios for both HOLSR and flat OLSR. Compared with the flat OLSR, the packet-delivery ratio achieved by HOLSR is much higher. Such improvements are a result of the low overhead introduced by the HOLSR. As per our simulation, it may be observed that the excessive overhead introduced by the flat OLSR engenders a large number of collisions of the OLSR packets, which contain network topology information. When these packets are lost, the IP routing tables cannot be correctly updated. Consequently, many data packets cannot be delivered to their intended destination because of incorrect IP routing table entries. In addition, many data packets possessing the correct route may also be dropped as a result of data congestion in the wireless media.

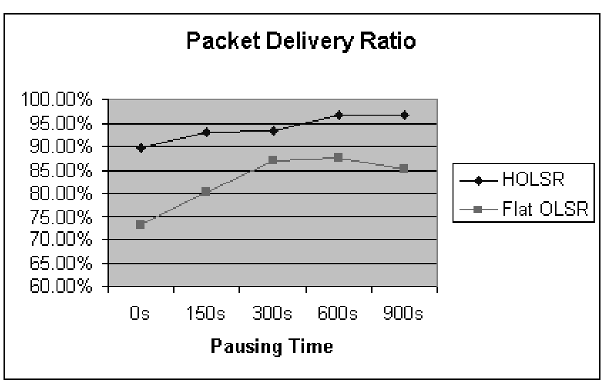

Fig. 3 . Packet-delivery ratio comparison for HOLSR and flat OLSR

End-to-End Delay: the average elapsed time between transmission and reception of individual data packets.

Figure 4 compares the end-to-end delays of the two versions of OLSR protocols under each of the five mobility scenarios.

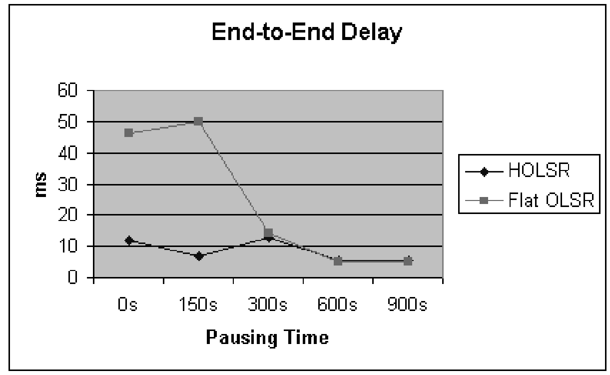

Fig. 4. End-to-End delay comparison for HOLSR and flat OLSR

HOLSR delivers data packets more quickly and efficiently than does the flat OLSR because under HOLSR the generated overhead is much lower. Reduced traffic in the wireless media allows the HOLSR to realize a shorter queuing delay, resulting in shorter end-to-end delays. Also, the HOLSR groups nodes into different levels of clusters, whereby those nodes equipped with multiple interfaces become cluster heads. These cluster heads employ higher data-rate wireless interfaces, acting as the “backbone” for the data packet transfers between different clusters. Thus, the HOLSR makes use of the higher-capacity wireless media for data transmission and is therefore more efficient in data packet delivery.

IV. CONCLUSION

In this paper, we introduced the concept of a hierarchical mechanism for use in large heterogeneous wireless networks and proposed an efficient approach for incorporating the hierarchical structure into the OLSR protocol in order to improve OLSR’s scalability. We have seen that implementation of this hierarchical mechanism also releases the OLSR from having to perform frequent route updates. Results of our military battlefield simulation confirm that, in comparison with the flat OLSR, the HOLSR dramatically reduces protocol overhead within the network, achieves a higher packet-delivery ratio while incurring shorter queuing delays and shorter end-to-end delays, and reduces or eliminates the incidence of lost packets resulting from high overheads. HOLSR thus successfully and significantly improves the scalability of the original OLSR protocol.

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