Beacon Assisted Discovery Protocol (BEAD) for Self-Organizing Hierarchical Ad-Hoc Networks

L. Raju, S. Ganu, B. Anepu, I. Seskar and D. Raychaudhuri
WINLAB, Rutgers University
Piscataway, New Jersey 08854
{lalit,sachin,bhaskar,seskar,ray}@winlab.rutgers.edu

***Abstract*— This paper describes a beacon assisted discovery mechanism for self-organizing hierarchical ad-hoc networks. The discovery protocol, which operates between the medium access control (MAC) and network layers, is responsible for topology formation in the ad-hoc network taking into account performance objectives such as throughput, delay, energy consumption and robustness. The proposed discovery protocol operates by listening to augmented MAC-layer beacons from neighboring radio nodes and then selects a subset of these for routing associations based on specified criteria. A distributed heuristic algorithm for topology formation is considered and compared with upper-bound centralized algorithms with optimization objectives such as maximum throughput, minimum delay or minimum energy. Simulation results (based on ns-2 models) are given for the performance of proposed discovery methods, demonstrating significant improvements in routing overhead when compared to an ad-hoc network without discovery. A proof-of-concept prototype implementation for an 802.11b-based three-tier hierarchical ad-hoc network is briefly described in conclusion.**

Key words: Discovery protocol, Ad-hoc wireless networks, Self-organization, Topology control, Hierarchical networks

I. Introduction and Prior Work

Ad-hoc wireless network protocols are becoming increasingly important for deployment scenarios with limited wired infrastructure. Examples of these are sensor networks, home networks and rapid deployment emergency networks. In each of these scenarios, self-organizing ad-hoc network protocols can help to create low-tier wireless networks which utilize multihop packet forwarding between radio nodes, potentially providing important benefits in coverage, throughput and performance relative to centralized cellular or wireless local-area network options in use today. The technical challenges associated with ad-hoc networks include the design of efficient medium access, discovery and routing protocols taking into account performance and scalability requirements.

In this paper, we focus on an important class of ad-hoc networks, namely a self-organizing, hierachical ad-hoc network designed to scale well and to provide an effective means for integrating ad-hoc wireless networks with existing wired infrastructures. The hierarchical network is theoretically motivated by Gupta and Kumar's result [1] showing that the per-node throughput of a flat ad-hoc network decreases as $\sqrt{n}$, where n is the number of radio nodes in the network. Also, in

[1]Research supported in part by 1) NSF ORBIT Testbed Project, NSF NRT Grant #ANI0335244 and 2) a grant from Cisco University Programs, 2003

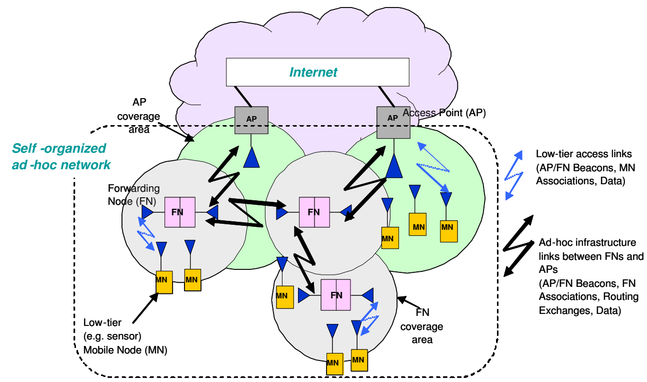

Fig. 1. Structure of three-tier hierarchical ad-hoc network

[2], the authors have analyzed the capacity of a hybrid wireless network consisting of a base-stations connected together by high-speed wired links and have shown that the capacity scales well if the number of base stations is at least $\sqrt{n}$, where n is the number of radio nodes in the network. In [3], the authors demonstrate that a hierarchical ad-hoc network with three tiers of nodes (end-user mobile nodes, radio forwarding nodes and wired access points) scales well and can provide good performance while retaining many of the deployment advantages of an ad-hoc radio network. The self-organizing hierarchical ad-hoc network (SOHAN) concept was further validated via proof-of-concept prototyping described in [4]. This work focuses on the design and performance of a novel discovery protocol called BEAD (beacon assisted discovery) that plays a critical role in the proposed hierarchical ad-hoc network.

The self-organizing ad-hoc wireless network has the structure shown in Fig 1. The specific 3-tier hierarchy shown in the figure consists of mobile nodes (MN) at the lowest tier, higher powered radio forwarding nodes (FN) at the second tier and wired access points (AP) at the third and highest tier. The MN's, FN's and AP's in the network create ad-hoc associations to form a topology that meets required performance and robustness criteria.

In traditional ad-hoc networks, there is no discovery phase and the routing protocol itself is responsible for building up topologies either using on-demand broadcast of route requests or by exchanging neighbor information proactively with one hop neighbors and building the topology based on this information. While this may be sufficient for smaller networks, as the number of nodes increases, it results in denser physical topologies, leading to extensive routing message exchanges. The problem is more severe in a multi-channel network where the multiple nodes that need to communicate could be on different radio channels. In this case, the routing messages need to be propagated across multiple channels in order to enable data transfer from one node to the other.

Most of the work done so far focuses on architecture having homogeneous nodes with identical processing capabilities. Therefore, the basic assumption is that every node is capable of supporting multihop routing. In [5], the authors present mechanisms to maximize the network life for a homogeneous set of nodes which generate data destined for the base station. In [6], two types of nodes are used: nodes which discover data and nodes which disseminate data. A hierarchical architecture is formed in this case, with special immobile router nodes acting as the backbone for data dissemination. In [7], transmit power control is used to configure the topology of the network. In [8], the authors propose power control for homogeneously spaced nodes to maximize the traffic carrying capacity of the network. This idea is extended in [9] to include networks in which nodes are placed non-homogeneously.

In this paper, we propose BEAD, a beacon-assisted discovery process for self-organizing hierarchical networks that helps reduce the routing overhead and also improves the system performance. We study the performance of discovery with three different objective functions - energy consumption, end-to-end delay and throughput - and its effects on topology formation. Based on these results, the trade-off between these optimizations is examined.

In Section II, we describe the system architecture of the hierarchical ad-hoc network. In Section III, we motivate the need for discovery and also present the design of the discovery procedure for different optimizations. Section IV discusses the simulation results for centralized and distributed discovery algorithms and the effect of discovery on routing under various network conditions. Section V describes our proof-of-concept implementation of BEAD. Section VI concludes the paper and discusses possible future enhancements.

II. System Architecture

In order to better understand the discovery mechanism, we briefly present the underlying self-organizing hierarchical ad-hoc network architecture that is three-tiered and comprises the following nodes with different capabilities at each tier.

- *Mobile Node* (MN), is a mobile end-user device (such as a sensor or a personal digital assistant) at the lowest tier (tier 1) of the network. The MN attaches itself to nodes at the higher tiers of the network in order to obtain service using a discovery protocol. The MN uses a single radio operating in ad-hoc mode to communicate with other MNs through the point(s) of attachment i.e FN/AP and is incapable of forwarding data for other MNs or communicating directly with another MN
- *Forwarding Node (FN)*, is a fixed or mobile intermediate (tier 2) radio relay node capable of routing multi-hop traffic to and from all three tiers of the network's hierarchy. As an intermediate radio node without traffic of its own, the FN is only responsible for multi-hop routing of transit packets. An FN has two radio cards, one for traffic from MN to FN and another for inter FN and FN-AP traffic flows (typically carried on a different frequency)
- *Access Point (AP)*, is a fixed radio access node at the highest tier (tier 3) of the network, with both an 802.11 radio interface and a wired interface to the Internet. The AP, unlike typical 802.11 WLAN deployments, operates in ad-hoc mode

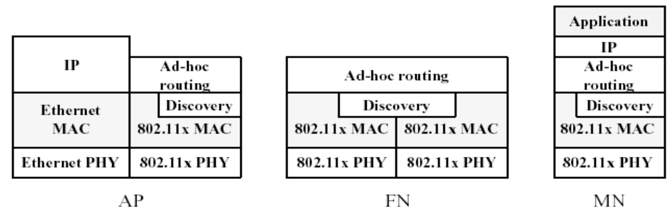

Fig. 2. Protocol stack of hierarchical ad-hoc wireless network with discovery

In the next section, we describe the discovery mechanism for the three-tier architecture discussed earlier.

III. Neighbor Discovery and Topology Control

Discovery in wireless networks can be described as the process through which a node becomes aware of its surroundings, that includes determining the presence and type of neighbors, assessing quality of links to other nodes, and providing information to the routing protocol to identify the most efficient path to the destination. While the MAC layer detects the physical topology, the discovery protocol processes this information to determine the logical topology that should be visible to the routing protocol. Routing overhead is thus reduced as the routing protocol has to deal with fewer links. In addition, the discovery protocol may also provide a metric that can be used by the routing protocol for choosing paths to forward data. This information should form a network that performs well in terms of the power consumption, throughput and/or delay. The discovery protocol is responsible for keeping track of changes in the neighborhood of a node and in a multi-interface forwarding node scenario, the discovery protocol utilizes the multiple channels so as to minimize interference and maximize throughput of the system.

In order to determine bounds on the performance of BEAD, we first consider a centralized approach using linear programming and formulate the problem with three objective functions - minimum delay, minimum energy and maximum throughput. The minimum delay optimization finds the topology which will minimize the number of hops from each MN to an AP. This represents the shortest-path metric commonly used in routing protocols. For sensor networks, however, an important criteria is energy consumption. We consider transmit power as a source of energy consumption. We further note that in the hierarchical architecture, the cost of energy at the FNs is at least an order of magnitude less than that at the MNs, while the cost at the AP is negligible. For the throughput maximization, we assume that the MNs offer identical loads to the network and are the only sources of data. We observe that in the case of the dual-interface FN, uplink and downlink traffic need not be time-shared, thus removing the bottleneck experienced in single-interfaced networks over multihop traffic. Therefore, maximizing the throughput is done through balancing the MN load over the various APs of the network.

We now describe BEAD which is a distributed discovery algorithm based on the insights obtained from the above centralized topology study. As shown in Fig. 2, the discovery protocol is placed as a sub-layer between the MAC layer and the network layer. It gathers information about neighbors from the MAC layer (Neighbor Discovery Phase using beacons) in a neighbor table, N, and determines the neighbors which are relevant to the objective of the network (Neighbor Selection Phase). This information is then provided to the network layer in the form of a reduced neighbor table, N*.

A. BEAD: Routing Topology Control

The discovery protocol uses augmented MAC beacons as per the format shown in Fig. 3. Each AP and FN in the network sends out these beacons periodically on a selected channel out of eleven 802.11 channels. An MN when powered on, scans all the channels and records the information received from beacons of its neighboring nodes. This includes objectives such as energy, delay and throughput, information about the node including node type and address, and the channel on which the particular beacon was received.

B. BEAD: Neighbor Selection Phase

Once the MN scans all the channels for beacons, based on the objective of the network, it then identifies the "best" parent(s) to associate with and sends an association request to that parent(s). To complete the handshake, an acknowledgement of the request is transmitted by the parent AP or FN. This parent is then added to the reduced neighbor table (N*) for use by the routing protocol. FN to FN links are also established through the procedure of scanning and association.

The reduced set of links formed through associations with "best" neighbors is referred to as the *reduced* topology, T*, while the full set of links is referred to as the *complete* topology, T. At the lowest level, the MNs do not perform any routing and simply forward all data to their parents. The FNs on the other hand, use T* formed by the discovery protocol to find new routes. While T* will result in lower routing overhead, it should be consistent with the paths likely to be chosen from T by the routing protocol (in the absence of discovery).

The objective chosen for T* in the distributed algorithm was based on the observations of topology plots of the minimum energy network subject to a delay constraint (specified by number of hops). We observed that minimizing the energy at

Source MAC	Broadcast MAC	Node ID	Packet Type (beacon)	Cluster ID	Seq. No	Node Type	Hop Count	TxPower

Fig. 3. Beacon format augmented for discovery

the MN is most important due to the higher costs involved at this layer. Another key observation from this objective was that tighter delay constraints resulted in changes at the FN layer, leaving the MNs attached to the nearest neighbor. Therefore, we considered a distributed discovery heuristic algorithm that minimizes energy at the MN layer, and minimizes delay at the FN layer. The algorithm we have implemented in ns-2 is such that every MN associates to the nearest FN or AP, while the FNs associate with another FN or AP that has the least number of hops towards an AP.

IV. Simulation Results and Discussion

Using ns-2 [10], we built a simulation model that extends the existing 802.11 protocol to support the hierarchical architecture, including support for APs, FNs, and MNs. We also extended the ns-2 model to support the dual-interface FN operating on multiple 802.11 channels.

We compare our distributed discovery algorithm with the results obtained from the centralized topology study. We also show the effect of neighbor discovery on the routing overhead of the network.

The parameters and terms used in analyzing the simulations are explained below.

- *Net Throughput* - Useful data bits sent per second by all the nodes in the network
- *Average End to End Delay* - Average delay in seconds experienced by packets from source to destination
- *Routing Overhead* - Ratio of the number of routing protocol bytes to the number of data bytes
- *Energy consumption*- Energy consumed (in Joules) by the MNs during the entire simulation

We consider an arbitrary set of node positions for 2 APs, 4 FNs, and 10 MNs over an area of 500mx500m to compare the performance of BEAD with the centralized approach. Each MN offers the same load, destined for the Internet through any available AP.

A. Centralized Algorithm

Fig. 4a shows the minimum energy topology. Each MN associates to the nearest FN or AP, and each FN associates in turn to the nearest AP to deliver data from the MN to the AP. However, the minimum energy topology yields a poor performance in terms of delay and throughput. It can be seen that most of the MNs are at least two hops away from the APs, resulting in high delays, while there is a bottleneck at the AP in the bottom right corner, to which most MNs send their data.

In Fig 4b is shown the minimum delay topology. The delay optimization results in the MNs transmitting at a much greater power to reach the APs directly where possible and through

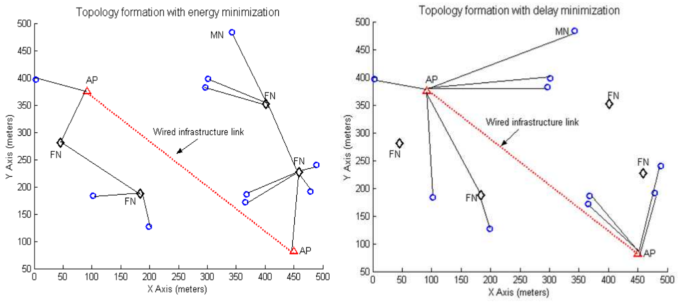

Fig. 4. Topology formation with a: minimizing energy b: minimizing delay

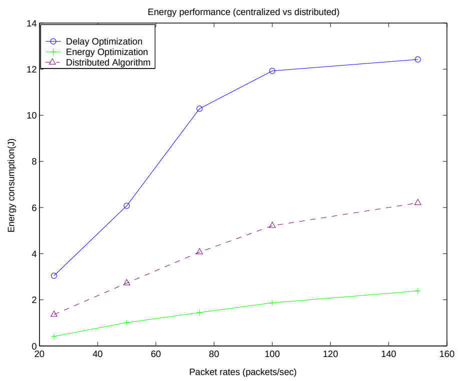

Fig. 5. Energy consumption for distributed algorithm (compared with centralized algorithm bounds

an FN where limited by the transmission range imposed on the MNs.

B. Distributed Algorithm

In Fig 5. we compare the energy consumption of BEAD with that of the centralized approaches for energy and delay minimization. While BEAD has energy consumption higher than the minimum energy centralized topology, it is well below the energy consumption of the minimum delay topology. Likewise, as shown in Figs. 6 and 7, the average delay and throughput for BEAD also lie between the delay and throughput for centralized minimum delay and the minimum energy topologies respectively. Thus, we see that performance of BEAD protocol is comparable to the centralized case that uses AODV routing (without discovery). This implies that topology chosen by BEAD (using discovery and routing) is close to the set of optimal paths chosen by the routing protocol. The introduction of discovery as a separate layer is further justified by studying the routing overhead reduction as described in the next subsection.

C. Effect of discovery on routing overhead

The topology consisted of 100 MNs, 10 FNs, and 4 APs in which the FNs and MNs are mobile. Fig. 8a shows the routing overhead with increasing node mobility. There is a significant reduction in routing overhead with the introduction of the discovery mechanism. We also observe that the difference is greater at higher mobility rates. The reason for this is that

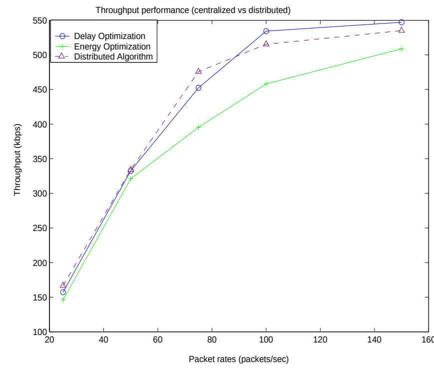

Fig. 6. System Throughput for distributed algorithm (compared with centralized algorithm bounds

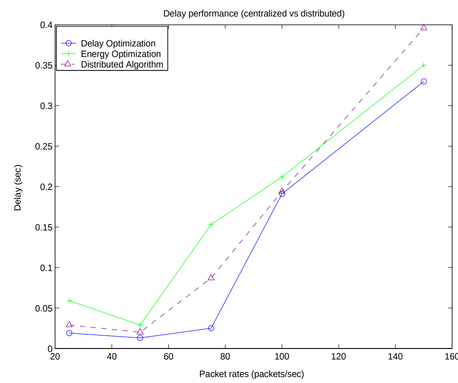

Fig. 7. Delay for distributed algorithm (compared with centralized algorithm bounds

discovery reduces the links along which routing messages are propagated.

In Fig 8b, we compare the routing overhead for networks with and without discovery for a node speed of 10m/s for increasing number of MNs. We can see that the routing overhead is significantly lower for routing preceded by the discovery protocol.

V. Prototype Implementation

We implemented the above discovery algorithm as a proof-of-concept prototype on a Linux testbed using 802.11b radio nodes operating in ad-hoc mode on multiple channels. The implementation was done using C programming with the Libnet [11] package to handle packet transmission and reception functionality. The experimental setup comprised 3 APs, 3 FNs and 10 SNs.

We enhanced the existing beacons in the 802.11 MAC layer to support BEAD protocol. For ease of implementation, the beacons used in the prototype were application-level packets generated using Libnet and not 802.11 beacons that are typically generated by the firmware of the wireless adapter.

The beacon message contained the node identifier information as well as a sequence number. This could be further augmented to contain information about the current load and energy levels at each node which may be used by the other

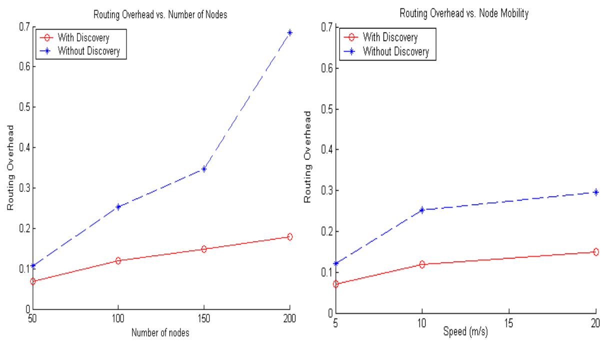

Fig. 8. a. Routing overhead with increasing nodes b. Routing overhead with increasing mobility

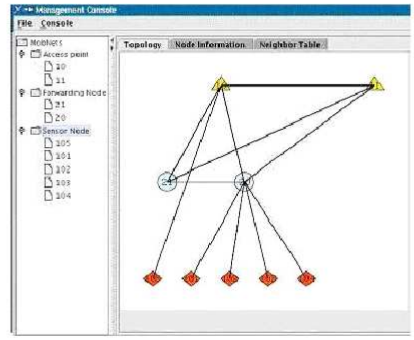

Fig. 9. Snapshot of the topology formed using BEAD in the prototype implementation

nodes to determine whether or not to send an association to this node. After the initial setup, the AP and FN nodes transmitted beacons on predetermined channels periodically based on a configurable beacon interval (set to a default value of 250 ms). Each node (FN/MN) scanned through all the channels and recorded the received beacon information in their local neighbor tables. The structure of the neighbor table is shown in Table 1. After scanning through all the channels and collecting the beacons, the MNs (and FNs) decided the best "cost" parent for association and sent an association message to that node. After the associations were received, the initial topology was formed. The nodes periodically went into rescan mode in order to determine the status of their links to one-hop neighbors, recalculate their best "cost" parent and send associations to that node.

TABLE I

LOCAL NEIGHBOR TABLE FORMAT AT FN/AP

MAC Addr	Node Type	Refresh Timer	Channel to Next Hop	Cost to Dest.	Iface to Next Hop	Next Hop

Discovery metric

For our implementation, we chose energy conservation at the MNs as the objective function and the discovery metric was based on minimizing the transmit power consumption at the MNs. We modified the device drivers to append transmit power to each outgoing beacon at the APs/FNs and the received signal strength for each incoming beacon at the MNs. Using this information and assuming reciprocity of channel, the node with the minimum transmit power was chosen as the next hop neighbor. In case, there were two or more such nodes, the node whose beacon was received with the higher signal strength was chosen.

We also implemented a custom distance-vector based routing protocol (similar to DSDV) that used the neighbor tables formed during the discovery process to form routes to deliver data from MNs to APs. Fig. 9 shows a snapshot of the topology comprising 2 APs, 2 FNs and 5 MNs formed using discovery and routing as seen at the management console.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, a novel discovery protocol (BEAD) is presented to establish a desirable topology based on different obejective functions prior to routing for a hierarchical, multi-channel ad-hoc network. We have shown the advantages of using a separate module for neighbor discovery are significant and the routing overhead is significantly reduced when coupled with a discovery mechanism. We also presented a proof-of-concept prototype to validate our discovery protocol. In future, we intend to study the tradeoff between robustness of reduced links and reliability to find out the degree of topological redundancy desirable after the discovery phase. Further work on integrated discovery and routing mechanisms is also planned.

REFERENCES

[1] P. Gupta and P.R. Kumar, "The Capacity of Wireless Networks", *IEEE Transactions on Information Theory*, vol. 46, March 2000, pp. 388-404.

[2] B. Liu, Z. Liu, and D. Towsley, "On the capacity of hybrid wireless networks", *IEEE INFOCOM 2003*, March 2003.

[3] S.Zhao, I.Seskar, D. Raychaudhuri, "Performance and Scalability of Self-Organizing Hierarchical Ad Hoc Wireless Networks", *to appear in the Proceedings of IEEE Wireless Communications and Networking Conference (WCNC 2004)*, March 2004, Atlanta, GA.

[4] S. Ganu, L. Raju, B. Anepu, I. Seskar, D. Raychaudhuri, "Architecture and Prototyping of an 802.11-based Self-Organizing Hierarchical Ad-Hoc Wireless Network (SOHAN)", *to appear in the Proceedings of the International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2004)*, Barcelona, Spain

[5] W. Heinzelman, A. Chandrakasan and H. Balakrishnan, "Energy-efficient Communication Protocol for Wireless Microsensor Networks," *Proceedings of the 33rd Hawaii Internation conference on System Sciences (HICSS' 00)*, January 2000.

[6] L. Subramanian and R.H. Katz, "An architecture for building self-configurable systems", *Proceedings of the IEEE MobiHoc*, 2000.

[7] R. Ramanathan and R. Rosales-Hain, "Topology control of multi-hop wireless networks using transmit power adjustment", *Proceedings of the IEEE INFOCOM 2000*, Tel Aviv, Israel, Mar 2000.

[8] Swetha Narayanaswamy, Vikas Kawadia, R. S. Sreenivas, and P. R. Kumar, "Power Control in Ad-Hoc Networks: Theory, Architecture, Algorithm and Implementation of the COMPOW protocol", *Proc. European Wireless*, pp. 156-162, Florence, Italy, 2002.

[9] Vikas Kawadia and P. R. Kumar, "Power Control and Clustering in Ad Hoc Networks", *Proceedings of the IEEE INFOCOM 2003*, San Francisco, 2003.

[10] CMU Monarch Group. CMU Monarch extensions to ns. *http://www.monarch.cs.cmu.edu/*.

[11] Libnet Packet Library, *http://www.packetfactory.net/libnet/*.