

SCALABILITY OF DYNAMIC WIRELESS TACTICAL NETWORKS

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ABSTRACT

This paper focuses on the scalability of two classes of wireless networks: 1) mobile, base-station-oriented networks, for which we address routing and mobility protocols and 2) energy-efficient peer-to-peer wireless broadcasting, for which we focus on tree construction. Using discrete event simulation, we investigate two basic aspects of scalability, performance scalability and complexity scalability. Performance scalability addresses the effect of network size on system performance. Complexity scalability consists of computational complexity (i.e., amount of computation needed to construct routes and trees) and communication complexity (i.e., amount of control information needed exchanged to create and maintain network connectivity).

I. INTRODUCTION

Significant research, development, demonstration and standardization in wireless network routing algorithms [1] and unified, dynamic infrastructures (e.g., [2],[3],[4]), has taken place over the past five years. However, there is a lack of compelling data to support the scalability of wireless networking in dynamic, tactical operations. Accordingly, we have focused on the scalability of two fundamental approaches to wireless networks that have been recently under investigation: 1) networks based on dynamic base-stations and hosts, including their associated routing, mobility, and quality of service models [2]; and 2) ad hoc (peer-to-peer) networks, with an emphasis on energy-efficient wireless multicasting [5], [6], [7].

For dynamic base-station networks ([8], [9]), we are investigating the scalability limits of both routing and mobility management protocols and services. In this approach, the routers in the base stations are dynamic, and hosts move within and between IP router domains. We are considering networks with as many as thousands of dynamic users, links and routers, and our simulations include physical, link, network and transport layer models and associated processes.

For session-oriented multicasting in peer-to-peer networks,

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we are exploring scalability limits of energy-efficient wireless multicasting in the areas of *performance enhancement* (e.g., reduction in transmitter energy required and increase in network throughput) and *computational complexity* (e.g., reduced resources involved in computing multicast trees).

Base-station-oriented architectures are inherently hierarchical, with mobile hosts connected to “advantaged” base station nodes (routers, switches, high data rate transmitters and receivers, high speed encryption devices, etc.). Such nodes, may be satellite-, airborne- and/or terrestrially based, and their topology (links and switches) is dynamic. Routing and mobility management occurs within the mobile domain or network subset, and mobile users move within and between the mobile base stations — in a cellular-like fashion. Such networks are hierarchical and, as such, hold promise for scalability.

Ad hoc networks (also referred to as peer-to-peer, or “infrastructure less” networks) [1] are multihop wireless networks that typically consist of nodes with both host and router functionality on a single platform. There are often no advantaged nodes, and it may be necessary to transform an initially “flat” architecture into a hierarchical structure, such as the Linked Cluster Architecture [10]. In ad hoc networks, operation is often limited by the constraint of finite user battery life because it may be impossible to recharge batteries during a mission. Thus, there is a need to develop networking techniques that make efficient use of the limited energy that is available. Additionally, complexity issues must be addressed in network organization and control.

We have investigated the scalability of both types of architectures in this paper, with implications for a hybrid network architecture based on the distinct advantages of both. For example, scalable techniques for backbone network formation can be a useful component of the multicast tree construction process. In addition, the organization of base stations into subsets (e.g., OSPF areas) is analogous to the clustering of ad hoc network peers. Our base-station approach is a complete systems view of scalability including physical, link, network and transport, and application layer models and associated processes. It builds on technology developments in the On Board Switch (OBS) project [2]. The ad hoc network

approach focuses on session-oriented multicasting. For base station-oriented modeling, we use the OPNET simulation package, which permits the detailed modeling of the entire protocol stack. For session-oriented multicasting, for which our current studies address performance and complexity, but not detailed protocol issues, we program our simulations in C.

II. BASE-STATION ARCHITECTURE

The OBS project, and the Warfighter’s Internet [9] provided for a unified wireless infrastructure, which included the convergence of Internet (packet switching, quality of service, routing, transport), cellular telephony (mobility, handoffs, base stations), and wireless multiple access (802.11, dynamic TDMA) technologies [11,12]. The underlying architecture includes mobile hosts and base stations (routers) forming a network as seen in Figure 1. The base station nodes, which consist of routing, mobility and radio functions, form a wireless, high data rate backbone. Mobile hosts can affiliate with any router through a handoff process.

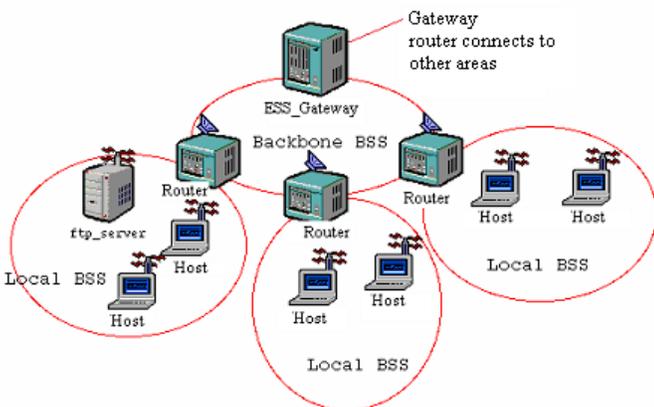


Fig 1. Base Station Architecture

The hierarchical nature of base-station oriented wireless networking architecture is a major factor contributing to its scalability. As represented in Figure 1, a set of hosts and their associated router form a local area network (LAN). All hosts directly attach to the router through the LAN. At the next level, a set of routers forms a backbone LAN, and at a higher level, a set of gateway routers form a backbone linking the various other router areas or subnets.

In our current investigation, the IEEE 802.11 standard [13] is used for both the router backbones and the mobile host LANs. All nodes are capable of movement on a configurable trajectory. Each router interface as well as the nodes affiliated with that interface forms a Basic Service Set (BSS). A group of these sets forms an Extended

Service Set (ESS). Thus a hierarchical base station model is possible by localizing routing and mobility information within the ESS areas. In the case of the router backbones, we use a modified version of the wireless Open Shortest Path First (OSPF) protocol in order to implement “areas” or subnets.

Our modeling and simulation is based on wireless models in OPNET versions 7 and 8. It was necessary to make enhancements to OPNET as part of this project because our base-station-oriented model could not be characterized accurately using the previously released version 7. We developed the following additional features:

- Multiple wireless interfaces were added for the router node to implement wireless backbones and hierarchical networks. Version 7 allowed only one wireless and one wire line interface per node. Each wireless interface is mapped to a unique 802.11 BSS, which, in turn, is identified by a unique BSS ID. Having a router with multiple interfaces allows multiple BSS to exist in one OPNET subnet. Thus, mobile hosts are capable of moving across the 802.11 Basic Service Sets. In addition, we modified OPNET to allow broadcasts over wireless interfaces.
- An exclusive control channel was added to the mobile hosts and router nodes. Mobility packets are transmitted on this channel (global frequency), providing a mechanism for controlling mobility overhead.
- Mobility “handoff” processes were developed for the hosts and the routers, enabling hosts to affiliate with new router nodes based on preferences (e.g., status of the router, congestion) signal strength measurements.
- Automatic node frequency assignment was developed based on membership in an 802.11 BSS.

III. MOBILITY OF HOSTS AND ROUTERS

Following were key features of the OBS design [14] that were incorporated into our models:

- All router nodes periodically advertise the services they can provide as well as a preference set (e.g., status of the router, congestion).
- The host may request its router node to advertise its preference set by sending a solicitation message.
- The mobile host binds to the router node providing the best service as determined by the preference set and signal strength measurements. The host periodically evaluates its binding status with respect to the latest set of preference advertisements and may

affiliate to a new router node by initiating a local binding.

- The mobile host, after acquiring a local binding, may perform a remote binding to its home router. The remote bind is sent as an IP message to ensure that the home router learns the current location of the host even though it is out of the 802.11 range. The home router node is then capable of forwarding all packets addressed to the mobile host to the address of the router node with which the host is presently affiliated.

Scalability of the Mobility Protocol

By design, all mobility messages except for the remote binding request message are transmitted via the global control channel. Therefore, the mobility overhead is isolated from the primary data channel. Factors that determine mobility channel overhead are: 1) number of mobility advertisements, 2) the number of bindings (local and remote), and 3) the number of routers and hosts in the network.

To study the load in the mobility channel, a network with 50 routers distributed over 5 areas and 10 hosts affiliated with each router was simulated for 30 minutes of real time. The routers in each area are fixed and configured in a horizontal line. The hosts are mobile, and the trajectory assigned to them will cause the hosts to move towards the right-most router. After each advertisement interval, the routers broadcast their preference sets and all hosts subsequently make the binding decisions based on these preference sets and signal strength measurements.

Figure 2 shows the relationship between load and the number of bindings. As can be seen the load varies linearly with the number of the bindings. The peak load in the channel is approximately 123 Kbps, with 340 of the 500 hosts simultaneously exchanging binding messages. The binding messages as well as the preference advertisements constitute the mobility channel load, and the total load is less than 3.5% of the effective capacity (30%) of the 11 Mbps mobility channel.

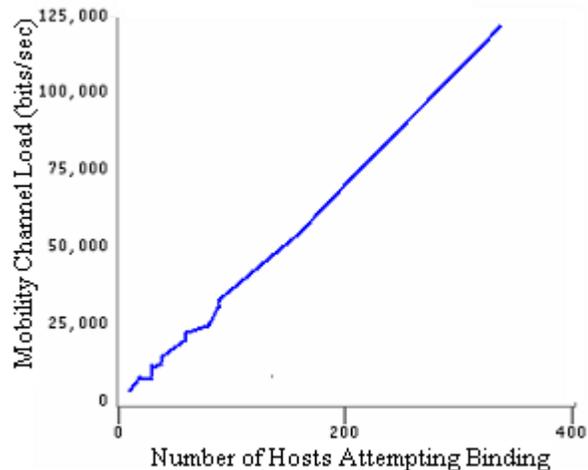


Fig. 2. Relationship Between Mobility and Bindings

IV. BASE STATION ROUTING

In the base-station model, we cannot guarantee the availability of a mobile router that is one hop from all other routers; hence, the single Designated Router (DR) used in standard OSPF was eliminated. To compensate for the lack of a centralized routing database, each router has to exchange topology information with every other router it can directly reach to form an adjacency, thereby creating dynamic point-to-point links between all routers in a range. With this capability, each router is represented as a vertex and the dynamic link as an edge on a topology graph.

If this were implemented using a wire line version of OSPF, the communication complexity would be $O(N \times E)$, where N is the number of routers and E is the number of links [15]. Since wireless transmissions can often reach multiple destinations, it is hypothesized that communication complexity in the wireless model should not exceed the wire line model.

Routing Scalability Analysis

To simulate mobility conditions for the routers, we established an initial topology of 20 routers configured in a linear path; the distance within the routers was set at 250 meters. Based on maximum communication range limits that we set, only adjacent routers could communicate with each other. Then, in successive 3-minute intervals and from left to right, the routers moved until there was an overlap in physical location, creating new adjacencies each time. The effect of this mobility scenario was to change

and create new adjacencies, thereby allowing us to analyze the respective OSPF traffic overhead [Hello and Link State Update (LSU) messages].

The routing update time as it relates to the number of adjacency (router) changes is given in Figure 3. The intervals associated with link state updates due to adjacency changes and router movement range from 7 to 28 seconds. There appears to be no relationship between number of adjacency changes and associated update interval. In a reverse experiment, represented by the dotted line in Figure 3, the adjacencies were reduced from the maximum of 18 to 2; similar results were found. Similar observations were noted for experiments involving 5 areas (55 routers including 5 gateway routers). Therefore, the OSPF update interval time does not depend on number of adjacency changes.

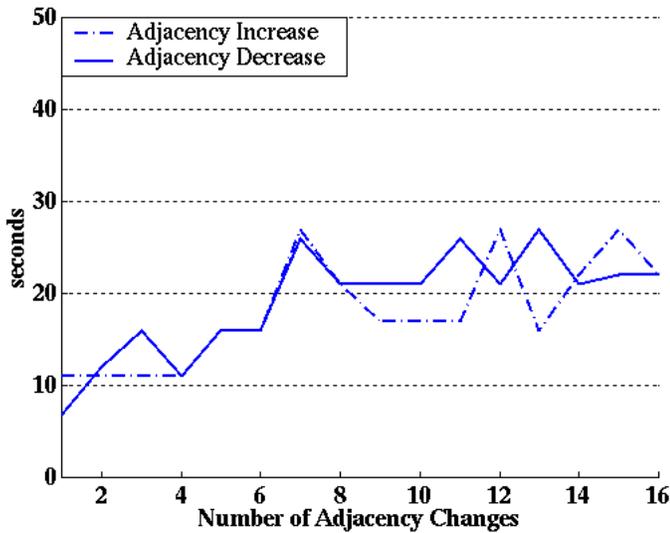


Fig. 3. Routing Update Time

Figure 4 below shows the total number of messages transmitted as a function of adjacency changes. As the number of adjacency changes increases, the number of OSPF message exchanges increases. As in the previous analysis, similar observations were noted for experiments involving 5 areas (55 routers including 5 gateway routers). Our observations on communication complexity support the earlier hypothesis that wireless networks can exploit the ability of a single wireless transmission to reach multiple destinations.

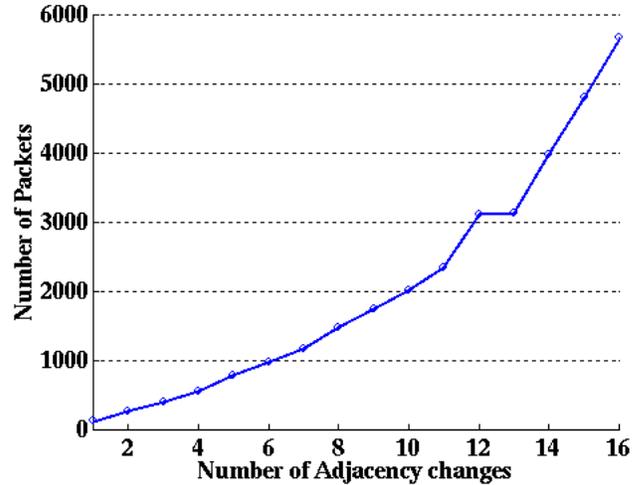


Fig 4. OSPF Message Complexity

V. PERFORMANCE OF COMBINED MOBILITY AND ROUTING MODELS

A combined experiment was designed to test the scalability of both routing and mobility protocols using traffic based on the File Transfer Protocol (FTP) and the Transfer Control Protocol (TCP). In a large-scale scenario, simulated for 15 minutes of real time, we configured five OSPF areas – each area or subnet included 10 routers and 10 hosts affiliated with each router, and both routers and hosts were assigned trajectories that resulted in the linear movement of the nodes. Within each of the areas, we distributed five FTP servers to generate application traffic. A backbone LAN consisting of five gateway routers, which had an interface to both the respective area router backbone and to the gateway router backbone (see Figure 1), was also included. However, this backbone of 5 gateway routers was implemented as an Ethernet. Nevertheless, it should have no real effect on the results as these gateway routers are not mobile, and, in effect, are fixed wireless. With the above configuration, the experiments included 500 hosts, 55 routers, and 25 FTP servers – the total number of nodes was 580 nodes. Hence, a unified wireless, mobile base station architecture was implemented, including full operation of physical, link, routing, transport and application protocols.

Application traffic generation by all hosts was based on file transfer requests to any of the 25 FTP servers, with 80% of traffic sent to servers destined within the originating area, and 20% was sent to servers destined across areas. The distribution of these requests was configured as exponential with mean of 5 minutes for light FTP and a mean of 1 minute for heavy FTP. The file size was fixed at 1500 bytes for light FTP traffic and 3000

bytes for heavy FTP traffic.

Figure 5 below shows the relationship between OSPF overhead and amount of application traffic (FTP data) as a function of time for this experiment. The OSPF and FTP traffic is averaged over 10 second intervals for the 15 minutes of simulation time. The OSPF overhead traffic is generally indistinguishable for both the light and the heavy load scenarios. This is to be expected as OSPF traffic is independent of application load (FTP traffic). As stated previously, OSPF overhead depends on the dynamic nature of the routers (i.e., router adjacency changes) and the number of routers in an area.

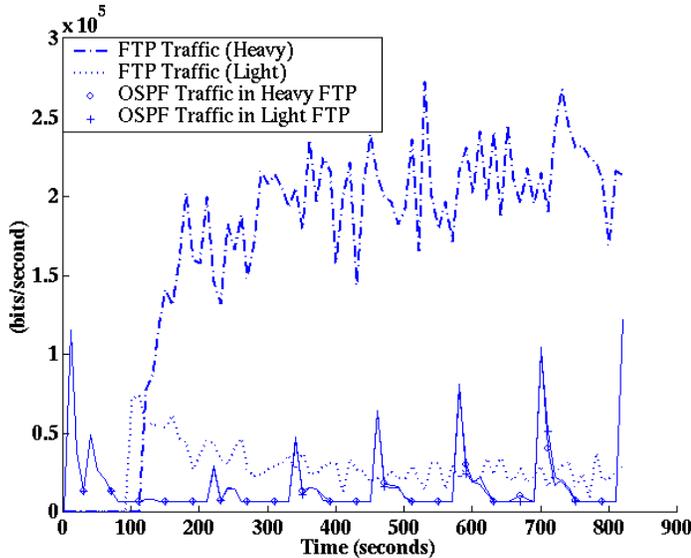


Fig 5. OSPF vs. FTP Traffic

Table 1 below summarizes the average traffic between heavy and light traffic (in bps). The overhead in the heavy traffic scenario is approximately 9.4% of the offered IP load but 40% in the light load. This indicates that overhead is relatively the same regardless of application traffic, but becomes less of a factor as traffic increases.

Table 1. OSPF and Application Offered Load(in bps)

	Avg. FTP	Avg. OSPF	OSPF/(FTP +OSPF)
Heavy FTP	167,884	17,392	9.4.%
Light FTP	26,210	17,396	40%

In Figures 6a and 6b, the aggregate offered load in the MAC layer for heavy and light FTP traffic scenarios and the respective packets dropped during the 15 minutes simulation is given. It is interesting to note while the load is increased by a factor of 6, in the case of heavy FTP

traffic relative to light FTP traffic, packet loss only increased by a factor of 3.6. This indicates that the network is not yet saturated and that capacity for increased offered load exists. Further empirical analyses are required to investigate this limit.

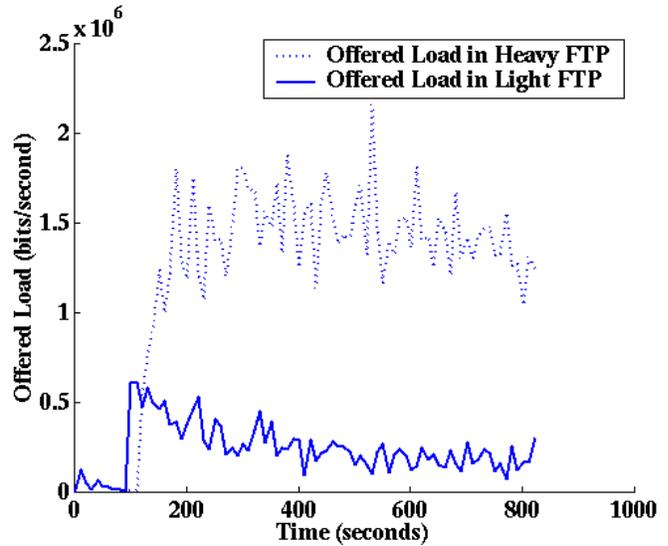


Fig 6a. Aggregate Offered Load (MAC Layer)

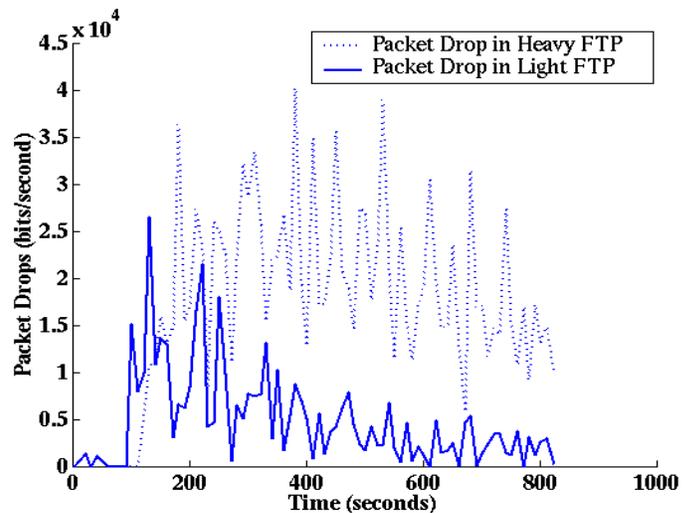


Figure 6b. Packet Drop

As noted in Table 2, the relative packet loss rate for both scenarios is not significant. Therefore, OSPF overhead and packet loss rate are nearly the same for a wide range of

application traffic.

Table 2. Offered load and packet lost

	Avg. offered load (bps)	Avg. packet lost (bps)	Packet loss rate
Heavy FTP	1419045	19774	1.4%
Light FTP	265165	5434	2%

VI. SCALABLE ENERGY-EFFICIENT SESSION-ORIENTED BROADCASTING AND MULTICASTING

In this section, we address the problem of broadcasting in all-wireless (i.e., infrastructure less, ad hoc, or peer-to-peer) networks with omni directional antennas, and we focus on the case of session-based (i.e., circuit-switched) traffic. A desirable goal is energy efficiency. We consider two basic approaches:

- a common backbone network;
- a source-based tree.

In the first approach, a common backbone network is used to support all broadcast sessions, regardless of the source node. The use of a common backbone network is attractive because (as long as connectivity remains stable) it does not require recomputation for each newly arriving session request. For example, the Linked-Cluster Algorithm (LCA) [10] can be used to set up such a backbone network. Using the LCA, in a network consisting of N nodes, a set of cluster heads (and gateways to link them) can be determined in two TDMA frames of N slots each. After a total of five such TDMA frames, a complete backbone network structure can be determined in which all nodes are within direct communication of a backbone node. Thus, the time complexity of the LCA is linear. But, since the computation at each node is proportional to N , the overall computational complexity (summed over all nodes) is $O(N^2)$. Although this order of complexity is relatively low by algorithmic standards, the resulting time complexity is impractical for large values of N ; e.g., if time slots of length 10 ms are used, for $N = 100$ each frame would have a length of 1 second. A simple approach to reducing the overall execution time is to limit the number of nodes that actually take part in the LCA. This can be done by locally choosing such nodes, based on the interchange of connectivity information.

Three highly desirable characteristics of the LCA are that it is fully distributed, it has a fixed manageable overhead, and that it has a fixed time to completion. No prior knowledge of node locations is needed; connectivities are discovered in the course of the execution of the algorithm, which can be re-executed periodically to respond to

changes in connectivity. The LCA does not actually optimize a performance index (such as energy expenditure); its function is to create a backbone network whenever the connectivities needed to support it are available. Furthermore, the backbone produced by the LCA is not necessarily a tree; it may have some loops. To eliminate such loops, we apply Prim’s algorithm to the set of links in the backbone to produce a minimum-power tree.¹ The computational complexity of Prim’s algorithm is $O(N^2)$, where N is the number of links in the backbone, not in the complete network.

In the second approach, a tree is constructed for each newly arriving session request. The Broadcast Incremental Power (BIP) algorithm [5] is a heuristic that tries to minimize energy expenditure in the tree. It exploits an important property of wireless omni directional communications, namely the “wireless multicast advantage,” which permits several neighboring nodes to receive the same message without additional expenditure of transmitter power [5]. In [7] it was shown how the residual energy at the nodes can be included in the cost function, resulting in significantly extended network lifetime. The advantage of source-based trees is that better trees are formed for each session. The disadvantages of BIP are that it is centralized, it requires knowledge of the RF power required to form links between all pairs of neighboring nodes, it must be executed for each new arrival, and that its complexity is $O(N^3)$.

An alternative approach for broadcasting is the Broadcast Link-based Minimum Spanning Tree (BLiMST) algorithm [5], whose complexity is $O(N^2)$. BLiMST is based on the use of the standard MST formulation (as in wired networks) in which a link cost is associated with each pair of nodes (i.e., the power to sustain the link). Thus, the wireless multicast advantage is ignored in the construction of the MST. Advantages of BLiMST are that it can be implemented in a distributed manner, and that the resulting tree is the same for each possible source node; thus, it does not have to be re-executed for each source as long as connectivity remains constant. However, like BIP, it does require nodes to know the required RF transmitter power to reach each of their neighbors.

In highly dynamic networks, response to mobility is a difficult problem. Of the algorithms we have considered, the LCA is the most robust (in terms of maintaining connectivity) because it provides a mechanism for nodes to discover their neighbors as they form the linked cluster structure. BIP and BLiMST can benefit from the type of message exchange used in the LCA’s TDMA frame

¹ This tree has minimum power among the set of broadcast trees that contain a subset of the links in the backbone. This approach ignores both the availability of additional links, as well as the wireless multicast advantage, which is discussed shortly.

structure.

Wireless Networking Issues and Complexity

Although some networking models and protocols that were developed for wired applications can be adapted to wireless networks, they do not reflect properly the properties of the all-wireless network environment and cannot be expected to provide nearly optimal performance. Wireless networks that use omni directional antennas may be viewed as being *node-based*, whereas wired networks are *link-based*; these concepts are defined in [5].

The problem of multicasting in wired networks has been studied extensively in recent years. It is well known that the determination of optimal multicast trees in wired networks is equivalent to the NP-complete Steiner Tree problem [16] even though the determination of optimal broadcast trees in such networks can be formulated as the minimum-spanning-tree (MST) problem, which has relatively low complexity $O(N^2)$, where N is the number of nodes in the network]. By contrast, for wireless networks we do not know of any scalable solutions even for the determination of optimal (e.g., minimum-power) broadcast trees, and we conjecture that this problem is NP-complete; moreover, the multicasting problem is certainly at least as difficult as the broadcasting problem (based on insight obtained from wired network examples).

Here, we compare the average total power of broadcast trees produced by three algorithms, namely the LCA backbone, BLiMST, and BIP. Recall that the computational complexity of the first two is $O(N^2)$, while that of the third is $O(N^3)$. Also note that LCA and BLiMST are distributed algorithms, while BIP is centralized.

In our experiments the nodes are randomly located in a region with dimensions 5 by 5 (arbitrary units of distance). The same node locations are used in all of our examples to permit a fair comparison of the algorithms. We let $\alpha = 2$, i.e., the required RF power value is r^2 , where r is the transmission distance.

To evaluate performance for BIP and BLiMST, we form N broadcast trees, each rooted at a different node, and then take the average value of total transmission power in all such trees.

For the LCA, the situation is a bit more complicated. For example, since the backbone produced by the LCA is not necessarily a tree, we have applied Prim's algorithm to it to eliminate loops, as discussed in the previous section. The LCA differs from the other algorithms in that it assumes a specific value for transmission power (the same for all nodes) when constructing the backbone; however, when evaluating tree power, we reduce the nodes' power to the minimum value needed to reach all of the nodes they

are supposed to reach. Additionally, the structure of the backbone network depends on the node numbering (unlike BIP and BLiMST). To eliminate the impact of specific node numberings, we have averaged our results over 180 randomly generated sets of node numberings (for the same node positions).

Table 1 shows the average broadcast power for LCA, BIP, and BLiMST as the number of nodes in the network varies from 10 to 150. Thus, we are increasing the *density* of nodes in a region of fixed size. In evaluating the performance of LCA, runs were made for several communication ranges (which were the same at each of the network nodes) to search for the best communication range for a network of that size (i.e., the communication range that results in the lowest overall power). Typically, the best communication range results in the formation of several clusters to cover the 5 by 5 region described above. It is not surprising that the best performance is provided by BIP, which is a node-based centralized algorithm with computational complexity of $O(N^3)$. By contrast, both LCA and BLiMST are distributed, and have computational complexity of $O(N^2)$. The performance of BLiMST is not much worse than that of BIP. Thus, we have a trade-off between complexity and performance, i.e., better performance (lower-power trees) is obtained at the expense of additional computation.

Table 3 — Average broadcast tree power for LCA, BIP, and BLiMST as a function of network size

# of Nodes	LCA	BIP	BLiMST
10	15.41	11.47	12.90
50	16.46	10.35	12.13
100	19.29	10.10	11.44
150	18.37	10.54	11.52

VII. CONCLUSIONS

Our results confirm the scalability of the base-station oriented model, using large numbers of dynamic hosts and routers. The design of the routing and mobility protocols in a hierarchical network should contribute to performance and complexity scalability.

Enhancements that we made to the OPNET wireless software modules as well as to our mobility and routing models greatly eased the modeling of dynamic, wireless networks.

We determined that the wireless OSPF update interval time does not depend on the number of adjacency (mobility) changes. In addition, the communication complexity mentioned in Section IV does not exceed that

of wire line complexity.

In a unified, systems-oriented, large-scale simulation experiments, the routing overhead due to wireless OSPF remained constant regardless of the amount of application traffic. Furthermore, for a wide range of application traffic load, OSPF traffic and relative packet loss rate remained relatively the same. This supports the scalability of our approach.

We have studied the scalability and performance properties of three algorithms for energy-efficient wireless multicasting, and have discussed some of the trade-offs in terms of complexity, robustness, and performance. For example, the best performance is obtained by the incremental power algorithm, which has the highest computational complexity and requires complete knowledge of the required communication power to implement connectivity. On the other hand, the one based on Prim's algorithm, which is distributed and has lower complexity performs nearly as well. Finally, the algorithm based on the linked cluster architecture (which also has relatively low complexity) provides a means to maintain network connectivity in dynamic scenarios, but does not inherently optimize any performance index.

This study has provided greater insight into the issues associated with complexity versus performance trade-offs in wireless networks, and suggests that good performance can, in fact, be achieved with scalable network algorithms and architectures.

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