INTEGRATING SHORT-RANGE AD-HOC RADIO TECHNOLOGIES INTO NEXT-GENERATION WIRELESS NETWORKS[1]

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Abstract

This paper considers the use of short-range ad-hoc radio technologies for next-generation wireless networks. In particular, we examine the application of 802.11 WLAN radios to construct metropolitan area mesh networks of particular interest for rapid deployment of broadband Internet access in developing countries like India. A system model for an 802.11 metro-area mesh is developed and used to estimate capacity, performance and cost for sample scenarios. Enabling technologies for mesh networks such as topology discovery, self-organization and multi-hop routing are discussed and open technical problems and solutions are identified. A specific system design based on WINLAB's self-organizing hierarchical ad-hoc network (SOHAN) prototype is presented. System-level experimental prototyping results using the ORBIT radio grid emulator testbed as a platform are provided as a proof-of-concept validation.

I. INTRODUCTION

Wireless technologies have become an increasingly important component in public access networks because of several advantages including rapid deployment, low capital investment cost, high statistical multiplexing of resources, and portability of user terminals. For example, WLL systems such as PHS [1] and digital cellular systems such as GSM and CDMA are considered to be viable alternatives to wired infrastructure for telephony and low-speed data applications and many such systems have been deployed worldwide [2,3,4]. The growing demand for high-speed Internet access services can be met by a number of wired technologies such as fiber PON [5], DSL [6], digital cable [7] and power-line [8], but the high capital investment required for each of these is considered to be a barrier to timely deployment. As a result, there is a great deal of interest in high-speed wireless Internet access solutions that can be deployed quickly and have modest capital costs for entry. Wireless options under consideration include third-generation cellular approaches such as CDMA-2000 [9] and UMTS [10], wireless local loop (WLL) approaches such as 802.20 [11] and 802.16a [12] and short-range 802.11-based solutions. Each of these approaches has relative advantages and disadvantages in terms of capital cost, system capacity and end-user quality-of-service (QoS). Although the above wireless solutions are still at an early stage, wireless technologies hold out the promise of an order-of-magnitude or better improvement in cost/performance for high-speed access networks, and are thus of particular importance to developing countries.

In this paper, we investigate the use of mesh networks formed by low-cost short-range 802.11x radios as a system solution that provides scalable network capacity that grows with the number of subscribers, while also requiring a relatively low capital investment in network infrastructure and end-user terminal devices. The basic concept of the mesh network is to use multi-hop packet communications between large numbers of subscriber nodes and relay nodes so as to cover the entire service area without the use of centralized base stations (BTS) or access points (AP). The mesh network concept, which originated with tactical networks used in military applications [13], uses distributed ad-hoc network protocols to create a self-organizing and robust system without requiring a centralized wired infrastructure. Mesh networks with 802.11 radios can provide significant capacity and service quality advantages over single-

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hop WLL or extended WLAN approaches because they take advantage of the fact that achievable radio bit-rates to relay neighbors tend to increase exponentially with node density, thus making it possible to operate each ad-hoc network link at relatively high-speed (e.g. 11-54 Mbps for 802.11a/b/g radios). Even after accounting for the increased overhead of multi-hop networking, the higher speed on each radio link results in a significant increase in system capacity (as measured in Mbps/sq-Km) relative to more traditional WLL or extended WLAN approaches.

Ad-hoc mesh networks have been studied at the research level for over a decade [14,15,16,17,18], and many of the component protocols and routing algorithms are well understood. A number of research prototypes have also been built, including MIT RoofNet Project [19], Ad-Hoc Protocol Evaluation Testbed at Uppsala University [20] and WINLAB's Self-Organizing Hierarchical Ad Hoc Wireless Network [21]. With the availability of low-cost 802.11 radios that can be used in the ad-hoc model, it has now become possible to actually deploy both 802.11 WLAN and ad-hoc mesh networks in public access scenarios. Several projects aimed at applying 802.11 radio technologies for urban or rural public Internet access have been reported, with some of the notable ones being the Taiwan CyberCity project [22], the Locust World project [23] and the Digital Gangetic Plain project [24]. Based on early results reported by these and other projects, it is clear that 802.11 WLAN and mesh solutions are extremely promising for delivery of high-speed Internet access services in dense urban/metropolitan and possibly also suburban areas.

This paper starts with a review of prior work on 802.11 mesh systems for public Internet access applications. We identify serious capacity scaling and performance limitations of the conventional "flat" mesh network and describe a novel hierarchical approach currently under development at WINLAB. The proposed hierarchical approach organizes mobile nodes (MN), forwarding nodes (FN) and access points (AP) into a three-tier hierarchy that significantly improves achievable capacity, coverage and QoS. We also provide some insights into the issues related with the design of such hybrid mesh networks including neighbor discovery, media access control issues as well as multi-hop routing architectures that support the QoS requirements of different applications. A system model for determining the number of FN's and AP's required for a typical urban coverage area using extrinsic parameters such as the density of users, area of coverage, penetration, traffic profile, etc. is also presented. Using design guidelines obtained from this system model, we conduct realistic proof-of-concept experiments for a scaled version of typical urban wireless usage scenario using WINLAB's 64 radio-node wireless experimental ORBIT testbed [25]. Results for system performance are given in terms of network throughput, average end-to-end delay and packet loss. Our results show that the proposed hierarchical mesh network can achieve good coverage and capacity properties suitable for urban and dense suburban deployments at relatively modest capital equipment and operating cost levels.

II. 802.11 BASED TECHNIQUES FOR WIRELESS INTERNET ACCESS

In this section, we briefly discuss the existing 802.11 radio based approaches for metropolitan wireless access broadly classified into two categories: Infrastructure-mode WLAN based and ad-hoc based multi-hop mesh-based wireless access.

A. *Infrastructure WLAN Based Wireless Access*

Pure infrastructure-based AP deployments provide users with wireless access within their areas of coverage as shown in Fig 1 below. Each AP is configured to operate on a specific channel and serves a limited number of clients within its coverage area. It is connected to the backbone network through Ethernet, DSL or cable modem connections. Deployments are usually preceded by some site specific spectrum measurements to build a coverage map for specific AP locations. Based on these studies, the APs are appropriately located and assigned channels so as to maximize coverage, capacity and minimize interference with neighboring APs.

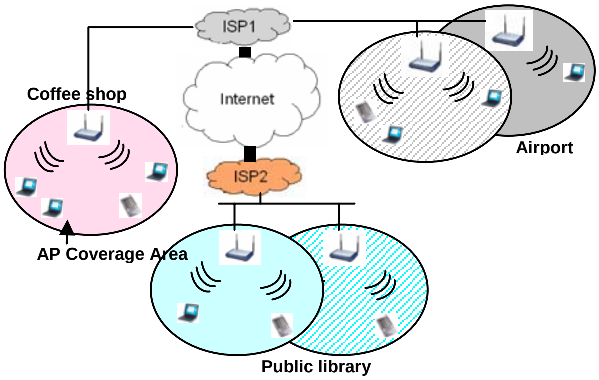

Figure 1 Fixed Wireless 802.11 Infrastructure Mode Based Access

Some metropolitan areas such as Philadelphia, San Francisco, Taipei are following the approach of deploying thousands of access points throughout the city to provide city-wide high speed wireless Internet access. Taipei's CyberCity project aims to make Wi-Fi ubiquitous outdoors. The city-wide network will consist of at least 20,000 access points. However, in this approach, there are a few considerations that must be taken into account. City-wide ubiquitous coverage will also cause interference with other private wireless networks and even home appliances. This approach also assumes that wired backbone connectivity is readily available at every access point location, which may not be necessarily true in developing countries. It is noted that the capital cost requirements for this approach are relatively high because of the large number of wired access points.

B. Ad-Hoc Mesh Networks

Hybrid mesh networks, as shown in Fig. 2, provide an alternate to the above infrastructure AP-based approach. Here, the idea is that individual devices connect to each other through other devices within their radio range using ad-hoc mode of operation [26]. Each device has to manage and maintain known optimal paths, which can change very often due to mobility in order to route data traffic to the particular node that provides access to the external IP backbone. Since user traffic can be relayed using multi-hop links, there is no need to provide wired backhaul connection to every node. Thus, one could deploy a WLAN mesh to provide service over a large geographic area, but with only very limited backhaul connections. Since, there are a large number of nodes, meshes can adapt to route failures by re-routing traffic dynamically through other nodes within coverage.

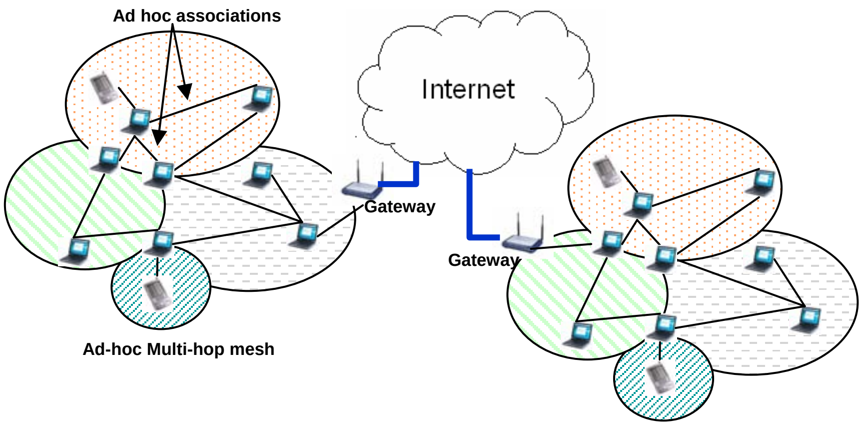

Figure 2 Ad-hoc Mesh network with multi-hop connections to gateway

The mesh network however needs a routing infrastructure that forwards traffic between mesh nodes, detects link outages and re-routes data. Multi-hop links also introduce variable delay which may affect voice and video traffic. Also, in the absence of incentives, intermediate nodes may be unwilling to forward packets for other nodes because they have to spend their resources for forwarding these packets. Finally, security may be a concern if user traffic is flowing through intermediate nodes in a mesh.

Intermediate nodes might be able to eavesdrop on data not intended for them. We describe a few such mesh networks currently deployed.

1. MeshNetworks™

MeshNetworks is a mesh network technology with proprietary radios, routing protocols as well as transport protocols that is together known as MEA (MeshNetworks Enabled Architecture). The primary target for this product is delay-sensitive applications such as police, emergency response services and the products are customized for minimum delay performance. This solution is designed with specific applications in mind using proprietary radios, MAC, routing as well as transport layer mechanisms [27, 28] and may be expensive to be deployed for more general community wireless usage.

2. LocustWorld Project

The LocustWorld Mesh is a community wireless mesh network using 802.11 radios and standard routing protocols such as AODV. Users can participate in this mesh by simply downloading the mesh software on their devices and connecting to the mesh using wireless cards. Recently, a voice over WLAN support was also announced by this project using SIP messaging. An issue with mesh topologies described above that are based on a flat peer-to-peer communication model is that they do not scale well due to multi-hop routing overhead. As shown by Gupta and Kumar [29], for n nodes with a common transmission rate, W over the wireless channel, the asymptotic throughput per node is $\Theta\left(W/\sqrt{n \log n}\right)$, which goes to zero with increasing number of nodes for such a flat architectures. Subsequent work by Towsley [30] has shown that for a hybrid network with n nodes each transmitting at W bps, if more than m= $\sqrt{n}$ base stations are added, then the maximum capacity scales linearly as $\Theta(mW)$. This indicates that a proper mix of wired access points and wireless relay nodes is required to achieve capacity scaling in mesh networks, and is a topic that needs further work.
All the above approaches to provide metropolitan wireless access to end-users have some limitations as described above. In the next section, we propose a short-range radio based mesh network architecture to address the shortcomings of the above approaches.

III. WINLAB'S HIERARCHICAL MESH NETWORK ARCHITECTURE

Our approach is based on a multi-tier hierarchy that scales well and integrates naturally with existing wireless access points or base stations, while retaining much of the robustness, coverage and power advantages of ad-hoc wireless networks. This architecture is applicable to a number of emerging ad-hoc networking scenarios including extended wireless local-area networks, home wireless networks and large-scale sensor networks. In each of these scenarios, the introduction of one or more tiers of ad-hoc forwarding nodes (FN) as intermediate radio relays between the MNs and APs helps to scale network throughput, reduce delay and lower power consumption at end-user devices. In this section, we present the system design details, protocols for self-organization, node discovery, and routing as well as a proof-of-concept system implementation. The hierarchical approach proposed (henceforth referred to as SOHAN) is based on the following components.

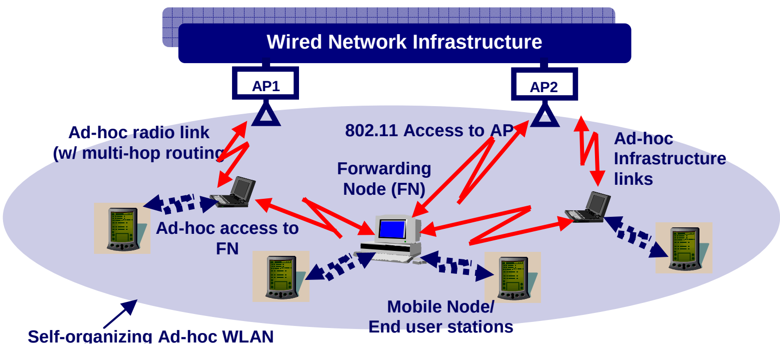

Figure 3 Hierarchical architecture with short range radios

A. System Components

The tiered hierarchical ad-hoc network consists of the following components: End-user "mobile nodes" (MN) at the lowest tier (which could be laptops, PDA's or other handheld devices with an 802.11 interface), higher powered radio "forwarding nodes" (FN) that support multi-hop routing at the second level, and wired access points (AP) at the third and highest level act as Internet gateways for the infrastructure. Each of the network entities in the proposed system is defined in further detail below:

Mobile Node (MN), is a mobile end-user device (such as a laptop or a personal digital assistant) at the lowest tier (tier 1) of the network. The MN attaches itself to one or more nodes at the higher tiers of the network in order to obtain service using a discovery protocol. The MN uses a single 802.11b/g radio operating in ad-hoc mode to communicate with the point(s) of attachment. As an end-user node, the MN is not required to route multi-hop traffic from other nodes. It is noted that as a battery-operated end-user device, the MN will typically have energy constraints

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. A forwarding node with one 802.11 radio interface uses the same radio to connect in ad-hoc mode to MNs, other FNs and the higher-tier APs defined below. Optionally, an FN may have two radio cards, one for traffic between FNs and MNs and another for inter FN and FN-AP traffic flows (typically carried on a different frequency). The FN is typically a compact radio device that can be plugged into an electrical outlet, but in certain scenarios, may also be also be a battery-powered mobile device. Thus, the FN is also energy constrained, but the cost is typically an order of magnitude lower than that of the MN defined above.

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 is capable of connecting to any lower tier FN or AP within range but unlike typical 802.11 WLAN deployments, it operates in ad-hoc mode for each such radio link. The AP also participates in discovery and routing protocols used by the lower tier FNs and MNs, and is responsible for routing traffic within the ad-hoc network as well as to and from the Internet. Since the AP is a wired node, it is usually associated with an electrical outlet and energy cost is thus considered negligible.

B. Protocols

The following protocols are proposed to enable the mesh network architecture. *Note that security and management layers have been omitted here.* The protocols include mechanisms for bootstrapping whenever the nodes are powered ons, methods for neighbor discovery as well as multi-hop routing that are used to find paths from the sources to the sinks that are connected to the backbone. We assume that a suitable naming convention (either IP address based or node ID based) is used to address the nodes and the discovery and routing protocols described later are consistent with this convention. The protocol stack at each node is shown in Fig 4 below.

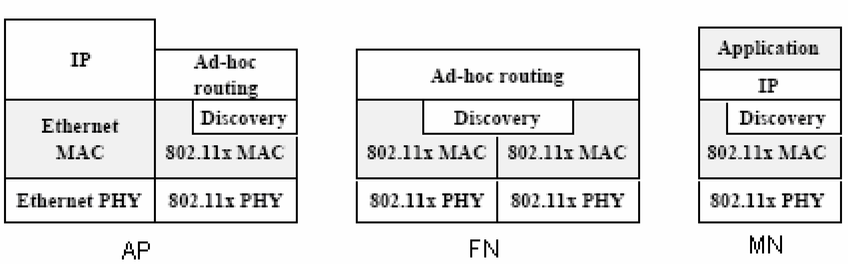

Figure 4 Protocol Stack at each node

1. Bootstrapping Mechanism

The bootstrapping can be thought of as a process by which a mesh node becomes aware of itself and its surrounding when powered on. The information about initial transmit power levels as well as frequency assignment could also be passed on additionally along with the node identifier. This information could be obtained from some DHCP-like spectrum server based on its perception of the current spectrum usage in the particular geographic area. Alternatively as described in [31], this could be done in a distributed manner at each node, by briefly scanning the environment across all channels and estimating ongoing "activity" across different channels. The channel with least activity could be used for communication. To estimate the power level, a few probe messages could be sent to a dummy sink and based on the feedback received from the sink, the node can adjust its power level accordingly.

2. Discovery

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. 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. Also, some of the proposed approaches consider that the nodes in the network are homogeneous and hence make the same routing decisions based on some common metric. The discovery protocol allows heterogeneous nodes to make local decisions based on their constraints to control topology formation by associating with only a subset of nodes. For example, nodes at the lowest tier that are power constrained may choose to associate with "nearby" FNs or APs in order to reduce their local power consumption, where as the nodes at the second tier (FNs) may choose neighbors that minimize the distance towards the AP. In our prototype implementation [32], we use augmented 802.11 beacons and associations to support neighbor discovery and determination of the logical topology. Note also that for ease of implementation, the beacons used in the prototype are application-level packets, since actual 802.11 beacons are generated by the firmware in most of the existing 802.11 a/b/g network adapters do not allow modification of these packets. The beacon format in SOHAN is shown in Fig 5.

```
typedef struct wl_beacon
(or wl_assoc)
{
  uint32 msg_type;
  uint32 node_type;
  uint32 node_id;
  uint32 channel;
  uint32 beacon_no;
}wl_beacon (or wl_assoc);
```

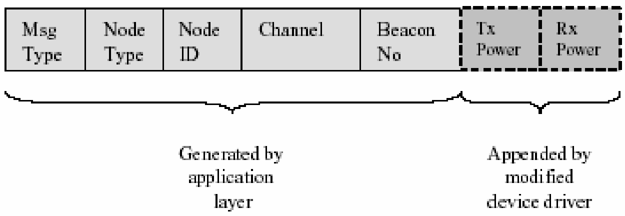

Figure 5 Beacon and Association Message Format

As shown in Fig 6, the FNs and APs periodically send beacons while the MNs scan different channels listen to the beacons and send an association message to the best "cost" parent using the discovery metric described below.

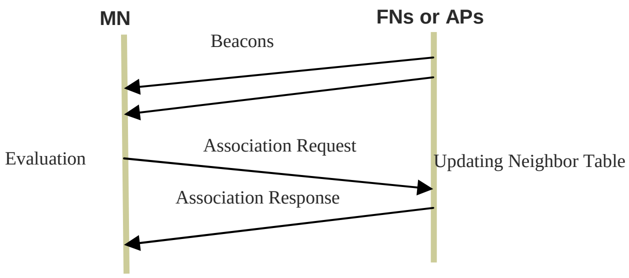

Figure 6 Discovery Protocol handshake

Discovery metric: The discovery metric can be chosen according to the local constraints at each node. For example, end user devices such as laptops, PDA's that typically run on battery power may choose to associate with an FN or AP that takes minimum transmit power to reach. In our prototype implementation, we use augmented beacons as shown in Fig. 4 and append transmit power to each outgoing beacon from the FN/AP while the MN that receives the beacon appends the received power for that packet. Using this information and assuming symmetric link between FN/AP and MN, the MN chooses the parent with the maximum received power/transmit power ratio as its neighbor.

3. Integrated Discovery/Routing Schemes

The "logical" topology information obtained during the discovery phase is used to create and maintain local neighbor tables at each of the FNs and APs. These neighbor tables are then exchanged using a proactive routing protocol such as DSDV. The neighbor table format is shown in Table 1. Each entry is associated with a refresh timer that is reset or decremented respectively based on whether or not beacons are received from that neighbor every beacon interval. FN and APs exchange their local neighbor tables based on this exchanged information.

Table 1 Local Neighbor Table Format

MAC Addr	Node Type	Refresh Timer	Channel to Next Hop	Cost to Dest	Interface to next Hop	Next Hop

The MNs are not involved in the routing mechanism and simply forward their data to the best cost parent selected by the discovery procedure.

Note that any existing proactive (DSDV) or reactive (DSR, AODV) routing mechanism can be implemented on top of our discovery mechanism. For DSDV, the "forwarding table" at each node could be replaced by the neighbor table provided by discovery, while in AODV (or DSR), the route requests could be propagated only to a subset of nodes as selected by the discovery mechanism. After the table exchanges, each FN computes a path that it can use to route data to the AP. The FN maintains a latest "best" path towards the AP at every instant and whenever it receives data packets (originated at the MNs), it consults the neighbor table to forward the data to the next hop on the appropriate channel and interface. If an FN is disconnected from the network (there is no entry for an AP that exists in its neighbor table), it discards the packet and indicates a routing failure. Note that this routing implementation is based on the assumption that most of the traffic flow is from the MNs to the APs.

C. SOHAN Prototype Implementation

The implementation of the SOHAN prototype was done using C programming on embedded devices running Linux. The software architecture and the hardware platforms are discussed below.

1. Software Architecture and Protocol Implementation

We used the Libnet [35] and Libpcap [36] open-source libraries to generate, send and receive custom packets. Fig. 7 shows the software architecture of the prototype.

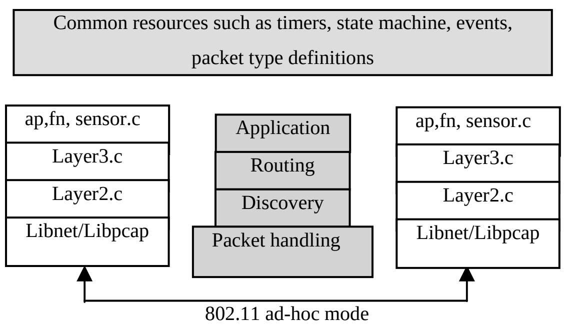

Figure 7 Software architecture of SOHAN

The modular software design as described below is consistent with the protocol stack and thus provides an easy way to modify functionality and add features at any layer

- **Physical Layer**: The functionality of transmitting and receiving packets is handled using Libnet and Libpcap packet handling libraries that provide a simplified interface for low-level network packet shaping, handling and injection.
- **Layer2.c**: This layer handles the discovery layer functionality. Whenever a packet arrives from the lower layer, this layer handles the packet processing and passes the information to the higher layers.
- **Layer3.c**: This layer is responsible for handling the maintenance of the local neighbor tables and periodic exchange of neighbor tables amongst one-hop neighbors. The neighbor table is maintained and updated based on the beacons and the associations that are received from layer2.c. Upon the expiration of the route update timer, a periodic neighbor table exchange takes place. Entries are purged upon expiration of the refresh timer.
- **Application Layer** (Sensor.c, fwnode.c, ap.c): This layer handles the application specific functionality that depends on the type of the nodes.
- **Common functions**: The common functionality such as timer management, event management, finite state machine, packet type definitions and common wireless utilities is handled by programs common to all layers.

2. Hardware Platforms Used

The APs were based on a US Robotics 2450 Access Points running customized AP code for ad-hoc mode. The FNs were built on Compulab 586 CORE platform running a 133 MHz processor with two PCMCIA slots for two wireless interfaces. The MNs were built on the embedded Cerfcube platform and were battery operated. The selection of the hardware platforms was consistent with the system architecture and operated under the same set of constraints at each tier. Fig. 8 captures the different platforms used for the devices. Further details can be found in [21].

AP FN MN

Figure 8 Hardware platforms used for SOHAN prototype at WINLAB

IV. A SYSTEM MODEL FOR URBAN 802.11 BASED WIRELESS ACCESS

In this section, we propose a system model for provisioning 802.11-based infrastructure using our hierarchical architecture for a typical urban coverage scenario. We use the underlying assumption that deploying APs incurs a relatively high cost considering that it needs to have backbone access to the Internet. FNs are lower than the APs in terms of the cost since they do not need backbone access. As per our system design, only the FNs and the APs participate in the ad-hoc routing. The system model uses a few extrinsic parameters such as coverage area, density of users, service penetration, peak and average bandwidth requirements of end user applications as inputs and calculates the approximate number of FNs and APs for supporting the required capacity and coverage. Also, the appropriate number of backhaul links for capacity provisioning is calculated. This output can be used to derive the approximate cost of deployment based on typical costs of commercial off-the-shelf products.

A. Choice of system parameters

To provision adequate number of FNs and APs for coverage and capacity, a careful consideration of the system parameters is needed. We make the following assumptions.

1) User Density: We use the numbers from the last census[2] to estimate the average density of population per square km. The user density is assumed to be uniform at 250 users/ sq.km.

2) Service penetration: This system takes into consideration that initially about 10% of the users will make use of the wireless access and this number will gradually grow to about 50%. Hence, we design the system based on a 10%-50% usage.

3) Area of coverage: A small town (2.5Km x 2.5Km in size) is considered for this system model.

4) Coverage percentage: We provision the system to cover about 75% of the potential user population.

5) Average and Peak Bandwidth requirements per user: In [33], the authors characterize user behavior collected from user traffic traces in a typical WLAN environment and report the peak and average bandwidth requirements for a scenario with 32 Access Points and 195 users. The authors have translated actual traffic from various applications such as HTTP, SSH, FTP, Email into peak and average bandwidth requirements per user for low, medium and high loads taking into account typical duty cycles of these applications and usage profiles. We use the results for the low load case in our analysis corresponding to an initial usage scenario in India. Table 2 summarizes our choice of parameters.

Table 2 System parameters

Coverage area	2.5 km × 2.5 km = 6.25 sq km.
Typical outdoor coverage of an 802.11b/g FN or AP	~250 meters@11 Mbps ~500 meters@1Mbps
User Density per sq km	250
Service penetration	10 - 50 %
Desired coverage	~75%
Average bandwidth per user	15 Kbps
Peak bandwidth per user	50 Kbps
Average number of users in the system = Density of population × Coverage Area × Penetration	250×6.25×0.1 ~ 156 (10% penetration) 250×6.25×0.5 ~ 780 (50% penetration)
Average system bandwidth required	156×15 Kbps = 2.34 Mbps (10% penetration) 780× 15Kbps = 11.7 Mbps (50% penetration)
Peak system bandwidth requirement	156 × 50 Kbps = 7.8 Mbps (10% penetration) 780 × 50 Kbps = 39 Mbps (50% penetration)

B. Coverage: Number of FN's and AP's

In our model, the problem of coverage is handled by provisioning enough FNs while the issue of capacity is dealt with by having the required number of APs and backbone links. We use MATLAB simulations to generate a uniformly distributed population of *n* users in the square grid of the size mentioned above. We then add a few FNs uniformly in the grid and keep increasing the number of FNs until 75-80% of the population is in range of at least one FN. The transmission range of each FN is about 250m and we use r=2 as the path loss exponent. This simplifies the analysis to calculating Euclidean distance between the users and the FNs. The results are averaged over several hundred simulation runs to get a range for the number of FNs needed to cover the area.

We consider two cases: 1) when the number of users is 156 and 2) when the number of users is 780 corresponding to 10% and 50% service penetration. We find that for the first case, roughly 35 FNs were needed to cover 77% of the users such that the average number of users per FN was about 4. For the second case, the number of FNs to cover the area is ~55 such that the average load per FN is about 11 users. Note that if we use lesser number of FNs, we may still cover the area, however the average load per FN will be higher, leading to more contention and hence poorer system throughput. The coverage map for these runs is shown in Fig 9.

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[2] Based on reports from Census 2001, http://www.mapsofindia.com/census2001/populationdensity.htm

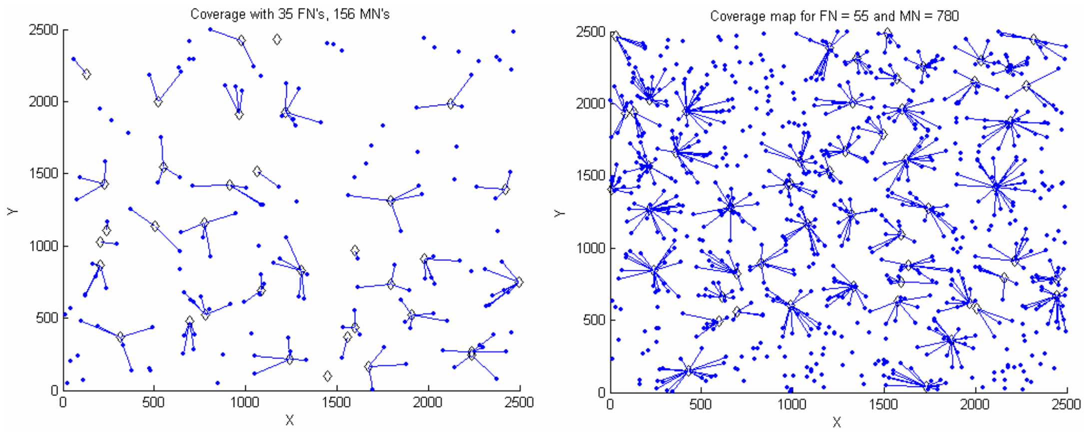

Figure 9 a) Coverage = 73%, average # of users/FN = 4 b) Coverage = 77%, average # of users/FN = 11

Further, we use the analytical results from [30, 34] to derive the number of Access Points needed to meet the capacity requirements. Using $X_{AP} = k \times \sqrt{X_{FN}}$, we propose about 10-12 APs for the first case and 16-20 APs for the second case. Also note that by using FN's with dual interfaces operating on orthogonal channels, the delays incurred in multi-hop communications are minimal since the FN is capable of receiving from the MN and forwarding to the AP simultaneously using the two radio interfaces.

C. Capacity: Number of backhaul links

The advantage of introducing the FNs to extend coverage is to reduce the number of AP's that need to be deployed instead, thus reducing the number of costly backhaul or wired connections per AP. As calculated in Table 3 and 4, the average and peak system bandwidth required is 2.34-7.8 Mbps for 10% user penetration, and 11.7-39 Mbps for 50% user penetration. For initial deployment, we consider the case of 10% user penetration that requires about 2.34 to 7.8 Mbps backhaul capacity to support the requirements of the end user applications. This can be scaled at a later stage based on a revised estimate of service penetration and subscriber demands. Note that based on the cost of leasing E1 links (2 Mbps) or 64 Kbps links per annum, we can use an aggregated capacity from 80 links of 64 Kbps. We choose 64 Kbps links over 2 Mbps links since the leasing cost/capacity ratio[3] is significantly lower for the case of 64 Kbps links.

D. Estimate of deployment costs

We estimate the deployment cost for a system that supports about 160 users using 35 FNs and 10 APs tabulated as follows. Note that the backbone access costs form a significant portion of the total costs.

Table 3 Estimated deployment costs (fixed)

Item	Unit Price	Total Price
10 Access Points	~$1000	$10000
35 Forwarding Nodes	~$400	$14000
Total fixed costs		$24000

Table 4 Estimated deployment costs (recurring)

Item	Unit Price (per month)	Total Price
80 leased lines (64 Kbps each) = 5 Mbps	(Rs 24000 p.a.)/(12 × 50) ~$40	$3200 per month

[3] Cost based on the price estimate of Rs 8.2 lakhs per annum for a 2 Mbps leased line upto 500 Km and Rs 24000 per annum for a 64 Kbps link over the same distance. Based on the "Consultation Paper on Revision of Ceiling Tariff for Domestic Leased Circuits", http://www.trai.gov.in/cpaper22.htm

We consider the total cost of operating the system for a period of three years. For the 10% service penetration level, the total cost = (fixed cost + 36× recurring cost per month) = 24000 + 36 × 3200 = $139200. For the 50% service penetration level (with 780 users, 55 FNs, 20 APs and 188 64-Kbps leased lines), the total cost = 42000 + 36 × 7488 = $311568. The total cost of building the system amortized over the number of users for the two service penetration levels can be calculated as follows. For the 10% penetration case (160 users), the total cost per user per month = 139200/ (36*160) = $24 dollars. For the 50% penetration case, the cost per user per month is 311568/ (36*780) ~ $11. We could add $2 of operation and maintenance costs to this and this leads to a monthly charge per subscriber of about $13. These costs are comparable to the costs of dial-up Internet access but offer much higher access speeds to end users similar to those achievable with wired DSL or digital cable solutions.

V. SYSTEM VALIDATION USING THE ORBIT TESTBED

In order to validate the system model described in the previous section, we conducted an experimental evaluation of the model on the ORBIT testbed. The testbed comprising 64 nodes with two 802.11a/b/g wireless interfaces arranged in an 8×8 grid. The testbed overcomes the limited real-world physical layer modeling of existing simulators and provides a realistic environment to perform capacity studies of a microcosm of the outdoor deployment scenario (see www.orbit-lab.org for further details). In particular, we consider the case with 10% service penetration comprising 156 users, 35 FNs and 12 APs. We consider a scaled area which roughly covers 0.9 sq. km having 20 users, 4 FNs and 2 APs. The traffic generated at each user can either correspond to an individual source or an aggregated source coming from several users.

A. Experiment details

In this experiment, we created two topologies as shown in Fig 10 to represent a flat multi-hop mesh network and a hierarchical architecture with FNs. Each run has 20 users generating increasing offered loads in steps of 0.75Mbps (from 0.75 - 3 Mbps) towards the sink (AP). These flows represent a few users who are trying to access the Internet using a gateway. We measure the total system throughput, average delays and packet loss for both the flat and hierarchical topologies under increasing offered loads. The experiment parameters are summarized in Table 5.

Table 5 Experiment Parameters

Number of users	20
Number of APs	2
Number of FNs (for hierarchical case)	4
Packet size	1024 bytes
Offered load per user	750Kbps, 1.5 Mbps, 2.25 Mbps, 3Mbps
Total offered load	15 Mbps, 30 Mbps, 45 Mbps, 60 Mbps
MAC	802.11a (Atheros chipset)
Flat topology Hierarchical topology	AP1 on channel 40 (5.2 Ghz) AP2 on channel 56 (5.28 Ghz) AP1-FN1,2 links on channel 40 (5.2 Ghz) FN1,2-MN links channel 64 (5.32 Ghz) AP2-FN3,4 links on channel 56 (5.28 Ghz) FN3,4-MN links channel 48 (5.24 Ghz)

B. Experiment Topology

As seen in Fig 10a and b, the nodes use multi-hop links (as many as three hops) to reach the AP in the flat topology, whereas in the case of a hierarchical topology, the nodes use the FN's to reach the AP's. Note that since the FN's have dual wireless interfaces operating on orthogonal channels, the penalty incurred in going over multiple hops is not that severe, since simultaneous reception and forwarding can happen at the FN using the two interfaces.

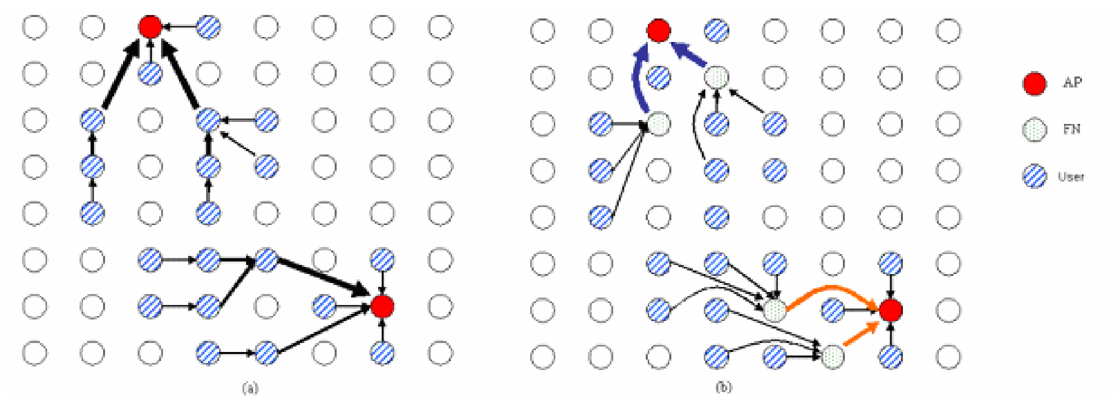

Figure 10 a) Flat topology b) corresponding hierarchical topology (arrow colors represent channel used, arrow thickness represents the offered load carried)

C. Experimental Results

Figure 11a, b and c show the system throughput, average end-to-end delay and fraction of packets lost for the flat and the hierarchical topologies with increasing offered loads. It is observed that the hierarchical system scales to about 50 Mbps system throughput with reasonable packet delay and packet loss. This capacity of ~50 Mbps per sq-Km is sufficient to handle the traffic density in our urban coverage area scenario. By comparison, the flat ad-hoc network reaches a capacity limit at 20 Mbps and has much higher packet delay and packet loss.

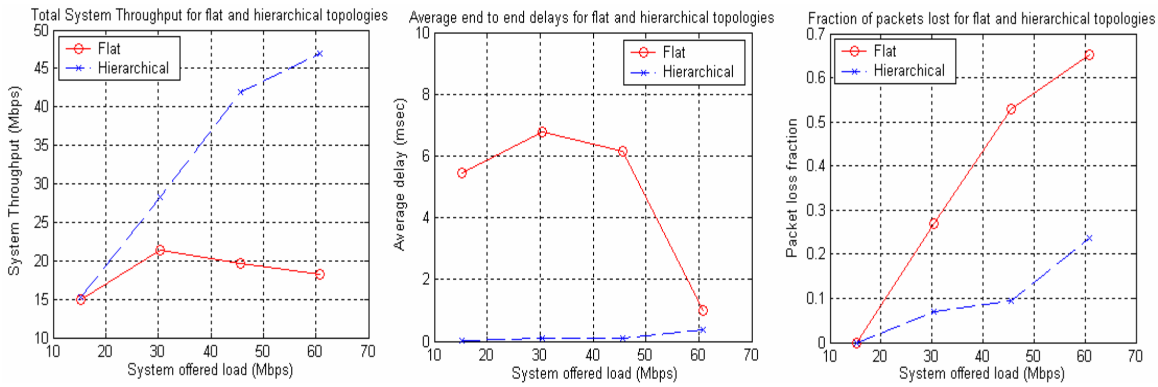

Figure 11 a) System throughput b) average end-to-end delay c) packet loss with increasing offered load

Note that, in the flat topology, the nodes use multi-hop links to reach the AP. All nodes have one interface and they use the same channel. In the hierarchical case, the MNs use the FNs to reach the AP. FNs operate on orthogonal channels as shown by the arrows of different colors. The thickness of the arrows also indicates the total offered load carried by the link. It can be seen from the figure that the hierarchical approach performs much better than flat mesh networks and yields about 2.5:1 performance improvement in terms of total supported system throughput, average end-to-end delays and packet loss.

The results presented are intended only as a representative example to show that ad-hoc mesh networks can scale to urban deployment scenarios and provide reasonable end-user quality-of-service in terms of delay and packet loss. It is noted that the experiment from which these results were obtained includes a full protocol implementation of the ad-hoc mesh and thus corresponds very closely to the real system with only the radio links being emulated.

VI. CONCLUSION

Alternative approaches to designing wireless networks for high-speed Internet access using 802.11 radios were discussed and compared. Mesh networks with short-range 802.11 radios were identified as a promising technology that offers a combination of high system capacity, good end-user performance and low capital cost. A specific hierarchical mesh network architecture concept under development at WINLAB, Rutgers University was introduced and described in terms of major system components and protocols. An urban deployment scenario was analyzed in terms of capacity and cost, and it was shown that this approach is viable for medium to high subscriber density and can lead to significantly lower cost per subscriber than alternative wired technologies such as DSL or digital cable. A proof-of-concept validation of the system capacity and hierarchical ad-hoc network protocols was carried out using the ORBIT testbed, and experimental results on throughput, delay and packet loss were presented to further validate these conclusions.

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