HomeMesh: A Low-Cost Indoor Wireless Mesh for Home Networking

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ABSTRACT

Wi-Fi access technology has become popular in recent years. Many users nowadays use Wi-Fi to gain wireless access to the Internet from offices, public libraries, shopping malls, homes, and other places. However, current Wi-Fi deployment is limited to areas where wired LAN is available. Due to its relatively short transmission range in indoor environments (typically several tens of meters), Wi-Fi coverage needs to be extended significantly to full coverage of a certain area. The wireless mesh network (WMN) is a practical and effective solution. In this article we present HomeMesh, an off-the-shelf, simple, and cost-effective WMN for the indoor home environment. HomeMesh is based on simple protocols, implementable in normal notebooks or PCs, and is compatible with existing Wi-Fi APs and clients (i.e., no AP and client modifications). To achieve better end-to-end delay and throughput, HomeMesh dynamically selects its access path based on the ETX metric. We have implemented HomeMesh and conducted proof-of-concept experiments in an indoor environment. Our mesh solution is shown to be effective in improving Wi-Fi services.

INTRODUCTION

Wi-Fi provides broadband wireless access to the Internet in enterprise offices, public libraries, shopping malls, homes, and so on However, indoor Wi-Fi access points (APs) normally provide access only within several tens of meters (depending on the number and types of walls). To provide Wi-Fi services over a larger area, the traditional approach is to lay down cables and deploy more APs. This is not a cost-effective solution, especially for some unpopular areas where cabling is expensive (e.g., backyards).

In order to extend wireless coverage, the wireless mesh network (WMN) has been studied as an effective solution [1]. A WMN consists of mesh routers and mesh clients. Mesh routers form the backbone to provide wireless access to mesh clients. They self-configure to maintain connectivity for clients. Besides routing, they play additional roles to support mesh connection (security, load balancing, etc.). The communication between mesh routers is transparent to end clients, who regard mesh routers as APs. A lot of research on WMNs has been conducted in recent years. However, most of the proposed solutions are mostly industry-oriented with the focus on municipal or large enterprise wireless networks instead of the indoor home environment. Therefore, they often need to modify the APs and are based on complex protocols. Meanwhile, expensive hardware or equipment is required. Therefore, the solutions are not suitable for home users due to high cost and high power range.

In this article we study and prototype a simple and low-cost mesh network for the home environment. In HomeMesh the algorithm is adaptive to network dynamics and changes due to continuous message exchanges within mesh routers. As a result, the routing table that reflects the current network environment and departure is adaptive to router mobility and churns (i.e., joins and failures).

An AP is used to serve Wi-Fi clients such as desktop PCs, notebooks, PDAs, and Wi-Fi phones. Due to its limited indoor coverage range, a single AP cannot provide home users full area coverage. Building a cost-effective home WMN without the hassle of cabling is important. We present HomeMesh, a practical and cost-effective system to build a WMN in an indoor environment. HomeMesh achieves Wi-Fi extension by using existing nonproprietary off-the-shelf technology. The mesh routers in HomeMesh may be normal desktop PCs or notebooks. The routers are compatible with existing Wi-Fi products; hence, no modifications are needed on the APs and Wi-Fi clients. To achieve high system throughput and load balancing, the routers dynamically select the access path to the Internet based on the expected transmission count (ETX) metric. A simple yet efficient channel assignment algorithm is used to improve the system performance. We have implemented the solution and conducted experimental measurements to show that indeed HomeMesh is effective by achieving coverage extension and good throughput. Our main contribution in this article is providing a low-cost solution for the indoor home environment to build a wireless mesh using existing nonproprietary off-the-shelf technology, and we also conduct proof-of-concept experiments to verify our design.

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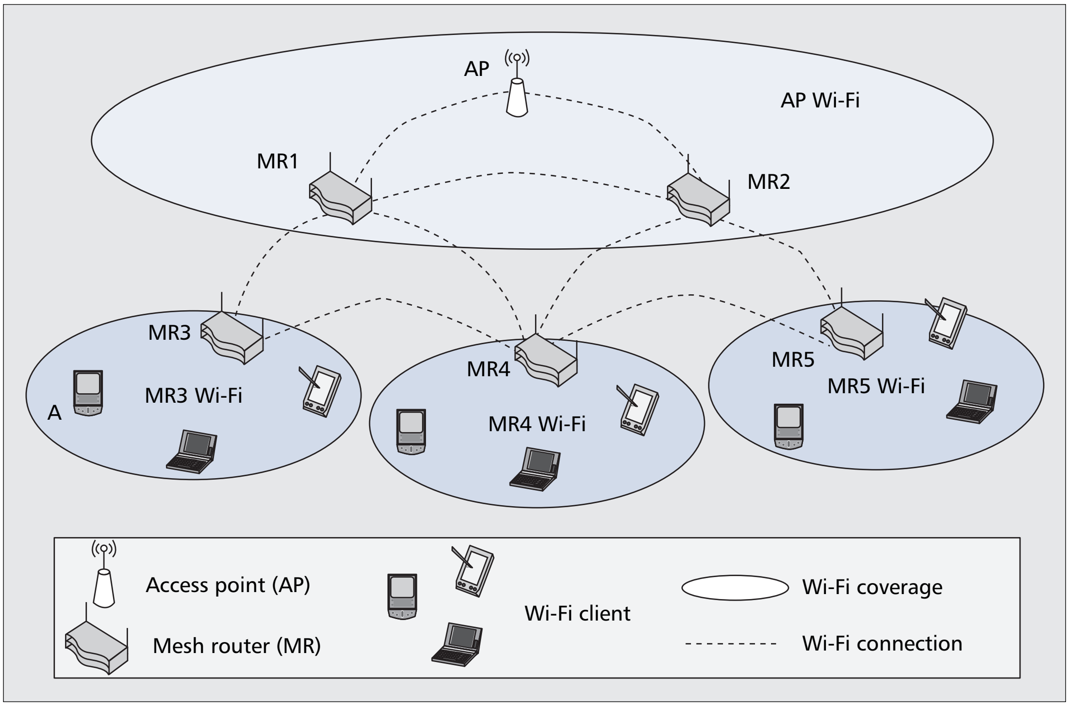
HomeMesh routers are built on general-purpose computer systems and no extra hardware is required. Each mesh router operates on two orthogonal channels and its access path to the Internet is formed dynamically based on ETX metric.



■ **Figure 1.** *HomeMesh system architecture.*

Many WMNs have been deployed worldwide. An example is Taipei's M-Taipei Project, in which more than $100 million has been invested [2]. However, the wireless mesh APs and routers needed in the network are generally too expensive for home users. Meraki,[1] another mesh product evolved from MIT's Roofnet, achieves relatively lower cost [3]. However, since it is based on a single radio channel, its throughput is not high. Study has shown that using two radios on each router may improve the network throughput by a factor of 6 to 7 over that of a single radio [4]. In HomeMesh, each mesh router uses two radios on different frequency channels. The system throughput and end-client goodput can hence be greatly improved. The protocol in HomeMesh is simple and can be implemented in any existing desktop PCs or notebooks, and hence is cost-effective.

The rest of this article is organized as follows. In the next section we discuss HomeMesh system architecture and its strengths, and compare it with other mesh implementations. We then describe the channel assignment algorithm, and present its access path determination. We then discuss how we implement the mesh router prototype and the results of proof-of-concept experiments. We conclude in the final section.

HomeMesh System Architecture

System Architecture

HomeMesh consists of APs, mesh routers, and clients. The mesh routers can self-configure to form a backbone connecting to the Internet. They provide wireless access to their clients. Traditional gateway/repeater functions are run on the mesh routers with additional routing functions (e.g., load balancing and security) to maintain mesh connectivity. As opposed to other commercial routers that are built on dedicated computer systems, HomeMesh routers are built on general-purpose computer systems, and no extra hardware is required. Each mesh router operates on two orthogonal channels, and its access path to the Internet is formed dynamically based on the ETX metric (discussed later).

We illustrate the HomeMesh system architecture in Fig. 1. There are three components in the system:

- Wi-Fi AP
- Mesh routers (MRs)
- Wi-Fi clients

The AP shown in Fig. 1 is a normal Wi-Fi certified AP widely available on the market. It accesses the Internet through a wired connection (e.g., Ethernet). The service coverage is shown as an ellipse (AP Wi-Fi). Five mesh routers (MR1 to MR5) are placed in the system. The service coverage of MR3, MR4, and MR5 is shown as three small ellipses: MR3 Wi-Fi, MR4 Wi-Fi, and MR5 Wi-Fi (MR1 and MR2 service coverage is not shown in the figure). The dotted line indicates that MR1 is reachable by MR2, MR3, and MR4, while MR2 is reachable by MR1, MR4, and MR5. In each MR one radio operates in managed mode, the other in master mode. The one operating in master mode accepts association from Wi-Fi clients or other MRs, while a managed mode associates with the AP or other MRs to get Internet access.

For example, the managed mode radio in MR1 associates with the AP and hence gets Internet access. MR1's master mode radio accepts MR3's association through the managed mode radio. MR3 therefore gets Internet access through MR1. The Wi-Fi clients in MR3's area associate with MR3 and thus access the Internet through the path MR3 → MR1 → AP. As a result, the AP's limited service coverage is extended.

[1] http://meraki.com/

STRENGTHS

HomeMesh enjoys the following strengths.

Wi-Fi coverage extension: The Wi-Fi AP is attached to the wired connection directly and serves as a gateway for its clients to the Internet. Since its coverage is very limited (around several tens of meters), mesh routers can be introduced to extend the Wi-Fi service (mesh protocols can be installed in any normal desktop PC/notebook). For example, the Wi-Fi coverage in Fig. 1 is successfully extended to the areas labeled MR3 Wi-Fi, MR4 Wi-Fi, and MR5 Wi-Fi, with client A connecting to the Internet through the path MR3 → MR1 → AP.

Low deployment cost: As the mesh protocol can be installed in desktop PCs/notebooks for home users and no extra expensive hardware (e.g., commercial wireless mesh routers) are needed, the cost can be greatly reduced. For example, the Wi-Fi AP can be placed in a family room, reachable by a desktop PC located in the living room. This desktop PC can work as a mesh router to extend the Wi-Fi coverage to a farther area like the backyard. By deploying more mesh routers, wireless blind spots in the house can be eliminated.

Load balancing and fault tolerance: Our mesh routers are self-configurable and self-organizing. They continuously monitor the network traffic and maintain a list of available paths to the Internet. The traffic is diverted to a better path if the original one is congested. For example, in Fig. 1 MR4's original path to the Internet may be via MR1. When more clients are associated with MR1, MR4 automatically switches to MR2 to gain better throughput. By continuously monitoring the mesh network situation and switching to a better path, mesh routers can respond and recover from link failure in a short time, and achieve load balancing and high throughput. For example, MR3's original path to the Internet is via MR1. If MR1 fails, MR3's traffic can be automatically diverted to MR4.

Compatible with existing Wi-Fi devices: As mentioned, there is no need to modify the AP and Wi-Fi clients; HomeMesh deployment is transparent to these devices. From the AP viewpoint, MRs are normal Wi-Fi clients since they associate with it using Wi-Fi managed mode. Similarly, from the Wi-Fi client viewpoint, the MRs are normal Wi-Fi APs since they are operating in Wi-Fi master mode to accept the association. Making MRs compatible with existing Wi-Fi devices leads to simple deployment of HomeMesh.

COMPARISON WITH OTHER EFFORTS

We compare HomeMesh with two other WMN approaches (one from the academic and the other from the commercial domain) and summarize them in Table 1. Hyacinth [5], developed by A. Raniwala *et al.* in academic sector, is an IEEE 802.11-based multichannel WMN. In [5] they propose a novel multichannel WMN architecture that can readily be built using IEEE 802.11 a/b/g technology. Hyacinth equips each mesh network node with multiple 802.11 radios. Compared to HomeMesh, Hyacinth has a more complicated channel assignment algorithm and hence higher routing overhead. Furthermore, it uses centralized system management, which hinders its scalability. Meraki is a commercial wireless mesh product that aims to provide affordable Internet access to consumers. In order to reduce the manufacturing cost, Meraki MRs use only a single radio, which lowers its overall system throughput. Compared to Meraki, HomeMesh only requires an extra off-the-shelf wireless card (rather than a new MR), which is more affordable. In addition, by using multiple radios, HomeMesh achieves higher throughput than Meraki.

	Hyacinth	Meraki	HomeMesh
Hardware requirement	Existing PC/notebook	Need new mesh routers	Existing PC/notebook
Deployment cost	Low	Medium	Low
MAC layer modification	No	Yes	No
Radio channel	Multiple	Single	Multiple
Channel assignment	Complicated	Simple	Simple
Routing overhead	Relatively high	Relatively low	Relatively low
System management	Centralized	Distributed	Distributed

Table 1. *Comparison among different approaches.*

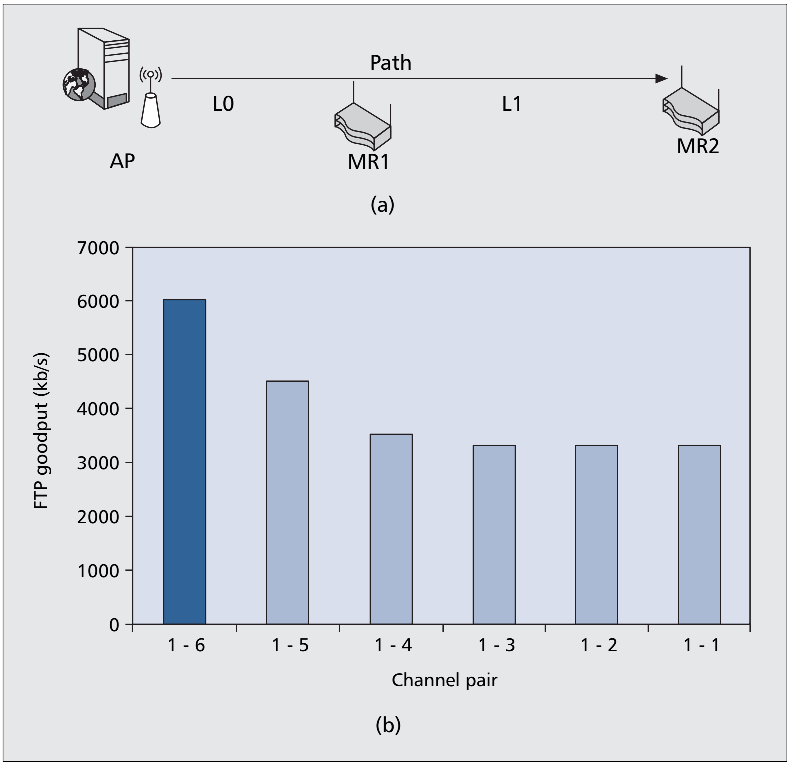
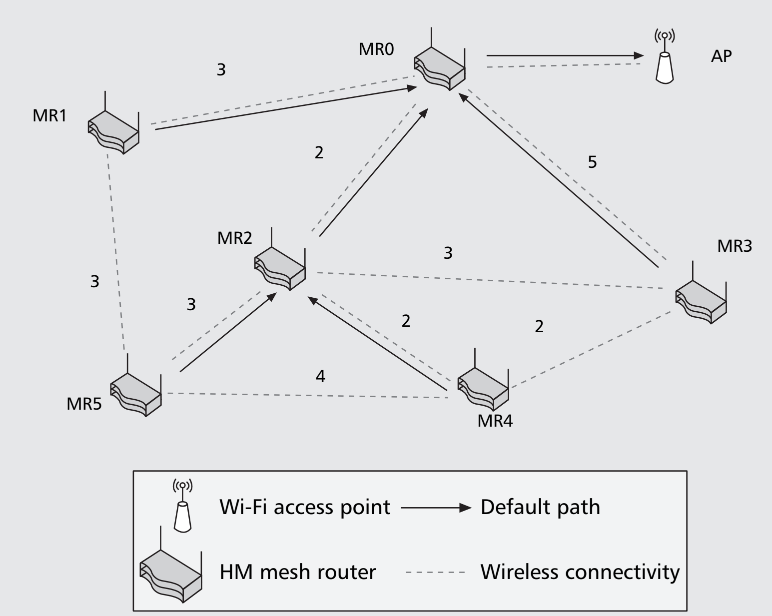


Figure 2. *Contention and interference experiment: a) two-hop FTP transfer; b) FTP goodput vs. channel pair of a HomeMesh mesh router.*



(a)

ID	Sum of ETX	Hops to gateway	Valid
MR2	5	2	True
MR1	6	2	True
MR4	8	3	True

(b)

ID	Sum of ETX	Hops to gateway	Valid
MR0	5	1	True
MR2	5	2	True
MR4	6	3	True

(c)

Figure 3. *HomeMesh access path formation: a) an example of an access tree; b) MR table of MR5; c) MR table of MR3.*

HomeMesh Channel Assignment Algorithm

In a wireless mesh the access path cannot achieve good performance without a proper channel assignment algorithm because of contention and interference. IEEE 802.11b defines a total of 14 frequencies of which only three are nonoverlapping (1, 6, and 11) and can be used simultaneously without causing interference. There has been some research effort in exploiting multiple radio channels in the literature [6]. However, these strategies often require modifications to the medium access control (MAC) protocol or introduce new techniques, which is not straightforward to install into commodity 802.11 wireless cards. In HomeMesh we employ a simple, efficient, and practical channel selection strategy. All MRs use nonoverlapping channels in their two wireless interfaces. For example, if one wireless interface uses channel 1, the other will use 6 or 11. This minimizes the interference during packet forwarding and leads to throughput improvement.

We validate our channel selection strategy through an experiment. In this experiment, as shown in Fig. 2, we use the path AP → MR1 → MR2, where the AP serves as the FTP source, MR1 serves as the relay, and MR2 serves as the FTP client. We fix link AP → MR1 (L_0) to use channel 1 and vary the channel of link MR1 → MR2 (L_1). In Fig. 3b we show the experimental results. Clearly, by using nonoverlapping channels (1 and 6), MR2 has the highest forwarding efficiency, and hence achieves highest goodput among all channel pairs.

Access Path Determination

The access path to the Internet affects the throughput of the connection. In HomeMesh our MRs continuously monitor the mesh network by periodic message exchange and maintain soft-state routing tables. From the routing tables, routers select high-quality paths to the Internet. In this section we first discuss HomeMesh's path selection metric and its routing table. We then discuss its path selection algorithm.

Path Selection Metric

In HomeMesh traffic is relayed in a multihop manner. The routing path of the traffic is decided by the MRs. There may be numerous possible paths to the gateway. Traditional routing protocols use minimum hop count as the performance metric to select the routing path due to its simplicity and low routing overhead [7]. This is effective in some situations (e.g., mesh nodes are mobile). However, the effects of link loss and interference of adjacent links have not been properly taken into account in the minimum hop count metric. To improve the throughput, in HomeMesh, the access path to the Internet is selected based on the sum of ETX. Routes selected based on ETX have been shown to achieve significantly higher goodput thanusing the minimum hop count metric, particularly for paths with more than two hops [8, 9]. Y. Yang *et al.* have conducted a more extensive simulation with the NS-2 simulator to further support the importance of using ETX for larger-scale networks [9].

ETX calculates the number of transmissions, including retransmissions, needed to send a unicast packet across a link [8]:

$$ETX = \frac{1}{d_f \times d_r},$$

where d_f is the successful forward delivery ratio and d_r is the successful reverse delivery ratio (the acknowledge [ACK] packet). In HomeMesh we use the sum of ETX to select paths, which is simply the summation of the ETX value along the routing path.

HomeMesh may use other routing metrics, such as minimum loss (ML), expected transmission time (ETT), weighted cumulative ETT (WCETT), and interference aware (iAWARE) [10]. We choose ETX because it is relatively simple, effective, and lightweight. Furthermore, no hardware modifications are needed. These all fit the requirements of building a low-cost indoor wireless mesh for home users.

Mesh Router Table

Topology discovery and calculation of the sum of ETX are done by message exchange in HomeMesh. Messages are periodically broadcast by MRs to maintain mesh connectivity and update routing information. The broadcast interval can be defined by users. The information loaded on each message is reduced to minimum to lower routing overheads. Each broadcast message contains the ID of the MR, the sum of ETX to the gateway, and hop number to the gateway. After receiving the messages from its neighboring routers, each MR constructs a soft-state MR table containing a list of MRs within its transmission range. Every change in the network will be updated in the MR table through periodic message exchanges. An example of an MR table is shown in Fig. 3b. Each entry contains four fields: ID identifies the neighboring mesh router, sum of ETX is the total ETX to the gateway through this MR, hops to gateway identifies how many hops it takes to reach the gateway, and valid indicates whether the entry is valid or not.

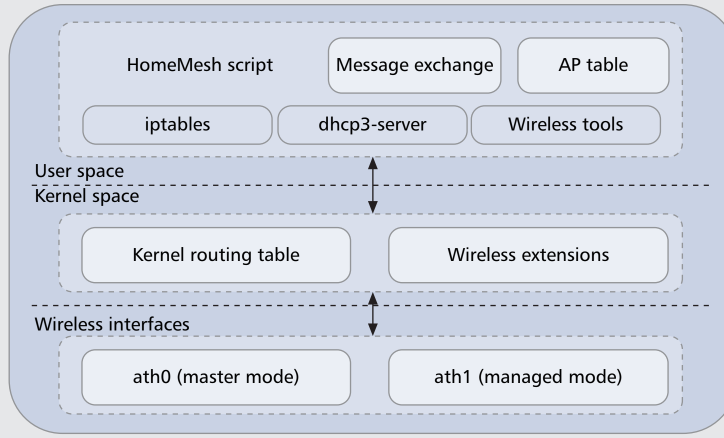
Path Selection Strategy

The path selection strategy in HomeMesh is quite straightforward. For each MR, the entries of its MR table are ordered ascendingly by sum of ETX and then hops to gateway. The first entry is selected as the default path to the gateway.

We show in Fig. 3a an example of HomeMesh deployment. The AP is a gateway to the Internet. There are six MRs, MR0–MR5. The connectivity among the MRs is shown by dotted lines. The numbers on the dotted lines indicate the link ETX. For example, the link ETX between MR1 and MR5 is 3. The arrows show MRs' default paths to the gateway. MRs choose their default paths by selecting the least sum of ETX from their MR tables. For MR5 (Fig. 3b shows its MR table), path MR5 → MR2 → MR0 is selected. If the sum of ETX is the same, the least hops to gateway entry is chosen. Figure 3c shows such a situation where MR3 has two paths to the gateway with sum of ETX equal to 5. The fewest hops to gateway path is selected (i.e, "Path MR3 → MR0").

Prototype and Proof-of-Concept Experiments

This section describes the MR's implementation, software architecture, and proof-of-concept experiments. A special feature of HomeMesh is that it uses off-the-shelf low-cost products to build the mesh network. The mesh routing protocol has been implemented and installed in normal PCs/notebooks and is compatible with existing Wi-Fi devices. In our proof-of-concept experiments we use MadWifi[2] to manipulate the master mode radio. MadWifi supports a wide range of popular wireless cards based on Atheros' chipsets. We present experimental measurements for an indoor environment to validate our design and implementation.



(a)

```
#create a managed mode interface
wlanconfig ath1 create wlandev wifi1 wlanmode sta
iwconfig ath1 rate 54M
udhcpc -i ath1

#create a master mode interface
wlanconfig ath0 create wlandev wifi0 wlanmode ap
iwconfig ath0 rate 54M channel 1
iwpriv ath0 mode 1
ifconfig ath0 192.168.0.1 netmask 255.255.255.0 up
udhcpd &
iptables -t nat -A POSTROUTING - O ath1 -j MASQUERADE
```

(b)

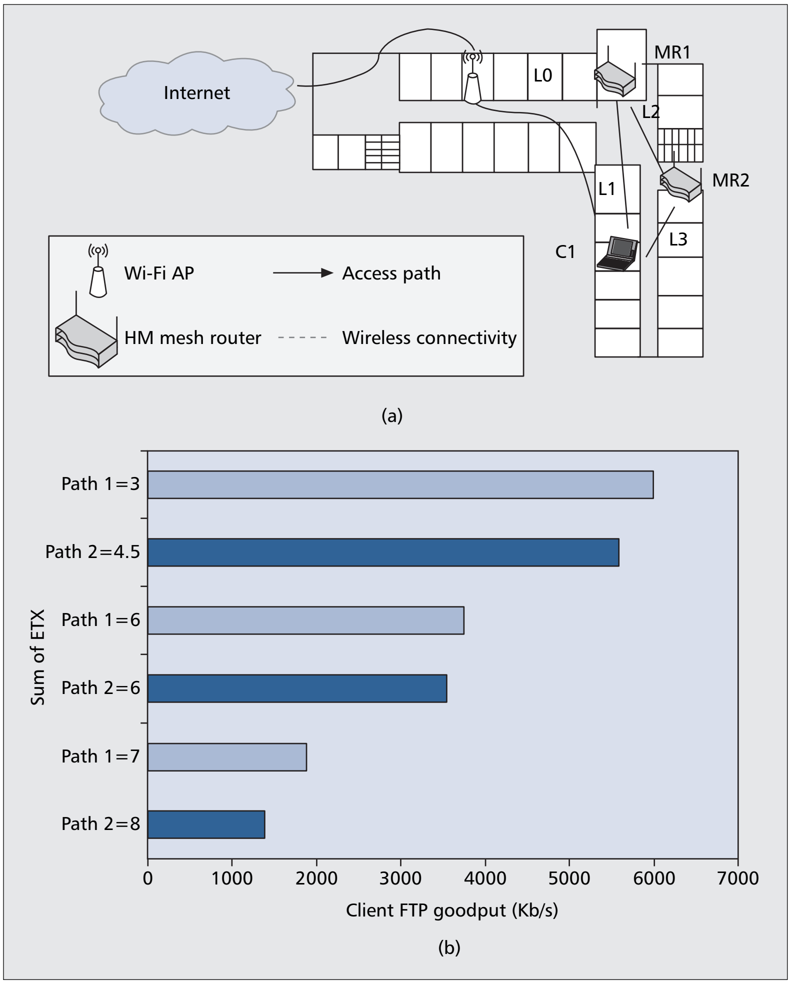
Figure 4. *HomeMesh software architecture and sample script: a) HomeMesh mesh router software architecture; b) a sample configuration script.*

Software Architecture

In Fig. 4 we show the software architecture of the MR and a sample configuration script in Linux, although our implementation is by no means limited to Linux (it can be done in Windows as well). To turn a desktop PC into an MR, you just need to run the HomeMesh script in the user space; no other configuration is needed. The script initializes an MR table, puts an interface into managed mode (*ath*1 in the figure), obtains broadcast messages from other MRs to find an optimal path, and associates with the best parent from its MR table using standard Linux commands such as *iwconfig* and *iwlist*.

After being associated with a parent, the router puts another interface into master mode (*ath*0 in the figure) and sets its operation channel based on the rule described previously. This can be done by Linux commands. When both interfaces are ready, the script starts the address allocation function for its clients by starting a *dhcp3* server. After that, it enables packet forwarding between the two interfaces by using Linux *iptables*,[3] which also enables the network address translation (NAT) function in the kernel routing table. After the initialization step, the

[2] *http://www.madwifi.org/*



■ **Figure 5.** *HomeMesh proof-of-concept experiment: a) experimental setup on the second floor of Postgraduate Hall II at HKUST; b) client FTP goodput for different paths with different sums of ETX.*

MR can be used to accept connections from mobile clients.

The routing information is obtained by message exchange. As shown in Fig. 4a, there is a message exchange daemon in the HomeMesh script. The message broadcast interval is defined by users. The information loaded on each message is very limited (ID, sum of ETX, and hop number) in order to lower the routing overhead since MRs have to carry both routing and user tasks.

PROOF-OF-CONCEPT EXPERIMENTS

We have carried out proof-of-concept experimental measurements to validate our HomeMesh implementation. We conduct our experiments on the second floor of Postgraduate Hall II at Hong Kong University of Science and Technology (HKUST), which is similar to a home environment. Figure 5a shows the map of the experimental environment. There is only Ethernet access in the student hall. With an AP and MRs (students' own notebooks, Wi-Fi coverage is successfully extended to the whole floor.

The ETX is obtained by message exchange among MRs. We run experiments to show that the smaller the sum of ETX along the path, the higher goodput it can achieve. In the experiment we adjust the distance between machines to obtain different ETX values on L1, L2, and L3 in Fig. 5a. Client C1 runs an FTP client to download a file of 10 Mbytes from the FTP server at the AP. Two paths are available for C1: path 1, AP → MR1 → C1, and path 2, AP → MR1 → MR2 → C1. We show in Fig. 5b the client FTP goodput for different paths with different values of L1, L2, and L3. For the same transmission rate, path 1 with sum of ETX 3 has higher goodput than path 2 with sum of ETX 4.5. This is obvious since both the hop count and sum of ETX of path 1 are lower. However, if packet loss is high, the link transmission rate will be adjusted accordingly. Suppose path 1's sum of ETX becomes 6. In this case path 2, with sum of ETX 4.5, has higher goodput than path 1. This shows that the hop count metric does not perform well.

In the above experiment we have seen that the value of goodput on a path is consistent with the sum of ETX of the path. For example, path 1 has hop counts of 2, while their goodputs vary according to their sum of ETX (of value 3, 6, and 7, respectively). If there are two paths with equal sums of ETX, the hop count metric can decide which path is better. For example, for path 1 (sum of ETX 6) and path 2 (sum of ETX 6), path 1 achieves better goodput because its hop count is lower.

CONCLUSION

Wireless mesh networks can effectively extend Wi-Fi coverage. Most of the proposed and implemented solutions are industry-oriented, with high power consumption, and require expensive hardware. Their focus is on municipal or large enterprise wireless solutions and hence are not suitable for indoor home usage.

In this article we present HomeMesh, a practical and cost-effective implementation of a WMN that extends Wi-Fi coverage in the home environment. It uses existing nonproprietary off-the-shelf technology to build a low-cost mesh network. Our router protocol is simple and lightweight, and may be installed on any desktop PC or notebook. The mesh routers are compatible with the existing Wi-Fi products, and therefore are transparent to APs and mobile clients. To achieve high system throughput, mesh routers in HomeMesh dynamically select the access path to the Internet. A simple yet efficient channel assignment algorithm is used to further improve the system performance. We have presented the design and prototype of the mesh router and conducted proof-of-concept experiments in an indoor environment. Our experiments validate the benefits and correctness of our design.

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BIOGRAPHIES

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