ECE1548 Final Project
The Development of Mesh Networks

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Abstract

Wireless mesh networking is a promising technology that will enable improved wireless connectivity. This report examines the current solutions available for delivering wireless LAN access using mesh networks. Based on this survey of current techniques, the limitations of mesh networks are examined and issues such as scalability, security and cost are found to be limiting the growth of mesh networks. Possible solutions such as architecture changes and security standards are investigated. Assuming that solutions to current problems will be found, the future of WLAN mesh networks is considered and the current analysis leads to the conclusion that these high speed mesh networks will coexist with future wireless wide area network solutions. Features such as fast handoffs, advanced quality of service and improved radio technology promise to increase the usefulness of mesh networks and a future in which integrated medium to high speed wireless networks enable connectivity over virtually all populated areas appears likely.
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1 Introduction

For most users, the access network has historically been based on wired networking technologies based on coaxial cable, copper wire or fiber optic links. These technologies have proved exceedingly useful for delivering access to the many homes and businesses that require network access. However, the wired nature of these links inherently limits their practicality since users remain tethered to the wired connection. Wireless networking technology has evolved to make this fixed link unnecessary in some cases. While such networks are being widely deployed, their usage model is typically hotspot-based. In this approach, islands of wireless access exist but they are frequently poorly integrated and they do not enable widespread connectivity. Therefore, while users have been freed from having to plug in for network connectivity, they remain confined to the relatively small fixed region served by a single radio or access point. Applying the ideas of mesh networking to wireless networks offers a chance to change this situation and enable true wireless freedom. This report will examine the current state of wireless mesh networking technology and then based on these developments assess the future development of wireless mesh networks.

These mesh networks can be used in many different niches ranging from small scale wireless personal area networks (WPAN) to wireless wide area networks (WWAN). These technologies represent the two extremes in wireless networks with WPAN handling connections in close proximity to a user and WWAN delivering access over massive geographic regions. In this report, the focus will be in between these two extremes in what is known as wireless local-area network (WLAN) access. This area is the most interesting since it is potentially the most revolutionary. A mesh-based wireless LAN has the potential to offer high-speed access over relatively large areas. Users have already shown significant interest in wireless LAN connectivity as evidenced by the recent popularity of IEEE 802.11 b, g and a networks. The challenge in the next decade will be deploying connections of this speed across larger areas.

To further support this assertion that WLAN may enable significant changes, the cost for varying data rates is given in Table 1. With the cost of WLAN access an order of magnitude less than alternative WAN technologies, it is clear that WLAN can have a significant impact.

Table 1 – Estimated Costs of Wireless Connectivity [25]

<table>
<thead>
<tr>
<th>Technology</th>
<th>Data Rate (kbps)</th>
<th>$/kbps</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Packet Radio Service (GPRS)</td>
<td>53</td>
<td>$118.91</td>
</tr>
<tr>
<td>1xRTT</td>
<td>153</td>
<td>$25.42</td>
</tr>
<tr>
<td>Ricochet</td>
<td>248</td>
<td>$2.43</td>
</tr>
<tr>
<td>WLAN</td>
<td>5,500</td>
<td>$0.27</td>
</tr>
</tbody>
</table>

At the other extreme, compared to personal area networks, the impact of wireless LANs will also be more significant. WPAN networks do have many possible uses ranging from removing the wiring clutter around typical computers today to enabling new applications
such as massive sensor networks for monitoring any number of variables. New sensor networks may provide massive amounts of information that were previously unavailable but, in general, these applications will not impact the user experience as significantly.

Thus, it is clear that WLAN technology will likely have the most impact. This will make mesh networks increasingly important because they promise to simplify the use and deployment of such these wireless LANs. This report will examine the likelihood of such changes and the way this increasing importance of wireless LANs will reshape mesh networks.

The report is organized as follows: Section 2 will present background on mesh networks to determine what the fundamental issues with these networks are. This section will also examine current implementations to highlight the current difficulties faced when deploying mesh networks. To better understand the network requirements for mesh networks, Section 3 will next consider typical applications for WLAN mesh network connectivity. In the context of these applications, Section 4 will describe the current fundamental issues limiting the use of mesh networks for WLAN and some possible solutions will be appraised. Section 5 will examine possible immediate uses for meshes despite these limitations. Moving beyond these present day limitations, Section 6 will examine the future role of mesh networking. Then, in Section 7, the future changes to mesh networks to enable this role will be considered. Finally, Section 8 will close with some conclusions.

2 Background
To assist in the examination of mesh networks for WLANs, some background on mesh networks will first be considered. Then, the key differences between wired and wireless networks will be examined as this is central to understanding the challenges faced by mesh networks. Following this examination some of the current protocols used for routing in mesh networks will be examined. The performance and scalability of these approaches will be then be analyzed. Finally, sample current approaches for mesh networking will be presented. These implementations will be divided into two categories: client meshing where peer-to-peer communication occurs and infrastructure meshing in which clients do not directly communicate.

2.1 Mesh Networks Defined
Before discussing mesh networks further it is worthwhile to examine a strict definition as to what mesh networks are. One such definition given by [10] is as follows:

\[
\text{A mesh network is a network that employs one of two connection arrangements, full mesh topology or partial mesh topology. In the full mesh topology, each node is connected directly to each of the others. In the partial mesh topology, nodes are connected to only some, not all, of the other nodes.}
\]

In the past such networks were strictly wired networks but within the last decade wireless networks have evolved to enable wireless mesh connections. In these configurations, clients, which in this context are frequently mobile, are interconnected via wireless links. Each client can communicate with all the other clients within its transmission range. This
complete interconnection makes this a mesh network. To reach all the clients in a network or to reach the gateway to an external network or the Internet, transmissions typically must hop across multiple wireless links. This has come to be one of the defining features of a mesh network.

These networks have also been termed ad-hoc networks since they typically must be self-configuring. The movement of clients and radio interference changes the topology of the network and ad-hoc/mesh networks are designed to handle such occurrences. However, some people do distinguish mesh and ad-hoc networks [9]. The difference lies in the traffic patterns. In ad-hoc networks traffic typically flows between pairs of arbitrary clients. In mesh networks, most traffic is between a client and a gateway. The routing and bridging issues are similar in both networks since their topology is the same but optimizations can be made based on the traffic pattern. However, this distinction is not widely used. Therefore, this report will examine both such topologies and in later sections the likely uses and future for each approach will be considered.

The general idea of wireless mesh networks has been around for decades. Much of the work in this area started from DARPA projects aimed at battlefield communications. In those applications, the focus was on peer-to-peer communications between soldiers or tanks since no infrastructure might be present in a battle zone. These initial mesh networks suffered from the fact that custom radios and software were typically needed.

However, recently, wireless solutions have begun to appear everywhere. In particular, standards such as IEEE 802.11 have hastened the acceptance of wireless systems and, as a result, 802.11 radios have become much cheaper. These significant drops in price are one of the driving factors that are making WLAN mesh networks possible.

At the same time as wireless radios have become ubiquitous, users have come to desire more constant network connectivity. For example, in the same way a client expects their cell phone to work everywhere, they want the ability to connect to the Internet throughout their office and even throughout a city.

Wireless mesh networks may allow these two trends to be combined. A wireless mesh of radio links could be formed which might enable a user to maintain connectivity over relatively large regions. This presents a challenge though, because wireless links are very different from ordinary wired connections. With wireless links, people may move around or other objects may be moved that alter the signal path. Something as innocuous as turning on a microwave can cause interference and, ideally, the network should tolerate such occurrences. This means that in some cases the network topology will have to change in order to ensure that the users’ connections are maintained.

For mesh networks to grow in popularity, it is important that the underlying technology is transparent to the user. Therefore, it is most appropriate to examine solutions that enable this. In particular, techniques that enable bridging and routing across a mesh at the layer 2 level will be considered. This is necessary so that later limitations of mesh networks
can be understood. However, not all solutions to wireless meshing are implemented purely at the layer 2 level so other techniques will be considered as well.

When examining these approaches, the two central issues considered will be performance and scalability. These are the central issues for practically any network deployment and therefore, these terms will be defined in Section 2.4. Once the definitions are clear, theoretical and academic investigations will be examined to learn the major issues impacting performance and scalability.

### 2.2 Wireless and Wired Network Differences

One of the first questions that arises in this examination is why are wireless networks different than wired networks. The main source of difference arises from the difference in physical transport mediums. Radio links have improved dramatically over time but they still suffer from a range of environmental factors.

Factors such as interference dramatically affect the links between network nodes. This interference can come from any number of sources ranging for the use of a cordless phone to the positioning of walls which may worsen multi-path fading problems. As well, this interference may cause transmission links to have asymmetric capacities. Clients can also move more readily when using wireless links and, in fact, the clients may be in constant motion. In such a case, the link to other clients or hosts will be changing continuously.

This situation is very different than a wired connection. For example, the condition of a link from a computer to a router using CAT5 cable will not vary as significantly with time and the speeds will be symmetric over the link. While clients can move components of wired networks, for example, when an office is rearranged or a user plugs in a laptop in a conference room, these changes are much less frequent than in a wireless network. There is definitely no continuous source of client movement.

Another difference lies in the available throughput. Despite significant advances in the technology enabling wireless links, the throughput still pales in comparison to that available in wired networks. Standards such as IEEE 802.11a and IEEE 802.11g support 54 Mbps links only over a relatively short distance which compares poorly to wired technologies where Fast Ethernet operates at 100 Mbps over much longer links.

Finally, radio links suffer from the fact that radio is inherently a shared medium. This gives rise to what is known as the hidden terminal problem. The potential problem is depicted in Figure 1 where because the transmitter cannot directly communicate with all the nodes that can transmit to the receiver there is the potential for interference. This was not a problem with wired Ethernet even though it too is a shared medium because components such as bridges enable concurrent transmissions.
2.3 Routing Protocols

One of the significant challenges with mesh networks is ensuring efficient routing. Therefore, in this section, the particularly difficulties in routing across a wireless mesh network as compared to a wired network are examined. Then three techniques that are being considered for routing in these applications are considered.

2.3.1 Routing Challenges in Wireless Mesh Networks

Traditional routing protocols such as open shortest path first (OSPF) are not always suitable for routing in mesh networks particularly for meshes in which all clients are acting as routers. There are numerous reasons why this is the case [19]:

1. Asymmetric links can cause problems for conventionally determined routes
2. Wired networks do not have as many routers. When every node in a mesh is capable of routing, there are many paths to be considered. As a result the size of the routing updates grows which can consume a significant amount of the limited available bandwidth.
3. Periodic transmissions of routing updates may waste network capacity. This is made worse by the fact that when many network nodes are in close proximity these updates interfere with each other thereby reducing everyone’s available capacity.
4. Mesh networks may also change frequently. In some cases these changes may occur faster than the routing protocol’s updates and, therefore, the routing information obtained by the protocol will never be used.
5. Battery power may be an issue for mobile network nodes. Radio transmissions and their required computations consume significant amounts of power. Therefore, transmissions should be avoided if possible.

One central theme in these issues is that attempting to maintain accurate routing tables at all times may be ineffective for mesh networks. Approaches that attempt to always maintain valid routes are termed proactive protocols. An alternative to such approaches
is to only determine routes on demand. Those techniques are called reactive protocols. Such techniques typically only generate network traffic when they must transfer information to a destination which is currently unknown.

Both approaches can be used for wireless mesh networks and each has specific advantages and disadvantages. A few popular techniques will now be described.

### 2.3.2 Dynamic Source Routing

One technique developed for multi-hop wireless networks is dynamic source routing (DSR) [8]. As the name implies the protocol is based on the idea of source routing. The source of a packet determines the exact path that will be taken by the packet. Each node the packet passes through then simply forwards the packet to the next hop indicated in the path given by the source.

When the source wants to initiate a transmission to a destination, it checks to see if it knows the route to the destination. If it does, it can immediately transmit the packet across that known route. If not, it must perform route discovery.

The route discovery process involves flooding the network with a query for the destination. A response to the query will be returned either by the destination or a node that knows a current path to the destination. All nodes simply forward the query to all the nodes they communicate with if they do not know the route to the destination. Before forwarding the query, the node adds itself to the query list. This will allow the complete route to be determined once the destination is found. To avoid loops the host does not forward the query if it has already been seen or if it is already listed as part of the query’s path. (A query ID number allows the node to determine if the query has been seen previously). As queries pass through a node, a host can also update routing information by looking at the addresses currently on the query list.

If a packet is sent and it fails to reach the destination as might happen if a link is broken or is suffering from interference, an error is returned to the source node. The source node then starts searching for a new route.

This protocol is suitable for networks where only a few sources communicate with destinations that are only accessed occasionally [19] since the overhead is relatively small in that case. The disadvantage though is that it scales poorly to large networks because the flood of query information can consume significant bandwidth. This is made worse by the fact that paths become larger in a bigger network and this leads to an associated increase in the size of the packets since each packet contains the complete address list. Finally, this initial search for a route may be time consuming and that can lead to large delays.

### 2.3.3 Ad Hoc On-Demand Distance Vector

The Ad Hoc On-Demand Distance Vector (AODV) protocol is another routing approach geared towards self-configuring multi-hop networks [22]. It is also a reactive protocol
that discovers routes as needed. It is not source routing-based which means that each node in the network must determine the next appropriate hop for a packet.

Unlike DSR, with AODV each host maintains a routing table in the same manner as a traditional wired host. In the table is one entry per destination. (In DSR, multiple possible routes are maintained). The node also maintains a list of neighbors using the route. When it discovers that a link to a given destination is broken, it informs its neighbors that the route is no longer available. To avoid loops, sequence numbers are used to track routing packets. These sequence numbers also serve to determine the relative age of the routing information. Query flooding to determine a route to unknown destination is done in a similar manner to DSR. All nodes that are aware of a path to the destination respond to the query.

However, like DSR, this approach suffers from a potential lack of scalability because of the flooding-based approach to route finding. Attempts to address this weakness have focused on using a structure such as TTL in an IP header to search only in rings around a source [19].

2.3.4 Destination-Sequenced Distance Vector

Unlike the other two protocols that were described, the Destination-Sequenced Distance Vector (DSDV) Routing Protocol is a proactive technique. To maintain its routing tables, each node performs both periodic and triggered updates. The triggered updates ensure that information such as link outages are transmitted as quickly as possible to all appropriate nodes.

Routing is performed based on the routing table maintained by each node. In these tables, entries track the next update for each destination along with a measure of the quality of that link to the destination. Typically, but not always, this will be the number of hops to a destination. A sequence number is also maintained to enable the node to determine how current the information is. When a link is found to be broken the metric to the next hop is set to infinity. Then, when a node requiring that link encounters a metric of infinity, it will broadcast an update if it knows a better route to the destination.

The main drawback to this scheme is that, as a proactive protocol, it may consume excessive bandwidth when performing its periodic updates. The approach also suffers from a potentially long settling time before stability is reached [19].

2.4 Performance and Scalability

Two of the most important parameters for a network are performance and scalability. Therefore, it is essential to examine the behavior of mesh networks with respect to these attributes. Performance expectations are typically centered are two major concerns: latency and throughput. Latency is a concern because for many applications, such as VoIP or more specifically when considering wireless meshes VoWLAN (Voice over a Wireless LAN), excessive delay is intolerable. Throughput is also important since users
frequently desire the ability to download or upload large files such as those containing movies or television shows.

The definition of scalability though has not always been clear. For example, there has been much work at producing scalable routing protocols but each project defined scalability differently with emphasis varying from packet delivery ratio to delay to average path length [2]. In an effort to focus scalability efforts, in [24], an attempt at a proper definition of scalability was made. The authors defined scalability as:

*the ability of the network to support the increase of its limiting parameters.*

A network can be limited by any number of factors such as the number of nodes in the network, the amount of traffic supported by the network, and the mobility of the network users. In the proceeding examination, the focus will be on scalability with respect to the number of users.

Scalability and performance though are not independent attributes. In the context of the routing protocols underlying mesh networks, scalability has been defined as “the ability of a routing protocol to support the continuous increase of network parameters without degrading network performance” [24]. The key aspect of this statement is “without degrading network performance”. Later, it will be shown that the overhead of some protocols increases significantly when the number of users increases. This issue is significant if mesh networks hope to expand to cover large regions such as cities where there will undoubtedly be many users.

Before examining specific routing protocols, it is important to consider the potential performance limits. One of the limits on performance is a result of the specific MAC protocol used since the MAC layer provides an upper bound on throughput. As the numbers of nodes in a wireless mesh increases, this capacity must be shared between all the nodes in the network. In [9], the authors present an analysis of the problem which demonstrates that as the number of nodes increases, the available throughput scales as $O(1/n)$.

The impact of this is shown in Figure 2. The figure plots throughput over varying offered load. Throughput is defined as the amount of traffic reaching the destination and offered load is the amount of traffic sources transmit. Under ideal conditions, offered load should match throughput. The figure clearly demonstrates that eventually the offered load no longer matches the throughput and the network is saturated. This demonstrates the capacity of the network. It is also interesting to observe the impact of having multiple active sources. As the number of sources increases, the throughput available to each node decreases significantly.
This is potentially problematic since in mesh networks the goal is to interconnect many users at high speeds. Any mesh network solution must deal with this inherent limit imposed by the radio media. It is also possible that this will be made somewhat worse by the hotspot nature of mesh network traffic since most traffic is towards a gateway node. In more general ad-hoc networks the throughput limits may be somewhat higher because not all traffic goes to a gateway and, therefore, collision issues are less significant.

It is also important to note that this examination also did not consider the impact of routing. As the number of nodes increases, routing protocols require increased overhead which further reduces the network capacity available to a user.

### 2.4.1 Routing Protocol Performance

Various studies have looked at the performance of the routing protocols that were just described. In Figure 3, taken from [21], the throughput when using AODV and DSR is compared. It is not important to note the absolute throughput and routing load numbers; instead, the general trends observed are more significant.

The experiment for the figure is from a simulation that used the ns-2 simulator with the 802.11 models from Carnegie Mellon’s (the group has since moved to Rice) Monarch group added to the simulator [21]. The network consists of 100 nodes and in Figure 3(a) 10 nodes are active while in Figure 3(b) 40 nodes are active. This experiment also
assumed the nodes are mobile. Offered load is the throughput transmitted by the senders and the measured throughput is the traffic received at the destination.

A few key trends emerge from this data.

1. The throughput decreases as more nodes become active. This is expected based on the limitations of wireless communication.

2. Another interesting observation is the amount of throughput available. When the offered load is low regardless of the number of sources, the throughput increases linearly with increasing offered load. However, as one would expect, such a trend cannot continue and the throughput eventually saturates when the medium cannot handle more throughput.

3. Routing load is significant. In both cases the load jumps significantly as the number of nodes is increased from 10 to 40. This is far from ideal since this takes away from the throughput that is available to the end user.

The conclusion from this data is that very low throughput can be readily delivered but higher throughput will be challenging. As well, scalability is a major concern if larger networks are to be considered. One can also see that AODV tends to perform better than DSR.
Latency is also an important parameter and in Figure 4 the latency under the previously described test conditions is reported. Based on this data, one can see that AODV does slightly better in terms of delay. It is also significant to note that the delay increases when DSR is used with an increasing number of nodes. At very high offered loads, the delay appears to be significant. However, this is well after the network has been saturated and both protocols are losing over half the packets sent. The network is essentially no longer functioning.

The primary conclusion from this data is that delay can be kept relatively small when the network is lightly loaded. Scalability however will be a concern as increasing the network size appears to lead to an appreciable increase in latency.
2.5 Current Client Meshing Implementations

One class of mesh networks that is currently in use is known as client meshing. As described earlier, with this approach all nodes are essentially equal and typically every node must serve as a router. The benefit to this approach is that no infrastructure is required. Users with wireless radios can simply form ad-hoc groups that enable connectivity within the group. Two implementations based on this philosophy will be now be described.
2.5.1 MIT Roofnet

One well-developed prototype implementation of a client mesh network is the MIT Roofnet [1]. The network is located in Cambridge, MA and is based on 802.11b/g radios. The system can be used for Internet access but its primary mandate is for wireless network research. The current status of this mesh is continuously available on-line with information such as link speed and routing tables easily accessible from any browser. The network is self-configuring and nodes can be added or removed generally without disrupting the network.

In Figure 5, the network status with the different colors indicating different link speeds is shown. Clearly, there is a great diversity in link quality which makes routing a very interesting problem. Since there is no planning in terms of addresses, the network exists as a single flat entity and that further complicates routing. In the Roofnet project, they are able to successfully address these problems and they report that their longest routes consist of 4 hops. In terms of performance, they do not report exact numbers and instead indicate that latency is on the order of dozens of milliseconds while throughput is on the order of dozens to hundreds of kbps. These results are interesting so the routing protocol will be examined further.

Figure 5 – MIT Roofnet Network Conditions
Unlike other projects, the MIT Roofnet is not focused on clients with high mobility. Instead, it focuses more on applications such as community wireless networks (CWNs) and, therefore, their routing protocol was designed primarily for maximizing throughput.

One of the main innovations in their design is that the routing protocol, which is called SrcRR, does not use hop count as the path metric [1]. Instead, a new metric called ETX is used. This metric predicts the number of data transmissions that will be needed to successfully transmit a packet over a link. ETX is calculated as:

\[
ETX = \frac{1}{d_f/d_r}
\]

where \(d_f\) is the forward delivery rate and \(d_r\) is the reverse delivery rate. Both these rates are determined for each link using dedicated packets that are periodically transmitted. The average numbers of packets in each direction can then be averaged over time to produce the delivery rate. For an entire path, the metric is taken as the sum of the ETX for each link. For example, the ETX for a path requiring 3 hops across perfect links is three. For a one hop path with a 25% delivery ratio, the path would have an ETX of four.

The developers believe such a metric is needed because of the varied characteristics of wireless channels. In these channels interference and asymmetric capacities need to be considered. To demonstrate this Figure 6 shows the throughput in packets per second of various network links. If just hop count was considered the path 23-19-36 would be favored. However, that is clearly not optimal since both 23-19-20-36 and 23-19-7-36 deliver higher throughputs. With the ETX path metric these alternate routes will be considered.

The SrcRR protocol uses the ETX metric as part of its DSR-based algorithm. Routing is done at layer 2. Each SrcRR node uses its own 32 bit address. (The standard case uses the nodes randomly assigned IP address as the 32 bit SrcRR address). Previous implementations were based on DSDV but this was found to scale poorly with traffic. At high traffic loads, the routing data would be drowned out and packets ended up taking random routes. The DSDV approach did work successfully in lightly loaded conditions.
The task of internet connectivity is handled through gateways. Any arbitrary node can serve as a gateway. Each wireless network node checks periodically to see if a wired internet connection is available. If there is a connection, this availability is broadcast to all the nodes in the network. Each node selects a gateway from its list of possible gateways. All internet traffic is encapsulated in SrcRR packets and then routed to the gateway node until that node is no longer available. Such an approach ensures that connections such as TCP connections will not be interrupted until absolutely necessary but it also means that in some cases the current gateway may no longer be optimal. This highlights the lack of flexibility in layer 2 approaches. They are often unable to handle issues such as roaming between gateways. This would be a definite problem for mobile users.

While this approach is fully functional and delivers reasonable throughput (although the exact throughput is not explicitly stated) the project developers admit that the routing protocol is not scalable [1]. Once the network increases beyond hundreds of nodes, routing traffic will overwhelm the network but the authors do note that the protocol could be optimized for the case when most traffic is towards the nearest gateway. This is left as a future improvement.

2.5.2 MeshNetworks (Motorola)

MeshNetworks was a small startup offering a range of products including software packages that enable mesh creation and hardware ASICs and reference designs for routing engines and radios. It was recently purchased by Motorola to expand their wireless product offerings [17]. The most interesting part of the MeshNetworks solution was the MeshConnex software technology. This package implements a Layer 2 routing protocol that they believe enables “high performance, scalable ad-hoc mesh networking”. [13]. A digital ASIC that handles all this layer 2 functionality is also available from MeshNetworks.

This layer 2 implementation makes the system protocol-agnostic with respect to the higher network layers. Unlike other commercial offerings this means that IPX, NetBIOS and IP can all be used without a problem. Layer 2 also has the advantage that the protocol is aware of the radio state. Using information such as signal strength and error rates, the routing protocol is able to respond more quickly to changing conditions and MeshNetworks believed this is essential for applications such as VoIP which are very sensitive to latency.

The foundation of the MeshNetworks architecture is a routing protocol developed by MeshNetworks known as the MeshNetworks Scaleable Routing (MSR) Protocol. The protocol was designed explicitly for multi-hop ad-hoc wireless networks. This protocol requires no fixed infrastructure and it is reported that it can operate in both a pure peer-to-peer mode without access points and an infrastructure meshing mode with fixed access points. The protocol reportedly combines both proactive and reactive routing techniques. This hybrid technique is called situation-aware routing. It claims to avoid the flooding and latency that commonly occur with pure reactive techniques while also reducing the
overhead of proactive approaches. Regardless of the condition of the system, MeshNetworks reports that the routing algorithms avoid loops.

The protocol leverages the information made available by its layer 2 implementation. The link status metrics are tracked by MeshNetworks’ Adaptive Transmission Protocol (ATP) services. These services monitor many aspects of the radio environment. For instance, the system estimates the impact of transmission power on network capacity. This enables the MSR protocol to determine the most appropriate transmission power. The protocol also reduces data rates based on radio conditions while still maintaining a relatively high throughput [14].

Unfortunately, aside from this marketing-level description of the MeshNetworks implementation little reliable information is available. The company reported that a MeshNetworks-based implementation has been operational in Maitland, FL but no throughput or client capacity statistics are provided. A potential upcoming installation claims that it will deliver symmetric speeds of 512Kbps to 1.5Mbps [15]. The system is being created for a Traffic Engineering department so it is unclear if issues such as latency would be problematic for such an installation. A MeshNetworks-based design is also being planned for Beijing to be used for reporting information during the 2008 Olympics. Current plans call for it to support up to 5000 clients. Performance and scalability specifications beyond this 5000 client target have not been released so the exact capabilities of the system remain unknown.

2.6 Current Infrastructure Meshing Implementations

The past approaches focused on mesh networks in which all the clients are equal. In such networks, routing is a significant challenge since the number of routes is diverse and each node must participate for the network to function. Now networks in which the wireless connections are infrastructure-based will be considered. This arrangement is called infrastructure meshing. In these networks, fixed access points typically serve as bridges connecting wireless clients to the wired network. These networks more closely resemble wired networks and in some cases when dealing with 802.11 links, it may be called a Wireless Distribution System. Routing is significantly less complex and it is even possible to use conventional routing algorithms. However, this arrangement raises new issues such as roaming between access points.

It is worth noting that these arrangements are at best partial mesh topologies. In some cases, such networks may more closely resemble a star or hub and spoke topology. However, the industry continues to apply the term wireless mesh network to these cases and therefore they remain relevant when considering WLAN mesh solutions.

2.6.1 IEEE Standards

A task group was formed earlier this year to develop a standard for mesh networks based on 802.11. The standard will be 802.11s and it will be known as an Extended Service Set (ESS) mesh. Its goal is to develop a Wireless Distribution System (WDS) using the IEEE 802.11 MAC and PHY layers. This system will be self-configuring and it will support multi-hop broadcast/multicast and unicast delivery [6].
The existing standards envisioned the eventual creation of this WDS and left a four-address frame format that could be used to support this functionality. However, it is not defined how this frame format will be used. It is hoped that the standard will enable interoperability while still allowing for varied path selection metrics. In terms of scalability, the standard is only targeting arrangements with up to 32 access points which may not be adequate for all applications of mesh networks. The project proposal for 802.11s does indicate that larger networks will be considered. The 802.11s task group formed only recently and has yet to accept proposals for the standard. Therefore, performance issues remain unanswered.

The future of the 802.11s standard is definitely promising. The standard may not resolve all bridging and routing considerations for mesh networks but it will offer a tremendous improvement over the current situation since no standard exists. Currently, each vendor has developed their own solution and the lack of interoperability is likely slowing the adoption of mesh networks.

### 2.6.2 MeshDynamics

MeshDynamics focuses on delivering mesh networks for hotspot or city-based deployments. All the full-mesh topologies considered previously suffered from the lack of scalability. According to MeshDynamics [12], throughput degrades by a minimum of $1/n$ for $n$ hops and more typically $1/2^n$. They believe that this scalability is the limiting factor for meshes and have developed a multi-radio solution to avoid such limitations. The network structure for this solution is shown in Figure 7. Their decision to use this technology is predicated on the assumption that most clients want to connect to the wired network and that few if any desire client to client communication. They argue that this multi-radio solution is not appropriate for a full ad hoc style mesh.

![Figure 7 – MeshDynamics Multi-Radio Solution](image)
Their multi-radio network, which they call a *structured mesh*, connects access points together in a tree-based structure. The radios linking the access points can use different radios thereby avoiding interference with the clients. Routing is much simpler because this tree structure ensures that there are no loops. This also keeps each access point’s basic service set manageable.

In the case of 802.11 networks, the structured mesh builds on the four-addresses in the frame that support WDS. This enables the bridging of the access points and it is possible that this specific solution could be a proposed as a standard for 802.11s.

They have also proposed a four radio solution that builds a true mesh of access points. However, no implementation details are provided other than that it operates below the network stack at the layer 2 level. To enable this meshing they introduce what they call the “Mesh Control Layer” which monitors radio information and makes appropriate adjustments to the network.

Unfortunately, while they boast about their promising implementation, they do not provide concrete measurements in terms of performance or scalability. However, the fact that they use this multi-radio solution does acknowledge the previously described scalability problems with full client meshing.

This multi-radio solution appears promising and suggests significant capacity increases are possible. Since MeshDynamics does not provide details of the increased throughput, other multi-radio solutions were examined. In [18], a wireless mesh network in which each node was equipped with two wireless radios was tested. A new path metric described in [18] and called the Weighted Cumulative ETT (WCETT) is used for routing in this network. The aim of the metric is to account for interference among links on the same channel. This implementation is called a layer 2.5 implementation since it exists between the link layer and IP.

The results from this implementation demonstrate that multi-radio solutions offer definite performance improvements. In Figure 8, this performance improvement is shown graphically for paths of varying lengths where lengths are measured in terms of hop counts. Clearly for two and three hop paths the throughput increase is substantial and, in many cases this might be worth the cost of an additional radio. For longer paths though the increase is less pronounced. While this technique is promising because of the throughput increases, the fundamental scaling problems remain.
2.6.3 Tropos Networks

Tropos Networks [27] aims to make wireless connections such as 802.11 more readily available. Therefore, this work is very relevant because this report aims to address the same problem which is that of making meshes more widely available. The approach taken by Tropos is based on the model used for cellular networks. Their proposed scale is similar to that cell networks since they propose to serve entire cities and they dismiss the simple hotspot approach used for past networks. They do not refer to their product as a mesh network but its topology is very similar to the previously considered mesh networks.

With the Tropos Network approach, each wireless “cell” is self-configuring and once supplied with power interacts with the existing cells to broaden the coverage of the wireless network. This arrangement is shown graphically in Figure 9. In this system, clients can connect to any wireless access point. As with the previous systems, the assumption is that most traffic is towards the wired backhaul. There are many possible links between “cells” and therefore, this topology once again raises the issue of routing. They believe that past attempts at mesh networks have failed because the focus on client to client interaction which leads to excessive routing overhead while failing to optimize the most frequently traversed path between a client and the backhaul.
To address these past deficiencies, Tropos Networks developed their own protocol known as Predictive Wireless Routing Protocol (PWRP) [28]. Its design goal was to ensure scalability. To do this it focused on the communications between a client and a wired server. Figure 10 illustrates qualitatively the supposed benefits of Tropos Networks’ solution to wireless mesh routing. The main benefit is that the routing protocol is designed to scale well with the number of nodes in the network. Since each node only maintains a route to one connection (the server), it is asserted by Tropos Networks that the network can scale to cover wide geographic regions. However, without numbers in the figure the precise degree of scalability is difficult to assess.
While details are not described, it is reported that hop count or RF signal strength are both not appropriate metrics when high throughput is desired. In [28], it is stated that decisions made based with such parameters tend to be uncorrelated with throughput. The PWRP protocol takes frequent bidirectional measurements to determine link status. Those measurements serve as the input to predictive algorithms that determine the most appropriate path. With these algorithms they are able to deliver twice the throughput of competing implementations [28].

This is at least partly a layer 3 solution, since at each wireless cell, a network level operating system controls the setup of the mesh. However, the discussion of link quality suggests some layer 2 information is needed. Unfortunately, few concrete details are provided about the algorithm or its implementation.

Furthermore, only limited information is available regarding the performance and true scalability of the system. A case study in [29] described a city wide deployment of 230 Wi-Fi “cells” with a target audience of 7500 customers. This implementation suggests that scaling on this order is possible. The system is reportedly able to deliver throughput on the order of 1 to 5 Mbps but no detailed information is available.

2.6.4 Chantry Networks (Siemens)

All the previously examined solutions focused on the multi-hop radio implementations. The obvious limitation with these approaches is scalability. Before further considering the future of WLAN meshes, it is necessary to examine competing solutions. One such solution is from Chantry Networks which has developed what they consider to be one of the first routed Wireless LAN solutions. Using current technologies clients are able to connect to the wireless LAN throughout an enterprise-wide deployment. All the clients communicate exclusively with Chantry Networks’ infrastructure products. These products called a BeaconPoint and a BeaconMaster connect together to support large wireless networks. Routing to clients is done at the IP-level which enables an enterprise to leverage their current IP-based networks. Since the architecture consists of a wired backbone between access points (BeaconPoints), the complexity of multi-hop mesh networks is avoided.

The major innovation is in the management and scalability of this approach. There is significant complexity in the management of a distributed range of access points and to aid this process Chantry co-developed the CAPWAP Tunneling Protocol [3]. Through this protocol control information is distributed from an Access Controller such as the BeaconMaster to the Access Points. The access points then control the client’s access to the network. This solution addresses many of the current concerns with managing large deployments. It has many advantages. For example, an Access Controller may be connected via a slow WAN link. With this setup, only control information need be transmitted over the link and the access point can allow the clients access to the local wired network based on the policies set by the controller.

1 It has been announced that Chantry Networks will be acquired by Siemens [4].
This wired backbone approach to wireless LAN deployments also avoids many of the problems faced by multi-hop mesh implementation. With current deployments in use at places such as the Metro Toronto Convention Centre, it is apparent that this approach is feasible. However, no performance measurements have been provided by Chantry Networks. They do report that each access controller (the BeaconMaster) can support 100-200 access points each of which can support 10’s of users. Clearly, this approach is more scalable than other mesh-based wireless alternatives. However, this is not a fair comparison since the wireless devices, unlike those from Tropos Networks for example, require wired Ethernet connections. This makes deployment impossible in regions where wired connections are not available.

This approach by working at a higher layer also presents some interesting capabilities. For instance, users have the ability to roam between access controllers which may serve as Internet or wired network gateways. With pure layer 2 solutions this is difficult as was seen in the MIT Roofnet implementation. A recently published patent application (October 28, 2004), offers some insight into their implementation [30]. Tunneling between access points allows these connections to be maintained. The network topology is then similar to that of a GPRS network which is logical since the entire implementation resembles the structure of the cellular phone network.

3 Mesh Network Applications

Before proceeding with the analysis of the future for mesh networks, it is instructive to first examine the applications of the technology since the current and potential applications will shape any future developments. From a network perspective, there are two key features of an application that must be considered: the bandwidth requirements and the latency tolerance of the applications. Table 2 lists some potential applications along with the bandwidth requirements and latency tolerance classified into three broad ranges.

<table>
<thead>
<tr>
<th>Application</th>
<th>Bandwidth Requirements</th>
<th>Latency Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional WWW</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Traditional E-mail</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>File Sharing</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Streaming Radio</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Streaming Video</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Instant Messaging</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td>Voice over IP</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Video over IP</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Sensors</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>On-line Gaming</td>
<td>Low-Moderate</td>
<td>Medium-High</td>
</tr>
</tbody>
</table>
Clearly, most of the listed applications are applications that users currently use when connected via wired links. This is no surprise since users have come to expect the same behavior from wireless systems as they expect from their wired links. The main point in considering these applications is to note the diversity in requirements. Some applications put only minimal strain on the network as they have low bandwidth needs and a high tolerance of latencies. However, other applications such as Video over IP require high bandwidths and since such a technology would be used for real-time communications the tolerance of latency is low. With such diverse demands, it is clear that any mesh networks solutions cannot be engineered for one specific application or even class of applications. It will not be acceptable to users if they must physically reattach to the network when it is desired to use a specific application such as a latency intolerant VoIP phone.

One other noteworthy factor is that most of these applications involve communication from an end-user to a central host or server. While much of the past work focused on the generic case of peer-to-peer communication, this does not seem to be required for many applications. The servers that a client may access would typically be wired and at a central location. Therefore, it appears important that the wireless mesh network deliver efficient access to the wired network or Internet. There are however some peer-to-peer applications such as instant messaging and Voice and/or Video over IP. While these applications cannot be neglected, these observations suggest that there is some freedom in mesh network solutions to optimize for the communication between wireless hosts and the gateways to the wired networks.

These observations were predicated on the assumption that users of mesh networks will demand access quality similar to that of current wired access technologies. It is reasonable to question the validity of this assumption. For small WPAN mesh networks, usage patterns may be very different than typical LAN access but, for the LAN-like access which is the focus of this work, it appears only logical that users will utilize wireless meshes in a similar way wired networks are utilized today. In the larger WWAN sector, it is also likely that similar usage will emerge. One need only consider the migration of many typical desktop activities such as web browsing, e-mail and voice over IP to current cell phones to see that users’ application demands are relatively consistent.

While some vendors claim to offer current mesh network solutions, in general such technologies are not widely deployed currently. Therefore, it is also worthwhile to consider if application demands will change by the time wireless mesh technology becomes prevalent. In fact, it is most likely the case that applications will change as innovation leads to the development of new uses for the Internet and new ways to communicate across it. Such changes may increase the bandwidth requirements but latency concerns will always remain. In this respect, mesh networks will be no different than wired networks where users are continuously demanding more bandwidth.

There will however be some differences that must be considered with these mesh network applications and the most significant is mobility. With the ubiquitous connectivity promised by mesh networks, users will expect all applications to work
flawlessly when they connect at the office, at home, and as they move around. This can pose a problem and this issue of mobility will be revisited in the following sections.

To summarize, it is clear that the potential applications of WLAN mesh networks will have widely variable demands. Users will likely expect connectivity quality that is equivalent to wired approaches and, therefore, mesh networks will have to evolve to satisfy needs such as for high bandwidth and low latency. With the needs of the network more clearly defined, the current limitations can now be examined to understand what must change in the future if mesh technology is to become more prevalent.

4 Difficulties with Mesh Network

Users have been quick to adopt wireless technologies and the number of users using IEEE 802.11 for network connections has exploded recently. However, much of the growth has come from simple non-mesh approaches in which hotspots are created simply by connecting access points to the wired network. This approach is ad-hoc and has not yet enabled ubiquitous connectivity. The background presented in the preceding sections suggested that mesh networks are at least possible which raises the question as to why mesh networks are not deployed more widely. One of the reasons the deployment is not more widespread is that mesh networks continue to suffer from some limitations. This section analyzes these limitations and considers possible avenues for future improvements.

4.1 Mesh Network Limitations

Based on the background presented in Section 2, the primary limitation with mesh networks is clearly scalability. However, there are many facets to this scalability problem. One element to this problem is the challenge of routing, particularly for client meshing solutions. The protocols described earlier such as the AODV and DSR do not scale well to handle wireless meshes with hundreds of users. While commercial implementations naturally claimed to have resolved some problems, projects such MIT’s Roofnet reveal that real-world implementations continue to have problems scaling the routing protocol for higher client capacities.

Another element to scalability problem is managing the large number of access points in a wide-scale mesh deployment. When standard off the shelf equipment is used, it is very difficult to configure all the access points to enable appropriate connectivity. These difficulties are the reasons companies such as MeshNetworks, MeshDynamics and Tropos Networks, whose solutions were discussed previously, offer unified solutions for mesh networks. It is also these management difficulties that led to implementations such as that from Chantry Networks which aimed to simplify management so that users simply have to connect a box into the centrally managed system.

One other issue that is potentially slowing the acceptance of wireless meshing is security. Most mesh network solutions are based upon technologies such as 802.11 in which security problems have not been fully resolved. While average users are typically unconcerned about security, adequate security is necessary for commercial deployments.
Authentication in particular is the primary issue since commercial systems typically want to limit access to their network.

Another issue that has not been examined extensively is the impact of competition. While this has not proved to be an issue today, it could become problematic in the future if WLAN meshes become a widely deployed access medium. In such a case then it is likely that multiple providers of such solutions will emerge. As described in the background, multi-hop meshes face significant capacity issues. These issues will only be compounded if competing mesh solutions are forced to coexist. The reason for these problems is that electromagnetic waves (radio or infrared) are inherently a shared medium. When one user is broadcasting at a specific frequency then all other users in the vicinity are forced to listen. This is acceptable when there is only one network, as the management of that network ensures the network remains efficient. However, with two competitors vying for the same media, significant problems may emerge.

In the past, because of this potential for conflict, bandwidth has been viewed as a scarce resource and, therefore, its use has been highly regulated. Such regulations have enabled competitive environments within the radio, television and cellular phone markets. With wireless mesh networks, the situation has changed significantly because most wireless solutions operate in unlicensed portions of the spectrum. IEEE 802.11b, for example, operates in a 2.4 GHz Industrial-Scientific-Medical (ISM) band [23]. The use of such unlicensed bands has been necessary to enable their widespread deployment. The bands are not unregulated so equipment must satisfy certain power and frequency specifications. Unfortunately, these limitations do not resolve the issue of competition.

Competitive solution providers can use standard equipment such as 802.11 access points but the bandwidth available to them will be shared. The IEEE 802.11b standard does allow for multiple channels that can be used to facilitate the use of non-interfering communications but this is only a partial solution. As a result if two (or more) competitors deploy mesh networks then the available bandwidth to one company’s network may be reduced if a competitor has more customers. This would be the case because the media-access control in the 802.11 standards attempts to ensure fair access for all parties without any knowledge of which user is on which network. This is clearly an important limitation that must be addressed if commercial mesh deployments are to be successful.

Finally, one other factor that has been a limitation is cost. Wireless equipment is generally more costly than regular wired equipment. Wired solutions do have their downside such as higher installation costs, but, once cabling is installed, wired solutions become very cheap. In cases where wired solutions are already place, the transition to wireless meshes will be much slower. Mobility is the driver for wireless but other factors are often important to users such as bandwidth. A switch to any current wireless technology will likely be a downgrade in terms of bandwidth. For example, wired LANs have generally long ago migrated to 100 Mbps but current wireless LAN standards offer transmission rates of 54 Mbps at best. This performance downgrade may limit users’ willingness to switch to mesh networks.
In summary, there are many issues that are slowing the adoption of mesh networks. Some of the primary issues are scalability, security, ease of competition, and cost. Of these scalability is by far the most significant. Without forthcoming solutions to resolve this problem, large mesh deployments may not be feasible and, therefore, there is an immediate need for solutions to this scalability challenge.

4.2 Potential Solutions to Mesh Network Limitations

Fortunately, none of the current problems with mesh networks appears insurmountable. Each of the limitations will now be considered and potential solutions will be examined.

The scalability limitations of mesh networks are well known and each of the commercial implementations described in Section 2 claims to have at least partially addressed this problem. Without definitive performance and scale numbers it is difficult to assess whether this is true. However, it is possible to examine some approaches to determine if they may potentially resolve the scalability problems.

One solution that is already being used is to put multiple radios into each of the network nodes. For infrastructure meshes in which the access points are connected with a wireless backhaul, this is very likely to be the preferred solution. The reason for this is that as past results demonstrated, there is simply too much congestion when the infrastructure portion of the mesh must compete with the clients for access. The only downside of this approach is the cost of the additional radio but the incremental cost of adding a second radio to a mesh node is relatively small especially given the significant benefits.

The other approach to addressing scalability particularly for WLAN access will be a shift away from full client meshing. The routing overhead to support these client meshes is too high and it is unlikely new routing algorithms will adequately address this difficulty. Instead, it appears more likely that the focus will shift to an infrastructure mesh where network clients do not directly communicate. This will provide more stable coverage and dependable coverage as compared to approaches that rely on the clients themselves to broaden the reach of the network. The components of the infrastructure mesh may however rely on client meshing because at that stage it may be manageable. Since most traffic will likely remain focused on accessing on wired networks or the Internet, the routing within the infrastructure will be optimized for this case. Client meshing will be considered for this portion of the network because it can potentially simplify deployment while still remaining manageable when routing is optimized for traffic towards a gateway.

Finally, another possible solution that will emerge is the introduction of hierarchy into the mesh. One of the difficulties with mesh networks is that since many operate at the layer two level the view of the network is flat. This makes routing difficult but it is not necessarily clear how hierarchy should be introduced. The logical approach is to have the hierarchy resemble the physical topology of the network. In the same way CIDR advocated an IP address scheme that reflected the physical topology of the network, mesh
networks need to adopt similar approaches if they are to scale to large sizes. The issue with mesh networks is that because of mobility, the topology is changing which has made hierarchy difficult to introduce in the past. The likely solution to this mobility problem is to make use of location information. Knowing the physical location of a user or an infrastructure node could make organization much easier. Since manual configuration of location is not a desirable option, the best approach for location management would be to use existing technologies such as the global positioning system (GPS). Using that location information, a hierarchical structure of nodes in close physical proximity could be created. This hierarchical approach could make routing more efficient. For example, if the current location of a node were tracked in a similar way to cell phones then this information could be retrieved and used to guide routing decisions. This might help avoid the massive query flooding which causes problems with routing schemes such as DSR and AODV.

The security concerns described earlier are important and similar problems are faced by regular IEEE 802.11 deployments even without mesh. Therefore, there is an abundance of work aimed at resolving issues such as authentication and the recent approval of the IEEE 802.11i standard should address most of these issues. As new equipment is deployed that satisfies the standard then security concerns should ease and this should not significantly hold back the adoption of WLAN meshes.

The issue of cost will also likely not be a long term problem. It has been reported that the cost of WLAN equipment, which is essential for WLAN meshes, has been dropping by 40% per year [25]. Accompanying this trend has been the increasing bandwidth of wireless solutions as shown in Figure 11. Given both the decreasing cost for the equipment and the increasing available bandwidth, it is very likely that mobile meshing will become a more accepted solution. Wireless speeds will continue to trail wired speeds but with advanced wireless technologies, users will likely transition to wireless in many activities for convenience. The freedom to maintain a connection everywhere appears to be very powerful and this will override the slight cost and bandwidth penalties.
One other factor that was raised as a potential limitation was the limited ability of WLAN-based mesh solutions to foster competition. There are many possible remedies to this solution. One possibility is that future deployments could rely on licensed channels for communication with subscribers. This is the same model used in the cell-phone market where each competitor purchases the rights to a set portion of the spectrum. However, this solution appears unlikely. First it would necessitate a change in all currently deployed hardware and customers would be hesitant to perform such a change with little perceived benefit. As well, the interoperability of current WLAN equipment (such as WiFi approved radios) is a core feature that would be lost. It is convenient that a user may potentially use their 802.11g card on a commercial mesh network when away from home and then use that same 802.11g card to communicate on their home network. That home network may in turn connect to a mesh network provider but connecting to a local mesh may be advantageous to avoid the cost of using the commercial network when transferring data locally.

The biggest potential for problems will arise from the multi-hop nature of mesh deployments and the final wireless link to end customers will likely not prove to be as significant a limitation. If the back-haul link from an access point to a gateway uses the same radio as that used for customers and by competitors then significant capacity problems will result. This is similar to the scalability problems examined earlier and therefore the solution is the same, multi-radio meshes. These multi-radio meshes could be based entirely on standard unlicensed links such as 802.11b/g for customer links and 802.11a for the backhaul. Alternatively for installations which desired more reliable performance, the use of licensed spectrum for backhaul links may be feasible. This may prove to be the solution of choice for public infrastructure links such as those that may eventually be used for emergency responders.

Another alternative instead of using licensed spectrum may be the use of highly directional solutions on the backhaul to reduce interference from competing solutions. This however defeats one of the planned advantages of mesh solutions which is the ease of installation. The goal of many mesh solutions is to simplify installation to only involving plugging in an access point. Therefore, it is unlikely such a solution would be adopted.

Finally, one last solution may be that providers may cooperate and allow customers from competitors to use their infrastructure. This approach would essentially be similar to that used in the telephone and coaxial cable markets where some providers resell services on the existing infrastructure. Cooperation in a similar manner for mesh networks is likely in a limited form but the history of such arrangements suggests it is unlikely to be common place. A more plausible form of cooperation might be more like a peering arrangement. Two competitors with installed solutions may allow traffic from the other network to be routed across their access points. Such cooperation might reduce congestion problems that would otherwise happen with multiple mesh deployments. While such an approach seems ideal, it is not clear if it would be accepted because of the
many complexities such as proper billing to ensure one provider is not taking advantage of another provider.

5 Integrating Mesh Networks

The preceding sections have revealed that, while mesh networks have their strengths and are interesting technologically, these networks do have their limitations. Given these limitations then it is interesting to examine how this style of networks can be integrated into existing networks in the near term. Understanding these near term uses is essential to understanding the future of mesh networking.

The most popular feature of mesh networks from a user’s perspective appears to be the mobility they enable. This is a popular attribute because many users have grown accustomed to the plethora of information available on the Internet and would like that information to be continuously available. As well, wireless connectivity simplifies installation for the user and avoids the complications that come from wired connections.

The following analysis will be based on this assumption that mobility is one of the driving forces behind mesh network. It is first necessary to observe that while mobility is pushing mesh technology, it will not eliminate wired connections in the near term. Even with a longer term outlook of ten to fifteen years, wired connectivity will remain in widespread use. The reason for this is simply the available bandwidth of the solutions. Both wireless and wired technologies continue to improve but it is likely that wired speeds will always surpass wireless speeds. With the emergence of bandwidth intensive applications such as video-on-demand, it is clear that current and near-term wireless solutions will not be able to compete. Such applications will drive demand for faster wired access links. With faster access links comes the need for faster links throughout the network to fill these links. It is likely that none of these links will transition to wireless mesh or even wireless fixed links for the foreseeable future. Therefore, given the existence of wired links, the issue is how mesh networks will complement this wired infrastructure.

In developed markets the role of wireless meshes will be to facilitate network access and enable access to the network from locations where it was previously infeasible. The first step in this will be a shift from “hotspots to hot zones” [7]. This shift will occur because the current hot spot approach to WLAN access is cumbersome. Hot spots are growing in popularity with hotspots available at locations ranging from McDonalds [11] to Starbucks [26]. While these restaurants may appear to be everywhere, the reality is such pockets of wireless connectivity cover relatively little area. Therefore, the hotspot is convenient while at McDonald’s but, a block away, there is no longer a connection available. This is clearly inconvenient for the user and a better solution is needed.

Hot zones instead of hotspots are therefore clearly a better solution since they promise to enable wireless access over a wider area. However, with the costs of technology in the near term, this will only be possible over small geographic areas that are either highly populated or regularly traversed. Deployments in such areas are already starting to appear at facilities such as convention centers and airports. The rate at which these
installations are deployed is likely to increase as equipment gets cheaper and users come to expect better connectivity. The mobility these installations enable will also only be at pedestrian speeds. Maintaining connectivity at faster speeds will require improved technology.

Aside from the cost issues, current mesh deployments will also be limited by the aforementioned scalability problems in the short term. While mesh advocates believe mesh-based networks could be a suitable access technology for the home, this is unlikely to be the case in the short term particularly in developed markets. In such markets, cable and copper technologies are typically already installed. There appears to be healthy competition in these markets and users are benefiting from fast speeds and relatively low prices. Typically, with the addition of a single wireless access point, users will have resolved most of their current in home mobility needs. Mesh technology then does not offer any benefits. Obviously there are some areas that are not served by current copper or cable infrastructure; however, these areas are frequently the less densely populated areas where deploying a mesh is unlikely to be cost effective.

Community wireless networks similar to the MIT Roofnet project do appear to be rapidly developing. However, such community oriented networks are likely to be a niche market. For most of these community wireless networks, users offer up their Internet connection to be shared via the wireless links. However, this is likely not to be tenable. Internet connectivity is becoming more like a utility and, in the same way you do not expect random strangers to offer electricity and water for free, offering a network connection for free seems unlikely. Billing schemes to reimburse users for such access are also likely to be difficult to implement for many reasons with one reason being that fixed link providers are unlikely to permit individual users to resell their currently low priced connections.

The near term outlook for mesh networks is very different in regions where the existing infrastructure is relatively immature. In these markets, mesh is much more likely to be used as an effective access technology in the short term. Without any in place infrastructure, wireless access is the logical solution and mesh deployments of WLAN technology are one of the most viable candidate for delivering this access. Furthermore, users in such regions will not have as high expectations for throughput and latency and, therefore, they will be more tolerant of the potential problems that may arise from scalability. As scalability problems are addressed then service quality will improve. In these deployments it is also likely that multi-radio infrastructures will be used to minimize scalability problems. As well since the only infrastructure required by these multi-radio infrastructure nodes is a power supply, these solutions will be ideal for deployments where existing little wired infrastructure is available.

6 The Future Role of Mesh Networks

As technology improves, the role of mesh networks is also likely to change. In this section some of these potential changes will be examined. The general trend that is likely to emerge is the continued spread of wireless access. This trend is not hard to predict because users generally expect improved coverage for wireless access as time progresses.
Given this general trend of spreading wireless access, the likely role for mesh networks is to complement new and upcoming wireless wide area network deployments such as 3G and 4G cell phone networks. These technologies are likely to complement each other rather than compete with each other because of the relatively short reach of WLAN technologies as compared to WWAN technologies. As a result of this technological limitation, it will not be cost effective to deploy WLAN solutions over the massive areas needed for WWAN access. With time, costs of WLAN solutions will improve and this technology may be deployed for WWAN access. In such cases the wide area network will start to resemble the wireless LAN topologies. However, new technologies will also emerge for WLAN access which will lead to this continued need for two approaches for wireless access. Therefore, while the architectural distinction between WWAN and WLAN may become increasingly blurred a disparity in technology and therefore connection speeds will continue to exist.

The other reason for this trend towards coexisting WWAN and WLAN solutions is that the two will always serve slightly different needs. At work, users will want WLAN access for the same purpose they currently use the wired LAN. These will be private wireless LANs and for companies where a single access point is not sufficient then mesh solutions are the best approach for providing this LAN access. These installations will remain private because many companies particularly technology companies will not be willing to rely on publicly accessible networks for their internal communications. The risks from outside attackers will be one factor which will make companies hesitant to use public mesh networks. As well, it is unlikely to be cost effective for companies to have all their internal traffic travel through commercial meshes. Outside of these private installations, users will still want connectivity but it will be necessary to rely upon commercial deployments of mesh networks because speeds similar to that of the private LAN will be desired. Finally, when beyond the coverage of these commercial meshes slower but more broadly covered WWAN approaches will be used.

With this expectation of complementary WLAN mesh and WWAN networks, the other trend that is certain to emerge is the seamless transition between the two networks. Single devices that can operate on both networks will soon emerge. For in-building coverage and in densely populated regions WLAN speed connections will be available but it sparsely populated remote areas WWAN access will be necessary. This difference however will barely be noticed by users for many classes of application such as VoIP. Eventually, new cell phone networks will be IP-based and WLAN networks are already designed for IP. Therefore, voice will simply be transmitted over IP packets and, to the application, it will be immaterial which underlying access technology is used.

Another trend that is likely to emerge is the reliance upon mesh networks for access to new sources of information. Other classes of mesh networks such as sensor networks will enable the collection of detailed information for subjects ranging from the weather to traffic. Such networks will not rely on the same techniques as WLAN meshes but users may require access to the information through WLAN meshes.
Finally, with improvements in mesh networks, IP-based Voice over WLAN (VoWLAN) is certain to become increasingly popular in a similar way regular VoIP solutions are becoming increasingly important. With WLAN mesh networks providing connectivity throughout an entire workplace or home, it will be possible to displace wired VoIP solutions. However, such a transition would not be possible with poorly integrated hotspot style WLAN deployments and, instead, a well integrated mesh network is crucial if future VoIP connections are to be made wirelessly because voice service brings expectations of high quality service. Therefore, the transition to voice, particularly in workplace deployments, cannot be expected to occur until the mesh networks become significantly more mature and reliable.

7 Future Mesh Network Evolution

Given this changing role of mesh networks, the technology and approaches used for WLAN meshes are likely to evolve to enable these changes. This section examines some of the most significant changes that will be necessary.

7.1 Infrastructure Meshing

The single most significant change will be in the topology of the network. Currently, there is a great deal of interest in client meshing but this client meshing is of limited use. To ease the scalability problems, an infrastructure-based approach is more appropriate as described earlier. This is acceptable because the general usage pattern is towards a network or Internet-connected gateway. While applications such as VoIP suggest that the peer-to-peer communications enabled by client meshing are important, this is not enough motivation to merit a switch to full client mesh approach. Applications such as VoIP do involve peer-to-peer communication but architecting the network specifically for this class of applications is unlikely. Instead, it will likely be easier to design the network such that the path to common gateways has relatively high bandwidth and low latency. Peer-to-peer applications will simply be connected via connections through these gateways.

One of the supposed benefits of client meshing is that it enables the region of coverage to be extended since one node with access to the wireless network can spread that access to other users. However, in the future, if mesh networks take hold it is unlikely that people will tolerate such random coverage. Network access is much more useful if it can be depended upon. If a system relies on client meshing, the coverage may be by its very nature ad-hoc and this potentially leads to intermittent gaps in coverage. Therefore, the more likely deployment model will be a more infrastructure-based approach.

There are exceptions to this and client meshing techniques will continue to have their place in augmenting infrastructure-based approach. For emergency service providers such as fire fighters, the peer-to-peer model may be useful because such users may have to work in environment where the infrastructure is not stable. Therefore, for these classes of users, client-based meshing will continue to exist. However, this coverage will likely be more focused on simple communication and not the higher speed WLAN communications that are the focus of this report.
While this shift away from full client meshing is likely to occur, the infrastructure meshing is likely to incorporate some of the concepts from client meshing. In particular, infrastructure nodes may be connected together wirelessly to form a full mesh topology. This is very different than full client meshing where the end users themselves form part of the mesh and therefore must serve as routers. Connecting some infrastructure nodes with a full wireless mesh is much more manageable than the client meshing since it still allows the network operator control over where coverage will be provided. The benefit of this approach will be simplified management. Infrastructure nodes can be deployed as needed throughout an area and the mesh network that is created will enable integrated and widespread coverage while avoiding complex tasks such as frequency planning.

However, this shift to a full mesh of infrastructure nodes will not be accompanied by a shift to the peer-to-peer routing protocols considered previously. As described earlier, the focus in the routing protocols will remain on optimizing the path to wired gateways. This focus will be maintained because most traffic will continue to exist towards the wired network. As well, this approach will be necessary to avoid the scalability problems that plague routing protocols that focus on peer-to-peer routing. This approach then should enable these mesh deployments to be scaled up to handle thousands of concurrent clients.

This shift to a more infrastructure-based approach is interesting since it means a shift away from true fully interconnected mesh topologies. In the same way, metal-oxide semiconductors continued to be called MOSFETs long after the gates were no longer metal, these new networks that will emerge will continue to be called mesh networks after the clients no longer form a mesh. WLAN mesh networks will likely instead come to stand for well integrated WLAN solutions irrespective of the exact connection topology.

### 7.2 Mobility and Handoffs

As described in Section 6, it is likely that future mesh networks will develop to complement 3G and 4G WAN systems. It will be necessary for these systems to be effectively integrated and one of the significant challenges is the transfer from one access point of one technology to another access point potentially on a different technology. This handoff process will be improved by necessity in the future to enable seamless transfers between access points and between networks.

The reason improvements will be necessary is because the current situation is not acceptable. Fast handoff is essential because one of the drivers for WLAN meshes and WWAN deployments is mobility. With wireless connections, users want to have the freedom to move around and remain connected to the network. Eventually given this movement, users will need to transfer between access points. While these transfers may not impact some applications, other applications such as VoIP may be severely impacted by such handoffs. In the case of VoIP, it is recommended that the latency of the connection remain below 50 ms [16]. Yet, current WLAN equipment does not satisfy such criteria and average handoff latencies ranging from 59 ms to 398 ms appear typical
[16] depending on the specific equipment used. Therefore, it is clear that improvements will be necessary.

To address these concerns protocol changes will be necessary. Work to address a subset of these problems has been started with the IEEE 802.11 R Task Group. Once complete this standard will enable fast handoff between 802.11 access points. However, more work will be necessary in the future to enable fast roaming between potentially different access technologies such as 802.11 and 802.16. Supporting such handoffs will be necessary again because it is likely WWAN and WLAN approaches will coexist. The urgent need for handoff solutions particularly between 802.11 access points mean that standards are likely to be adopted as soon as they are finalized. In the interim it is likely that vendors will start developing WLAN equipment that at least addresses the problem for deployments with homogeneous equipment (i.e. equipment from the same vendor).

### 7.3 Radio Technology Improvements

With time, the underlying radio technology used by mesh networks will certainly change and this may lead to changes in the approaches to mesh networking. Emerging standards such as IEEE 802.11n, IEEE 802.16 and IEEE 802.20 bring potentially new features to mesh networks. As a result, once ratified or potentially even before the standards are finalized, mesh networks will begin to be created using these new radios instead of the 802.11 a, b, and g variants currently used. This change however does not appear to be a radical change and instead will simply address the current weaknesses in mesh technology. The first obvious factor that the 802.11n and 802.16 standards will address is bandwidth since they offer significantly more throughput than currently available solutions. Each standard may serve a specific niche within mesh networks so it is interesting to examine what role each of these standards will play in future mesh networks.

IEEE 802.11n is essentially an evolutionary improvement in WLAN connectivity with speeds greater than 100 Mbps promised. As this technology is first introduced one can expect it to be adopted for use as the wireless backhaul in multi-radio meshes. This is similar to the way some installations use 802.11a links for the backhaul [20] and it is the logical evolutionary step since the transition to this technology will likely not be rapid. Therefore, introducing it in the infrastructure first saves users from the burden of upgrading. It will also potentially ease the congestion problems that may be experienced in mesh deployments. Such uses can be expected in the next five year timeframe since pre-802.11n products are already appearing. However, 802.11n technology will eventually be deployed to end users and then it will likely displace the 802.11a, b, and g solutions that are currently used.

The 802.16 standards or WiMAX will serve a similar role to 802.11n in offering a wireless backhaul link for mesh networks and eventually migrating to being an access technology if costs fall sharply enough to make this technology competitive with 802.11 solutions. From a mesh network perspective, the role of 802.20 will be slightly different. This standard targets full mobility and is intended to support communication with vehicles moving at up to 250 km/h. Therefore, this could prove to be an important
technology to enable access to mesh networks from cars and trains. Given this role, it is likely that once this technology is available, it will be used as the final link to end users instead of just for the back haul of the infrastructure.

### 7.4 Managing Mesh Networks

One of the scalability issues that was described earlier is the challenge of managing the large collection of access points needed to create large meshes. In particular, one of the difficulties lies in ensuring access policies are appropriately distributed. There are current solutions to this problem such as the equipment from Chantry Networks which allows for centralized management of a collection of access points. However, these solutions remain immature. In the case of Chantry Networks, the reliance on a wired backbone for connecting access points limits the usefulness of their products. In the future, it is likely that simplified management solutions that are similar to the approach of Chantry Networks will be developed but with the ability to manage a collection of wirelessly connected access points.

This idea of simplified management will also need to be taken even further to enable easy solutions for deploying mesh networks in the home. As the number of wireless appliances grows in the home market, the WLAN must be available throughout an entire house. Ensuring such coverage may require mesh networks but even current single access points are far too complicated for the average home user. Due to the complicated configuration, potential issues such as security problems may arise. In the future to address these difficulties, easily configured mesh-enabled equipment will be necessary; however, it is not yet clear what approaches to simplification will result.

### 7.5 Quality of Service

To support voice traffic across mesh networks, it will be increasingly important that quality of service concerns are addressed. As described previously, voice service, while not bandwidth intensive, places significant demands on the network in terms of latency. Along with voice traffic, it is advantageous for commercial providers to supply different quality connections to different users. This has proved to be a concern in wired deployments and there has been much work aimed at addressing these QOS concerns. However, with mesh networks, QOS is even more important because of the potentially limited bandwidth of most mesh networks.

To address these concerns, future mesh networks will need to incorporate many of the same mechanisms used in wired networks for ensuring QOS. When the bandwidth is limited, proper labeling and the assignment of appropriate per hop behaviors is essential. Therefore, particularly in multi-hop wireless meshes, it will be necessary to perform such labeling at the earliest possible point in the network and, thus, the access points will require the intelligence to perform this traffic prioritization. This will increase the importance of efficient management solutions for distributing such priority assignments. The solutions used to address these QOS considerations are likely to be similar or the same as the approaches used for wired networks. This will be done to simplify management and it appears reasonable to expect solutions such as multi-protocol label switching (MPLS) or DiffServ to be used to assist in this traffic prioritization particularly
as mesh networks grow in size. However, such approaches will not be as necessary in smaller wireless meshes with only one or two wireless hops.

8 Conclusions

Wireless mesh networks are poised to develop into an important approach for enabling network access. These networks currently face many challenges with the most significant being a lack of scalability. Mesh networks will evolve to address these challenges and, once these issues are resolve, WLAN mesh networks will enable ubiquitous network coverage over areas significantly larger than those covered by existing WLAN hotspots.

Going forward, WLAN mesh networks and large-scale WWAN deployments can be expected to co-exist. These networks may appear to be relatively similar in the future but the wide-area and the local-area will continue to have disparate speeds. Solutions will be developed that enable the seamless transition between both networks and access points. Faster handoffs will be a key feature in these new multi-technology networks. This will be necessary to enable applications such as VoIP. As well, to reduce the scalability challenges deployments will generally follow an infrastructure meshing model. Both the radio technology and the ease of network management will facilitate the continued spread of WLAN meshes.
References


