Municipal Wireless Mesh Networks as a Competetive Broadband delivery Platform

by

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ABSTRACT

Recently there has been a growing interest in deploying Wireless Mesh Networks by municipalities. This interest stems from the desire to provide broadband connectivity to users lacking access to broadband alternatives. The ubiquity of these networks will create more opportunities for new wireless-based applications and services that will generate revenue to the local businesses.

The current plan is primarily focusing on the use of the WiFi, which was originally designed for indoor LAN applications operating in unlicensed spectrum. Also, the Municipalities claim that their main targets are Public Safety and the low-income neighborhood that cannot afford DSL or Cable broadband. There is a doubt, however, that the current plan will deliver on its promises in terms of coverage as well as cost.

In this research, the goal is to first study the current business model for the current Municipal Wireless Mesh networks under deployment. As such, we will attempt to examine the networks under development in Brookline, Boston, Cambridge, and other cities in the US. We will also examine the technical limitations of these networks. This will lead us to suggest modifications to both the business model and a new system design. The goal for these modifications is to enhance the chance of these networks to succeed in the market place.

Thesis Supervisor: Professor Michael Cusumano
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Chapter 1
Introduction

In this chapter, we will discuss the main drivers for adopting wireless mesh networks by municipalities along with the primary issues that these municipalities are facing. In order to assess the pros and cons of these networks as a broadband platform, we need a framework for evaluating all aspects of the platform. This can be achieved by using a set of metrics that will help conduct the assessment.

We will start with background information about the municipal mesh networks and then we will define the platform metrics built on previous works.

1.1 Background and motivation

Over the last several years, there has been a rapid increase in the number of municipalities that have become interested in offering Internet access using wireless mesh networks. Cities such as San Francisco, Mountain View, Philadelphia, and Boston (to name a few) have initiated projects with the aim to provide wireless broadband service to their citizens. It is also important to note that some of the municipalities have chosen to use a fiber technology (fiber to the home or FTTH) instead[1], however, in this thesis will not discuss this technology. There is a raging debate currently ongoing as to the propriety of municipalities acting as ISPs, possibly skewing the market and leading to undesirable outcomes. This is especially believed to be true because the immaturity of the

[1] ESD.68, class note on Municipal broadband, 2006.

wireless mesh technology. However, from the municipalities point view, there are three main reasons for pursuing this goal:

1. Promoting economic development and stimulating innovation.
2. Providing broadband connectivity to the government offices, public safety, schools, and law enforcement personnel on duty. This will increase the efficiency and performance of the government operations as captured in this chart[38]:

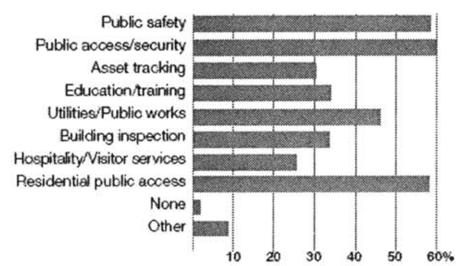


Figure 1 Survey for why municipalities are interested in wireless broadband[38]

3. Bridging the digital divide that is engulfing a large segment of the US population, such as in poor neighborhoods, rural areas, or areas where the broadband operators have no intention in providing this service there.

In order to give a more realistic picture about how the municipalities advocate their involvement in deploying wireless mesh networks, the following chart show how Corpus Christi (TX) municipality sees their network (which is already deployed in 2006) being useful for municipal operations.

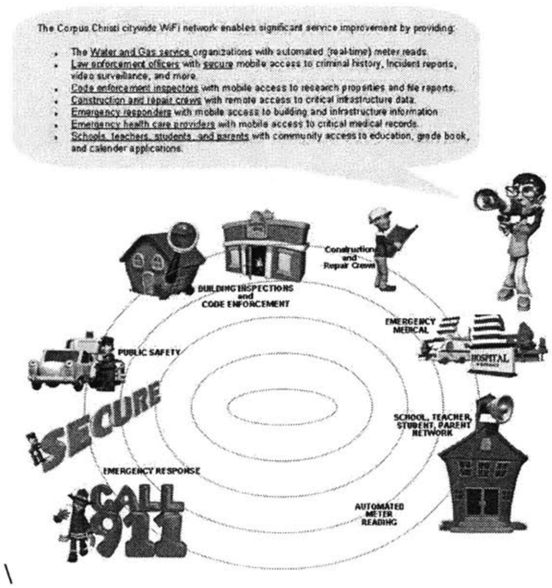


Figure 2 Corpus Christi usage of wireless mesh in the city operations [39]

Furthermore, the following chart shows how they see the advantages of these networks to the citizens of Corpus Christi.

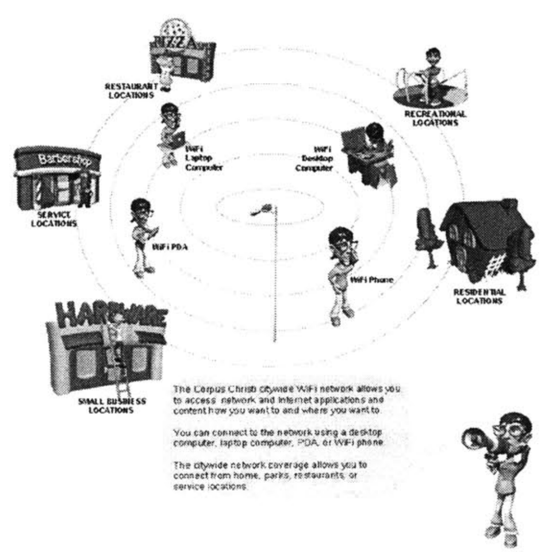


Figure 3 Corpus Christi usage of wireless mesh for the citizen of the city [39]

On the official website for the Corpus Christi project, they explain the advantages of they have built to their city [40]:

Table 1 Goals of the Corpus Christi wireless broadband [40]

Work	• Work from home, the park, or the beach as using VPN, video conference, and VoIP applications. • Use VPN (virtual private network) to securely access business network applications the same way you do from the office. • Use video conference applications to conduct effective meetings with an unlimited number of people around the world. See the people your talking to and allow the see your presentation step-by-step.
Learn	• Get access to thousands of live and interactive university, business, and self improvement education programs. • Access your child's school network to view their progress report, upcoming assignment, online library, and online training programs. • Research medical issues. • Access online video news programs.
Communicate	• Use VoIP applications to make low cost phone calls anywhere in the world. • Send a live video feed of your child's soccer game to the grandparents who live in another city or country.
Shop	• Take a virtual tour of real estate property in another state. • Browse through online malls.
Relax	• Download your favorite music, video, or movie. • Play a virtual video game with your friend who lives across the country.

In a more holistic perspective, Boston wireless mesh project considers the project value chain to be including many more than just the municipality and the Wireless ISP (WISP). The following diagram extracted from the project RFP [41] captures who they think benefit from such a network.

Mudhafar Hassan-Ali© (2006).

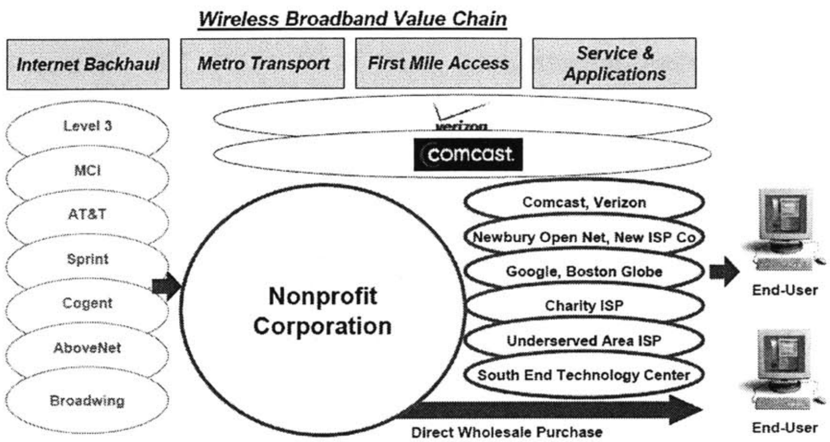


Figure 4 Boston's view of the value chain [41]

They say that even the incumbent companies in the broadband access (Verizon and Comcast in this case) will be benefiting from wireless mesh project. They argue that the demand on broadband will increase as a result of deploying this network, which in turn leads to more adoption of the end users to the incumbents' services. This view does not necessarily coincide with the views of the incumbents, which they feel very much threatened.

1.2 Technology Background

Wireless Mesh technology has been the key enabler to the municipal broadband deployments. In the mesh architecture, multiple access points (APs) called also Mesh Gateway Routers (MGR) are interconnected with each other. They are designed to route packets to one another until they find their way to the destination (more to talk about in Chapter 2). By allowing access points to route traffic, networks only have to run physical cables to a fraction of these APs, greatly reducing up-front costs.

In a wireless mesh, all communication between MGR APs is carried out via wireless transmission. The specific parameters of the communication are based on standards developed by IEEE. The APs can serve a variety of wireless clients simultaneously, ranging from fixed desktop computers to cell phones. The MGR APs are connected to the rest of the Internet infrastructure either by wire-line infrastructure (Fast or Gigabit Ethernet), or wireless infrastructure, such as WiMAX. The former offers more bandwidth, while the latter offers convenience in deploying these Municipal wireless networks.

1.3 Advantages of Municipal Wireless Mesh

Municipal broadband advocates have argued that their proposed systems will address two key failures in the current market-based broadband industry: universal service and a lack of competition. Although DSL and Cable have been spreading rapidly, there are still areas of unavailability. It may not be economically or physically feasible to run cable to every household that desires broadband. DSL access is especially difficult, as the consumer must be located within certain distances from the central office (CO).

According to [27], the DSL/Cable penetration in North America will be around 60 million households (~50% penetration) in 2006. This indicates that there are still many American consumers without access to broadband. This deficit has not impacted all demographics equally, however. Rural and impoverished areas are less profitable to extend traditional broadband to due to lower customer densities. Broadband is rapidly becoming an essential part of 21^{st}-century citizenship and as such may become part of the public infrastructure (just like public transportation or terrestrial TV broadcast). As such, there may be overriding social incentives to providing public broadband. Even in areas where broadband has been provided, consumers may not be reaping the benefits of the broadband connectivity due to high cost.

The high fixed costs of DSL and cable have created a market structure that is very likely a natural monopoly. Due to the extremely high costs of running cables to every customer, firms that already had such networks in place were able to quickly establish dominant market positions, leading to a duopoly. This has led to limited options for consumers and higher monthly charges, which hamper the notion of social-equity for broadband connectivity. Wireless networking promises to mitigate the high fixed costs of broadband through the increased use of commodity hardware, and by only requiring physical cables to be run to access points. Wireless mesh will be even cheaper, as only a fraction of the nodes require a physical network connection.

1.4 Criteria for defining platforms

In this section we will try to answer the question of how to assess a platform, more specifically a platform used in telecommunication. In order to do that, we need to find a set of metrics that will server the criteria for characterizing the competitiveness of a telecom platform from business, technology, regulatory, and social standpoints.

The literature survey yields very little in the field of telecom platform metrics; let a lone specific to the wireless platform. However, other fields in business and technology have received a significant amount of effort in defining these criteria or metrics. In this section we will review them in order to come up with a new set of criteria tailored specifically for the problem at hand (wireless mesh networks).

1.4.1 Platform for leadership

Gawer and Cusumano's work pioneered the concept of platform leadership. Their work attempts to answer the question: how is a platform leader characterized? According to them [1], the platform leadership refers to the common objectives sought by the companies to drive innovation in their industry. A platform leader usually deals with complex products where they singled out two main forces that a leader drives to: interdependency and innovation. The increased breadth of innovation will create the necessity for one firm or a group of firms to ensure the integrity of the evolving product. This will also create a strategic opportunity for complementary modules or products. According to their work, the platform leadership is framed in four levers, which are:

Scope of the firm

This decides how much the platform leader should develop complementary modules or sub-products internally or let other firms provides complementary components.

Product technology (architecture, interfaces, IP)

This shapes the extent to which the firm should make the platform modularity and openness for others to make products around it.

Releationship with external complementors

The platform leaders must determine whether the relationship with their partner complementors should be competitive or collaborative.

Internal organization

It is important for these leaders to reconcile to relationship with the complementors and the internal structure. This should lead more flexibility in case changes happen in the relationship between a leader and its complementor.

From these four levers, we can derive the characteristics of a platform that would be ideal for a platform leader. They are:

- Platform must have interfaces that are well standardized
- New services or products innovation must easily complement the platform.

These concepts help define the relationship between the municipalities and the operators on end, and between the municipalities and the end users on the other end. As a result, they will help define our metrics presented in section 1.4.3 .

1.4.2 Platform for product development

This section is based on the research work of K. Holtta-Otto and K. Otto [3] and M. Meyer and L. Lehnerd [2]. In particular, the first reference is a recent work which provides a comprehensive metrics for assessing a product platform. In this work, there are six groups of criteria; each group has a number of metrics. These metrics are then assigned numerical weights equivalent to the effectiveness of the metric. The metrics are captured in the following table:

Table 2 Platform criteria and metrics (Meyer and Lehnerd) [2]

Criteria group	Metrics	Brief definition
Portfolio customer satisfaction	Cost-worth distribution	Trade-off between cost ($) and customer utility.
	Customer needs	Desirability of the customer for a feature.
Product variety scorecard	Planned upgrade carryover	Retaining of a function or a feature of a module during upgrade; i.e. preservation of legacy function.
	Common modules	Commonality of a module or a function in various variants of a product line
	Specification variety	Variety of a function or a module.
After sale support scorecard	Partitioning for reliability	Decomposition of functions in modules so as to have equal reliability for the individual modules.
	Partitioning for service	Decomposition of functions according to the service performed by the functions.
	Environmental friendly	As oppose to environmentally harmful.
Organization alignment scorecard	Ease of assembly	Less time required to assemble the platform from modules.
	Align with the organization	Organizational structure should be aligned with the platform modules.
	Make-buy	Outsourcing (or not) specific modules.
	Testability	How easy and reliable the test of individual module.
Upgrade flexibility	Unknown isolation	The isolation of functions that show uncertainty in to distinctive modules.
	Change flexibility	Platform must be able to support several product variant and their evolution (planned or unplanned).
Development complexity scorecard	Function and form alignment	Each function should be mapped into a distinctive module.
	Interface flexibility	Each module should be fairly isolated from others so as to make upgrade easy (not affecting others).
	Anti-synergy avoidance	Changes (upgrades) in one variant of a product line should find their way to the other variants. Otherwise it is anti-synergy.
	One degree of freedom (DOF) adjustments	It is the feature of needing little adjustment to a module that replaces another with single degree of freedom as a reference for the adjustment (such as line card slot).
	Limited extremes	It is important to avoid requirements that lead to extreme modes of operation, since they may force poor performance on moderate requirements.

From the above table we can extract platform metrics that could be helpful for our wireless metrics:

- Cost effective platform fulfilling customers needs.
- Easy to upgrade
- Commons standard interfaces between platform and products or services
- Easy to deploy and to test

1.4.3 Platform for wireless networks

After a comprehensive research, the platform metrics for wireless systems have not been defined in a comprehensive way. The aim here is to use the results of the previous sections a long with the author's experience in the field, the platform assessment criteria are to be defined. It is worth mentioning that recently [4] published a paper on metrics for Sensor Network platforms, which is akin to the wireless mesh based on WiFi. According to this work, two metric groups were composed; one on system core and another about radio systems. For the system core, the metrics selected in this work were:

Table 3 Sensor network platform metrics [4]

System Core	Radio Properties
CPU architecture	Frequency
Speed	Data rate
Program memory	Setup time
Data memory	Tx power
Storage	Sensitivity
External IO	Outdoor range
Onboard sensors	Channels
Physical size	

From the table above and the previous sections, we propose the following metrics that will be useful to use in order to assess a wireless platform.

Table 4 Telecommunication platform metrics

1	Standard interface	
2	Attractiveness	Cost effectiveness
		Convenience (portability, mobility, expandability)
3	Operation simplicity	Deployment
		Maintenance (including upgrade)
		Resiliency
		Security
4	Bandwidth efficiency	Rate
		Coverage
5	Open system	New applications
		Support multiple parties
		Network neutrality
6	Environmentally friendly	Safety (for technicians and customers)
		Low radio power

The metrics have different impact on the various stakeholders depending on what they value most. For example, the regulators care more about metric-1 and metric-6, since for the former makes it easier to realize the latter. On the other hand, for business reasons, the operators care more about metric-3 and metric-4 to some extent to metric-1 and metric-5. The users favor metric-2, since it ensures all the things that make their lives easier and more fun. Ultimately, all these metrics represent all the elements required for a business or technology to flourish. They are also the elements required to create an eco-system around a new technology.

The aim in this thesis is to assess the level of these various metrics for the wireless mesh networks. The assessment is performed in the relevant sections of the thesis. In the conclusion, the overall assessment will be then concluded to give the final picture.

1.5 Structure of thesis

This thesis is structured in to the following chapters:

Chanpter-2: An overview for the technologies and the practices of this technology as well as the services provided on its platform. The goal is to introduce in a simplistic way the wireless mesh networks along with the characteristics of the technology.

Chapter-3: Having explained the technology in Chapter-2, the business models for deploying these networks in a few municipalities are reviewed and contrasted. The goal is to provide the motivation and drivers for the municipalities business cases.

Chapter-4: After various deployment scenarios, we will look at the economics of deployment wireless mesh networks. In order to do that, we will have to decompose the activities and the bill of material necessary to build these networks. Also, we will project the adoption model so that we could estimate the cash flow.

Chapter-5: In order to complete the picture, we will also look at some of the dynamics for shaping up the technology and the market for these networks.

The thesis will conclude in chapter-6 with a number of recommendations to the stakeholders and a few predictions about the dynamics of the business developed around this technology.

In chapters 2, 3, and 4, we will assess the competitiveness of the wireless mesh as a telecom platform using the metrics presented in this chapter.

Chapter 2
Wireless Mesh Networks (WMNs)

2.1 Technology background

In order to provide Internet connectivity ubiquitously to end-users, WMN is claimed to be one of the solutions to achieve that. Specifically, there is a rising interest by many municipalities in the US to provide Internet to their citizens over a wireless mesh network infrastructure. The belief is that this will alleviate the last mile inequity in their neighborhood. The following figure depicts the settings where WMNs could be deployed.

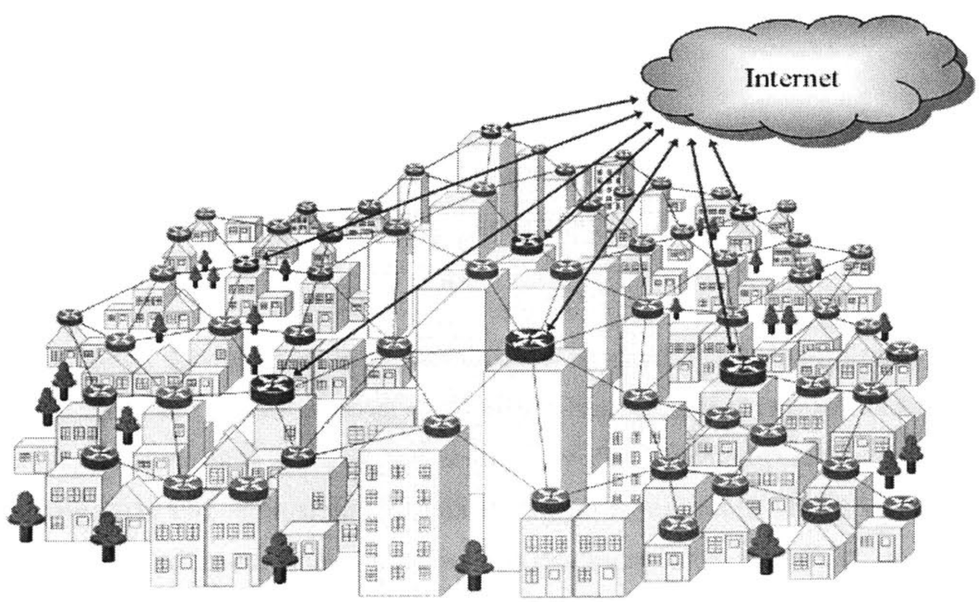


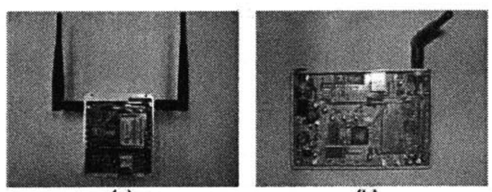
Figure 5 Wireless Mesh Network in a neighborhood[2]

[2] www.ece.ncsu.edu/wireless/MadeInWALAN/wmnTutorial.ppt

Network architecture

The position of wireless mesh networks is in the access domain, where numerous technologies are used. This type of network is based on two concepts:

1. Mesh architecture, where multiple access points (APs) called Mesh Gateway Router (MGR[3]) are interconnected with each other via a mesh-based protocol. This protocol[4] allows them to route packets to one another. The following figure show typical AP [14].



(a) (b)

Fig. 1. Examples of mesh routers based on different embedded systems: (a) PowerPC and (b) Advanced Risc Machines (ARM).

Figure 6 Mesh routers [14]

2. Wireless physical layer, where the communication between these MGRs is carried out with radio signal. The parameters that govern the wireless communication are determined by multiple factors, such as policy, standard, regulation, economics, etc.

The basic operation of a mesh network is depicted in the following figure, where there are 7 APs that users and server can communicate through. The APs are connected with all their immediate neighboring APs via wireless link. Each AP is aware of the connectivity. Depnding on the destination of the information that needs to be routed through network, the next AP that the information will be handed to is determined. In the Figure, there is an active route between a Laptop and a Server, however, there are other backup (standby) routes that will be used should any AP fails along the active route. This ensures the

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[3] The conventional WiFi access point will be called here Access Point (AP)

[4] Just recently (April 2006), the IEEE 802.11 Working Group approved a draft for the Mesh protocol (802.11s) over Wireless LAN.

connectivity with high degree of reliability. The issue with mesh in 802.11 is the performance degrades as the active route hops too many APs along the way.

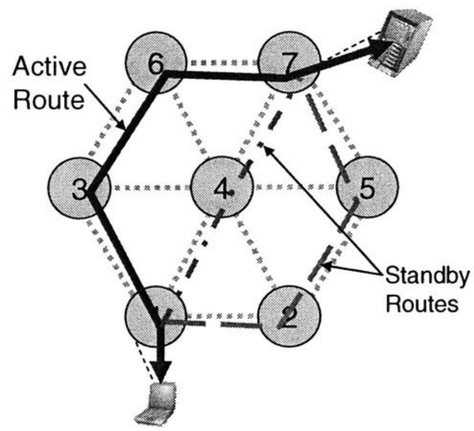

Figure 7 Mesh network routing

In addition to the APs, there are the wireless clients. The APs provides networks access for their clients. The following figure shows typical clients that use mesh networks [14].

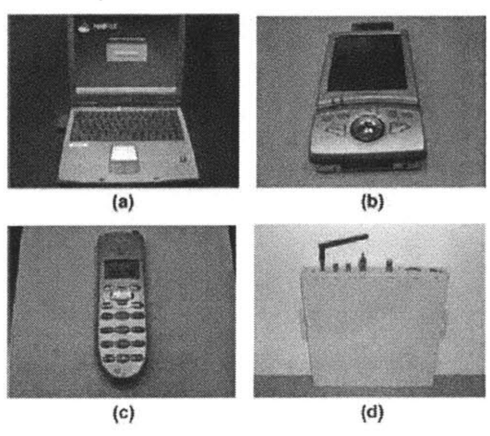

Figure 8 Typical WiFi clients [14]

The APs are also connected to the rest of the Internet infrastructure via a number of methods. The two main methods are:

1. Wireline infrastructure: In this case, a selected number of the APs are connected directly to the wireline infrastructure via a Fast Ethernet (100Mbps) or a GE (1000Mbps) link.
2. Wireless infrastructure: In this case, a selected number of the APs are connected via a long-reach wireless link, such as WiMAX.

The latter offers convenience in deploying these WMNs, whereas the former offers more bandwidth. As a rule of thump, the connection to the infrastructure is made with one AP out 7 APs connected in tandem over the mesh.

In addition what is already mentioned, the wireless mesh architecture has many benefits, as capture in the following chart:

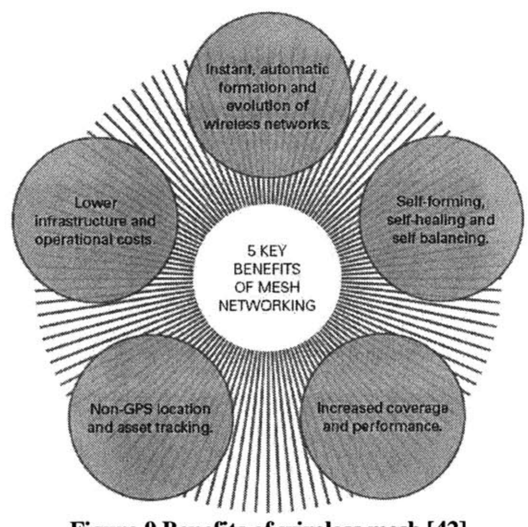

Figure 9 Benefits of wireless mesh [42]

As indicated in this chart, in addition to better reliability, mesh networks are more scalable. So if more coverage or more bandwidth is required, adding more of these APs will partially achieve that.

2.1.1 Current dominant design

In Mastering the Dynamic of Innovation by Utterback [43], a dominant design is the one that wins the allegiance of the marketplace. To be specific, a dominant design is a new architecture which puts together individual innovations that were introduced independently in earlier products. A dominant design makes many performance requirements and product features implicit. All products in the market must adhere to the dominant design in order to meet the fundamental customer needs and expectations.

Most of the mesh companies were formed within a few years of when first inexpensive 802.11 radios were available. As a result of the availability and relatively inexpensive radio platform, 802.11 has become the de-facto standard radio protocol for most mesh networks and is the main reason the mesh routers are relatively inexpensive compared to other wireless equipment like cell phone towers. Since most mesh equipment provides client access through the 802.11 protocols, it also defines a standard interface for all the vendors to communicate to client devices and also creates a large pool of devices that can connect to mesh routers since 802.11 hardware is readily available and built into many computers and consumer electronic devices.

Using WiFi in these networks has a compelling business case (available, standard, and cheap technology). So the current design is pure WiFi moving from a single radio to multi-radio (3 readios so far). However, due to the rapid adoption of the WiMAX as an evolutionary step from WiFi, there is a trend at the moment to integrate both WiMAX and WiFi in the design of APs, such that the former is used for backhauling whereas the latter is used for connecting end users. Due to the mobility support, high spectral efficiency and better QoS, we believe that eventually the APs will also support end user WiMAX connectivity in addition to WiFi. The following figure illustrates the dominant design evolution:

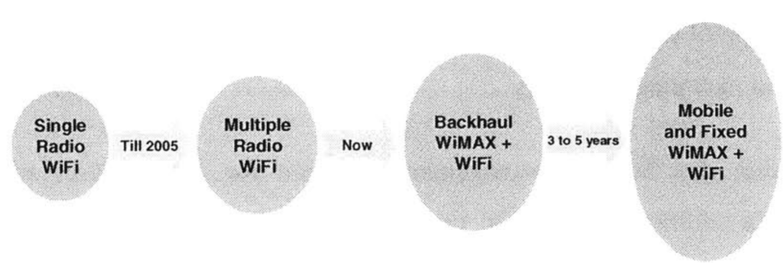

Figure 10 Dominant design evolution

On the service and business side, if mesh vendors started selling to community groups where consumers owned their own mesh routers instead of cities the dominant design might look very different. In this case, the AP would be a window mounted node that operated inside of a residence, which would be less costly but could still relay signal outdoors. The success of other companies, such as FON, suggests that there are alternatives like this to the high-cost outdoor nodes that have not been fully explored by the industry. FON loads its software onto commodity wireless routers and provides billing infrastructure so that one can by a FON router, sign up for their service, and then use other FON routers when they are not in their residence.

The success of companies like this suggest that there may be an opportunity for mesh vendors to target individual consumers that could use mesh-enabled consumer routers that have a slightly different feature set than the poletop-mounted outdoor nodes; for example, a much cheaper node, similar in functionality to most consumer access points, that users are able to mount on their windows may be more attractive to individual consumers. Most mesh networks require devices that repeat the mesh signal into the homes, and what isn't clear is if those nodes could be used as part of the mesh.

Hardware

It usually consists of multiple technological innovations introduced independently in prior product variants. Currently the main market that wireless mesh companies are targeting is municipal networks, which have very specific needs and have led to a standard hardware design for most of the mesh products that target this area:

- 802.11 client connectivity
- weather-proof casing
- light-top mounting capability

Each vendor also bundles management software for their routers when they sell hardware. In addition to software on the node, it usually consists of a management interface for diagnosing the network and determining bottlenecks.

Some of these properties, like the ability to mount on top of light poles, are common because mesh vendors are targeting municipalities as first adopters, who are the organizations with control over city infrastructure like light-poles. Most vendors sell their mesh nodes for a few thousand dollars and it usually costs them around a thousand dollars to manufacture the node. Most of this money is spend ensuring the device is weatherproof; a large part of the node is actually spent on the case and ensuring the electronics can withstand a wide temperate range.

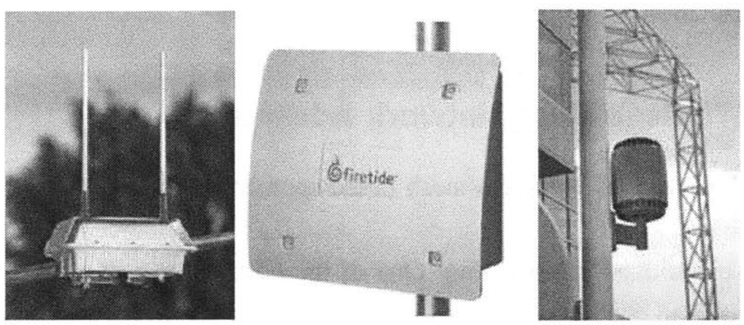

Figure 11 Examples of current outdoor mesh routers from Tropos, Firetide, and Belair. All are designed to be pole-mounted and provide 802.11b connectivity to clients.

Software

Industry regulation often dictates the dominant design through a standards process [43]. Many mesh companies have been working with the IEEE to define a standard for mesh routing using 802.11 technology. This standard is designed to regulate the communication over the 802.11 protocols between nodes in the mesh. The 802.11s working group is currently considering a few proposals for protocol specifications, but the standard is not targeted for approval until 2008 and [5]many of the largest vendors, such as BelAir, Tropos, and Strix, are not taking part in the standardization process. This is one reason that will prove the rollout of these network very difficult due to interoperability issues.

Perhaps the standardization process will force mesh vendors to use the same protocol specification, but even outside of this standardization process vendors still have a lot of

[5] http://en.fon.com/

options for differentiating their products, such as adding multiple radios. For now, there is no expectation of interoperability among different mesh vendors, but this may change once the IEEE standard is ratified.

Overall, there is not a dominant design that has emerged for all mesh markets. There seems to be a group of functionality that all mesh providers include for the mesh routers they sell to municipalities, but this set of features may not be appropriate for other situations; for example, Unstrung Insider reports that a $1000 node may be available by the end of the 2006.

2.1.2 Wireless Mesh Network Advantages

The core advantages of a wireless mesh-based approach include [44]:

1. Adaptive backhaul provisioning: One of the best features of a wireless mesh is the lack of the requirement to provide a wired backhaul connection to every node. Rather, user traffic is relayed over the air between nodes until it reaches its destination or a node with a connection to another network (like the Internet). Thus, one could deploy, for example, a WiFi mesh to provide service over a large geographic area, but only very limited backhaul initially. As more users come online, and thus generate revenue, backhaul can be added as required in a very cost effective way.
2. Fault-tolerance: Meshes are very adaptable to failures in nodes or dropouts in radio coverage - traffic is simply re-routed dynamically. The self organizing functions run continuously, so when changes occur to connections and reception the mesh will automatically re-route around blockages in real time.
3. Bandwidth scaling: Unlike most wireless networks, adding more nodes to a mesh increases overall network capacity and total available bandwidth.
4. Organization and business models: The decentralized nature of mesh networks lends itself well to a decentralized ownership model wherein each participant in the network owns and maintains their own hardware, which can greatly simplify the financial and community aspects of the system.

5. Affordable: Each mesh node is inexpensive. As there are no central controllers needed the costs are linear. The fact that each mesh node runs both as a client and as a repeater potentially means saving on the number of radios needed and thus the total budget.
6. Ease and simplicity: If you have a box that is pre-installed with wireless mesh software and uses standard wireless protocols such as 802.11b/g, the setup is extremely simple. Since routes are configured dynamically, it is often enough to simply drop the box into the network, and attach whatever antennas are required for it to reach one or more existing neighboring nodes (assuming that we can solve the issue of IP address allocation).

Wireless meshes are thus among the most flexible network structures ever created, and this amazingly adaptable and applicable to many different missions, applications, and markets. While meshes can grow to cover almost any geography, the use of radio dictates that a given implementation will be designed to cover a specific range between nodes. Metropolitan-area meshes could eventually compete with other broadband and even cellular wireless networks.

Among wireless networks, we can compare Mesh networks with other topology as below.

Table 5 Comparison between different network configurations[6]

Topology	Reliability	Adaptability	Scalability
Point-to-Point	High	Low	None (two end points)
Point-to-Multipoint	Low	Low	Moderate (7-30 end points)
Mesh Networks	High	High	Yes (thousands of end points)

On the other hand, reliability, adaptability, and scalability are the most important attributes of a wireless network for micro Mesh industrial applications.

6 Robert Poor, Ember Corp.

One opportunity for mesh networks is in distributed control systems. There has been a trend in recent years to place more intelligence throughout the control system. The IEEE 1451 standard Smart Transducer Interface for Sensors and Actuators is evidence of this. Distributed intelligence is naturally served by wireless multihop mesh networks. The control of the wireless system is distributed throughout the network, allowing intelligent peers to communicate directly with other points on the network without having to be routed through a central control point.

2.1.3 Issues with Mesh

No technology is perfect, so the core disadvantages of wireless meshes are as follows [44]:

- Backhaul/user traffic competition: If we're using a WiFi channel, for example, to implement a connection between two wireless mesh nodes, that capacity can not be used (at that moment, anyway) for user traffic. But this is normally not a problem - we just add more nodes, and capacity increases. We can also, for example, use licensed frequencies for backhaul while leaving unlicensed bands for user traffic, or use 802.11a frequencies to provide backhaul for .11b/g traffic.
- Time-bounded behavior - If we are relaying traffic between a large numbers of nodes, the latency involved in this relaying can affect time-bounded traffic, like voice or video. This problem is usually addressed via the routing protocols used to implement the mesh, but it is potentially a serious concern regardless.
- Security - Finally, if user traffic is traveling through intermediate nodes in a mesh (as it most often will be), security is an issue. Intermediate nodes might be able to eavesdrop on data not intended for them. This problem can be addressed via the end-to-end VPN techniques used on the Internet, where exactly the same problem exists. Still the network is vulnerable to attacks at the physical layer, which is difficult to circumvent.

2.2 Applications

In this section we will review the main applications that typically run by the end users over a broadband infrastructure. This will help us in two ways: 1) size bandwidth demand; and 2) the business opportunities for the broadband operators (including the Wireless Mesh operators). Each application creates certain traffic profile based on the nature of the application and the end user behavior. As such, certain quality of service (QoS) must be met in order to satisfy a user. The following table summarizes [37] the QoS requirement encountered in wireless networks.

Table 6 Application QoS requirements [37]

Application	Bandwidth	Latency	Jitter	Loss (Packet Error Rate)
Network Control Messages	Low ~(0.1-0.5 kbps)	Low (~10ms)	N/A	Low (10^{-3} to 10^{-2})
Video Streaming	0.1 - 10 Mbps	Medium	~5 sec (jitter buffer size)	Can tolerate some loss
Audio Streaming	20-320 Kbps	Medium	~5 sec (jitter buffer size)	Can tolerate some loss
E-Mail	No restriction	Medium	N/A	Medium-Low (uses TCP)
Gaming	Low	Low	Low	Low
Web Browsing	No Restriction	Low	N/A	Medium-Low (uses TCP)
Push-to-Talk	Low (~10kbps)	Setup time <1 sec; Bearer ~200 ms	Low (~20 ms)	Can tolerate some loss
VoIP	9.6 kbps	250 ms for mobile-to-mobile	~20 ms	Low (10^{-2})

There are a number of end users attached to the mesh networks, as follows:

1. Municipal users, which include offices and employees of various department such as law enforcing departments. For public safety and police, the plan is to allocate them a different spectrum (4.9GHz) from the one used the public users.
2. Public users, which include households as well mobile individual.
3. Business users, which include local business offices and employees.

It is also important to see how the wireless mesh (WiFi or WiMAX) fits in the whole telecommunication network (as seen in the following figure). This will give an idea as how to roll out various services over these networks. Hence, interconnecting them to the rest of the telecommunication network is essential to reap the benefit of the network effect.

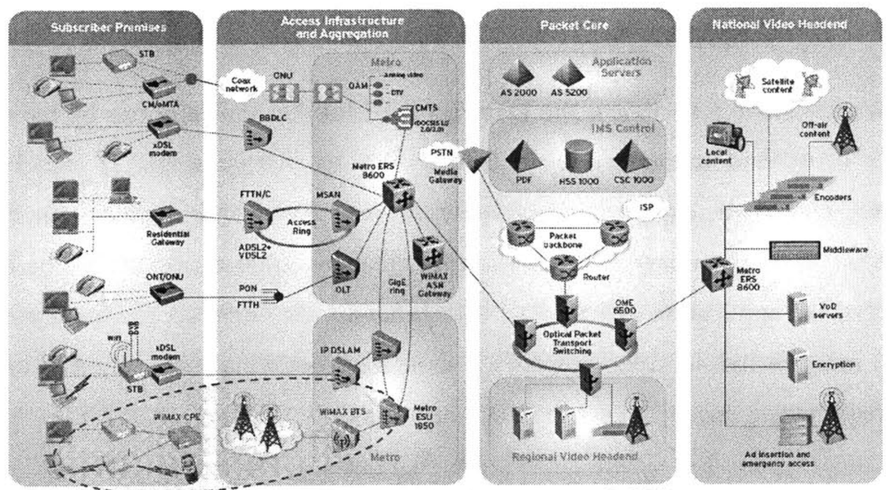

Figure 12 End to end Telecom network [45]

As can be seen in the figure above, the wireless mesh is connected to the core network via the aggregation infrastructure. This ensures the convergence of the services provided over wireless mesh network can be interconnected to PSTN, video, and other networks. In the following sections we will review the main services which are expected to be riding on the wireless mesh networks.

2.2.1 Internet access

This is the most fundamental service any broadband platform should offer to the end user. Internet access has been the main driver for the broadband adoption. The basic requirements for this service are:

1. Authentication and authorization
2. IP address allocation and routing
3. Best effort bandwidth allocation with fairness (network neutrality)

The mesh operators need to interconnect the users to the Internet backbone. This will allow users to surf the Internet as they please. They could a number of activity, such as browsing, sending email or messages, Netmeeting, downloading files, uploading files, etc.

The amount of bandwidth required for this type of service is bursty in nature; i.e. the user will be on and off in their activity. Therefore, the average bandwidth allocated to each user is usually very small compared to the peak rate.

This main driver for adoption and as such the take rate is expected to be impressive; i.e. reaching the peak adoption within a few years. The monthly charge has to be lower than the other alternative. As such, we think $10 to $15 would be competitive enough.

2.2.2 VoIP

The success of VoIP in providing cheap but good quality voice services is making a compelling business case for extending that to cordless and mobile to devices. If these wireless devices are capable of providing WiFi (and eventually WiMAX) connectivity, the voice call can be placed through wireless mesh networks instead of cellular networks. This creates two dynamics:

- Opportunity to both the end user (cheaper service – no need to count cell minutes) and the wireless mesh operators (stealing voice subscribers).
- Loss to the traditional mobile and wireline voice service providers.

A new wave of new mobile devices that will have WiFi and WiMAX integrated along with the traditional cordless and cellular capability (to switch back in case WiFi or WiMAX is not available)[7].

Also, in order to make more appealing it is anticipated that the wireless mesh operators will provide feature-rich voice services (to make even more appealing). The rich services are push-to-talk, video-phone, higher quality voice, etc. The roll out of this service will start with basic voice but as the time goes by and more adoption is seen in using IMS platform, the other voice services will follow. So we expect the monthly charge will be significantly smaller than the cellular charges, but increases over time.

[7] http://vowlan.wifinetnews.com/

The bandwidth requirement for this service varies from about 16Kbps to 100Kbps depending on the quality and whether video is also included. Also, it is important to support QoS (802.11e) to ensure low delay.

2.2.3 Video

The wireless mesh network as it stands is not the platform for traditional TV video (aka broadcast video). The reason for that the WiFi (or even WiMAX) does not have enough bandwidth to carry a large number of video channel. However, it is possible for low bit rate video channels (targeting mobile users) to be rolled out on this network provided that the number of these channels are kept small. For example there could be up to 5 video local or national channels that could broadcasted. Each channel should be kept less than 1 Mbps. The video on demand (VoD) is also possible, but this is like file download, which is best effort service. In this case, it is called Internet TV. On the other hand mobile TV is picking up pace in the market. The service provides low rate TV channels to mobile users.

It is not clear at the moment how these video ideas could be monetized. However, for VoD, this is a direct relationship between the end user and the content providers (such as Netflex). The mesh operator could also set up two types of service, a silver one (not good for video) and gold one (good for VoD).

We argue (as we did in the VoIP case) that over time the revenue generation from the service will increase. This could become significant if a new technology is adopted that lends itself to video delivery. Recently IEEE initiated yet another wireless based standard. It is called IEEE 802.22, which uses the terrestrial frequency for digital broadcast and unicast video delivery. If this picks up (and if it is operated by wireless mesh municipalities) it could pose a real threat to the incumbent video providers, such as cable, satellite, as well the burgeoning the telecom IPTV. As such as, the monthly charge could be as small as zero to as high as $10.

2.2.4 Location base service (LBS)

LBS exist for both the business and consumer sectors. The information on an end user's location is valuable to both that particular user and to other business. The end user does not have to be a person. The tracking of assets such as vehicles or goods in transit is also an important service. To the end user, knowing the location of a destination is useful for navigation (wireless mesh could be used instead of GPS). Other information concerning location, for example, about the restaurants or tourists sports, is useful and can generate revenue especially if it is tied to advertisement.

The revenue could be generated in the following was:

- Tracking; such as for locating children or assets
- Navigation, where the ensure could get the location and the map
- Location based advertisement, where the local businesses are allowed to post their ads to both fixed and mobile users.

In order for the LBS to be viable in the wireless mesh network, the following requirements must be met:

- The APs must provide mechanism for simple location triangulation.
- It must ensure the confidentiality and integrity of the location information.

It is not clear what the charges will be in this service and how it will be rolled out.

2.2.5 VPN (business)

The VPN is a mechanism for connecting physically-isolated business sites via public networks. This is enabled by the use of an IETF standard called tunneling which could be done at Layer 2 (Ethernet layer) or Layer 3 (IP layer). The idea is to encapsulate the information (carried over packets) in another packet container with encryption option before sent it to the remote site. Depending on the traffic carried in the VPN tunnel, bandwidth guarantee is required, which means that QoS must be supported by the mesh network along with L2 and L3 VPN protocols.

It is expected that this service type will be of lower percentage compare to non-business users (such as residential, official, or mobile individual).

2.2.6 Multimedia messaging service (MMS)

The primary driver of this service will be for mobile users as a quick way to send a note to others. This targets both consumers as well business. It delivers non-real time messages to a single or multiple users, with the messages consisting of text, audio and/or video. It is an extension to the popular text only SMS. The sources could be individuals, news sources (to update stock market, weather, sport events, etc.)

For business users, this will provide them with messaging to and from mailboxes in mobile devices and laptop.

The amount of bandwidth is very small and it does not require real-time. However, the revenue could significant and can be added as part of the VoIP subscription as an add-on.

2.2.7 Law enforcement and public safety

Having ubiquitous wireless broadband helps police access critical information about a person or vehicle in fast way while driving around. This feature in particular was the main drivers for deploying municipal wireless mesh, such as the case in Mountain View (CA). There is also a growing interest in connecting the parking meters to this network, which could lead to many applications useful to both traffic police as well the vehicle drivers. It also provides a platform to connect monitors and sensors required for public safety, as well as a communication infrastructure to its personnel as depicted in the following figure:

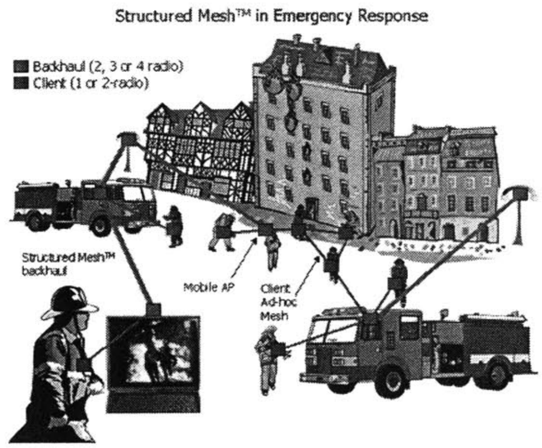

Figure 13 Public safety use of WMN [46]

It is worth mentioning that due to failure resiliency, WMN is considered by many to be ideal for public safety communications.

The traffic amount is significant since it contains multimedia for the personnel involved in law enforcement and public safety. Therefore, the trend in the new AP design is to have a separate radio (4.9GHz) allocated to this application. It is not clear how these departments will be charged for using these networks.

2.2.8 Industrial sensing [33]

The akin to the wireless mesh network is the wireless sensor networks. The availability of wireless mesh networks will make the wireless sensor network more prevalent, since the former acts as a backbone infrastructure to the latter. Wireless sensor networking is being used today for energy management, submetering, environmental monitoring, medical monitoring, and industrial automation. According to a recent market research report released by Wireless Data Research Group, the worldwide market for Machine-to-Machine (M2M) communications, including sensors, PDAs, and RFID tags, will grow to $31 billion in 2008. These projections, backed by continued deployment of high-performance mesh networks for real-time sensor monitoring and other mission-critical applications, point to a very promising future for meshed M2M communications[8]. Early

[8] http://sensorsmag.com

experiences with meshing sensors over wireless broadband networks show that the technology has a future in many settings. The Orange County Water Reclamation Div. (OCWRD), Orange County, FL, recently conducted tests using mesh-enabled sensors for real-time process control at one of its wastewater reclamation facilities. A number of mesh-enabled wireless sensors were deployed throughout the 40-acre facility. Each bit of data obtained was wirelessly routed back to the control center where performance, efficiency, and other parameters were collected and monitored in real time.

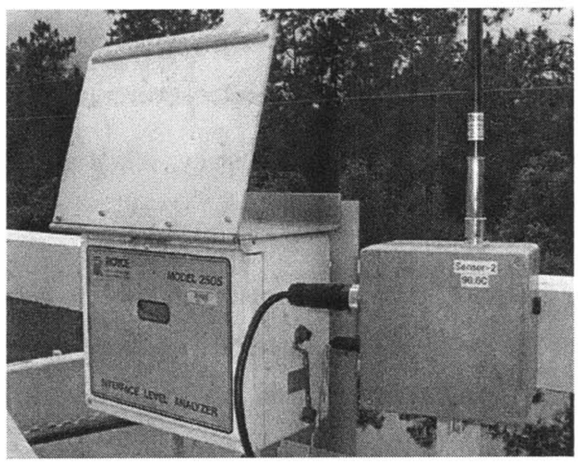

Figure 14 mesh-enabled sensors for real-time process control [33]

The business of connecting sensor networks to the mesh networks can fuel the need for more ubiquity of the mesh networks. The traffic type of this application is similar to LBS.

2.3 Vendors [33]

Below is a list of the major players in wireless mesh and a brief summary on what contributions and the direction that they are taking wireless mesh technology:

Cisco

Cisco is a market leader in the networking field with a market share more then 75% in worldwide market. A small group of computer scientists from Stanford University founded Cisco in 1984. Cisco Wireless Mesh Network solution enables cost effective, scalable deployment of secure outdoor wireless LANs, providing government agencies and individuals with access to fixed and mobile applications to enhance public safety, efficiency, productivity, and responsiveness.

Cisco's wireless mesh product is Aironet 1500 Series lightweight outdoor mesh access point to extend IP networks to metropolitan-area environments in a mesh-type architecture, the solution (Figure 1) primarily uses 802.11a, 802.11b, and 802.11g technologies for high-speed access.

Cisco launched it's first commercial product in November 2005. The mesh node is branded to the Aironet product line. Cisco also has a complementary product in its mobile router node, since it is so new to the market it is difficult to asses how competitive their mobile router is with other routers. In 2005 Cisco acquired Airespace, a privately held company from San Jose, Ca. Airespace brought a large array of WLAN management expertise to CISCO, which will help them in developing reliable and manageable wireless mesh technology.

Nortel

Nortel is more then a century old networking company. Since its 1895 founding as Northern Electric and Manufacturing, supplying telecommunications equipment for Canada's fledgling telephone system, Nortel has grown to become a global leader in delivering communications capabilities that enhance the human experience, power global commerce, and secure and protect the world's most critical information.

Nortel was an early entrant in the municipal wireless mesh networking market. Nortels key reference customer is the Taiwanese capitol of Taipei which is deploying a network of 10,000 nodes across in the city.

Nortel's wireless mesh products

- Wireless Access Point 7220 (Wireless AP)
- Wireless Gateway 7250

Motorola

Motorola's role as pioneer, innovator and visionary in mobile communications is well-known. Originally founded as the Galvin Manufacturing Corporation in 1928, Motorola has come a long way since introducing its first product, the battery eliminator. For more than 75 years, Motorola has proven itself a global leader in wireless, broadband and automotive communications technologies and embedded electronic products,

Motorola position is very interesting in Wireless mesh market. Motorola entry in to wireless mesh came through the acquisition of the startup MeshNetworks in November 2004. MeshNetworks is a start-up company from Orlando, FL who came with a portfolio of patens that prove mobile internet multi-media communication platforms for Mobile Internet were effective means of transferring voice and data.

D-Link

D-Link is the global leader in Revenue and market share for Wireless and Ethernet networking for both consumer and SOHO users. Founded in 1986, D-Link is dedicated to making networking easy and affordable for its customers, offering innovative, award-winning products that seamlessly integrate with a variety of devices and applications. Dlink main focus area is SOHO user. Product -DWL-7700AP .

Proxim

Founded in late nineties, Proxim Wireless Corporation is a wholly-owned subsidiary of Terabeam, Inc. (NASDAQ: TRBM). Proxim Wireless is a global pioneer in developing and supplying scalable broadband wireless networking systems for enterprises, governments, and service providers. From Wi-Fi to wireless Gigabit Ethernet - our WLAN, mesh, point-to-multipoint, and point-to-point products are available through our extensive global channel network, backed by world-class support.

Product- Tsunami QuickBridge II

Pronto Networks

Pronto Networks provides carrier-class Operations Support Systems (OSS) that enables network operators to deploy and manage large public hot spot networks. The company's software handles provisioning, configuration, authentication, access control, security, pre-paid and post-paid billing, and roaming settlement for large public WLAN networks, in addition to remotely managing and updating multi-vendor hardware and Wi-Fi switches. Pronto Networks is funded by BV Capital, Draper Fisher Jurvetson and the Intel Communications Fund. In 2003, Pronto Networks received several awards including Wired Magazine's Top 25 Wi-Fi Companies to Watch, the Always On list of Top 100 Private Companies, and Computerworld's Innovative Technology Awards.

Pronto has its headquarters in Pleasanton, CA and offices in Bangalore, India and London, UK.

Dust Networks

Dust Networks was founded in 2002 by a team of dedicated engineers, led by industry pioneer Kris Pister. They envisioned a world of ubiquitous sensing – a world of connected sensors scattered around like specs of dust, or smart dust, gathering information economically and reliably, that had previously been impractical or impossible to acquire.

Airgo Networks

As the pioneer and worldwide leader in Multiple Input Multiple Output (MIMO) technology — the foundation for next generation Wi-Fi — Airgo Networks is focused on delivering the best wireless connectivity solutions to free people to work and play, where, when and how they choose. Airgo's revolutionary wireless technology approach substantially improves performance and reliability, enabling all applications the wire supports and eliminating the need for cables at home, at work, and in public places.

BelAir

BelAir Networks is a wireless mesh infrastructure supplier, founded in 2001, that provides broadband wireless networking solutions built around Wi-Fi, WiMAX and cellular technologies, and optimized for high density hot zone and metro deployments.

Firetide

Company: Launched in 2003, FiretideTM Inc. is a privately held wireless mesh technology company that develops networking equipment to deploy high performance mesh networks quickly, easily and affordably.

Firetide's mesh networking solution is ideal for building backbone infrastructure for Wi-Fi networks, video surveillance, and temporary networks in a variety of environments, such as metro-area Internet access HotZones, airports, hotels, campus environments or other locations where wiring is difficult, disruptive, or expensive.

MeshDynamics

Founded in 2002, MeshDynamics is a privately held company offering software and systems for high performance mesh networks. In addition to our USA office in Santa Clara, CA, Meshdynamics also has a software development facility in Pune, India.

Product- MULTIPLE-RADIO MD4000 MODULAR MESHTM FAMILY

Skypilot

SkyPilot Networks is the leading provider of carrier-class wireless mesh solutions that enable service providers, municipalities, and public safety agencies to rapidly deploy cost-effective broadband access, voice over IP, public and private Wi-Fi access, video surveillance, and other wireless applications.

The SkyPilot solution utilizes a patent-pending synchronous mesh architecture with high-speed switched directional antenna arrays that extends reach, mitigates interference, and maximizes spectral reuse. The result is a highly scalable, reliable, and deterministic mesh network that simplifies design, increases deployment flexibility, and dramatically reduces equipment and operating costs. SkyPilot has proven scalability and reliability with over

200 customers in more than 40 countries. SkyPilot is a principal member of the WiMAX Forum™ and a privately held company based in Santa Clara, California.

Products:

- SkyGateway: Base station that provides a gateway from wired Internet connection to the 5 GHz wireless mesh infrastructure. Features 8-antenna array for extended range and 360° coverage.
- SkyExtender TriBand: Mesh AP that integrates 5 GHz synchronous mesh backhaul with two high-power access points, one dedicated to licensed 4.9 GHz public safety applications and one dedicated to 2.4 GHz public Wi-Fi access.
- SkyExtender DualBand: Mesh AP that extends wireless access via Wi-Fi (2.4 GHz 802.11b/g) or SkyConnector features 8-antenna array for extended range and 360° coverage.
- SkyExtender: Mesh point that extends wireless access via SkyConnector or Ethernet connection. Features 8-antenna array for extended range and 360° coverage.
- SkyConnector: Indoor and outdoor CPEs that provide subscriber access to wireless infrastructure.

Strix

Founded in March 2000, Strix Systems Inc. designs, develops and markets wireless network systems that enhance productivity and efficiency by providing employees with instant information via continuous, secure connections to company networks.

Strix Systems' Access/One® Network is a complete wireless LAN solution, with very low total cost of ownership, yet the highest level of management and security. Physically, the network is RF-independent to accommodate present and future RF solutions. The security and management are distributed instead of residing in a hierarchy of servers, providing scalability and redundancy. This generation of product answers the need for a system with an architecture that cannot be outgrown. This product makes wireless networks like wired networks.

Strix Systems is a venture-backed company in Calabasas, California, founded in 2000 and backed by El Dorado Ventures, Palomar Ventures, Windward Ventures, CMEA Venture, UV Partners and Crosslink Capital. Strix Systems specializes in wireless local area networking products including 802.11a, 802.11b, 802.11g, Ultra-Wide Band, and Bluetooth.

Tropos

Founded in 2000, Tropos Networks is the proven market leader in delivering metro-scale Wi-Fi mesh network products and services, with more than 300 customers and 40 resellers in eight countries around the world at the end of 2005.

Tropos products are providing an increasing number of public safety agencies and service providers with the benefits of Wi-Fi city-wide. These networks are enabling mission-critical broadband applications in mobile public safety environments, such as mobile database access, video surveillance, and GIS inquiries. They are delivering residential consumer access as well as serving small businesses and nomadic users. No one else has successfully deployed metro-scale Wi-Fi networks in as many outdoor, mission-critical applications as Tropos Networks. And, regardless of client technology, no one else has successfully deployed mesh to deliver up to 54 Mbps data rates with 99% coverage in such large numbers before founded in October 2000.

2.3.1 Implementation issues

The performance of WMN is constrained by the technology that the individual Mesh Gateway Routers use. At the moment, the technology of choice for WMNs is WiFi (802.11). As such, the limits of WiFi are the limits of wireless mesh networking. These limitations lead to the following problems with pure WiFi Mesh networking: Limited throughput, lack of scalability, line-of-sight requirements, limited range, and latency. WiFi has several limitations, including:

1. Interference in the operating spectrum, which is the spectrum for industrial, scientific and medical (ISM) applications. This is also called unlicensed spectrum (2.4 or 5 GHz bands)
2. Limited (20MHz) bandwidth allocated to each channel.
3. Power limits on MGR and end-user radios.
4. The maximum number of users per MGR, as imposed by the state of the art in WiFi chips. (~50)

The limitations of WiFi will lead to several deficiencies in a pure WiFi mesh.

Throughput will be artificially limited by the bandwidth and frequency characteristics of the ISM spectrum. The environment and the number of simultaneous users will interact with the spectrum parameters to determine the amount of throughput a WiFi mesh network could have. The environmental effect manifests itself in either signal power loss (due to buildings, trees, rain, etc.) or signal reflections (caused by objects located between the transmitter and the receiver). Signals that are lower power or highly attenuated will be much more lossy, driving packet loss rates up and effective bandwidth down. The number of simultaneous users that are actively using the network will also impact throughput. Each user becomes an interfering source to the other users both at the physical layer as well as the MAC layer. The mesh network requires that adjacent MGRs must connect with each other. This will exacerbate the interference problem. Furthermore, the current WiFi chips can support about 50 simultaneous users. This means that if the demand for access exceeds 50 users per unit area, multiple MGRs must be deployed. This will lead to even more congestion and thus lower performance.

The attenuation characteristics of the current unlicensed WiFi spectrum are such that high-throughput meshing requires line of sight between APs. This poses considerable logistical concerns for Municipal Wireless, as cities contain many obstacles, from vegetation to buildings. In addition, the city's layout itself can present obstacles, as winding streets will place buildings in the way of potential paths between APs. To mitigate this, APs must be placed such that they are able to route messages around obstacles. This solution maintains the connectedness of the network, but each mesh point has associated fixed costs as well as maintenance costs. More importantly, each extra router required to reflect the message around corners will increase the length of the average path, which will lead to delay.

Limits on power, combined with the attenuation characteristics of the 2.4-5GHz frequencies that compose the current WiFi bands greatly limit the range of traditional WiFi access points. Long-range WiFi access points exist, but they require expensive high-power electronics, and thus cost on the order of $2500. These high fixed costs make it economically infeasible to provide access to low-density areas.

It has been reported by Strix Systems [47] (one of the main suppliers of Mesh equipment) that the delay in 10-hop mesh network varies from 20 to 40 msec.

2.4 Service Providers[36]

EarthLink

EarthLink is a leader in the fast growing muni WiFi market and is looking to take advantage of the potentially lucrative opportunity. Philadelphia, Pennsylvania and Anaheim, California were the first two cities to select the ISP in 2005 to roll out municipal wireless broadband networks. The company is also involved in San Francisco, New Orleans, and Milpitas. EarthLink intends to charge $21.95 for use of its

WiFi network and expects to generate $10 in contribution margin per user per month with a low 2% monthly churn rate; total subscriber acquisition cost is expected to be $125 per customer.

Google

EarthLink and Google partnered to win San Francisco's RFP to offer wireless broadband in early April. While EarthLink will charge for its faster connection, Google's service will come free of charge. The company has not yet decided whether advertising will be used to pay for the service. In addition to San Francisco, Google will be completing a service rollout in its hometown of Mountain View. Management has previously stated it does not intend to go after other cities.

MetroFi

MetroFi, headquartered in Mountain View California, is a private company that designs and builds WiFi networks. To date, MetroFi has built WiFi broadband networks in Cupertino, Santa Clara, and Sunnyvale California. The service is free and is supported by local advertisers.

2.5 Other competing technologies

In this section we will review briefly the other competing technologies in the broadband market.

2.5.1 Wireless (3G, B3G, 4G)

Since the early years of this decade, the incumbent wireless operators were planning to roll a number of new technologies that categorically called the 3rd generation wireless infrastructure. Examples are: UMTS, WCDMA, CDMA2000, where high data services such as HSDRP were supposed to be the vehicle for mobile users to Internet access. The reality has been somewhat disappointing to these operators. The adoption and thus the revenue have not been as big as the early expectation. The main reason is cost and the monthly charges incurred to the subscribers.

As a result, the industry started looking out for the next generation wireless technology that could provide high throughput but cost effective. The terms used in the context are Beyond 3G (B3G) and 4th Generation (4G). Due to the tremendous success of IEEE 802.11 (WiFi) over the pass few years, the IEEE wireless standards are becoming more attractive for mobile as well as fixed broadband deployment. In fact, WiMAX (802.16) and the newly enhanced 802.11 are competing on wining the wireless broadband. The following chart shows the various wireless technologies:

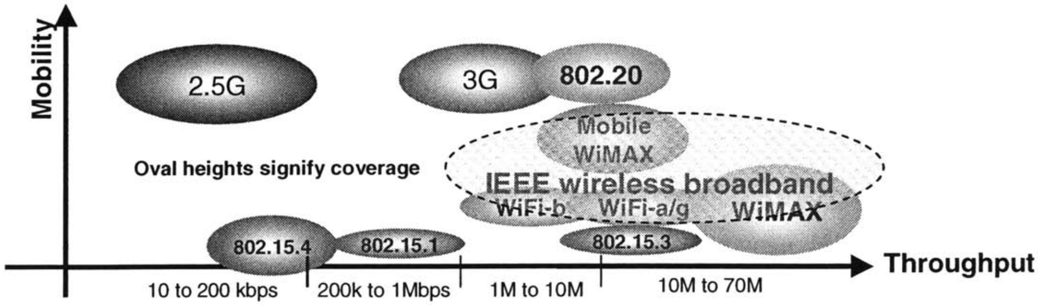

Figure 15: WiMAX relative to other Wireless Technologies (source WiMAX Forum)

It is not only the ubiquity that is attractive about WiFi and WiMAX for wireless broadband but also the higher performance compared to the 3G mobile technologies. In the following table (prepared by the WiMAX forum) shows clearly the superiority of WiMAX over the other mobile and wireless alternatives in the market.

Table 7 Comparing WiMAX [37]

	Channel Bandwidth	FDD/TDD	DL Peak (MBPS)	UL Peak (MBPS)	Standard Body	bits/sec /Hz
WiMAX	up to 20 MHz	FDD/TDD	up to 75	up to 75	IEEE	3.75
GPRS	200 KHz	FDD	0.16	0.16	3GPP	0.80
Edge	200 KHz	FDD	0.48	0.48	3GPP	2.40
WCDMA	5 MHz	FDD/TDD	2	2	3GPP	0.40
HSDPA /HSUPA	5 MHz	FDD	14.4	7	3GPP	2.88
3G1X	1.25 MHz	FDD	0.64	0.45	3GPP2	0.51
CDMA2000 EvDO	1.25 MHz	FDD	3.1	1.8	3GPP2	2.48
CDMA2000 EvDv	1.25 MHz	FDD	3.1	1.8	3GPP2	2.56

By looking at the spectral efficiency (last column labeled bits/sec/Hz) in this table, it is clear that WiMAX is more superior than the rest of the other technologies.

In August 2006, Sprint Nextel Corp. announced with much fanfare that it had selected WiMAX technology as a platform for its new wireless Internet network for fourth generation applications such as video streaming. Though Sprint owns the spectrum needed to roll out a WiMAX network, industry analysts predict that Sprint will spend $1 billion to $4 billion to develop the network. For a company that has struggled to meet financial expectations in 2006, this is an important investment. Sprint and other carriers will continue to use evolution-data optimized (EV-DO) 3G wireless broadband technology as they introduce WiMAX, according to analysts [48].

2.5.2 Wireline (DSL, Cable, PON)

The classical way to access Internet is to use dial-up, which it is shrinking as more broadband rollout is achieved. The DSL, Cable, and Passive Optical Network (PON) Broadband are spreading in most of the household in North America (as indicated in the following table).

Table 8 Broadband penetration in North America [49]

Broadband Internet Subs	2004	2005	2006	2007	2008	2009	2010
	000s, cumulative						
DSL	16,377	22,527	29,693	36,274	42,642	48,824	54,950
Cable modem	23,546	27,926	32,355	36,376	39,741	41,845	43,200
FTTC	600	895	1,643	2,447	3,157	3,731	4,193
FTTP	1,220	1,744	2,905	4,011	4,880	5,506	5,959
Other residential	390	536	761	1,009	1,263	1,519	1,785
Total	42,133	53,628	67,357	80,117	91,683	101,426	110,087

Of course, places such as rural areas and poor suburban have a long shot in getting Broadband in their areas.

There is no question about the technical superiority of these technologies in terms of bandwidth delivery compared to wireless. However, the availability and affordability of these broadband alternatives are questionable. Therefore, wireless mesh, due to cost effectiveness and ease of deployment, can compete with DSL, Cable, and PON.

2.6 Municipal wireless mesh policy

It is important to specify exactly who in the community that will be able to use the service. There are two models:

1. Common use; i.e. any one who physical in the area (just like municipal street lights or public parks or parking)
2. Only accessible by the residence of that community (residential or business).

The first one offers simple model, since in this case it will not require authentication when attempting to connect. The second one on the other hand authentication will have to be enforced. The second one may seem to have implication of affecting adversely the other Broadband business; i.e. a lot of subscriber to DSL/Cable who does not use for triple-play will find it cheaper to use free service. This will be mitigated by the fact that the service through WMNs is not available always (wireless link does not guarantee a good coverage always). Also, since authentication is required, it is anticipated that such a service will not be free. However, the first one may be offered for free (of course it will be paid by the tax payer dollar, just like it is for street light).

In any model, where the municipality has a direct role in the WMN broadband, the following are issues raised in [18]:

- It is argued that since municipal broadband can not be considered to Public Good but rather should be considered to be Natural Monopoly, this model should not be encouraged.
- There is a number of uncertainties: 1) whether WiFi is the right technology; 2) how much cost to the taxpayers (approx. $100K per sq miles.)

These arguments cannot be enough to discourage the municipal broadband simply because market failure rational [15]. Although, the other broadband alternatives are spread rapidly, a good portion of the society will not enjoy the spread. Therefore, the municipality WMN will be a solution. The other rational for justifying the entry of broadband municipality is to consider public wireless networks as being part of the public infrastructure (just like public transportation to over-air TV). Finally, since the municipalities have already invested in providing broadband connectivity to the state buildings, it can leverage that in building a public network (opportunistic rational).

It appears the Franchise model should be chosen such that the access is free for public use as well as for needy users. In order to get the idea of what the cost for installing a WMN in one mile (~1000 users), the current estimate (from San Francisco's case) is about $100K; i.e. $100 per user for equipment cost. It is likely this cost is doubled when the installation costs are also included.

2.7 Platform assessment

Given the information presented in this chapter, the task here is to assess the relevant platform metrics in order to assess the mesh networks:

Metric	Assessment	Scor
Standard interface	Since these networks will be using the ubiquitous WiFi technology (and in the near future WiMAX), this platform scores high.	H
Convenience	Since it allows for portability (and with the introduction of handover in WiFi and WiMAX), this is definitely more convenient than DSL/PON/Cable.	H
Resiliency	Since the architecture is based on mesh routing, in general it is more resilient than cellular or wireline access. However, the coverage percentage could be an issue which is less in the other wireline broadband (DSL/PON/Cable).	H
Environmental friendliness	Since it is wireless, there is always the concern whether it will ultimately hurt people (similar to cellular), which is less of an issue in wireline.	M

Chapter 3
Current business models for mesh

In this chapter, the current deployment will be reviewed in attempt to characterize the effectiveness of the business model for these networks. The methodology for achieving that is to conduct interviews with individual who have been involved in actual deployments and rollout of the wireless mesh networks. In particular, we choose the MIT neighborhood (Cambridge, Boston, and Brookline) as case studies. Other locations in the US were also studied.

But before we outline the results of our study to these deployments, we start out with an overview of the deployment strategies described in the literature.

3.1 Wireless mesh deployments

3.1.1 Introduction

As depicted in the figure below, the wireless mesh networks consist of overlapping WiFi hot spots, where APs provides wireless connectivity to the end users.

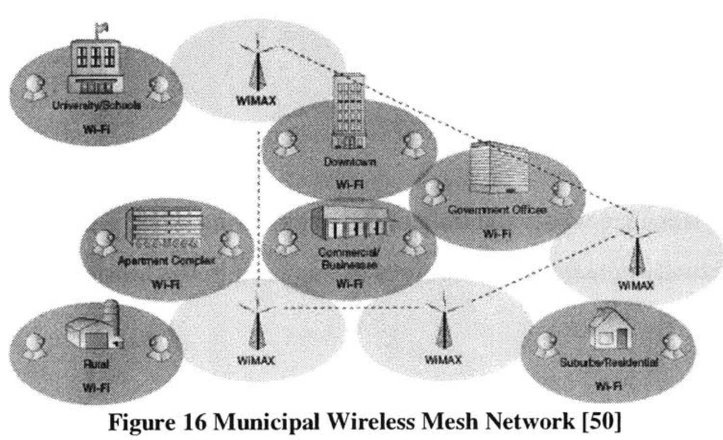

Figure 16 Municipal Wireless Mesh Network [50]

The connections between these APs are carried out via wireless mesh protocol. The backhaul connection can be either wireline or wireless. In particular, the wireless backhaul has the following deployment options:

1. Tower: this similar to the Macro-cellular wireless deployment, where a high rise (30 to 80 meters) tower is constructed for placing the basestation antennas on them. The towers can be either
   a. owned by the operator; or
   b. leased from a tower operators[9].
2. Low rise basestation: this is similar to the Micro-cellular deployment, where instead of using towers, backhaul antennas are place on highest building or objects.

In both case, the backhaul basestation is connected via a wireline (fiber – Ethernet) link to the wireline core network.

The municipalities follow a process in developing a plan for deploying the network. The plan has the following steps:

- Request For Proposal (RFP) submitted to public
- Bids submitted
- WISP and equipment vendor selection
- Project planning
- Wireless Mesh Deployment
- Maintenance

The last three steps are where the bulk of the engineering work is carried out. Each one of these steps actually consists of procedures as captured in the following diagram.

[9] The major tower operators in the US are: American Tower, Optasite and others.

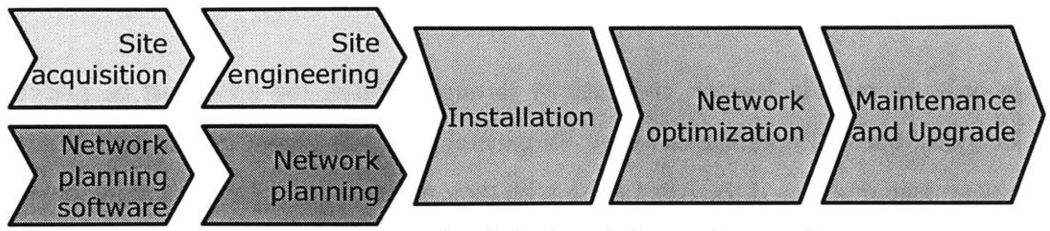

Figure 17 Procedure for deploying wireless mesh networks

3.1.2 Deployment scenarios

The WMNs will be deployed in a number of network scenarios, which are determined by the applications these networks are used for. In the case of the Municipal WMN, there are two scenarios:

1. Community network, targeting residential urban or suburban areas. This will include single family homes as well as apartment complexes.
2. Metropolitan network, targeting business districts or downtowns. This will include business offices, schools, state offices, and residential in high-rise building or complexes.

The following figure depicts these two scenarios.

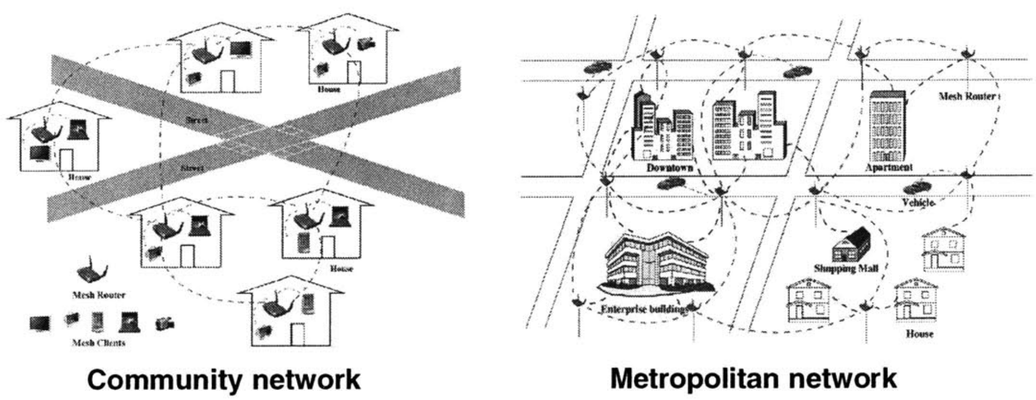

Figure 18 Deployment scenarios [14]

3.1.3 Installation and operation

In order to provide Internet connectivity through WMNs, the APs must be placed in locations that will optimize coverage. In general, the radio signal travels with relatively less propagation loss if the APs (along with their antennas) are placed as high above the ground as possible. Locations suitable for AP deployment are:

- Light poles (this is the more desirable locations)
- Traffic light at crossing
- High rise buildings
- Existing cellular towers
- Successful operation of these AP means ensuring the following elements:
- Powering the device continuously
- Performance monitoring
- Troubleshooting and repair
- Billing

It is likely most of the APs will be placed on top of city light poles. Otherwise, the other alternative is to locate them over state building or schools. The following figure illustrates how a AP is mounted on a pole, which requires a lift machine to achieve that.

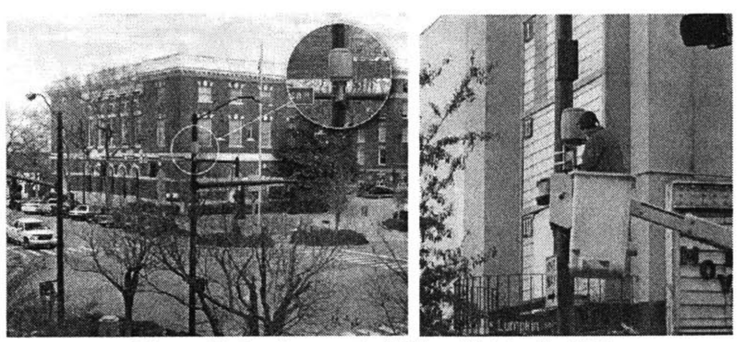

Figure 19 Deployment of AP on light pole [51]

On the other hand, the end user can connect to the wireless mesh using an outdoor or an indoor Customer Premise Equipment (CPE). This is for fixed application as seen in the following figure.

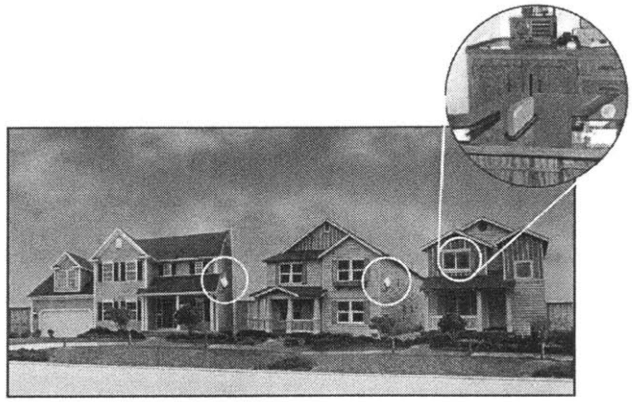

Figure 20 Outdoor vs Indoor CPE [52]

3.1.4 Coverage tradeoff

In this section, we will provide a framework for estimating the number of different service that can be attained given the amount of spectrum allocated to the backhaul used for connecting the mesh nodes. First we start with a node or a basestation that can transmit a certain amount of power (*P*). Given the antenna gain (on both transmit and receive) the receive sensitivity, it is possible to calculate the max distance for this system to attain the highest efficiency (max throughput) expressed by the bandwidth efficiency (bps/Hz). This is part of the power budget calculation. The simplest power loss equation is express as follows [53][30]:

$$P_L(r) = P_o(r_o) + 10\alpha \log_{10}\left(\frac{r}{r_o}\right) + \delta$$

Where

- $P_o = 20\log_{10}\left(\frac{4\pi r_o}{\lambda}\right)$ is the power at a reference distance r_o (usually 1 meter), which is 40 dB for 2.5GHz[10]. Note that λ is the wavelength ($= \frac{0.3}{f \text{ in GHz}}$).

[10] Note that if the frequency is 0.7GHz, we will have 10dB gain.

- α is a constant that characterize the environment, such that it varies from: 3 to 5 for urban areas, 2.5 to 3.5 for suburban areas, and 1.7 to 3 in the rural areas
- δ is a random number that represents the local variations of the surroundings, 3 dB to 12 dB

For example, in 64QAM, we need 22 dB of SNR plus 13 additional margin; i.e. 35 dB of SNR. For a combined antenna gain of 20 dB and processing gain of 10dB, the 64AQM at r_1 = miles (1600 meters) requires the transmit power of 12 Watts. When $r > 1$ mile, the power loss will increase, which have the effect of reducing the modulation from 64QAM to lower sizes (16QAM and QPSK). This will reduce the spectral efficiency beyond a certain distance (r_1). The tradeoff then is to find the maximum reach ($r < R$) that will attain the best combination of coverage and spectral efficiency. These two goals are contradictory to each other. The aim here is to find the combination as follows.

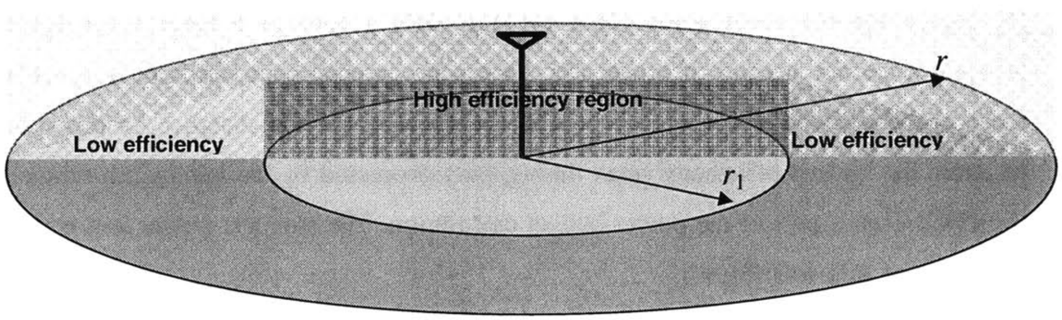

Figure 21 Coverage geometry

In the 64QAM, the max efficiency is approximately 3bit/sec/Hz [54] when $r \le r_1$, then we lose 1 bit for every 3 dBs in path loss. Hence for when $r_1 \le r$ and for m number of 3 dB losses, the distance r is:

$$3m = 10\alpha \log(r / r_1) \text{ or } m = \frac{\alpha \ln(r / r_1)}{\ln(2)}$$

The average efficiency is expressed as follows

$$\bar{\eta}(R) = \frac{3\pi r_1^2 + 6\pi \int_{r_1}^{R} \left(1 - \frac{\alpha \ln(r/r_1)}{6\ln(2)}\right) r dr}{\pi R^2}$$

Where $\int_{r}^{R} 2\cdot\pi\cdot 3x\cdot\left(1 - \frac{\alpha}{6}\cdot\frac{\ln\left(\frac{x}{r}\right)}{\ln(2)}\right) dx \rightarrow \frac{-1}{4}\cdot\pi\cdot R^2\cdot\frac{(-12)\cdot\ln(2) + 2\cdot\alpha\cdot\ln(R) - 2\cdot\alpha\cdot\ln(r) - \alpha}{\ln(2)} - \frac{1}{4}\cdot\pi\cdot r^2\cdot\frac{12\cdot\ln(2) + \alpha}{\ln(2)}$

If we assume that there is a total demand of n_i subscribers per unit area accessing service i through the network at any given time, then total throughput is expresses as:

$$BR_i = \pi R^2 n_i b_i$$

Where b_i is the bit rate (bit per second) required for service i. This leads to the calculation of the total spectral bandwidth (BW) for this throughput as follows:

$$BW_i = \frac{BR_i}{\bar{\eta}} \leq \text{Channel Bandwidth } (W)$$

It is also can be rewritten in the following way:

$$\pi R^2 n_i b_i = \bar{\eta} W_o \Rightarrow R = \sqrt{\frac{\bar{\eta}}{\pi n_i}\frac{W_o}{b_i}}, \text{ where } 0 < \bar{\eta} \leq 3$$

Note that $\bar{\eta}$ is a function of R itself and can be solved by iteration. This equation is used when there is only one service at a given area. However, the reality is that there will be a number of services (i = 1, ..., I). In this case the equation above can be rewritten as follows:

$$\pi R^2 \sum_{i=1}^{I} n_i b_i = \bar{\eta} W_o \Rightarrow R = \sqrt{\frac{\bar{\eta}}{\pi}\frac{W_o}{\sum_{i=1}^{I} n_i b_i}}$$

Next we would like to find out the best choices for n_i such that the revenue is maximized. If service i has a revenue of v_i, then the total revenue (V) is maximized as:

$$V_{\max} = \max_{R} \pi R^2 \sum_{i=1}^{I} \frac{v_i n_i}{p_i}$$

Where p_i is the activity ratio of service i, which represents the multiplexing (or oversubscription) gain. For example p_i is in the range of 0.1 to 0.02 for Internet access. This parameter can also be used to limit the number of users interested in service i in order optimize revenue. Substituting R in the last equation above yields:

$$V_{\max} = \max_{R, p_1, \dots p_I} \left(\left(\frac{\overline{\eta} W_o}{\sum_{i=1}^{I} n_i b_i} \right) \sum_{i=1}^{I} \frac{v_i n_i}{p_i} \right)$$

This is a typical multi-variable optimization problem, where W_o is constant. The solution is to find the best combination of p_i under maximum R.

3.2 Current mesh deployments

At the writing of this thesis, there is an increasing interest in deploying wireless mesh networks in the US municipalities, where the total number of networks deployed or planned for deployment is about 300 (out of 25,000 municipalities in the US). The following figure represents the deployments of municipal broadband networks.

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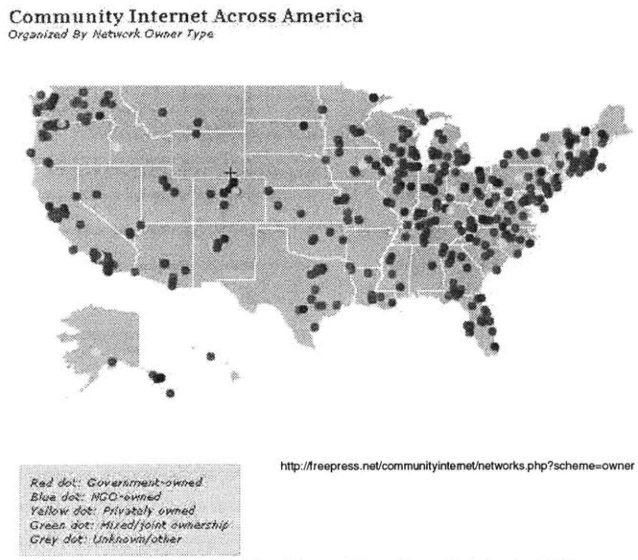

Figure 22 Municiapl broadband activities in US

To give an idea, the following table shows samples of municipalities that have started the deployment. It is clear from this table that the majority of these deployments are meant to provide broadband services to the public, whereas a few are for public safety purposes. Also it shows that the operation is still mix of city-run network and service provider-run (like Earthlink and MetroFi).

Table 9 Examples for the municipal deployments in the US[11]

Date	Region	Service Provider	Vendor	Application	Commentary
5/26/06	New Orleans	Earthlink	Tropos and Motorola	Broadband access	EarthLink announced that New Orleans has approved an ordinance to enable the company to build a Wi-Fi broadband network. Earthlink will be using Tropos mesh nodes and Motorola Canopy for this project
5/8/06	Toronto	Hydro Telecom	Siemens Canada and BelAir Networks	Broadband access	Hydro Telecom announced that Siemens Communications Group has been selected vendor of record for equipment supply, implementation and services in support of Toronto Hydro Telecom's plans to make Toronto the largest Wi-Fi zone in Canada. Siemens Mesh Øvantage MR product family is based on industry-leading wireless mesh technology from BelAir Networks
5/16/06	Arizona	Arizona	Strix Systems	Broadband access	Gilbert, Arizona, has selected MobilePro Corp. to design, deploy, and operate a citywide wireless service based on Strix's Access/One Network Outdoor Wireless System
4/22/06	Long Beach, California	Long Beach	PacketHop	Public Safety	PacketHop deploys mobile mesh broadband 4.9 GHz product for public safety in Long Beach California
4/6/06	San Francisco	Earthlink and Google	Motorola, Tropos and Wireless Facilities	Broadband access	San Francisco selected a joint bid by Earthlink and Google to provide Wi-Fi access citywide
3/22/06	Milpitas, California	Earthlink	Tropos and Motorola	Public Safety	Earthlink announced that it has signed a contract to build the city of Milpitas, California's Wi-Fi network
3/22/06	St. Thomas	Choice Communications	BelAir Networks	Broadband access	BelAir Networks and Choice Communications bring Wi-Fi to St. Thomas
3/7/06	Madison, Wis.	Cellnet Technology	Cisco	Broadband access	Cellnet Technology selected Cisco to provide outdoor "mesh" technology for a Wi-Fi initiative called Mad City Broadband undertaken by the city of Madison, Wis. Cellnet will build and manage a Wi-Fi network to serve the city
2/13/06	Florida	Access Anyplace	Tropos Networks	Broadband access	Access Anyplace announced a partnership with the City of Daytona Beach to deploy a metro-scale Wi-Fi mesh infrastructure for fixed and mobile broadband connectivity. Access Anyplace will deploy Tropos' mesh network
1/30/06	Cupertino and Santa Clara, CA	MetroFi		Broadband access	MetroFi announced free, wireless Internet access for residents in Cupertino and Santa Clara. WiFi will be available from over 100 access points in Cupertino and 180 access points in Santa Clara
12/12/05	Oregon	City of Lebanon, Oregon	Cisco	Broadband access	The city of Lebanon, Oregon announced that it is utilizing Wi-Fi mesh hardware from Cisco
11/15/05	Tucson, Ariz.	Tucson	Tropos Networks and Wireless Facilities	Public Safety	Wi-Fi networks in Tucson, Ariz. will be designed and deployed by Wireless Facilities
11/9/05	Temecula, CA	Temecula	Tropos Networks and Wireless Facilities	Public Safety	Tropos and Wireless Facilities were selected for network design and deployment services for the City of Temecula's proposed municipal Wi-Fi network
10/4/05	Philadelphia	EarthLink	Tropos Networks and Motorola	Broadband access	EarthLink announced that it will be the primary vendor for the rollout citywide network project called Wireless Philadelphia. The network will be built using equipment from Tropos Networks to cover 135 square miles and MOT's Canopy system will be used for wireless backhaul
10/1/05	Anaheim	Earthlink	Tropos Networks	Broadband access	Anaheim selected Earthlink in its Muni Wi-Fi network build
9/20/05	Mountain View, CA	Google		Broadband access	Google announced that it will offer free wireless net access service to Mountain View, California
7/26/04	Corpus Christi, Texas	Corpus Christi	Tropos Networks	Public Safety	City of Corpus Christi, Texas announced that it will deploy Tropos Wi-Fi system for use by the city-owned water and gas utilities, public works departments, and public safety agencies

In this section we will analyze so of these deployments in order to characterize the different business cases arising in the market. This will help anticipate how the business models will evolve. A number of interviews were conducted with the local municipalities (Boston area). Other municipalities (Corpus Christi and Mountain View) were also explored.

3.2.1 Boston

Just in October 2006, the plan was announced by the Boston Mayer for developing a wireless network throughout the whole city and its suburbs. The goals are the same one stated in the previous section. Specifically, the politicians believe that there is a great digital divide in the city, which needs to be bridged as quickly as possible. Their

[11] "Municipal WiFi Networks Gaining Momentum" Credit Suisse June, 6 2006.

conclusion came after a running survey in 2003, which yielded, among other things, the following chart.

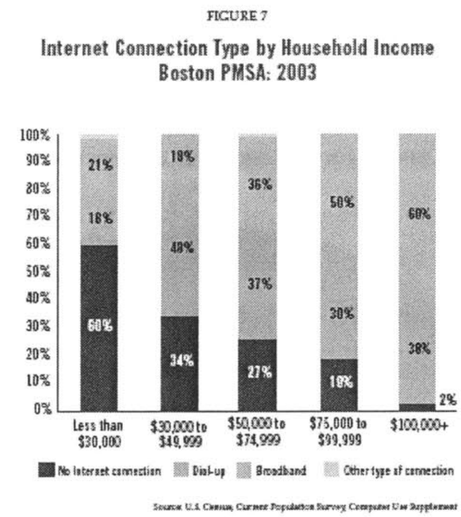

Figure 23 Survey of Internet penetration in Boston[12]

As can be seen for the chart, the broadband (or Internet access) is definitely more adopted by the well-to-do population, as compared to less rich population. Also, Boston would like to boast as a modern city with broadband available to all users everywhere.

After interviewing an official from the project, the business model is characterized as:

1. The city will own the equipment
2. The city will raise funds ($15 ~ $20 million) to pay for the cost of the deployment
3. The city has selected Galaxy as the Wireless Internet Service Provider, which has partnership with WiFi equipment maker Skypilot
4. The city can change the WISP when necessary (due to bad service delivery)
5. The APs will be located on city owned locations (such light poles) and buildings
6. The access fee is expected to be $15 per month
7. The target bandwidth to be symmetrical 1.5Mbps per user (peak rate)

[12] Boston Unplugged: Mapping a Wireless Future, Understanding Boston, 2/2/2006

8. The backhaul will be a mix of wireline and wireless, where the latter has a separate frequency (IEEE802.11a – 5GHz) for this purpose, as depicted in the following figure.

In this architecture, there are three types of APs: Gateways, Extenders, and Connectors. The first one is the gateway to the core network, the second one is the mesh AP, and the last one is for the end user connectivity to the municipal WiFi.

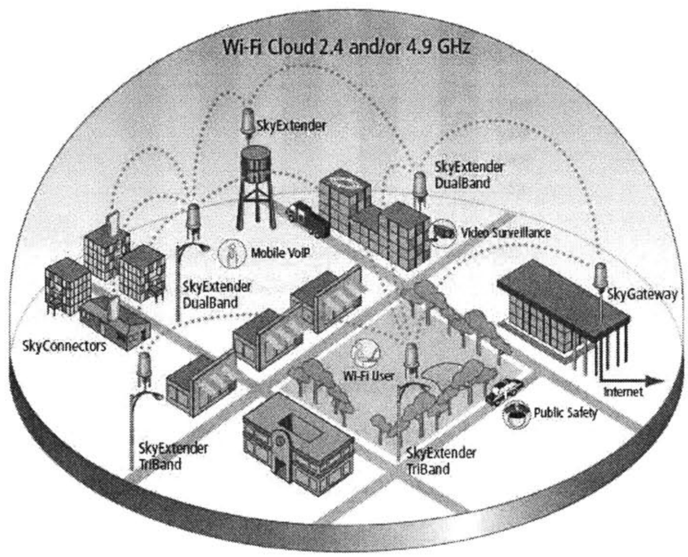

Figure 24 Skypilot Mesh architecture (used in Boston and Brookline)[13]

The following table captures the notes from the interview.

[13] http://skypilot.com/pdf/system_summary_01-002.pdf

Table 10 Notes from Boston interview

Name interviewee	Poisition	Date Duration Location
Brian Worobery	VP, Info Tech Mus Sci Boston	10/2/2006 1 hour Conf call
What are goals for the deploying MWM? Why municipalities involved?		Three goals: 1) reduce digital divid; 2) city services; and 3) stimulation of innovation and economic development. Commercial providers do not build out unless they make money leaving places behind, sity must act
What is the status of the deployment?		Approvement at end of July of non-profit project. Legal and operational decision made for pilot projects (2 within 2 weeks from date).
What are difficulties in this project:	Technical?	Uncertainty of WiFi coverage
	Personnel?	Not yet
	Finance?	Raise $15M to $20M
	Political?	Heavely supported by Mayor as a result other offices are very supportive. Same day response (no delay)
	Regulation?	Either allocate spectrum for manucipality or increase unlicense spectrum
	Competition (from incumbents)?	Two ways for reaction: 1) threat (like what happened in Phili); 2) Muni Mesh does not offer HBO or gold and no mobile phone
Who are involved in this project?	Municipality	Tech advistor, Policy advisor, CIO, Cable Comm Director
	Local organizations	South End Tech Center, Tech Goes Home, Tech SuperPowers, Museum Science, MIT, Harvard, Wentworth IT, Northeastern
	Wireless ISPs	Galaxy
	Consumer advocates	Altman & Vilandire
	Equipment vendors	Skypilot
How is the project financed?	Funding: how much the network costs	Build whole network which could cost $250K to $500K (excluding equipement). Fund of $15M to $20M
	Pricing: how the subscriber gets charged (if ever)	$15 per subscriber
	Ownership: who owns the network and who maintains it	City owns the network and its maintanence. WISP (Galaxy) operates the network
What is the technology used in this project	Network: how is the network constructed	Build open access network as whole sale network. Both wireless and wireline backhaul (through city buildings).
	WiFi: performance (coverage)	Lab test not conducted yet. Need to understand performance with topology.
	Devices: maker	Probabily Skypilot decided in two weeks.
	Deployment: rules	1.5M symmetrical per user.

3.2.2 Brookline

In general Brookline's project is similar to the one in Boston (at least they have selected the same WISP and the same equipment vendor). Historically, though, the reason for the town's plan to deploy wireless network was because the southern part of the town did not have cellular coverage (due to lack of towers). As such, there is a great pressure in the local political circle to find a solution. The incumbent wireless operator (Verizon) was not interested in rolling out anything other than their 3G cellular system, which was not possible with towers.

From the interview (see notes in the table below), this municipality is characterized as:

1. The WISP will own the equipment
2. The city has selected Galaxy as the Wireless Internet Service Provider, which has partnership with WiFi equipment maker Skypilot
3. The city can change the WISP when necessary (due to bad service delivery)
4. The APs will be located on city owned locations (such light poles) and buildings
5. The access fee is expected to be $20 per month
6. The target bandwidth to be symmetrical 1Mbps per user (peak rate)
7. The backhaul is only wireline (Ethernet).

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Table 11 Notes from Brookline interview

Name interviewee	Poisition	Date Duration Location
Kevin Strokes	CIO of Brookline	10/3/2006 1 hour Brookline Town Hall
What are goals for the deploying MWM? Why municipalities involved?		1) Public Safey; 2) Municipal operation; and 3) lack of wireless connectivity some portion of town (south) due to lack of wireless towers. Incumbent decided not build WiFi but offered to do EV-DO. Then other proposal (two years ago) to try DAS (dist anten
What is the status of the deployment?		License to be signed tonight for starting the project with Galaxy
What are difficulties in this project:	Technical?	Terrian and demographic effect on network not well studied. Looking at Tempe, Saint Charles, and Metro Fi.
	Personnel?	Since all done by WISP, not much effort imposed on Town; i.e. no more personnel added.
	Finance?	Cost is paid by WISP (about $5M to $7M)
	Political?	The Town can fire WISP if not perform. Not much political left between various Twon office, but zoning was an issue before.
	Regulation?	FCC not predictable
	Competition (from incumbents)?	Verizon does not like it.
Who are involved in this project?	Municipality	Town
	Local organizations	Resident volunteers, looking at technology
	Wireless ISPs	Galaxy
	Consumer advocates	
	Equipment vendors	Skypilot
How is the project financed?	Funding: how much the network costs	WISP pays for it
	Pricing: how the subscriber gets charged (if ever)	$20
	Ownership: who owns the network and who maintains it	WISP pays for it
What is the technology used in this project	Network: how is the network constructed	Wireline backhaul only. Only 7 ASs to be connected to backbone using fiber (Ethernet). There are 65,000 HH, only 20,000 to be served
	WiFi: performance (coverage)	35 AP per sq. mile
	Devices: maker	Skypilot
	Deployment: rules	Interoperable with WiFi, easy to change the electronics to move to newer technologies such as WiMAX

3.2.3 Cambridge

In Cambridge, the municipal wireless is significantly different from both Boston and Brookline. It is basically the humble effort exerted by a few officials of the municipality. The whole project is not well funded and considered to a conglomerate of contributors, primirely Cambridge, MIT, and Harvard. The contributions of the last two organizations are:

1. The wireless backhaul basestation (equipment and location)
2. Connectivity of the basestation to the Internet backbone.

The municipality has allocated a small amount of fund for procuring APs. The service will be free and it is best effort and as such it does not require much operational cost, which at the same time makes it less reliable and thus effective.

Table 12 Notes from Cambridge interview

Name interviewee	Poisition	Date Duration Location
Ash Dyer	CEO of Phlogisto	9/20/2006 1.5 hours Cambridge
What are goals for the deploying MWM? Why municipalities involved?		Digital divid, revive downtwons, cost saving in city operation such as real estate inspection, and emergency service
What is the status of the deployment?		Town, MIT, and Harvard offers as ISP conduit and Basestation owners.
What are difficulties in this project:	Technical?	Deployment by town technicians. Not much measurement done to verify issues. Not clear how to make money other than selling ASs.
	Personnel?	Just two person company, CES and Kurt Keville
	Finance?	Town allocated only $150K since exceeding $250K requires more complex procedure. Phlogisto built up 100 AS, only 3 deployed so far. Two $5K payment by town.
	Political?	None yet
	Regulation?	None yet
	Competition (from incumbents)?	None yet
Who are involved in this project?	Municipality	Supporter of effort in town hall Henrietta Davis. Working with Mary Hart CIO.
	Local organizations	MIT, Harvard
	Wireless ISPs	None
	Consumer advocates	None
	Equipment vendors	D-Link AS and Proxim BS
How is the project financed?	Funding: how much the network costs	Twon money and Internet connection from MIT, Harvard and town
	Pricing: how the subscriber gets charged (if ever)	Free
	Ownership: who owns the network and who maintains it	Twon owns network
What is the technology used in this project	Network: how is the network constructed	Installed by town
	WiFi: performance (coverage)	Coverage radius of 300 to 1,000 meters
	Devices: maker	D-Link AS and Proxim BS
	Deployment: rules	'50 users per AS, hoping to use power over Ethernet

Mudhafar Hassan-Ali© (2006).

3.2.4 Mountain View

It all started with the idea of providing broadband connectivity to the Mountain View (CA) police department especially to the officer driving in duty. Then, the municipality expanded to include the whole town. The WISP is Google and equipment vendor is Tropos. So far they have deployed about 460 APs (30 to 40 APs per sq. mile), of which they 50 gateways, which have wireless backhaul to a total of 3 basestation scattered around the area. Basestations and Gateways are placed on rooftops (high risers and schools) for a rent fee of about $10,000 to $20,000.

The project was completed in August 2006 and it has been serving the citizens of that area. Google reprehensive (Karl Garcia) interviewed about this project mentioned that there are already 3,000 registered users, of which 1,000 surfing simultaneously during peak hour (4PM). The peak rate allocated to each user is 1Mbps symmetrical.

3.2.5 Corpus Christi

Corpus Christi, a city of 277,000 residents, came upon the idea in 2003 while investigating ways to update aging water and gas meters, and to find a safe alternative to read utility meters remotely rather than sending field workers out. The result is an automated meter-reading system that streamlines services for city workers and makes their processes more efficient.

Currently, the WiFi network, or WiFi cloud, provides wireless coverage to areas representing 85% of the city's population, and will be 100% complete across the 147 square miles of the city by this fall. The total budget for the WiFi project is $7.1 million–$1.1 million for the pilot project and $6 million for the citywide build-out. Approximately 1,600 Tropos Networks wireless routers are being installed in a grid across the populous areas of the city's corporate limits to provide coverage, with a minimum throughput of 512 Kbps to 1 Mbps on average, which meets the qualifying standard for high-speed wireless. The mesh WiFi network provides a technologically advanced, multipurpose, open wireless system, with coverage and bandwidth available for a multitude of cost-saving applications in all city departments.

The city WiFi is run by Corpus Christi (CC) Digital Community Development Corporation[14], which is a non-profit corporation created by the City of Corpus Christi to leverage the City's information infrastructure for the advancement of the government, public safety, education, business, health care, and residential community. The primary service of the corporation is wholesale citywide network (i.e., fiber optic, WIMAX, WiFi) services that are sold to virtual ISPs (vISPs) through open access alliance programs. These programs provide the community with free access to community network services and subscription access to competitive ISP services. The Corporation provides the following services:

- Wholesale network access through alliance partnerships – fiber optic, WIMAX, and metro WiFi networks.
- Community portal services – free access to community network services (i.e., government, education, health care, human service, market place shopping).
- Portal advertising services – commercial and community advertising on captive portal.
- Digital community development – leadership and promotion of digital applications and services for government, public safety, business, health care, education, work force development, etc.

According to Russ Youn (interviewed on 10/18/2006), at the moment the service is free of charge for the community of CC.

[14] http://www.cctexas.com/wifi/

3.2.6 Tempe[15]

Starting the summer of 2005, certain businesses and residences in Tempe, Arizona, got both fixed and mobile broadband services available to them from a common WiFi mesh network infrastructure.

The city had the network installed in part to support all mobile municipal personnel (police, fire and water department workers and building inspectors) with broadband at vehicular speeds, says Dave Heck, deputy CIO for the city.

But Tempe has also licensed the network to a wholesale service provider so commercial services can be provided citywide. Businesses, for example, will have a wireless T1 alternative with mobility tagged on as an extra throughout the 40-square-mile Tempe area for about 20 percent less than the cost of a terrestrial T1 in the area today.

The WiFi mesh infrastructure, manufactured by Strix Systems, will comprise 400 access points used for both backhaul and access. Strix's routing algorithm supports handoffs among APs at vehicular speeds up to 180 miles per hour, he says.

Many emergency responders' laptops will be outfitted with PadCom client software to facilitate roaming among the WiFi network and older, lower-speed public safety networks.

There are six points of OC-3 ingress connected to 802.11a access points with single or double radios for backhaul within dense populations. There is a 4.9 MHz slot in the Strix mesh devices to support WiMAX at the outer edges; WiMAX will eventually be used to connect pockets of dense populations across the county.

The incumbent cable operator Cox will likely team with NeoReach to add mobility services to its cable-based broadband services. The following figure captures Tempe's website for the available services and their prices.

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[15] http://www.techworld.com/mobility/features/index.cfm?featureid=1871&pagtype=samecatsamechan

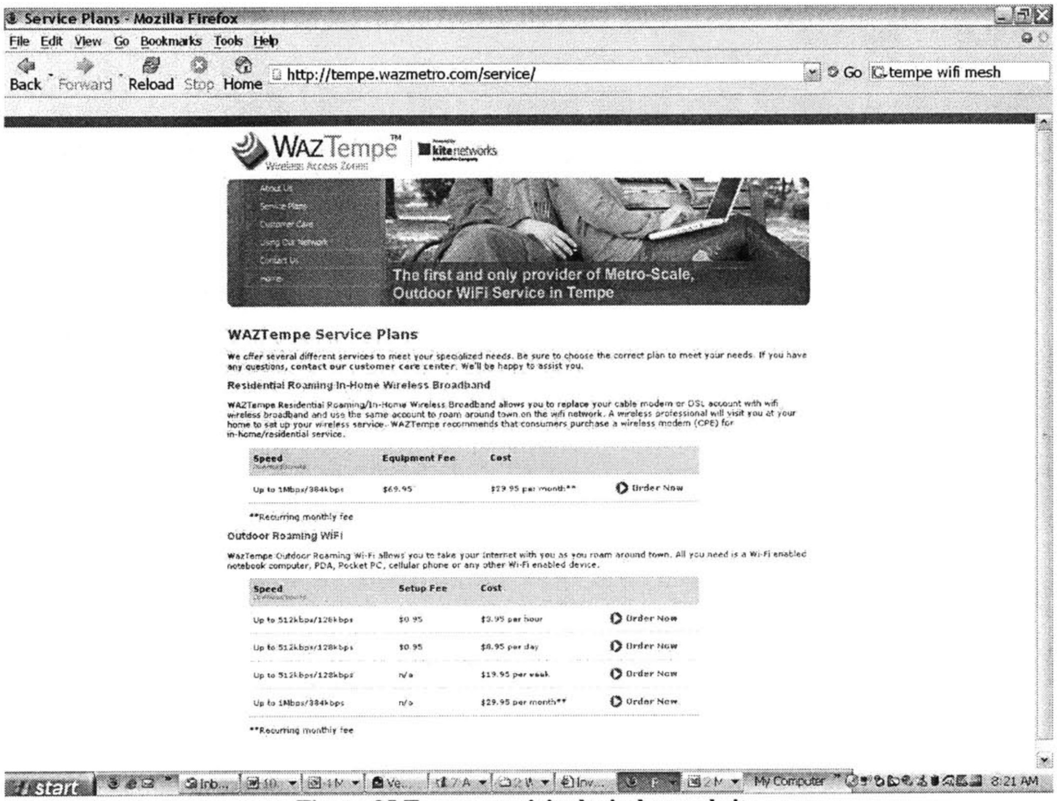

Figure 25 Tempe municipal wireless website

3.3 Issues with the current plans

3.3.1 Security [55]

Security concerns have held back WiFi adoption in the corporate world. Hackers and security consultants have demonstrated how easy it can be to crack the current security technology, known as wired equivalent privacy (WEP), used in most WiFi connections. A hacker can break into a WiFi network using readily available materials and software. In 2004, the IEEE has added 802.11i, which is a software standard that seeks to improve security features in various 802.11 wireless hardware standards. The purpose of 802.11i is to improve the safety of transmissions (management and distribution of the keys, coding and authentication). This standard rests on the Advanced Encryption Standard (AES) and proposes coding communications for transmission using technologies 802.11a, 802.11b and 802.11g.

As a stopgap measure for WiFi users until a new software standard from the IEEE is ratified, a new security technology known as WiFi protected access (WPA) has been commissioned. In an attempt to allay security concerns, the WiFi alliance has taken up the initiative to certify WiFi products for WPA. Products certified for WPA will feature several technologies not found in WEP, including improved key management technology and temporal key integrity protocol (TKIP). Users of current WiFi products will be able to upgrade to WPA through software updates.

802.11i contains a security protocol known as counter with cipher block chaining message authentication code protocol (CCMP). This adds an additional layer of security for the second version of WPA based on the completed standard.

3.3.2 Bandwidth

The performance of WMN is a function of the underline technology used in building the APs. At the moment, the technology-of-choice for WMNs is WiFi, which is based on 802.11 (wireless LAN – WLAN). As such, the limitation of this technology determines the limitation of the WMNs. The following are the main parameters for WiFi networks:

- The operating spectrum, which in the unlicensed spectrum (2.4 or 5 GHz bands)
- The bandwidth allocated to each channel, which is 20MHz
- The max transmitted power allowed from each AP and client
- The max number of user per AP (~50)
- The number of radios
- The antenna design
- Cost of equipment, deployment, and operation

One critical aspect of the AP is the bit rate, which is a function of many parameters, specially the received signal power to noise ratio determined solely by two main factors: 1) propagation loss (due to distance and obstacles), and 2) interference from other clients operating in the same spectrum. In order to mitigate these two elements, there are two techniques which are getting employed in the design of the APs:

- Multi-In-Multi-Out (MIMO) transceiver (just at the beginning of this year, IEEE ratified 802.11n which specifies the MIMO in WiFi).
- Multi-radio design such that:
    - One radio for communicating with clients
    - Two radios for communicating with two neighboring APs (ingress+ egress), as seen the following figure.

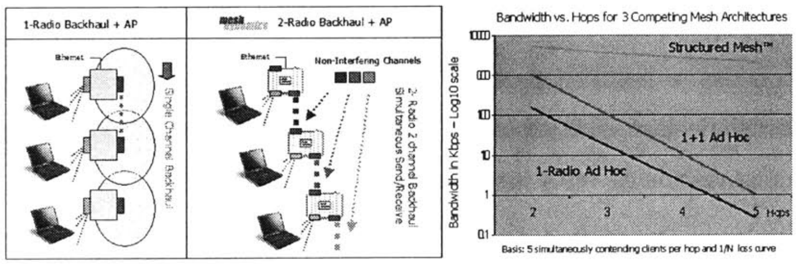

Figure 26 Multi-radio AP along with it performance[16]

It is clear that a single radio AP has a serious limitation when the number of APs exceeds 1. Therefore, for successful deployment of WMN, the three radio design has been recommended. However, this will increase cost and more importantly power consumption.

In the case of 802.11a/g, the maximum effective bit rate is about half the line rate (54Mbps). If there are maximum number of active client at any given time is 50, then the bit rate per client is 25/50 = 500Kbps. In order to estimate how much bandwidth required for a given number of clients connected to a Mesh Network, the user needs to be identified. We expect the following user-types:

- Light user, whose use of the network is for check email or short web surfing, or making a single VoIP call. The average bit rate generated by such a user is assumed to be 100Kbps. It is assume that 90% of the population is of this type.
- Heavy users, whose use of the network is download large files or making a video phone call. The average bit rate generated by such a user is assumed to be 1Mbps. It is assumed that 10% of the population of this type.

[16] http://meshdynamics.com/WhyStructuredMesh.html

Therefore, a typical WMN serving 1 square mile (1000 users over 25 APs), requires 100 Mbps. If WiMAX is used to connect to four (out of 25 AP) to provide 100Mbps, four WiMAX channels are needed each providing 25Mbps. The other alternative is to connect two of the APs to wireline infrastructure via Fast Ethernet.

It is important to notice that this type of service cannot match the Broadband provided by DSL or cable. As a matter fact, the network deployed in Mountain View (CA) has shown unsatisfactory performance as reported in [58]. Therefore, WMN is used to provide basic Internet connectivity (just better than dialup) for the following category of users:

1. Poor neighborhood
2. Public safety personal including police
3. Places where the DSL/Cable is not possible (Broadband equity), such as rural areas (although WiFi may not be ideal for it).

3.3.3 AP powering

The current deployments assume that most of the APs will be installed on top of the light poles usually owned by the municipalities themselves. This makes the deployment practical and economical. However, some these light poles are connected to a centralized control that switches of the electricity at day time. This is a very serious issue (as seen in cities like Boston). The solution is to change that electrical connection, which will result in an additional cost that was not accounted for.

3.3.4 Business model

There are mainly two categories for business models that the municipalities will be operating their networks under; i.e. the for-profit and the non-profit models. The latter was the dominant vision for these networks when the municipalities started expressing their plans to participate in providing Internet to their citizens. However, the reality of rolling out and operating these networks require significant capital that needs to be sustainable. As such, the paradigm has shifted towards the for-profit model. The following table quoted from Boston's "Wireless Task Force Report"[17].

Table 13 Business Model for municipal broadband

For Profit Model "RFP" or "Franchise"	**Non Profit Model** Some Non-Profit in the value chain
Details: • Multi-vendor relationship with a city agency or non-profit – "Liaison" • Private companies operate all parts of the value chain (with possible exception of digital divide) • RFP or Franchise arrangement • "Liaison" development requirements, metrics, penalties	**Details:** • Non-profit participation in the value chain o Backhaul/transport at minimum • Non-profit entity established with board and funding • Private companies server other value chain elements • Non profit conducts RFP ti find private partners • City has process to select non-profit and establish asset grant.
Risk: • City or "Liaison" does not receive attractive bids • Any vendor does not perform to requirements • Limited innovation opportunities	**Risk:** • Non-profit must assume some market, technology, demand, and funding risks. • Significant political, legal, and execution risk • Partner does not perform to requirements • No-attractive bids
Opportunities: • Private market absorbs all market, technology, demand, and funding risks • Low political/legal risk if vendor performs • Faster time to market	**Opportunities:** • Provides a unique platform for innovation • Platform for state-wide expansion • Universal digital divide support • Control over execution, management, operations, partnership, etc.

Note that in this table, "Non-profit" is the entity that manages the municipal wireless networks, also called "liaison". Also, the RFP, "Request For Proposal", is the contract between the municipality and the operator.

Within these two categories, many business models will form between the network owner and the network operator. In [32], they show a matrix for the business models between the two players, as seen in the following table:

[17] "Wireless in Boston, Wireless Task Force Report, Broadband for Boston", City of Boston, July 31, 2006.

Table 14 Municipal WiFi business models

Owner / Operator	City	One private actor	Multiple
City	Public utility	Hosted services	Public overlay
One private actor	Wholesale	Franchise	Private overlay
Multiple	Wholesale open platform	Common carrier	Organic mesh

In the following, each model is briefly described:

1. **Public utility**: This is similar to water or power utility. The reason for adopting this model is to take advantage of the municipalities' experience with other utilities. Through such an arrangement, cities can leverage their existing resources for subscriber acquisition, customer service, technical support, and billing. Example for this model is the city of Chaska (MN).
2. **Wholesaler**: The municipality resells network access to a private operator, like WISP, who then retails Wi-Fi service to the city residents. In this model, while a city funds the design, construction and operation of a municipal WiFi network, service providers perform customer acquisition, customer service, technical support, and billing. The city can receive benefits through reduced telecommunication costs by owning the network, instead of leasing it from private companies. Boston follows this model.
3. **Open platform**: offers a variant on the wholesaler model in which the city offers excess capacity in its network to several ISPs. This model has not been adopted yet.
4. **Hosted service**: A city choosing that approach would essentially set up a municipally-controlled ISP offering services on privately-owned WiFi facilities. So far, no city has explored that avenue.
5. **Franchise**: This is the most prevalent option for the private network owner to operate the WiFi service as well and sell it directly to consumers. This arrangement mimics the franchising of cable systems operators, and cities can structure agreements that carve out city benefits similar to the public/education/government (PEG) access channels in addition to eventual franchise fees and access fees for antenna siting. This

is becoming the model of choice. Brookline, Philadelphia, and San Francisco follow this model.

6. **Common carrier**: The private network owner plays the function of a common carrier, making its WiFi network infrastructure available to multiple ISPs, city services, and possibly others such as private networks. This model has not been adopted (and perhaps won't be adopted at all) by any municipality.
7. **Public overlay**: The municipalities will offer a common public overlay to these multiple networks, that could provide features ranging from a common city 'branding' to uniform login and authentication. A similar concept has been promoted by wireless community activist project "NoCat.net" in the form of a suite of software services including NoCatAuth (a centralized authentication system that works across multiple independent co-op networks).
8. **Private overlay**: Multiple network owners can outsource service provision and retail/billing operation to a private overlay operator such as Boingo or iPass: this is currently one of the prevailing models for commercial public WiFi provision in coffee shop and hotels, a model that could conceivably be extended to other types of venues. For example, Boingo currently lists free networks on its Wi-Fi location finder interface, although it obviously does not charge for access through them.
9. **Organic mesh**: a set of diversely-owned network facilities operated by multiple players would provide an interesting test of the self-organizing, organic mesh envisioned by proponents of a broadly open spectrum common. Optimistic visions expect that current WiFi deployments might naturally emerge into a more ubiquitous self-organizing coherent mesh network, where the multiple players seek interconnection or collaboration arrangements as they see fit. However, one could envision a local government taking an active role to usher in such an outcome, for example by promoting broader WiFi deployment in city-owned buildings such as libraries and municipal offices, or by making antenna sites available in exchange for a commitment to cooperate with other WiFi networks in the area.

3.3.5 Regulations

The embarking of municipalities in deploying these networks created two factions: pro deployment; and anti deployment. The former are the end users and the consumer advocates along the political system in the local governments. The latter are for obvious reasons are the incumbent operators. Their motivation is that it is not fair to their business to have the local government involved in deploying broadband networks. Those incumbents lobbied against this trend and managed to get 13 states to impose limitations on their municipalities[18].

The struggle between these two factions, however, the wireless mesh deployment is getting tremendous moment and it is difficult to reverse it.

3.4 Recommendations for improvement

3.4.1 AP powering

There are two avenues for resolving the issue with the electrical connections required to power the outdoor APs. For the APs that have electrical connection but switched off during the day, adding a back-up battery that could electrical power comes. This could cost somewhere between $50 to $150 and additional operation cost. The other alternative is to use solar panels with backup batteries as seen in the following figure.

[18] S. Gillet, "Municipal Wireless Broadband: Hype or Harbinger", Southern California Review, V.79, 2006.

Figure 27 Solar WiFi (Alpha Technologies)

Here again, cost will be an issue as well as the space and maintenance. The current belief is that 9 squared inches will yield 1 Watt (20% efficiency)[19], whose cost could be between \$3.5 to \$8[20].

3.4.2 Spectrum

The success of Municipal wireless networks will hinge on the policy imposed on the spectrum allocated to the operation of these networks. However, there are issues on the national spectrum policy as the followings.

1. Securing spectrum band
2. Decide the spectrum allocation model
3. Decide the spectrum band managing model

Since it is assumed that the end-user will be using regular WiFi to access the Municipal wireless networks, these network must be using 802.11a/b/g (WiFi) technology. The most serious problem with this model is that operating in an unlicensed spectrum (as the case with WiFi) could introduce uncontrollable interference (between home WiFi and

[19] Private correspondence with Peter Bermel [bermel@MIT.EDU].
[20] Private correspondence with Ron Elbersen [ron@elbersen.nl].

municipal WiFi). The impact of interference could be devastating especially to the home networks.

Apart from spectrum, it is also recommended that the APs are designed with three radios, as explained in section 3.3.2 . Recently the FCC submitted an NRPM (May 12, 2004 Docket 03-186) for proposing unlicensed use of unused TV channels 2-to-51. It is expected that by 2010 when DTV is completely transferred, 10 to 40 unassigned channels. The frequency of these channels is in the range of 700MHz. This frequency has the advantage of a low attenuation compared to 2.4/5GHz. If it were to be used for mesh infrastructure, the deployment will be easier for two reasons:

- The links between adjacent APs are more robust.
- It is more efficient to use WiMAX for connected the municipal networks to the infrastructure.

The question how much bandwidth required. It all depends on what type of services will be offered. For the basic case (non-competing with DSL/Cable), 40 (≡ 8 unused TV channels[21]) MHz seems to be enough in providing 100Mbps per mile. At this low frequency, it is possible to have a reach of several miles. The use of MIMO could potentially increase the spectral efficiency. For example 2x2 MIMO could double the bit rate, which means reduce the spectrum requirement by half (4 unused TV channels instead).

This recommendation is justifiable given the estimate of the unused TV channels (white channels) as stated in [17] and given the following table.

[21] For dual-backhaul radio, the required spectrum is doubled; i.e. 16 channels in this case.

Table 15 White Space as a share of TV Band in sample of U.S. media markets[22]

Market	Post-DTV Transition	
	No. of Vacant Channels Between 2-51	Percent of TV Band Spectrum Vacant
Juneau, Alaska	37	74%
Honolulu, Hawaii	31	62%
Phoenix, Ariz.	22	44%
Charleston, W.V.	36	72%
Helena, Mont.	31	62%
Boston, Mass.	19	38%
Jackson, Miss.	30	60%
Fargo, N.D.	41	82%
Dallas-Ft. Worth, Tex.	20	40%
San Francisco, Calif.	19	37%
Portland, Maine	33	66%
Tallahassee, Fla.	31	62%
Portland, Ore.	29	58%
Seattle, Wash.	26	52%
Las Vegas, Nev.	26	52%
Trenton, N.J.	15	30%
Richmond, Va.	32	64%
Omaha, Neb.	26	52%
Manchester, N.H.	23	46%
Little Rock, Ark.	30	60%
Columbia, S.C.	35	70%
Baton Rouge, La.	22	44%

Further, it has been found that the viewership of over-the-air TV is declining as shown the following curve [17].

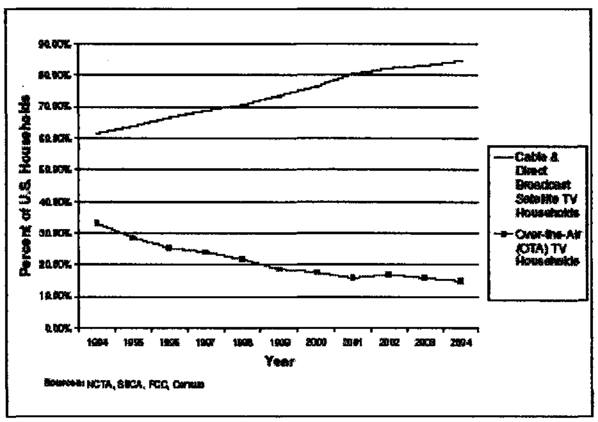

Figure 28 The decline of over-the-air Television

Hence the recommendations are:

- The FCC should allocate the spectrum as unlicensed for municipality use
- The spectrum should be as low frequency as possible.
- The FCC should allow for higher power allocations for backhaul operation
- A power control regime should be employed

22 http://www.newamerica.net/Download_Docs/pdfs/Doc_File_2898_1.pdf

3.4.3 Service integration and convergence [55]

Until recently networks for wireless, wireline, data and cable TV services have existed in isolation. The next-generation solutions represent a more efficient way to build networks using a common multiservice layered architecture. Having one converged network for all access types is a significant benefit of layered architecture. This can improve service quality and allows the efficient introduction of new multimedia services based on IMS. The following figure depicts such convergence.

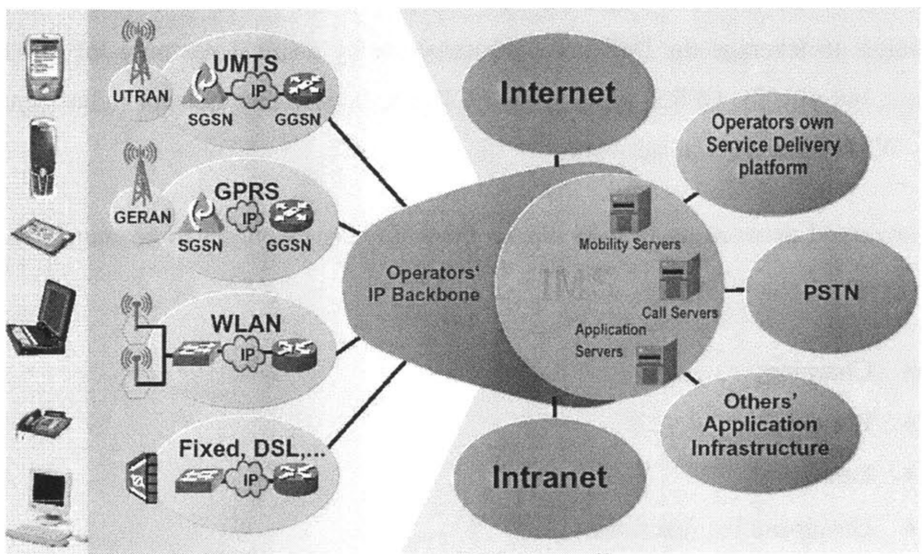

Figure 29 ISM architecture[23]

IMS provides a flexible architecture for the rapid deployment of innovative and sophisticated features. The IMS provides the control of applications, control of sessions and media conversion. Within the IMS, media control, session control and application control are separated in distinct entities. Some of the first applications expected to be launched using the standard will be push-to-talk over cellular (PoC), presence and instant messaging, and many other interactive applications eventually evolving to full fledged voice and VoIP. These applications can use a variety of basic network services offered by IMS like:

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[23] http://www.ist-breath.net/documents/BReATH/E5_Greece_workshop/Presentations/III_4_Eleftherianos.pdf

- Session control services including subscription, registration, routing and roaming;
- Combination of several different media bearer per session;
- Central service-based charging;
- Secure authentication and confidentiality based on the ISIM/USIM;
- Quality of service support.

Besides these basic services, the IMS supports interworking with PSTN and CS domains for voice, and with corporate intranets, ISP networks and the Internet. Further, IMS is access-flexible and works together with any packet-based access network. This allows operators to leverage the IMS core infrastructure by using it not only for UMTS radio access, but also for GPRS, EDGE, TD-SCDMA, license-free hotspot radio technologies (e.g. Wi-Fi) and wireline networks.

A converged network using IMS allows the following resources to be shared, regardless of service or access type.

- Charging;
- Presence;
- Directory;
- Group and list functions;
- Provisioning;
- Media handling;
- Session control;
- Operation and management.

It is therefore critical for the Wireless Mesh Network operation to be part of this integration. This will ensure the ease of rolling out new services on top of these networks. It is also important for interconnecting these networks operated and owned by thousands by municipalities and their operator partners.

3.5 Platform assessment

The relevant metrics for assessing a platform are evaluated in the following table.

Metric	Assessment	Score
Deployment	There is a significant uncertainty about what the position of the state and federal legislations could end up. However, in general the deployment is relatively easy than the wireline broadband.	M
Maintenance	Since the APs will be outdoor, and since wireless propagation could be changing with climate weather condition, it is likely that the complaint could be as much as (or a little higher) than the cellular and wireline counterparts.	M
Security	This main weakness of this platform as compared to DSL, and to some extent as compared to Cable, PON, and cellular. This will improve when WiMAX is adopted (of course using 802.11e/i will help as well.)	L
Rate	It is relatively better than cellular but less has less performance as compare to the wireline broadband.	M
Coverage	With WiFi coverage may not be as good as cellular, but with the introduction of WiMAX, which could beat cellular and wireline.	L
New applications	With the adoption of IMS and the neutrality of municipality, new applications may find their way better than the other broadband.	H
Support multiple parties	The environment of municipal wireless platform is based on multiple parties more the incumbent broadband providers.	H
Network neutrality	Assuming that the municipalities will keep their neutrality, it seems this platform will be better than the incumbent	H

	operators.	

Chapter 4
Economic analysis

After we discussed the technology and the deployment strategies along with the business models adopted by municipalities, in this chapter we will discuss the economics of municipal wireless broadband.

The survey conducted by S&P in the US show that about 13% of the telecom spending goes to the Internet access and 34% goes to the wireless communication. That is almost 50% of the total spending on telecom services.

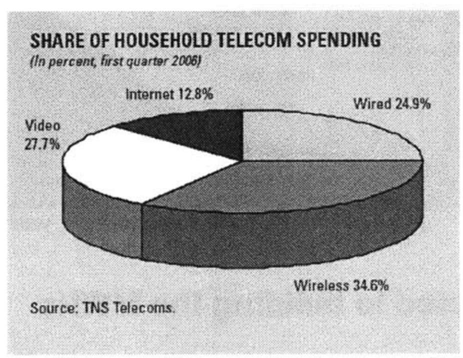


Figure 30 Share of household telecom spending[24]

If we assume that the spending is about $100 for the whole telecom services and the number of the telecom-served households in the US is 50 million, then annual revenue is $60 billion. The amount of money involved in the industry is huge and such if there is a new proposition, an economical analysis must be performed to see feasibility.

In order to do that, we will estimate cash flows for the municipal network (assuming eventually these networks will end up being For-Profit). We will also estimate the cost of building out these networks in various configurations.

[24] "Industry Surveys: Telecommunications: Wireline" Standard & Poor's, August 24, 2006.

4.1 Cash flow and investment analysis (NPV etc.)

In this section we will analyze the rollout economics of the municipal wireless mesh networks. In order to do that, the expected service pricing of the various services expected to be offered over these networks. Also, service penetration is also assessed through use of the technology diffusion theory developed by Bass [Sterman] and [Bass94/95]. This will give a attempt to predict the take rate of this service which will determine the cash flow. Note that the services provided to the public safety and other official use of the network will not be included in the analysis. It is assumed they will be folded as part of the business users.

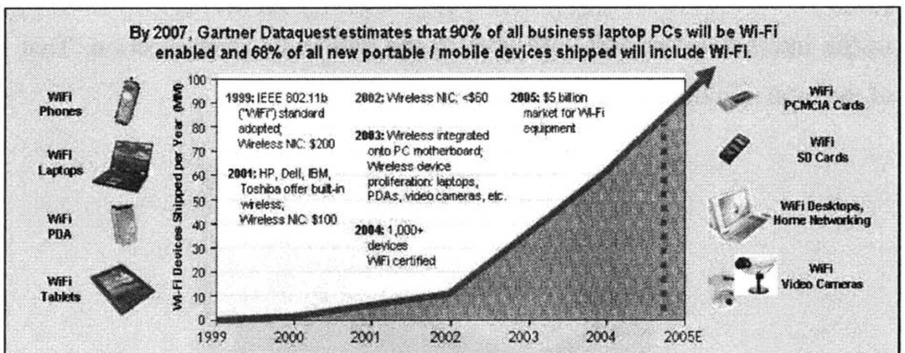


Figure 31 WiFi devices shipped per year[25]

4.1.1 Costs related to building the MWNs

In this section will analyze all the activities the municipalities or the franchised Wireless Internet Service Provider (WISP). There are fixed cost associate in building out these networks. There are also variable costs required for network operation. The cost estimates are based on interviews conducted with individuals who were officially part of actual deployment and vendor representatives attending the WiMAX World Exhibition took place in Boston from 10 to 12 of October 2006.

The following figure shows the components of the networks. These components incur fixed cost during the build-up and a variable cost for operation.

[25] http://www.wcai.com/pdf/2005/briefOct25_earthlink.pdf

Mudhafar Hassan-Ali© (2006).

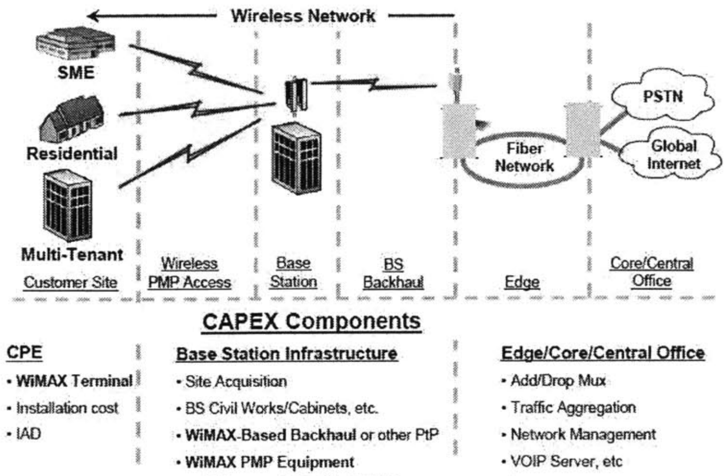


Figure 32 CAPEX components

AP associated cost

The Access Points are the outdoor wireless mesh gateways which are to be installed outdoor around the municipality area. There are a number of elements that determines the cost associate with an AP:

Table 16 AP associate costs

AP	For single radio: $200 to $500
	For multi radio: $1,000 to $3,500
Advanced antenna (MIMO)	Additional 15% to 30% in addition to the base AP cost
Installation	$500 to $1,000
Licensed spectrum cost (for backhaul only)	From $1 to $4 per subscriber
Location rental	Usually free, if not $1,000 per year.

The cost of a APs or a Basestation (see the following section) is a function of the number channels, the number of sectors, and whether it is equipped with advanced antenna such as MIMO. The following table illustrates the impact of equipping the Base or AP with MIMO in terms of bandwidth and cost.

Table 17 Cost factors in using MIMO systems[26]

BTS	Total Relative Cost	Capacity MB (payload)	Relative Cost/b/s
SISO	1.0	25	0.04
AAS 4x1	2.8	33	0.08
AAS 8x1	2.6	38	0.07
2 x MIMO	1.3	50	0.03
4 x MIMO	2.3	100	0.02

Note that AAS stands for Advanced Antenna System, which is a different technology from MIMO. The former attempts to concentrate the radiated power in a narrow direction (thus high gain an low interference), whereas the latter attempts to create multiple virtual radio links in the same spectrum (bandwidth gain).

Basestation assocoited cost

This cost is incurred only the backhaul from APs to the WISP backbone is done wirelessly. In which case, the basestation could be either WiFi based or WiMAX.

Table 18 Basestation associate costs

Basestation		$25,000 to $50,000 (for 4 channels)
Advanced antenna (MIMO)		Additional 15% to 30% in addition to the base AP cost
Installation		$5,000 to $10,000
Licensed spectrum cost (for backhaul only)		From $1 to $4 per subscriber
Location rental		$1,000 to $10,000 per year.
Tower (if owned)	Site preparation	$10,000 to $50,000
	Construction	$100,000 to $300,000
Annual OPEX		12% to 24% of the total CAPEX

Note that, the tower cost is included if the operator owns the tower. However, most of the operators do not own the towers where the antennas and basestations are placed. Instead, there are specialized companies in building and operating the cellular towers. The dominant name in this business is American Tower, which claims to have 22,000 in the

[26] http://www.nortel.com/solutions/wimax/collateral/nn118160.pdf

US[27]. The tower operators then lease space on their towers to the wireless operators. The cost of the tower depends on the size (hence the height) of the tower. In [Salema][28], the cost is expressed in the following formula (as estimated in the 90s)

$$C_{Tower} = \begin{cases} 4000 & for \;\; 10 \le h \le 30 \\ 22500 & for \;\; 30 \le h \le 80 \end{cases}$$

Where C_{Tower} is the cost of tower in $ and h is the tower height and measured in meters.

The Operation Cost (OPEX) per month is estimated to be around 1% to 2% of the total Capital Expenditure (CAPEX)[29].

CPE associate cost

The Customer Premise Equipment (CPE) is the point of entry of the wireless service to the fixed users (residential or business). There are two models that have noticed in the market:

- The operator will provide the CPE free charge or at a discounted rate
- The consumer will buy these devices from the electronics stores.

In all cases, the CPE cost varies depending on the application the end user wishes to achieve. For simple Internet connectivity, usually CPE will cost less. On the other hand, for business users, the CPE usually provides more than just Internet connectivity, and thus cost more.

Spectrum cost

In the US, since 1993, the radio spectrum used for wireless applications (such cellular telephony) has been auctioned by the FCC for the operators (or any interested parties for that matter) to bid. Billion of dollars of revenue this process has generated to the Federal government. Since it is licensed through auctions, the chunk of spectrum used in New York, for example, worth more than somewhere in the wilderness of Idaho! It is

[27] http://www.americantower.com/OasisPublic/Mappoint/default.asp
[28] Carlos Salema, "Microwave Radio Links, from theory to design", Wiley, 2003.
[29] Chuck Jackson: private conversation, August 2006. http://www.jac4ksons.net/

therefore, the spectrum cost varies from area to area. However, the following table shows the average cost of 1MHz of spectrum per population.

Table 19 Spectrum license cost per user[30]

	1997	1999	2001	2003	2004
Cost / MHz Pop	$.33	$1.20	$3.55	$1.35	$1.43

In the same report, it was also indicated for example that the spectrum cost is about $4.30 per MHz per Population.

This is cost is incurred only when a license spectrum is used. This is may be need for the wireless mesh backbone, since it will ensure more reliable and higher throughput than unlicensed channels.

Backhaul connection cost

There two main ways for the APs to be connected to the telecommunication infrastructure; either via wireline links or via wireless (microwave) links. In the former, depending on the network planning, selected APs (to be gateways) will be connected via an Ethernet link (Fast Ethernet 100BastT or fiber Gigbit 1000BaseSx). This link is usually connected to the operator wireline network or to a carrier network. The cost for this link varies based on the type and the amount of bandwidth. The expected cost is in the range of $12,000 to $18,000 per year.

On the other hand, for places, where there is no wireline infrastructure that provides Ethernet (such as rural areas), the alternative will be wireless link provided by a third party operator. This is more expensive and it ranges from $25,000 to $50,000.

4.1.2 Service pricing

The following bar chart illustrates the monthly revenue per subscriber attained by a telecom provider. This chart is published by Nortel.

[30] http://www.alohapartners.net/pdf/WhitePaper.pdf

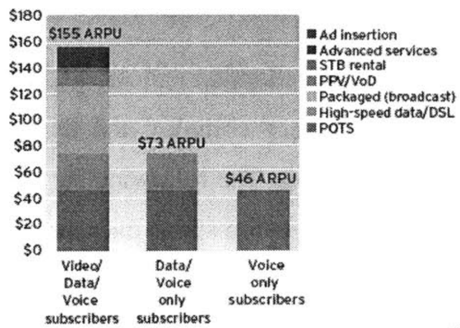


Figure 33 ARPU for teleco service bundles[31]

It is clear that Internet generates ARPU of about 73-46 = $27. However, in order to make the WMNs competitive given its unreliability of the WMNs, the charges must be significantly less. Same applies to the other applications.

For fixed users (residential or business), billing and pricing will follow the current schemes adopted by the incumbent operators (cable, telecom, and cellular). However, we believe the flat rate will be the dominant scheme, which is why cellular users will prefer the use of WiFi cell phones over a 3G cell phone (per month minute limit).

The ARPU is split among the stakeholders in the value chain. For example, the broadband Internet access alone could be $40, where the breakdown of how much each one stakeholder gets is shown in the following figure.

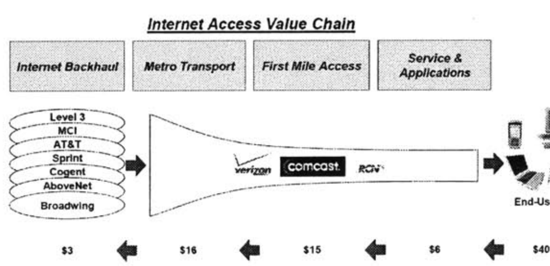


Figure 34 Internet Access value chain payoff[32]

As can be seen, if the First mile access and the metro transport can decrease through the support of the municipality, the internet access can be offered for about $15.

[31] http://products.nortel.com/go/solution_content.jsp?parId=0&segId=0&catId=I&prod_id=54980&locale=en-US#

[32] "Wireless in Boston, Wireless Task Force Report, Broadband for Boston", City of Boston, July 31, 2006.

4.1.3 Service adoption

It is always very difficult to forecast adoption and demand of new service or technology, simply because the ecosystem is very complex and dynamic. However, it is always performed never mind how flawed it is. The following bar chart shows a forecast for how much the US municipalities are expected to spend over the next few years.

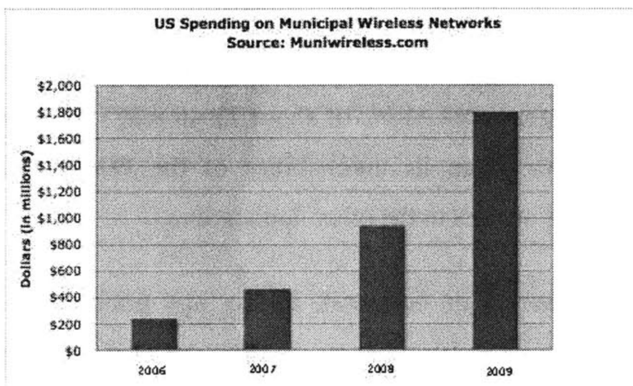


Figure 35 US spending on Municipal expenditure forecast[33]

This year (2006), for example, there are 50 municipal networks built out as seen in Table 20 below, where the average cost is around $4 million. This totals up to $200 million spent this year.

Table 20 Municipal deployments of wireless networks[34]

	Jul-05	Feb-06	Apr-06	Jun-06	Sep-06
Region/City	38	56	58	59	68
City hotzones	22	29	32	32	43
Municipal or public Safety use only	28	32	35	35	35
Planned deployments	34	59	69	121	135
Total	122	176	194	247	281

Given the rate of rollout, the forecast is the expenditure will be around $2 billion is 2009 (equivalent to 500 networks to be build by then). However, we would like to use the diffusion theory developed by Bass[35] for technology adoption given the recorded

[33] http://muniwireless.com/municipal/1431
[34] http://www.muniwireless.com/reports/docs/Sept-10-2006summary.pdf
[35]

adoption as seen in Table 20. The model is implemented in System Dynamic simulation tool called Vensim as seen in Figure 36. There the following parameters:

- Total population (N) represents the total number of municipalities in the US (about 25,000).
- Adoption fraction (i) represents the asymptotic adoption (over very long time).
- Initial contact rate is rate at which active adopters come into contact with potential adopters in the beginning (we assume to be 20%).
- Advertising Effectiveness (a) represents adoption due to adds (we assume to be 1%, meaning 1% of the municipalities that do not have wireless broadband will end up deploying it in that year.).

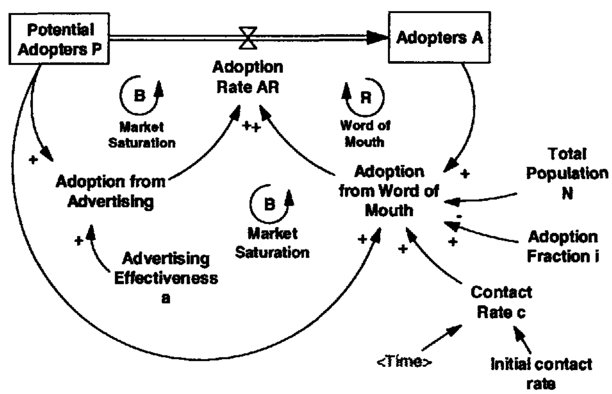


Figure 36 Bass Model for Adoption (a=0.01, initial contact rate = 0.2)

The assumed model parameters are chosen so as to best fit the available data in Table 20. After running the simulation, the diffusion behavior was obtained as see in Figure 36. It is curve is definitely an S curve. It starts in 2005 and ends in 2016 and has the inflection point (half the municipalities should wireless broadband) between 2010 and 2011.

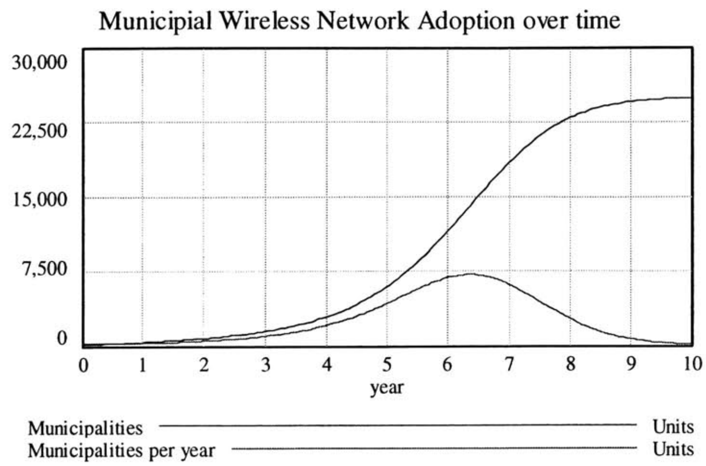


Figure 37 Adoption over time

We will use this model (the S curve) in estimating the cash flow in the next section.

4.1.4 Cash flow estimation

In order to estimate the cash flow, we need to build a deployment models in which the fixed and variable cost can be estimated. Also, using the adoption model discussed in the previous will help estimate the revenue generated over time. When this is done, we will have a net income (cash flow) per year, from which the net present value (NPV) for the cash flow for each deployment scenario. For this we need a discount rate (r), which is assumed to be 12%. This will assist us in evaluating:

- The economical feasibility of deploying the municipal wireless broadband;
- Which scenario could more economical and thus should be adopted.

We will the information about system cost presented in section 4.1.1 and the ARPU introduced in section 4.1.2 ; i.e.

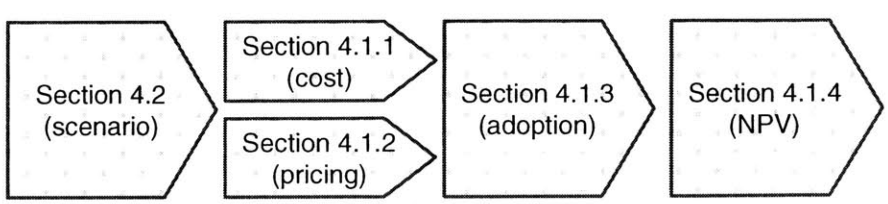


Figure 38 Cash flow estimation process

From the sections above, we concluded the following items ant their costs that will be used in the building the cash flow.

Table 21 Deployment items and their costs (in US $)

	Low	High
Site rental	1,000	**10,000**
Site prep	**50,000**	100,000
Tower construction	**100,000**	300,000
AP Installation	**500**	1,000
BS installation	5,000	**10,000**
Annual OPEX (% of Total CAPAX)	12	24
Backbone connection Fiber	**12,000**	18,000
Backbone connection MW	25,000	**50,000**
AP Single radio	200	500
AP Multiple radio	1,500	3,500
BS (WiMAX)	25,000	50,000
CPE cost	**200**	500
CPE subsidies %	**60**	80
MIMO cost (% AP or BS)	**15**	**30**
Spectrum cost (/MHz.POP)	1	4
Spectrum cost (/MHz.Sq M)	1,000	10,000

Note that the highlighted entries in this table are the one used in the following scenarios.

4.2 Scenarios

In this section we will estimate the cash flow for various deployment scenarios in an attempt to find the revenue maximizer. We will assume parameters for a fictitious deployment to be a representative for a typical municipality in the US:

Table 22 Deployment parameters

AP/sq m	20
Area (sq mile)	50
BS coverage (sq mile)	10
AP	1000
APs per BH connection	30
Discount rate	0.12
HH / sq mile	1000
Total HH	20000
PP/ HH	3

Also, we will assume that the cost of equipment will decrease over time (following a learning curve that is an inverse S curve).

Table 23 Learning curve (reduction of equipment cost over time)

100	95	90	80	65	50	40	35	30	30
year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10

We assume an adoption pattern along with the ARPU that has also an S curve as in the following table:

Table 24 Adoption and ARPU

	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10
Take rate %	10	15	20	25	28	30	32	34	35	35
Moth Charge / sub	15	15	20	20	20	25	25	25	25	30

Note that we assume that the ARPU will increase over time because more services will be offered over these networks, which creates more opportunities for more revenue. Also note that the maximum take rate over a period of 10 years is 30% of the whole population of this fictitious municipality, leaving 70% shared by cable and DSL/PON users.

4.2.1 Pure mesh (no towers)

In this deployment (similar to Brookline' project), a number of APs connected with each other via the mesh protocol but one AP will be selected as a gateway to be connected to the core network via wireline link (Fast Ethernet or GE). This deployment fits well in the urban and dense areas. The following capture the cash flow.

Table 25 Pure mesh

	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10
Cash Flow	-2505000	-161000	285000	577000	830200	1369000	1533800	1676200	1765800	2193000
NPV	2332855.289	5418398	6248926	6679597	6834908	6725273	5999026	5001053	3723836	2193000
Cumulative NPV	-2805600	-2966600	-2681600	-2104600	-1274400	94600	1628400	3304600	5070400	7263400

4.2.2 Microcellular mesh

In this deployment (similar to Mountain View' project), the gateway are capable of communicating with basestations over wireless links. The basestation are placed on buildings and not on towers (as in the Macrocellular case). Also, the basestation can be viewed as higher performance AP. These basestations are connected to the core network via wireline links (GE). This is good for suburban areas. The following table shows the cash flow.

Table 26 Microcellular mesh

	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10
Cash Flow	-2308750	162000	591000	849000	1051200	1539000	1669800	1795200	1867800	2295000
NPV	3692665.462	6721585	7346736	7566424	7523515	7248992	6395192	5292439	3916907	2295000
Cumulative NPV	-2585800	-2423800	-1832800	-983800	67400	1606400	3276200	5071400	6939200	9234200

4.2.3 Macrocellular mesh

This is similar to the previous case (microcellular mesh), however, the basestations (or at least their antennas) are placed on cellular tower (for farther reach). This model is good for rural deployment.

Table 27 Macrocellular mesh

	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10
Cash Flow	-2552500	106125	532125	784125	977325	1456125	1580925	1703325	1772925	2200125
NPV	3052823.415	6277962	6912458	7145973	7125269	6885698	6081121	5040220	3737322	2200125
Cumulative NPV	-2858800	-2752675	-2220550	-1436425	-459100	997025	2577950	4281275	6054200	8254325

4.2.4 Macrocellular WiMAX (direct basestation to user)

As a complete alternative to mesh (going back to pure cellular architecture), here we will investigate the cash flow where the communication between end user and the network goes directly to the basestation and municipal APs in between. In this deployment, technology like WiMAX will fit well and it fits all sort of topographical areas depending on the applications that will be offered.

However, there are two options the operator could consider: one where the tower is leased (most likely), and another where the operator owns the tower (seldom). The following table shows the cash flow for the first option.

Table 28 Macrocellular WiMAX model (lease tower)

	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10
Cash Flow	-1800000	-407875	52125	372125	844125	1452125	1604125	1740125	1864125	2332125
NPV	2696402.572	5035971	6097107	6770380	7166046	7080551	6303838	5263678	3946379	2332125
Cumulative NPV	-2016000	-2423875	-2371750	-1999625	-1155500	296625	1900750	3640875	5505000	7837125

The following table shows the class flow for the second option.

Table 29 Macrocellular WiMAX model (own tower)

	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10
Cash Flow	-1775000	-332875	127125	447125	919125	1527125	1679125	1815125	1939125	2407125
NPV	3121021.306	5483544	6514389	7153736	7511404	7383353	6558975	5465432	4088344	2407125
Cumulative NPV	-1988000	-2320875	-2193750	-1746625	-827500	699625	2378750	4193875	6133000	8540125

It is interesting to note that the owning a tower seems more beneficial than leasing it. This because that the tower is small and thus cost about $100,000. However, if the tower is large, it is likely leasing a tower would be more beneficial. Also we assume that the spectrum is license-exempt (no cost assumed) and the MIMO cost is 30% of the BS cost.

4.2.5 Comparison

The following chart shows the cumulative NPV for the cash flow expected for our fictitious municipality.

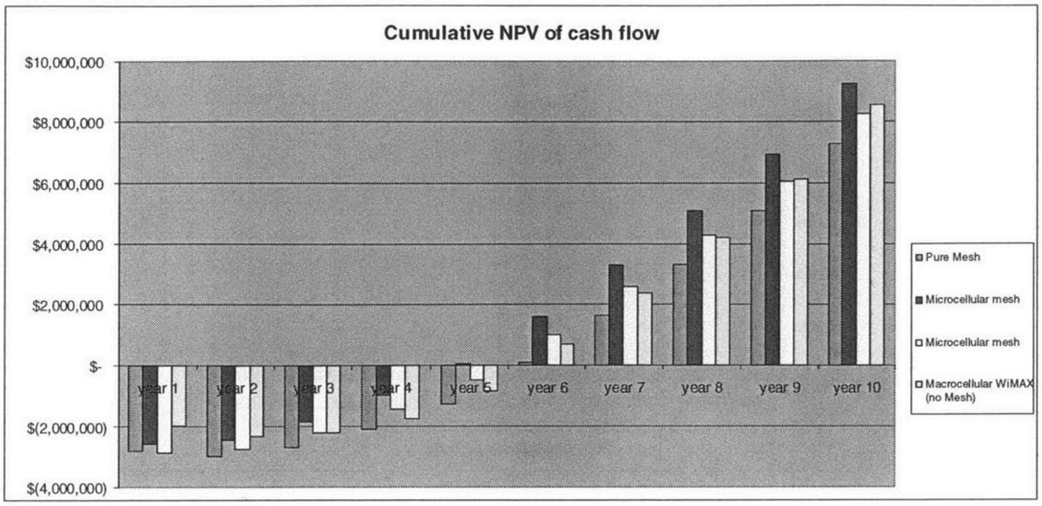


Figure 39 Cumulative NPV of cash flow for four scenarios

The conclusion from this chart is that the microcellular mesh provides the most income; i.e. the most profitable. The following chart provides the total cash NPV for each one of the four different deployment scenarios.

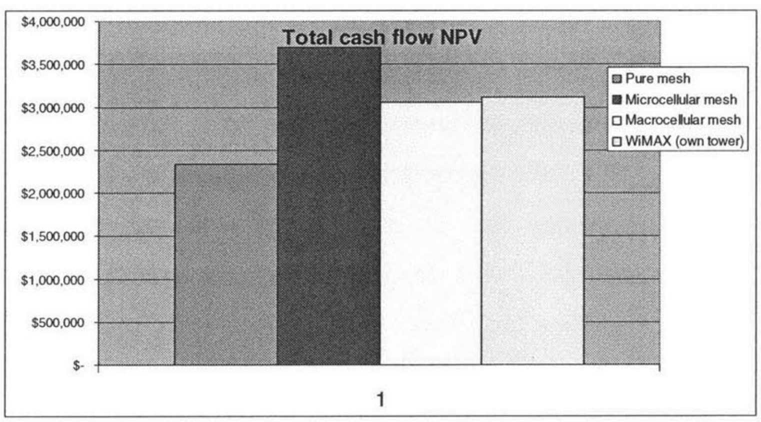


Figure 40 Total cash flow NPV

However, this may not be sufficient to determine the profitability (PI) for the various deployment scenarios. The following chart captures the PI calculated (cumulative profit NPV/ cumulative cost NPV) for each scenario over the time horizon of 10 years. Still the Microcellular mesh deployment is more profitable.

Mudhafar Hassan-Ali© (2006).

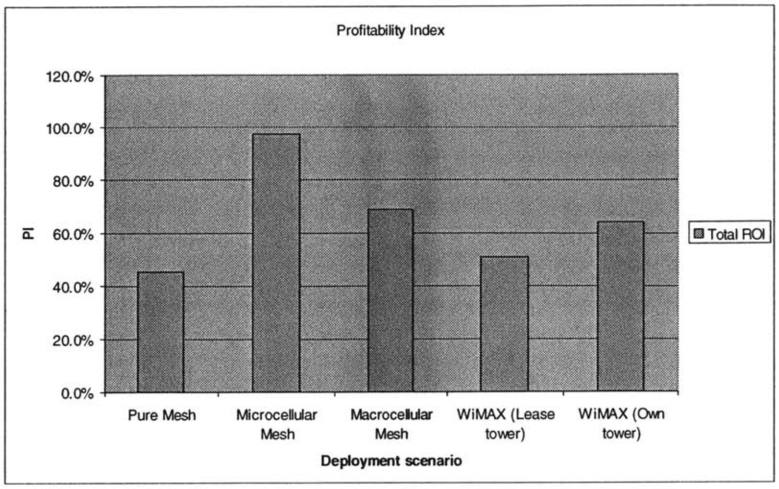


Figure 41 PI for various deployment scenarios

4.3 Platform assessment

With the economical analyses carried out in this chapter, the last metric is evaluated as follows:

Metric	Assessment	Score
Cost effectiveness	Since this platform is based on WiFi, the economy of scale will make the equipment very cheap, and since it uses mesh topology (pay as you go), this cost of deploying these networks will be more cost effective than cellular or wireline broadband. The upfront cost of one potential user is less than $350. In this case of PON, at the moment this is at least 3 times[36].	H

[36] Bob Mudge, "Transforming the Network & Creating a Unique Service Experience" in Verizon FiOS Briefing Session, September 27, 2006. http://investor.verizon.com/news/20060927/20060927.pdf

Chapter 5
Competitive analysis

In the previous chapters, the municipal wireless network deployments were analyzed in technological, operational, and economical contexts. In this chapter we will attempt to complete the analysis but in the competition context. In order to do that, we will look at the dynamics of the other players in this market along with their technological and strategic tools.

5.1 Competitiveness of the wireless mesh networks

In this section, we will follow the framework developed by Michael Porter of HBS, where he identified five forces that shape the competitiveness landscape of an industry [59]. We will apply that framework to the Telecom industry in general and Municipal Wireless Mesh networks in particular.

First, the following figure depicts these forces and how they are related in Porter's framework.

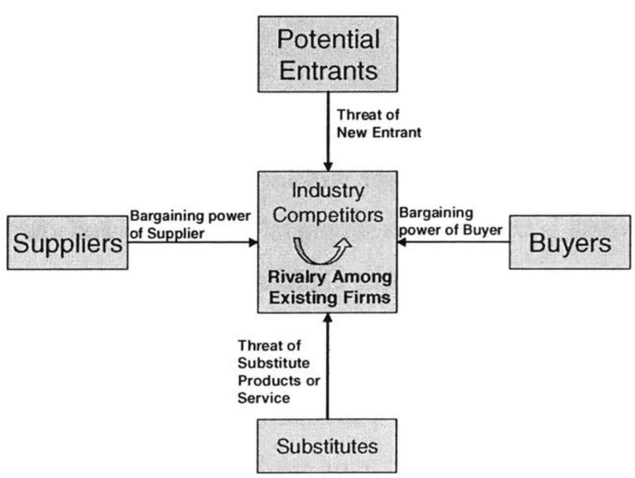


Figure 42 Porter's Five Forces of Competitiveness [59]

According to this figure, the five forces are: 1) The industry rivalry; 2) Potential entrants; 3) Substitutes; 4) Bargaining power of the suppliers; and 5) The bargaining power of buyers.

The competitive position of the Municipal wireless mesh networks in the Broadband Telecom industry will be analyzed according to this framework as follows. The center of Figure 47 represents the current Telecom (wireline and wireless) industry from the service operators' perspective. The wireless mesh networks, on the other hand, can be considered a "Substitute", since it competes with the incumbents sectors, such as DSL, Cable, and 3GPP. In this environment, the wireless mesh networks are touted to offer cheap broadband connectivity. If the mesh succeeds in attracting consumers, it is likely that the profitability of the Telecom incumbents will erode significantly.

At the moment, the market is highly fragmented and there are a number of players but with very small revenue, so the rivalry is very high. However, if the wireless mesh penetrates the broadband market significantly, the FCC regulation[37] could limit the rivalry by allowing a few operators to dominate the network deployment. This may not be the case if the cognitive radio proves to be a viable technology; where coexistent of multiple operators in the same geographical area is feasible. The rivalry in this case could become extremely fierce, thus driving the prices down. At the same time, the ubiquity of cheap wireless mesh service will ignite an explosion in developing new services that will generate more revenues.

Since the buyers (broadband users) will have more options to choose from to access the Internet, the buyers' bargaining power will increase resulting in service price reduction. However, the reverse is true with the suppliers' (equipment and chip vendors) bargaining power; i.e. the operators will have more choices resulting in equipment price reduction.

To sum it up, without an MSO-like status, the wireless mesh operators will have tough time fighting each other. When the penetration of this technology becomes high, both service and equipment prices will decrease while the number of service will increase.

[37] Similar to the CATV MSO franchising regulation.

5.2 Municipal Wireless Mesh outlook

So far, we have painted a rosy picture for the municipal wireless mesh networks. The reason is that the momentum is growing across the country for cities, towns, and villages to lay out their own broadband networks. At least rhetorically, for all good reasons: bridge the digital divide; help spread broadband in disadvantaged areas (due to poverty or due to being rural), and to also help make the government more efficient. The latter became important after the September 11 terrorist attacks; which fueled the desire by the government in strengthening the public safety and security. However, there are uncertainty elements that could play against the prospect of these networks' spread in the US, which are:

- There are doubts in the business community (thus affecting the political community) on whether the municipalities could run these projects. Their reasons are the municipality does not have the resources (technical and financial) to be able to get into this field. This argument has been voiced by the wireline and wireless incumbent operators. Even Sprint and Clearwire, who have spectrum for WiMAX, resent the idea of having municipalities compete with them[38].
- There seems to be a rush in deploying these networks without enough understanding about the maturity of the deployed technology or the right business model.
- In order to make these networks useful, it is not all clear how these networks could be interconnected and interoperated with each other.
- Since the current technology (WiFi) will likely be displaced with a more superior technology (such as WiMAX), it is not clear how the already deployed network could be upgraded.
- When the bandwidth demand is increased over time, it is not clear whether the FCC will allocate specialized spectrum for these networks. Otherwise, if they use licensed spectrum, the cost will be increasing, thus making it too expensive.

[38] Niel Random, private correspondence, December 8, 2006.

Due to these uncertainties, there are legislations and bills getting adopted in the at lease 19 states to define, restrict, or eliminate municipalities' ability to provide wireless Internet services[39]. Many of these bills require municipalities to undertake feasibility studies, long term cost-benefit analyses, public hearings, or referendums. On the other hand, the Federal bills would, variously, preempt state laws prohibiting municipal wireless Internet provision; define how municipalities may go about implementing wireless Internet networks; or prohibiting municipal wireless Internet provision altogether.

The recommendation therefore is to study the whole project and its financial feasibility. For example, in an analysis performed by "Jupiter Research", the breakeven monthly charges showed the difficulty in rolling out these networks. In dense areas, this can be competitive enough. However in spread-out areas, this can prove tricky (too high to be viable). However, the municipalities must then subsidize these areas (rural specifically). The following figure shows the break-even monthly charges for various municipalities in the US.

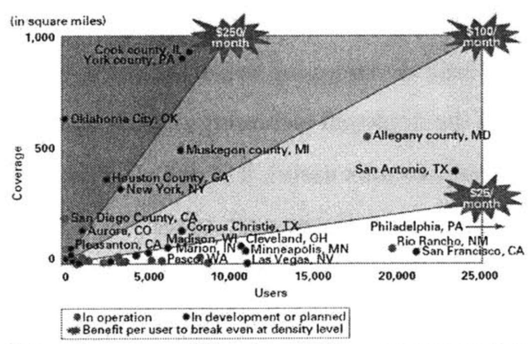


Figure 43 breakeven monthly charges for various municipalities[40]

5.3 Disruption and competition

[39] "Municipal provision of Wireless Internet", Federal Trade Commission (FTC), September 2006.

[40] "Municipal Wireless" Jupiter Research, MRS05-V02, 2005.

In this section will lay out our theory about the wireless mesh networks and how it may disrupt the market of other technologies. As an access platform, the mesh networks will be used for following applications:

1. Basic Internet connectivity to residential or mobile users. The bandwidth required for this application is 100Kbps average and 1Mbps peak.
2. Voice over WiFi (VoWiFi) access
3. Law enforcement hot lines access
4. Public safety network connectivity

In summary this technology is meant for a broadband basic connectivity, i.e. not suitable for triple-play services at least within the current technical capabilities.

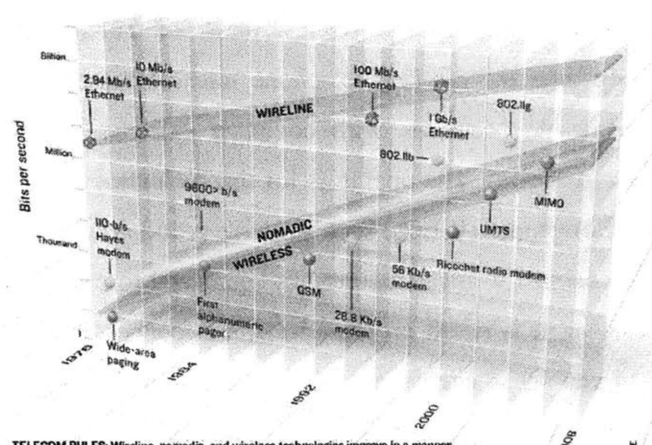
On the other hand the other technologies in this domain are:

1. xDSL: It has two main flavors (ADSL and VDSL). It can provide 20Mbps within a reach of 3Kft and 1Mbps over a reach of 18Kft. This is point-to-point connectivity over the existing telephone line. This technology is positioned to provide triple-play services with coverage can reach 80 to 90% of the all households in the US. The operators for this technology are the Incumbent Local Exchange Companies (ILECs) such as Verizon and AT&T.
2. Cable: The cable-TV infrastructure has been used to provide broadband signal to end customers. It is based on shared-medium concept (point-to-multipoint). The bandwidth can be in excess of several 10s of Mbps along with broadcast TV. Recently telephone has also been offered; i.e. true triple-play offering. The coverage is about 70% of the households in the US. The cable is operated by the MultiService Operators (MSOs), such as Comcast.
3. PON: Recently the major operator in the US (Verizon) has started to connected the subscriber to their fiber network; i.e. Fiber To The Home (FTTH). The technology used for this deployment is Passive Optical Network (PON). The idea here is to provide a future-proof broadband connectivity that could carry multiple Gbps to each subscriber. This technology will make the triple-play reality.

However, due to the cost of deploying it to every household, the coverage could be 50% at beast in the near future (in 5 years).

4. Mobile telephony (e.g. 3G): This is an evolution of the current cellular telephony available for use to every one. The topology is based on centralized radio base stations (BS) that provide connectivity to the end users. The main use is for basic mobile telephony with multimedia applications are also pick up. However, the bit rates are not as much as with the previous technologies.

Using WiFi, the Mesh Networks will not be the right technology to provide the end users with bandwidth enough for true-triple play (voice, Internet, and video). Hence, it will not be a real threat to xDSL, Cable, and PON. Actually it will complement them in areas where the broadband is not possible; i.e. leaving some room for wireless mesh to be used specially in developing countries where DSL and Cable are not prevalent. Figure 44 shows the evolution of the achievable rates over both wireline and wireless technologies.



TELECOM RULES: Wireline, nomadic, and wireless technologies improve in a manner reminiscent of Moore's Law. Soon, even slower communications channels like cellphones and radio modems will eclipse the capacity of early Ethernet, thanks to upcoming standards known as UMTS and MIMO, which will boost bandwidth by maximizing antenna usage. [Time axis shows dates of first use.]

Figure 44 Edholm's law of bandwidth[41]

In this figure, the trend of the wireless improvement is faster the wireline. As such it possible sometime in the future, wireless will offer equivalent performance (in terms of

[41] Edholm's law of bandwidth, Steven Cherry, IEEE Spectrum, July 2004.

bandwidth) to the end user. According to Christensen's theory, that is when wireless takes over. This trend is happening in stages, where waves of competing technologies are formed, as depicted in Figure 45. Municipal wireless broadband is shown in the middle of this figure.

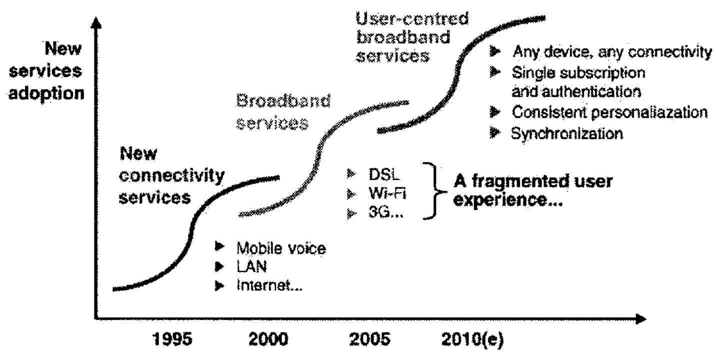


Figure 45 Connectivity evolution [55]

Since the trend is to integrate WiFi transceivers in the mobile sets, VoWiFi could turn into a real threat to Mobile telephony. If Wireless Mesh networks get deployed ubiquitously, then the licensed cellular telephony could be taken over by the wireless connectivity offered by the Mesh networks. This is especially true if the FCC allocates more unlicensed bandwidth (according to the new NRPM) that will make Wireless Mesh more reliable and faster. Also, more adoption of the Municipal networks by the local governments will make these networks available in downtowns. For low end broadband subscribers (basic Internet access), the wireless mesh networks could pose a threat to DSL cable if the service is significantly cheaper (or free) than what is charge with these technologies. The municipal wireless broadband is touted to have a month charge of less than $15 per month for basic Internet connectivity.

According to Clay Christensen's definition of Disruptive technologies, Mesh Networks characteristics can be assessed according to various applications in order to draw a more general conclusion. The following table shows the characteristic attributes of this technology along with the possible applications.

Table 30 Network attributes as a Disruptive Technology

Application (vs DSL or Cable)	**Cost**	**Performance**	**Ancillary features**
Real triple play	↑	↓	↓
VoWiFi	↓	↓	↑
Municipal Internet	↓	↓	↑
Public safety	↓	↑	↑

In this table, we can observe that wireless mesh in VoWiFi or Public safety could disrupt the cellular telephony. Furthermore, municipal Internet could disrupt the incumbent broadband technologies (DSL/Cable) if they are used only for basic Internet access.

This will create a backlash from the Incumbents (wireless and wireline). Two scenarios are possible:

- Price and feature-offering wars will start[42].
- The incumbent will use their clout to stop it by pushing the politician to issue regulations against municipal wireless.

It is therefore crucial for the municipalities to position their effort as ancillary to the whole broadband offerings and not a threat. For thing, the main drivers are to use it for public safety and for municipal operation.

5.4 Market segmentation

As discussed in section 3.3.3 , at the moment there are two mainstreams in the market of municipal wireless: Non-Profit and For-Profit. The first one indicates that the municipality will be in charge of the finance and operation of the network. The second one, on the other hand, dictates that the operation and partial finance are outsourced to For-Profit firm(s). It is interesting to note that at the moment the Non-Profit model is

[42] If the incumbents see that they are losing the battle, they may opt to jump in the band wagon and work with municipalities.

predominant, however, with time it is shifting to For-Profit. This is a typical adoption behavior, where the Non-Profit organizations (the local governments of municipalities) are considered to be Visionaries in Moore's "Crossing the Chasm" market evolution model. Those municipalities (as in Mountain View, Corpus Christi, etc.) are accepting an "immature" technology (WiFi) and deploying it. As the market proves its viability, more and more the Pragmatist (in Moore's model context) will enter the market. Her Pragmatists are the more conservative municipalities and telecom operators. This year (2006) has showed clear signs that the "Chasm" is getting crossed when Earthlink (as wireless operator) and Google (as Internet service provider) jointly enter for bids in San Francisco's (and elsewhere) WiFi. By 2010, we anticipate that the "Tornedo" (again in Moore's model context) will happen (as we saw that in Bass's adoption model discussed in section 4.1.3 . The following figure shows Moore's model as it relates to the municipal wireless market.

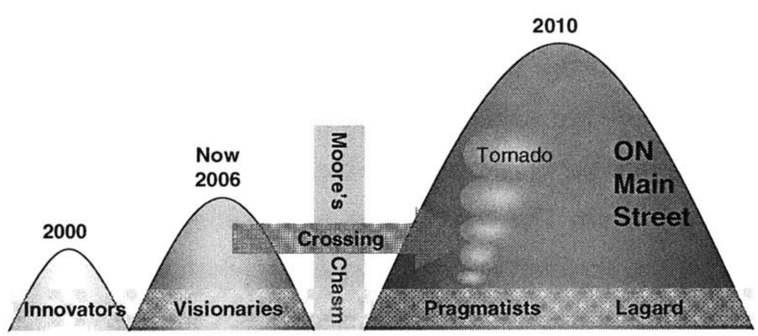


Figure 46 Moore's market model for municipal wireless

What we discussed is the adoption of the municipalities to the wireless mesh broadband. However, the adoption of the services offer by the municipal wireless broadband is dictated by the end user decision. The following chart why some users did not consider subscribing in the existing broadband. Form this chart we can see that there is the perception that the existing broadband services are just too expensive or not available.

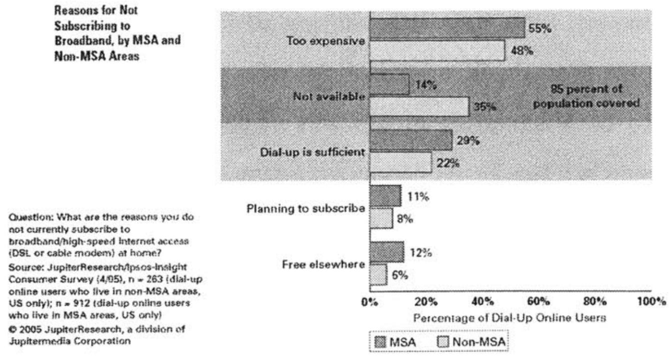


Figure 47 Survey results for why not subscribing in broadband[43]

It is therefore, therefore, these users will be attracted by the lower monthly charge. Additionally, the broadband is in the Tornado phase and move toward to "On Main street" (again in Moore's model context).

Given this adoption pattern, we believe that the main markets for these networks are:

1. **Mobile business**: In this market, business people traveling from one place to the other would like to have a ubiquitous wireless broadband to access their home office. The currently available services are too expensive (more than $75).
2. **Municipal operation**: This encompasses a suite of applications that municipalities would like utilize these network for. Typical applications are: public safety, meter reading, real estate inspection, education, and traffic control to name a few.
3. **Fixed business**: Many businesses would like to have broadband connectivity as cheap as possible. Also, they would like to send data, voice, as well as video conferencing over broadband.
4. **Advertisement business**: Perhaps this is the main driver for service provider (such as Google) to be involve in the municipal wireless bids (such as San Francisco's). For reduce (or even free) monthly charge, their clients (be it national or local such as restaurant or stores advertising for promotional offers).
5. **Residential users**: This is the typical residential Internet (maybe bundled with VoWiFi) with portability and even mobility.

[43] "Municipal Wireless" Jupiter Research, MRS05-V02, 2005. MSA: Metropolitan Statistical Areas

The market segments will be either new (such as Municipal operation or Advertisement) or competing with existing markets (such as Mobile business, Fixed business, and Residential users).

Chapter 6
Conclusions

6.1 Concluding remarks

The question that this thesis tries to answer is: can the municipal wireless mesh network be a competitive broadband platform? We tried to answer this question through multiple stages. One of which was articulated by choosing a set of metrics that will help assess any telecom platform, in our case it is the wireless mesh network. Also, we tried to analyze the platform from technical, business, regulation, and economical perspective. The results of these analyses are summarized as follows:

6.1.1 Metric-based assessment

Due to the lack of a standard and well adopted set of metrics for evaluating a telecom platform, we proposed a metric set in an attempt to fill this gap. The metrics contains a number of dimensions that are interesting to the telecom professionals as well users. That includes operational, business, and regulatory elements. For each chapter we identify the metrics relevant to the topic and the content from which we derive an assessment as well as rough score (High, Medium, or Low). The over all assessment is 5 for H, 4 for M and 2 for L. If all every metric is has the same weight, the score is **M+**, indicating that this platform is competitive enough that will cause significant changes in the telecom arena.

6.1.2 Deployment assessment

The evidence shows that there is a momentum picked up by many municipalities in the US. This moment will encourage more cities and towns to come on board and start thinking about their wireless network. However, it is just the beginning of the deployment and as such everybody is trying to learn how to do a better job. The quality of the networks is very much questionable, particularly the technology used in them are a modified version of a technology originally meant for indoor applications. A lot of issues such as roaming and quality of service are not well tested and verified. Furthermore, the market is also under development, and as such it is not clear whether the stakeholders could sustain their business in this environment and whether the services will meet the end users' demand. A more critical issue is regulation and legislation, where the battle between promoters and demoters of allowing municipalities to get involved in deploying these networks. However, the whole world is getting more advanced with respect to broadband but the US is lagging behind, which will assist the promoters in their argument. At least, the municipalities can build their own network for their operation, well justifiable though very expensive (costing tax payer dollars).

6.2 Recommendations

Throughout the course of studying this topic, there are a number of recommendations that we would like to offer to the stakeholders of the municipal wireless broadband.

1. It is critical to define the business model that shows that very little tax payer money is involved in building out these networks and the beneficiaries are the people of the municipality as well as the local business. This will help win the political battle with incumbents. We believe that the franchise or wholesale (to lesser extent) are the best business model.
2. The equipment vendors should build cost effective solution (and to be proven to be cheaper than other technologies). This will enhance the chance for the Tornado to happen.
3. Making sure the enough bandwidth and sufficient coverage are crucial for creating confidence in the services to the end user. If it is best effort, then near-free service should be sought. People do not tolerate for getting bad services if they pay money. Word of mouth could ruin the reputation of these networks.
4. It is recommended to phase the deployment in a number of stages so that pay as you go. However, it is important to deploy equipment that has modifiable output power

and to have advanced antenna system (such as MIMO). When the network sparse, the operator can dial up the power and activate the advanced features of the antenna.

5. Along the same line of better engineering, it important for the municipalities and all the stakeholders (such as operators, etc.) to lobby for the FCC to allocate spectrum for these network (preferably from the unused spectrum in the TV band; 700MHz). If allocated (it seems that is what the FCC wants as per the newest ruling on the matter), this should be used for mesh backhauling. This will create a mesh backhaul that is capable of delivering video context in broadcast, multicast, and unicast means.
6. More standard features (such as security, QoS, roaming, location, etc.) to the WiFi based equipment. However, these equipment must be made such that in site upgrade is possible and easy.
7. For VoIP, it is important to deploy the equipment that will solve the performance issues of WiFi as proposed in [35].
8. As WiMAX becomes available, it should be made the technology of choice for these networks, but can still provide WiFi towards the end users as well.
9. As a future work, section 5.1 can be expanded by analyzing the dynamics of market with respect to the five forces.

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