

From Applications to ROI: System Architecture for Wireless Meshes

A Farpoint Group White Paper

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While discussions of advanced wireless technologies for metro- and wide-area deployments tend to focus on such topics and technologies as EV-DO, UMB, UMTS, HSDPA/HSUPA, LTE, and WiMAX (with additions to this list likely over the next few years), it's very important to remember that metro-scale Wi-Fi installations are an important, and, in fact, *critical* element in this space. Most often implemented via wireless-mesh techniques (see Sidebar, *The Importance of Mesh Architectures* for an introduction to the topic), metro-scale Wi-Fi meshes have a number of key advantages that we believe will have a major impact on service providers and mobile users alike far into the future. The three most important of these are *architectural flexibility*, *application support*, and *total cost of ownership (TCO)* benefits deriving from the inherent nature of a Wi-Fi-based mesh. The purpose of this White Paper is to explore each of these attributes in some detail, and to illustrate how the architectural strategies used to implement wireless mesh networks can have a profound impact on the performance and financial success of a metro-scale wireless mesh deployments.

Applications for Metro-Scale Wi-Fi Meshes

According to Muniwireless [<http://www.muniwireless.com/article/articleview/5868/1/23/>], there are almost 400 metro-scale Wi-Fi mesh projects currently underway or in the planning stage in the US alone, and we expect this number to grow dramatically over the next few years. The enormous popularity of this form of metro-scale broadband is motivated in part by the worldwide acceptance of Wi-Fi in both the residence and the enterprise. The inclusion of Wi-Fi in essentially all notebooks and even some handhelds, permitting the same device to be used for broadband access essentially everywhere, has undeniable appeal. Moreover, the rapidly emerging integration of Wi-Fi into cellular phone handsets and similar mobile information and communications products is already a recognizable trend; we expect this movement will reach critical mass over the next few years, culminating in the broad availability of converged broadband voice/data services. In short, addressing these constituencies, metro-scale Wi-Fi is now past the experimental phase and well into production deployments. These networks are becoming fixtures and even an *expectation* on a global scale, as municipalities and wireless ISPs (WISPs) turn to them for a broad array of IT needs, government service and cost efficiencies, public safety applications, and as a vehicle for both economic development and a range of social benefits.

The growing interest in metro-scale Wi-Fi derives, in no small measure, from the broad range of applications contemplated for such infrastructures. These applications generally require much more substantial throughput than is available from the more traditional wide-area infrastructures such as those noted above, with demand more akin to wired broadband services like cable and xDSL. Throughput alone, however, is only a point of departure, however; we quantify metro-scale Wi-Fi mesh applications according to a number of factors, as follows:

- *Degree of mobility* – Wi-Fi has traditionally been thought of as a relatively fixed technology, in that clients are typically stationary or moving only at a slow pace while communicating with the corresponding infrastructure. Many describe typical users as being *nomadic*, in that they move from location to location, but communicate only when stationary. While such has been the norm, many Wi-Fi adapters are capable of maintaining a

Sidebar: The Importance of Mesh Architectures

For those who have not spent much time exploring the nature of wireless meshes, a few words at this point will demonstrate the power, flexibility, and scalability of the wireless mesh approach. A *mesh* is a network construct that allows each node in the network to act as a switch or router. In other words, a packet received by a mesh node is processed in much the same fashion as in Ethernet switches and routers; decisions are made as to how to forward each packet in real time.

This is very much how all modern networks, including the Internet, are implemented. In a wireless mesh, however, the links interconnecting nodes are almost always *wireless*, both with clients (subscribers) and between infrastructure nodes. The configuration options inherent in wireless meshes are thus far greater than in any other wireless architecture. A potentially very large area can be covered with minimal effort, without the need to license costly spectrum, and backhaul capacity (connections to points external to the mesh) can be added as subscriber density and traffic demands require. Multi-radio meshes have the reliability, capacity, and scalability necessary to address all contemporary applications, from basic Internet access to streaming video.

Note, of course, that many different types of radios could be used to implement a wireless mesh. For purposes of this document, however, we will only consider meshes based on Wi-Fi (wireless LAN) technology. Wi-Fi meshes, as we'll discuss herein, offer high performance, low cost, and support for all traffic types. Figure 1 shows a diagram of a typical Wi-Fi mesh. Wi-Fi links are used to implement both communications with client devices as well as interconnections between nodes. The key architectural requirement, as we'll discuss in this document, is the ability to provision *multiple radios per node*, increasing capacity and eliminating, in most cases, bottlenecks that would otherwise limit performance and increase costs. Given sufficient intra-mesh capacity, provisioned via these multiple radios, the number of off-mesh backhaul connections can also be minimized, resulting in a reduction of the impact of this key cost component.

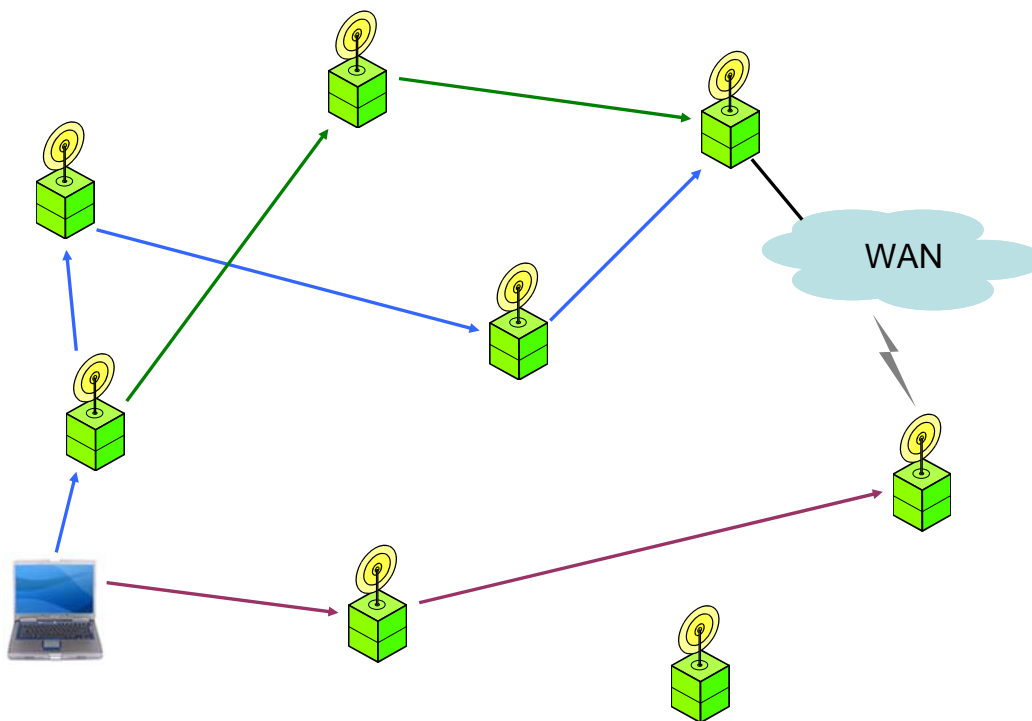


Figure 1 - Mesh network topology. Note how multiple paths are defined through the mesh, enhancing reliability. If these paths are implemented with multiple radios, capacity is enhanced as well. *Source:* Farpoint Group.

connection at vehicular speeds (to 100 KM/hour), depending upon the specific equipment being used and the distance between a mobile client and its associated access point. Additionally, some Wi-Fi mesh infrastructures are currently capable of supporting session continuity at speeds exceeding 200 KM/hour, enabling, for example, Wi-Fi connectivity to high-speed rail services. Moreover, the 802.11p Task Group is developing an extension to the 802.11 standard that will specify an increase in vehicular speeds to this rate. Such truly mobile communications will be of increasingly importance in the future, both for voice and the delivery of entertainment and other video programming to (hopefully just the back seats of!) moving vehicles.

- *Class of service* – Service class is usually defined by the time constraints (*time-boundedness*) associated with a particular type of traffic. Most data (e.g. Web browsing and e-mail) is *asynchronous* in nature and has no particular timing constraints, but higher performance is always desirable nonetheless. By comparison, voice and video are inherently time-bounded, or *isochronous*. Network complexity increases with a requirement for isochronicity – successful large-scale/metro-area network infrastructures of any form, we believe, must be able to handle the mobile “triple play” (sometimes incorrectly called “quad play”) of mobile data, voice, and video. Voice and streaming video represent significant challenges in that they consist of large data objects and tolerate only very minimal latency in transit. The multi-hop nature of meshes and the unlicensed nature of the radio spectrum used in these networks represent significant engineering and network-management challenges. Properly architected mesh infrastructures can effectively provision excellent quality of service (QoS) in Wi-Fi meshes. In the absence of such support, latency between hops (or simply the necessity of a large number of hops in order to reach the destination) can degrade overall performance and/or significantly increase backhaul requirements.
- *Government and private sector* – While indirectly related to class of service, three broad categories of traffic and their resulting applications are important in Wi-Fi meshes, as follows:
 - o *Government* – Government services are often the drivers of metro-scale Wi-Fi deployments, with two key objectives in mind: the cost-effective deployment of municipal and public safety communications, and provisioning broadband infrastructure so as to attract economic (often including residential) development. Government applications today include such important services as support for police and fire department communications, emergency response/first responder voice and data (and even video) services, real-time video and other surveillance, telemetry, monitoring, and control (sensor-based and public-works applications), support for inspectional and assessment services, and many more. The ability of a Wi-Fi mesh to handle truly broadband data will further, we believe, add to the popularity of this approach to municipal networking far into the future. For example, large data objects like photographs and video clips used for building inspection or police evidence, and streaming video for surveillance applications, can be easily sent over such a network, and real-time monitoring of, again for example, the condition of a patient in a moving ambulance, will easily justify the

adoption of a metro-scale Wi-Fi solution. We should also mentioned here that municipalities have the option of operating the licensed 4.9 GHz band reserved for municipal and public-safety use, effectively dealing with common sources of interference typically seen in Wi-Fi networks.

- o *Enterprise* – Many businesses now depend upon metro Wi-Fi services for remote access to key applications, remote messaging with broadly-deployed workers, and a variety of mobility scenarios. The client end of the connection, after all, is essentially free and included with essentially all business-class notebook computers. Enterprise applications typically involve access to enterprise networks (via VPN connections over the mesh) and Web access, but there are many more private-sector possibilities. Among the most notable are public utilities using the mesh for the IT and control aspects of large distributed facilities and applications such as sensor-based monitoring, control automation, telemetry, and management. WISPs can deliver branded services over the mesh (and competitive voice carriers using Wi-Fi could of course do the same), interconnecting distributed corporate facilities and/or provisioning first- or last-mile interconnect in a given metro area.

- o *Consumer* –This application of Wi-Fi is motivated by the need to extend cable or DSL-equivalent broadband within the residence, noting here that most homes are very difficult to wire regardless. The mobility and convenience inherent in Wi-Fi (and absent in wire) are powerful incentives as well. Metro-scale Wi-Fi can also be a primary broadband service for consumers and a competitive alternative to existing wire-line services. When implemented via the use of customer-premises equipment (CPE) devices (for an example, see Figure 2) that extend the mesh into the residence, the need for a residential user to deploy their own access point or wireless router is eliminated, and opportunities for interference are minimized. An additional attraction of metro-scale Wi-Fi has been the mobility and convenience inherent in connecting anytime and anywhere, even across a city - the fact that a single Wi-Fi client device can operate across enterprise, residential, and public-access venues is a powerful driver of Wi-Fi market growth. Consumers can, for example, telecommute from home or otherwise remotely access network resources at work (again, via a VPN) or from a coffee shop, while on a bus, or even commuter rail while en-route to work.



Figure 2 - An example of a customer premises equipment (CPE) unit, the Strix Systems EWS 100 Series. Source: Strix Systems. Used with permission.

Operators of metro-scale Wi-Fi networks are increasingly recognizing that such large-scale deployments need to be *carrier-class*. There's really no difference between operating a metro-scale Wi-Fi service and any other broadband infrastructure. This means that it's particularly important to have a carrier-grade operational support system (OSS) to handle provisioning, billing, and customer service. It's also important to be able to provision and control multiple classes of service within a single infrastructure, thus multiplying the value of the mesh significantly. This is usually done via multiple SSIDs, creating in effect multiple independent and secure virtual mesh networks.

Designing Metro Mesh Architectures to Maximize Application Performance

It should be clear at this point that user expectations for metro-scale Wi-Fi meshes are very high, and likely to increase further as these networks become increasingly mission-critical for all three categories of users noted above. The need to support both current and emerging applications requiring greater throughput and time-bounded performance motivates increased attention on the *architecture* of the products used to construct such networks. Farpoint Group has identified a number of key attributes that we believe will define production-quality metro-scale Wi-Fi mesh networks going forward, as application demands and user loads continue to increase.

First and foremost among these, of course, is *capacity*. By this we mean the ability handle potentially large amounts of data, including time-bounded voice and video traffic for potentially many simultaneous users and applications at any given location, but also the ability to *grow* and *scale* economically and cost-effectively. We have found that there are three key attributes of a Wi-Fi mesh architecture that address these goals, as follows:

- *Ability to provision sufficient capacity at any given point in the mesh* – The demands on networks of any form only increase over time, as the number of users, their transmit duty cycles, the size of the data objects they seek to transfer, and the degree of time-boundedness of an ever-greater percentage of those objects all grow. Meshes are in one respect no different from any other network – bottlenecks at any point will absolutely have a detrimental impact on throughput and capacity. Thus it behooves the designers of metro-scale Wi-Fi meshes to carefully consider the alternatives in addressing these concerns.

Unlike most other networks, the subscriber capacity of a mesh actually *increases* with each additional infrastructure node added. What differentiates one mesh architecture from another is the efficiency with which it transports subscriber traffic from a given point over a number of hops to either the destination within the mesh or a point of interconnect to backhaul. Some mesh architectures are extremely efficient, via greater intra-mesh connectivity, in carrying subscriber traffic over many hops and thus can also require fewer backhaul connections than other implementations as a result. Less-efficient implementations can also require more mesh nodes than might otherwise be required,

increasing costs and lowering total cost of ownership and thus return on investment. The key architectural difference that defines efficient mesh architectures is the ability to provision a *larger number of radios per node*. More radios, as is the case with more nodes, yield more capacity, although far more cost-effectively.

Note that the use of multiple radios includes support for both subscriber access and intra-mesh interconnect. A larger number of radios dedicated to each increases overall capacity, as we noted above, but it is also important that these two services be balanced so as to avoid congestion and blocking. Note also that more radios per node can minimize the requirement for additional (and usually expensive) off-mesh backhaul capacity bridging to external networks. These links can be provisioned less frequently in the mesh (albeit with greater individual capacity), minimizing costs again.

- *Mesh algorithms* – These are the “secret sauce” in all modern mesh implementations, as mesh-equipment vendors continue to work diligently to devise protocols with the right combination of throughput, resilience, and intelligence in adapting to multiple classes of service with highly-varying and usually unpredictable instantaneous data loads. Such protocols must also handle mobility, an enormous challenge in and of itself, and always have a key goal of minimizing both intra- and inter-node latency. The IEEE 802.11s Task Group is working on standards in this area, but we believe most vendors will continue to retain proprietary technology here as such defines their core competitive advantage. It is important to note that mesh architectures and their related protocols fall into two key categories - *routing* (or *Layer 3* protocols, referring to layer 3 in the International Standards Organization reference-model description) and *switching* (*Layer 2* protocols). Vendors of Layer-2 implementations make a convincing case for greater efficiency via the lower inter-nodal (and perhaps intra-nodal) overhead in this approach. In general, inter-node latency needs to be below 5 milliseconds (ms.), while aggregate inter-node latency over multiple hops should not exceed 50 ms. for time-bounded traffic. Regardless, less latency is always desirable.
- *Backhaul capacity* – Finally, we define backhaul here as the connection(s) between the mesh and external networks. Backhaul connections are typically provisioned using point-to-point radio, point-to-multipoint radio, or fiber. Dual- and single-radio mesh nodes may require substantially more individual backhaul links due to the lack of intra-mesh capacity required to reach a given backhaul connection. All this, of course, further motivates the provisioning of multiple radios per node as the preferred architectural strategy.

There are a number of additional architectural attributes that we believe are also important, as follows:

- *Centralized management* – A requirement for medium- and especially large-scale deployments is the ability to centralize provisioning and troubleshooting, and provide graphical monitoring, event logging, and control for potentially hundreds of infrastructure nodes and thousands of radios.

- *Field upgradeability* – While mesh nodes tend to be inexpensive, they become much more cost-effective when they can be provisioned with multiple radios and especially when these additional radios can be added in the field. This eliminates the requirement for a wholesale “forklift upgrade”, as it is known within the industry, and thus helps to minimize capital expense (CapEx).
- *Security* – While security must be largely addressed as a *network*, and is not just a *wireless*, concern, it is important that wireless meshes implement two key features. The first of these is support for Wi-Fi Layer-2 security techniques (WPA and/or WPA2), and the second is full support for user-directed encryption and authentication, including VPNs of various forms and 802.1x/EAP or other strong user-specified and -provisioned authentication.
- *Multiple classes of service* – As we noted above, it’s important to be able to provision multiple classes of service (and classes of users) within a single mesh network. Each of these can have different traffic prioritization levels, security, and pricing profiles as may be required. This capability can have a profound impact on both cost minimization and potential revenue opportunities. Typically, such facilities are provided as independent VLANs, each associated with a separate SSID. It is important to note that each SSID must have a unique MAC address for truly independent classes of service with separate encryption protocols and authentication mechanisms.
- *High mobility* – Finally, as we noted above, we believe that high-mobility applications involving moving vehicles will become much more important over time. The key element here is the ability to process an inter-node handoff for rapidly-moving clients in less than 50 ms. In addition, as we noted above, the ability to maintain session connectivity at speeds exceeding 200KM/hour is essential for commuter rail applications.

Total Cost of Ownership Return and on Investment: The Impact of Architectural Strategies

All this brings us to what is likely the most important question of all, how to evaluate the financial elements of a metro-scale Wi-Fi mesh deployment, and how the architectural strategies of a given solution can contribute to a superior result here just as they do with respect to applications. We begin with what may be the obvious, but it must be assumed that any metro-scale Wi-Fi mesh deployment will need to grow in terms of both coverage and capacity over time. The key elements influencing total cost of ownership (TCO) of a metro-scale Wi-Fi mesh are as follows: (a) the number and cost of mesh nodes, (b) the number and capacity of backhaul links to external networks, (c) network management and OSS, (d) non-recurring engineering and installation, and (e) mounting rights expense (attach fees). Maintenance expense is usually very low and will be therefore ignored here. With respect to each of these:

- *Mesh nodes* – This includes the cost of the nodes themselves, antennas, and associated hardware. An important point that we will return to below includes the ability to cost-effectively amortize additional capacity via the addition of multiple radios to existing nodes, providing the most cost-effective growth path over time. It is also important to select nodes that have excellent performance for a wide variety of traffic types, again on the assumption that all successful metro-scale implementations will need to transport traditional IP data initially and expand to include mobile triple-play over time. We make the assumption here that over-provisioning capacity is the preferred deployment strategy, just as is the case with wire, but tempered by the cost realities of deploying many nodes at once. Cost-effective *incremental growth* is thus the key.
- *Backhaul* – This is the other potentially large expense which can be mitigated by architectural choices. While many forms of both wired and wireless backhaul exist, all can add significant cost to a given installation. As we noted elsewhere in this document, the good news here is that appropriate architectural choices can materially reduce the cost of backhaul by provisioning fewer (if higher-capacity) backhaul links in the presence of sufficient intra-mesh interconnect capacity.
- *Network Management and OSS* – Significant cost benefits can be obtained via the effective use of mesh network management and operational support system tools. While traffic flows through the mesh are self-managing to the greatest degree possible, it's important to use automation to hold operational expense (OpEx) down. Appropriate and effective automation in the management and OSS space can reduce personnel costs, improve customer-facing responsiveness, and increase overall customer satisfaction while holding maintenance costs to a minimum. An excellent example of the benefits possible here would be in a network management system that monitors throughput and latency, across the mesh, automatically identifying potential areas where more capacity should be deployed, and providing advance warning of this condition.
- *Engineering and Installation* – Designing, installing, testing and certifying metro-scale mesh networks is an engineering-based discipline requiring significant expertise. The cost of engineering and installation is typically 25% to 30% of equipment cost. However, deployment circumstances can significantly increase this percentage. Examples of common situations leading to higher costs include the need to wire additional power to the mounting locations, and correcting installations for unexpected radio conditions such as low-than-expected signal penetration due to interference or intervening structures (the latter known as *shadow fading*). Again, effective mesh routing protocols can compensate here to a very great degree.
- *Attach fees* – This element, sometimes also called “roof rights”, is often cited as *the* major expense in installing and growing a metro-scale mesh. These are the fees paid to those holding the real-estate where the individual mesh nodes are mounted. All that is generally required is an appropriate location (determined by user-population density, distance between mesh nodes, and the laws of physics as they relate to radio propagation), access to electrical power, and an appropriate structure, meeting local codes, to

mount the node to. Streetlight poles are often cited as an ideal venue, but many others are possible, including the sides or roofs of buildings. Note again that the use of multiple radios per infrastructure node can be a very effective technique in minimizing attach expense. Generally, attach fees for light poles are modest and in some cases can even be zero. In other situations, pole-attach fees can be prohibitively expensive.

Other costs, which we group under the general heading of OpEx, include administration, legal, maintenance, office expense, utilities, marketing, sales, support, and related customer-facing expenses, but these are irrespective of particular architectural choices.

As it turns out, the primary variable in selecting an architectural strategy that results in a low overall TCO (and thus an optimal return on investment, or *ROI*) is the ability of a given node to support multiple radios, as was noted above. The impact that this element can have is detailed in Table 1. Farpoint Group believes that the best way to minimize costs, then, is to select an architecture that minimizes the number of off-mesh backhaul connections and that allows for the most cost-effective incremental growth over time - and the best path to this end is a multi-radio mesh with the ability to provision and field-upgrade a given node with additional radios.

	Single-Radio	Dual-Radio	Six-Radio
Nodes Required	6	3	1
Cost/Node	\$2,000	\$2,500	\$4,500
Total Node Cost	\$12,000	\$7,500	\$4,500
Attach Fee/Node	\$250	\$250	\$250
Total Attach Fees	\$1,500	\$750	\$250
Backhaul Connections Required	2	1	1
Cost/Backhaul Connection	\$1,500	\$1,500	\$1,500
Total Backhaul Cost	\$3,000	\$1,500	\$1,500
Total Cost	\$16,500	\$9,750	\$6,250

Table 1 - This example is designed to show the financial benefits of the multiple-radio-per-node approach. While this example considers only six radios, and dollar figures are approximate in all cases (and will vary with specific manufacturer/dealer discounts and local backhaul costs), it is clear that increasing the number of radios per node results in a significantly lower cost-to-solution - without even considering the additional capacity provisioned in the bargain. *Source:* Farpoint Group.

It should be quite clear that multiple-radio nodes can have a profound impact not just on performance, but on the ultimate cost-effectiveness of a given metro-scale mesh. And, as gross margin is computed by subtracting cost from revenue, maximizing revenue via multiple classes of users each with sufficient capacity and performance to meet their specific requirements and expectations, and minimizing costs via architectural innovations, is the best path to a successful metro-scale Wi-Fi mesh deployment.

Conclusions

It is very clear, we believe, that metro-scale Wi-Fi meshes are going to play a critical role in the future of broadband communications, and on a global basis. Properly designed and implemented, they provide the capacity and convenience to serve as a primary communications mechanism for essentially everyone. We are also now seeing the beginnings of a trend towards the convergence (what we call mobile-to-mobile convergence, or MMC) of such Wi-Fi networks and cellular broadband systems (and perhaps eventually WiMAX as well), coupling the capacity of Wi-Fi to the inherent coverage advantages of cellular. While a battle may be brewing between cellular and WiMAX, we see no replacement technology for Wi-Fi – ever. Today's metro-scale deployments, properly designed, architected, and deployed, will continue to support a broad range of applications far into the future - and with remarkable TCO and ROI along the way.



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