TRANZEO

WIRELESS TECHNOLOGIES INC.

Example Community Broadband Wireless Mesh Network Design

Version 1.1: 20 June 2007

General Information

Company Information

Main Office	Tranzeo Wireless Technologies, Inc.
Address	19473 Fraser Way
City, state, ZIP Code	Pitt Meadows, BC Canada V3Y 2V4
Phone number	866-872-6936
Fax number	604-460-6005

1. Executive Summary

This document provides an in depth wireless mesh network design to support community broadband access developed for a specific target municipality. The Community Broadband Network will be deployed to provide an alternative method of broadband access to community Internet users. This wireless mesh network will provide a means for offering converged services to end users that spans the typical triple play set of data, voice and video services.

This design uses community assets, including existing streetlights, 11 additional poles and towers to be installed by the community, and 17 traffic light locations. This design covers 88% of all service areas of the community with 613 mesh nodes, 74 900 MHz injection layer subscriber modules, 17 900 MHz access point modules, and 28 fiber points. This is summarized in section 6.

Due to the unique challenges of foliage density and rolling terrain, the injection layer technology becomes the bottleneck for delivering 2 Mbps to the user. In some areas where 900 MHz injection is used, the network topology presented falls short of the 2 Mbps objective when a statistical model for sharing the network is applied. Remedies are available and are discussed in section 4.6. This challenge will be resolved in the specific equipment selection through the RFP process.

2. Overview of Design Approach

This report covers a comprehensive “build-to” network plan and equipment bill of material covering all components needed to deliver a working system including network diagrams and system layouts for a selected municipality.

The “build-to” design approach used for the community differs from most, with a greater amount of up-front planning before funds are committed to install the network. We’ll illustrate the characteristics of this “build-to” approach against the popular “as-built” approach used by Earthlink and others.

Attributes of the “As-Built” design model:

- Conceptual network design crafted with predictive software tools
- Network is engineered as it is built
- Boilerplate architecture and systems adopted for all municipal projects
- Capital budgets are variable prior to deployment
- Risk absorbed by EarthLink business unit
- Relies heavily on Operations to work-out design gaps during installation
- Shifts costs from up-front engineering to installation and commissioning

EarthLink is spending on the order of $2M to $5M on their Philadelphia network in engineering, design and integration costs. This equates to approximately $1,600 to $1,800 per radio node for engineering, design, installation, and commissioning. This does not include the cost of network equipment. Therefore Earthlink sees benefit in this design approach for their business model and accepts the financial risks of this method.

Since the community cannot afford to accept large financial overruns in the build out of the network, a different approach must be taken. In this “build-to” design approach, more effort is placed in up-front design activity to gain more certainty in the predicted cost of the network implementation.

Attributes of the “Build-to” design model:

- Optimized capital expense budget for full network project
- Comprehensive network architecture, wireless, wired and IT
- Coverage of wireless access, mesh and backhaul layers
- Integration to community’s WAN and IT systems
- Integration to subscriber management system (AirPath or Pronto)
- Network management and monitoring system
- Final design package must be actionable for installation open-bidding

2.1. Network Design Deliverables

This wireless mesh network design contains the following deliverables:

- Network architecture description
- Network specifications and diagrams
- Capacity plan
- RF plan and measurement methods
- RF coverage maps
- List of equipment mounting sites
- Operational Support Systems (OSS) plan

This design proposal is vendor agnostic. Therefore an equipment description list with examples is provided rather than specific equipment recommendations. Also, a project timeline, material costs, and labor plus installation costs are deferred for the installation open-bidding process.

2.2. Service Standards and Design Criteria

The following criteria were used as a basis for the network architecture and design:

- WiFi Access: continuous coverage of community’s total service area
- Capacity: 2 Mbps up, 2 Mbps down at any WiFi access point in the network
- Street-level coverage into the front door/window of homes

- Potential service to all areas of the community
- Wireless-VoIP optimized
- Low latency and low jitter
- Skype and SIP application support
- Quality of Service, network wide
- Layer 2 802.1e WMM, ToS
- Layer 3 QoS
- Network-wide seamless roaming
- Authentication session persistence
- Layer 4 (W-VoIP) session persistence – stretch goal
- Low-speed mobile access for Police and Fire Departments
- Video backhaul and remote viewing

3. Network Architecture

This section describes the network architecture designed to meet the service standards and design criteria outlined in the previous section. It commences with an overview of current mesh technology trends followed by a description of the various wireless and wired layers of the network. These include the access, mesh and injection layers, as well as the wired backhaul layer known as the community fiber MAN. Furthermore, the architecture and functions of the networks operations center as the control and monitoring facility of the network are discussed in detail. Relevant terminology is introduced, followed by a description of each network component. While the figures illustrate typical examples of access, mesh and injection layer configurations, as well as the PoP and NOC topology, the architecture diagrams are intended to show the relationship of and interconnections between the individual layers and subsystems.

3.1. Mesh Technology Trends

Cities and municipalities worldwide are embracing WiFi and mesh networking technologies as an access equalizer and means for providing enhanced online services to the community. Wireless mesh networks have emerged as the extension to the infrastructure WLAN deployments in public and private outdoor installations such as large academic and corporate campuses, municipalities, city downtown areas, and, to some extent, multi-unit apartment and residential complexes.

Mesh networks have been deployed with both multi-radio and single-radio solutions. Single-radio mesh solutions use a single radio device, or transceiver, to provide wireless access to the end user and connectivity on the backhaul mesh network. The single-radio solutions, while benefiting from a simpler design, typically suffer from significantly diminished overall throughput that limits the scalability of the overall network. Usage of these devices typically results in either smaller coverage areas and/or lower available bandwidth to users compared to mesh networks built around multi-radio devices.

In contrast, multi-radio mesh designs allow separation of the user access and mesh backhaul operations of the wireless network, resulting in greater capacity for both network layers. This allows better scaling performance for the overall mesh network. Two radios per mesh node (routers) is typically sufficient to realize the benefits of separation of the user access and mesh planes, with more radios providing marginal performance gains and additional per-unit cost.

A major component of wireless mesh technology is the mechanism for forwarding data packets over the mesh multihop topology. This forwarding may be accomplished at OSI layer 3, an approach first used in Mobile Ad-Hoc Networks (MANETs), in which case units of information forwarded across the network would be IP packets. The data forwarding may also be accomplished at layer 2, in which case the units of forwarded data would take the form of 802.11 frames. In either situation a path/route determination is used. The design of this routing algorithm is one of the major variants in the mesh solution.

The portion of the network which we will refer to as the injection layer is comprised of point-to-point or point-to-multipoint high speed wireless links capable of connecting the mesh elements, or mesh neighborhoods, to wired backbones, points of presence or in some cases network operations control centers. The key qualities of the injection layer are high throughput, long range, and the ability to penetrate medium to high density foliage found in typical urban and suburban environments. The injection layer candidate technologies typically use fixed access mechanisms such as TDMA/FDMA, and require significant configuration of individual modules. There are a number of commercial products such as Tranzeo's point-to-point and point-to-multi-point radios that have enjoyed significant popularity as injection layer components.

WiMAX is a standardized technology that is suitable for use at the injection layer. Though mature 802.16e products are not widely available yet, the technology is promising in providing robust, broadband connectivity in the near future. The modulation methods and the use of MIMO allow the WiMAX systems to provide excellent coverage in environments with high levels of multipath, where Non-Line-of-Sight (NLOS) is the predominant mode of radio signal propagation.

3.2. Architecture Overview

The diagram shown in Figure 1 (the architecture diagram) depicts the network architecture of the community municipal wireless network. The design is comprised of three tiers or layers, each using a different connection technology. These include the access, mesh and injection layers, as well as the community fiber MAN (FMAN). The network consists of the Network Operations Center (NOC) located in the municipal building, a number of Point-of-Presence (PoP) locations with collocated poles or towers, as well as additional optical fiber termination points at select locations. Each tower features one 900 MHz injection access point and a mesh radio serving as the gateway for a local collection of 802.11 access points. Subscriber management is expected to be handled off-site by a third party provider as indicated in the diagram by the server labeled 'AAA Provider'. The following sections first establish the terminology of components and concepts used in the design, followed by a detailed description of each network subsystem and the associated building blocks.

Mesh Nodes: These nodes contain a WiFi radio operating as an access device and a second WiFi radio that participates in a local wireless mesh network. The primary functions of a mesh node include the provision of 802.11 access point capabilities and the forwarding of local and relaying of remote user traffic from other mesh nodes to and from the Internet via the injection and backhaul layers. Additional functions may include the enforcement of QoS rules for outbound traffic, as well as acting as endpoints for securing over-the-air traffic between subscriber and 802.11 access point.

Mesh Gateway: This device is responsible for passing traffic between a collection of mesh nodes and the backhaul network, serving as the single egress point for these nodes. A mesh gateway role is assigned to a standard mesh node upon deployment; however, mesh nodes dynamically select their mesh gateway based on shortest routing path. This approach allows mesh nodes to re-select an alternate gateway if the current one becomes unavailable.

Mesh Neighborhood: A mesh neighborhood is comprised of a number of mesh nodes that are logically and functionally controlled by and associated with a single mesh gateway. At a minimum, a mesh neighborhood consists of one mesh node and an associated mesh gateway, although in practice the number of mesh nodes is expected to be much larger in order to extend the reach and coverage of the wireless network and reduce the number of injection layer links.

Access Layer: This layer uses 802.11b/g technology to provide wireless access to end user devices.

Mesh Layer: The mesh layer is a self-forming, self-healing multihop ad-hoc network based on 802.11a radio technology. The mesh layer's purpose is to connect the 802.11 access points of a collection of mesh nodes to the wireless injection layer, or directly to the wired backhaul network. The self-forming capability refers to the ability of mesh nodes to discover their neighbors and establish efficient paths across the mesh to the Internet. The self-healing nature of the mesh layer indicates the ability of a mesh node to select a new path towards the intended destination in the event of individual mesh nodes failing along the original route (e.g. due to equipment failure or power outage). Figure 5 shows three mesh neighborhoods that differ with respect to how they connect to the backhaul network. Mesh nodes in neighborhood of type A connect via their mesh gateway to the PoP and FMAN, type B connects via an injection layer subscriber module and associated link to the PoP and FMAN, while type C connects via their mesh gateway directly to the FMAN.

Injection Layer: This layer provides a broadband wireless link to mesh neighborhoods by connecting a mesh gateway to a PoP. The injection layer operates in 900 MHz band. The 900 MHz frequency band has the best propagation characteristics for the dense foliage prevalent within the boundaries of the community. Figure 4 shows a typical configuration where one 900MHz access point, as part of a three-sector radio configuration, serves multiple mesh neighborhoods (a mesh neighborhood is indicated by the plane in the diagram).

Point of Presence: In the context of this network architecture, a PoP is an optical fiber termination point for the community fiber MAN. PoP locations typically serve multiple mesh neighborhoods. A PoP is attached to an element of the injection layer that provides point-to-multipoint broadband wireless links. A switch with traffic characterization and prioritization capability is required at each PoP location to limit the aggregate bandwidth to the traffic capacity of the injection layer. This switch prevents random packet drops and ensures QoS requirements on the payload and management traffic are met. In the context of this design, a PoP is also called a branch, denoting the collection of all associated mesh neighborhoods.

Network Branch: A collection of mesh neighborhoods that are served by a single PoP is called a network branch.

Optical Fiber Termination Point: These termination points typically provide access to the community fiber MAN for certain areas in the community that are not readily accessible via the wireless injection layer. A fiber termination point typically serves a single mesh neighborhood and hence is connected to a mesh gateway via an appropriate fiber to Ethernet converter.

Network Operation Center (NOC): The Network Operations Center is responsible for various network element management functions, as well as subscriber related administration functions. The network elements that require management include the 802.11 access points, the injection layer equipment (point-to-multipoint access points and subscriber modules), as well as traffic shapers at each PoP location. Element management functions include the provisioning and activation of software upgrades, configuration changes to support new services and alter existing services, as well as monitoring performance and state of the employed network elements and associated links. The network element management functions are implemented by EMS/NMS software running on the EMS/NMS server as shown in Figure 2. Subscriber administration functions include the dynamic assignment of IP addresses to subscriber devices, subscriber traffic routing, authentication, authorization and accounting (AAA) functions, per-subscriber policy enforcement (bandwidth limits, allowed service types, times of use, etc.), as well as subscriber usage statistics collection. While DHCP and routing functions are provided locally by multiple Wireless Internet Gateways (WIGs) in a load-sharing configuration, the AAA functions, along with per-subscriber policy enforcement, are implemented by an external AAA provider through standardized interfaces. The utilization of an external AAA provider reduces the burden of subscriber management by the network operator and simplifies the management of roaming agreements for visiting users. In Figure 2, two WIGs for routing and controlling client traffic are shown in a load-sharing configuration (indicated by the extra Ethernet connection between them), supporting a total of two thousand users. Subscriber-specific information is exchanged between the WIGs and the AAA provider via a secure VPN connection.

The diagram of Figure 3 depicts the internal architecture of a PoP. The traffic arriving on the fiber optic transport mechanism will be shaped by the traffic shaping switch. The rate of client and control traffic will be managed to prevent overloading of the injection layer and associated random packet drop. The traffic shaping switch may be configured and operation monitored centrally from the NOC. Note that the depicted PoP design also allows for the co-existence of 3rd-party network infrastructure at the PoP.

The diagram of Figure 4 shows the details of the injection layer. The point-to-multipoint injection layer is typically comprised of a central tower mounted access module and a number of injection layer subscriber modules, each of which is connected to a mesh gateway. The injection layer may use a single omnidirectional antenna at the tower. It is also possible to use directional antennas on the tower, where each directional antenna will be attached to an independent access module and serve one or more mesh gateways and associated neighborhoods.

The diagram of Figure 5 provides more detail about the design and operational aspect of access and mesh layers. There are three distinct mechanisms for a mesh neighborhood to be attached to the backhaul layer. These mechanisms are:

- The mesh gateway is collocated with the access module of the injection layer and will be placed on the injection tower itself. Refer to Figure 5 and the mesh neighborhood labeled Type A.
- Injection layer – A mesh gateway is directly attached to a subscriber module of a point-to-multipoint injection layer. This scenario corresponds to the mesh neighborhood labeled Type B in Figure 5.
- Fiber Termination Point – A mesh gateway will be directly attached to a fiber termination point. The fiber termination points would typically be present at the location of traffic lights in the city. This scenario corresponds to the mesh neighborhood labeled Type C in Figure 5.

Tranzeo’s network design takes advantage of standards-based technology components. The design philosophy follows a modular approach at various layers of the network, and as a result remains agnostic to a specific vendor to the extent possible. The modularity allows mixing and matching of specific technologies at each layer, and thus allows taking advantage of emerging technologies when they become available. The tiered architecture, separating the access, mesh, and injection layers, renders the overall network scalable.

3.3. Related Wireless Standards

The Task Group S (TGs) within the IEEE 802.11 standards body is currently working on ratifying a mesh standard. **802.11s** is the unapproved IEEE 802.11 standard for Extended Service Set (ESS) Mesh Networking. It specifies an extension to the IEEE 802.11 MAC to solve the interoperability problem by defining an architecture and protocol that support both broadcast/multicast and unicast delivery using "radio-aware metrics over self-configuring multi-hop topologies.

WiMAX is defined as **W**orldwide **I**nteroperability for **M**icrowave **Acc**ess by the WiMAX Forum, formed in June 2001 to promote conformance and interoperability of the IEEE 802.16 standard, officially known as WirelessMAN. The Forum describes WiMAX as "a standards-based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL“. Of the variants of 802.16, the 802.16-2004 (fixed WiMAX) offers the benefit of available commercial products and implementations optimized for fixed access. Fixed WiMAX is a popular standard among alternative service providers and operators in developing areas due to its low cost of deployment and advanced performance in a fixed environment. Fixed WiMAX is also seen as a potential standard for backhaul of wireless base stations such as cellular, WiFi or even mobile WiMAX. The later 802.16e standard, improves upon modulation and access methods of the 802.16-2004. The number of mature commercially available 802.16e products is limited at the time of this writing.

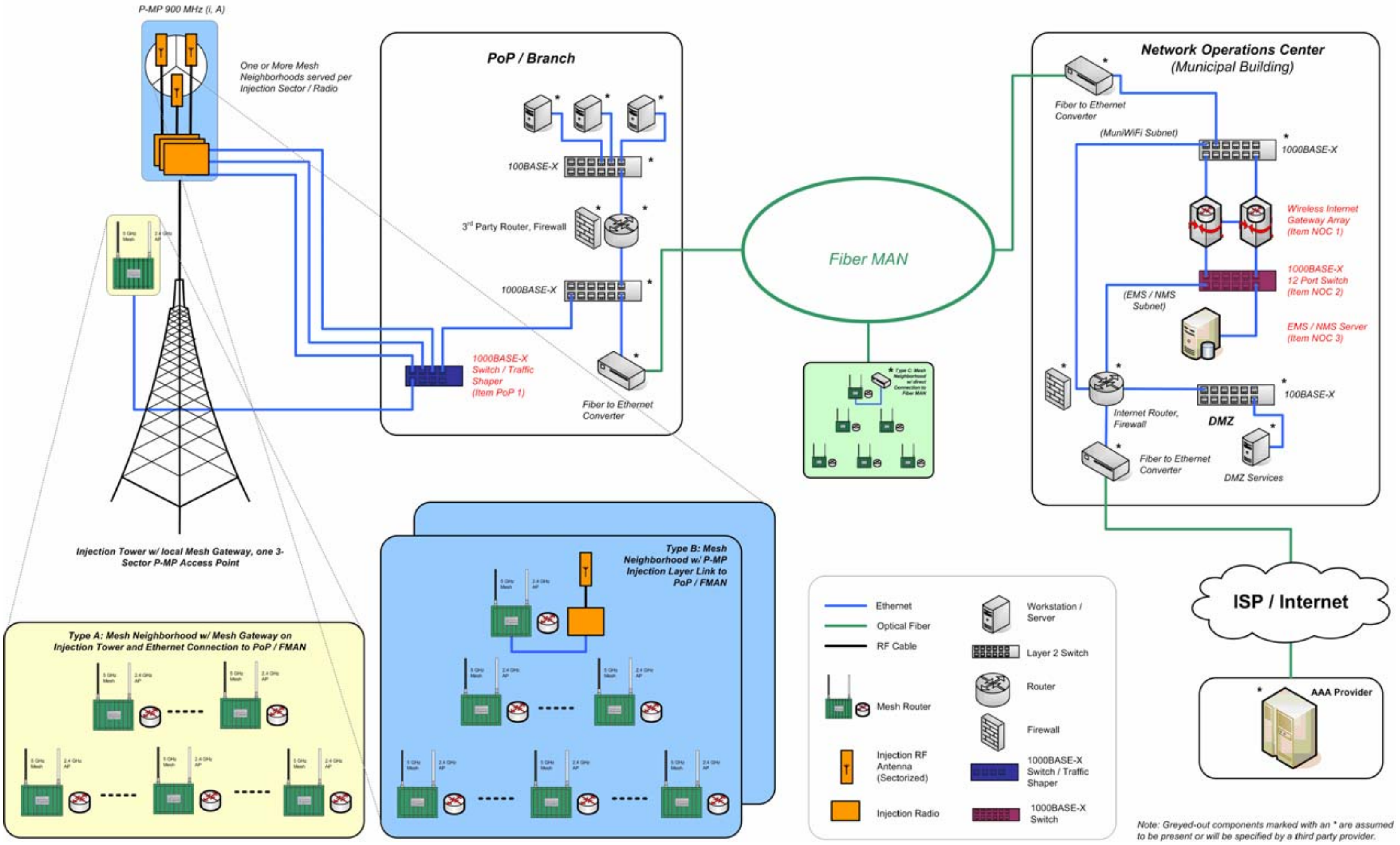
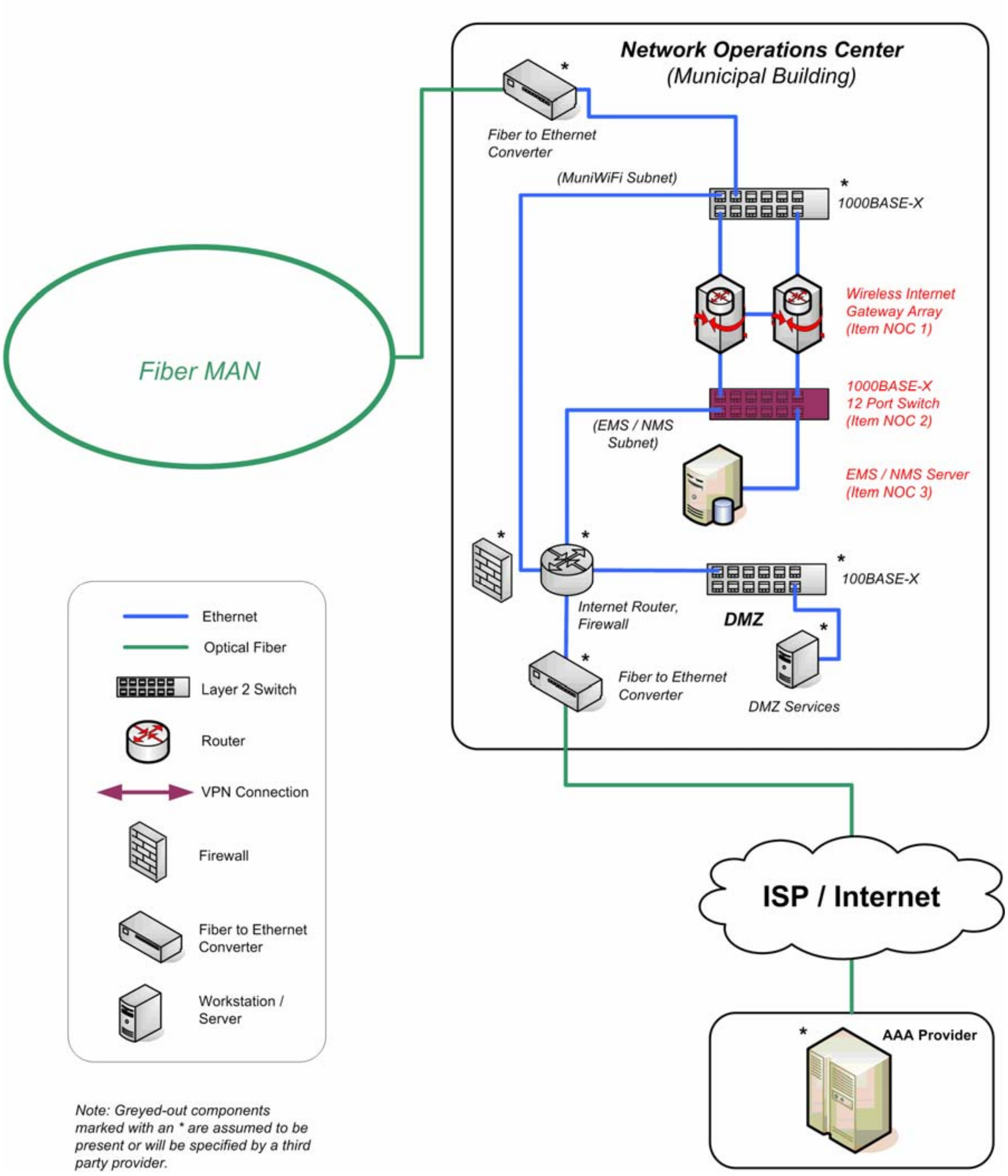
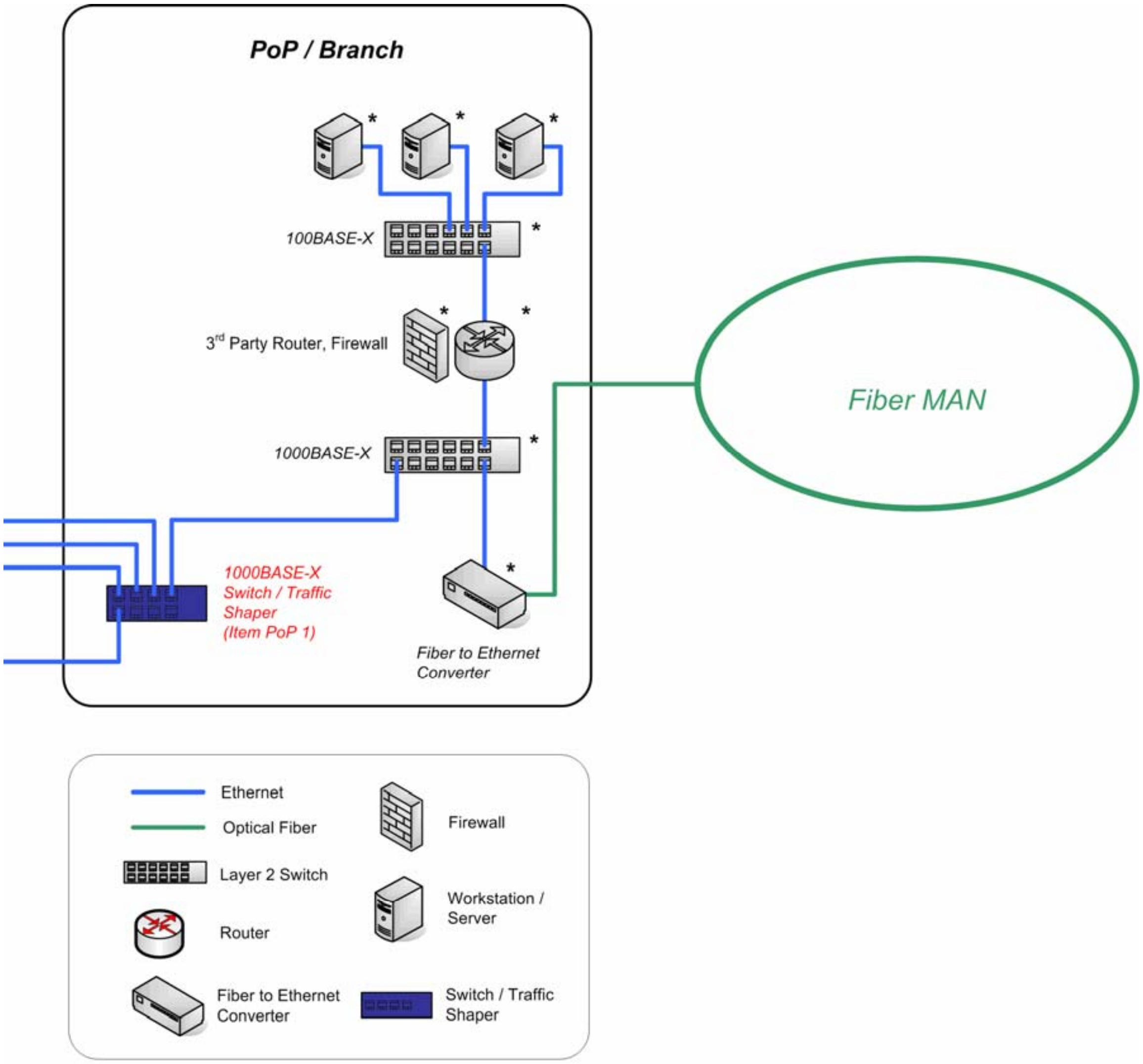


Figure 1. Architecture diagram



Note: Greyed-out components marked with an * are assumed to be present or will be specified by a third party provider.

Figure 2. NOC view



*Note: Greyed-out components marked with an * are assumed to be present or will be specified by a third party provider.*

Figure 3. PoP view

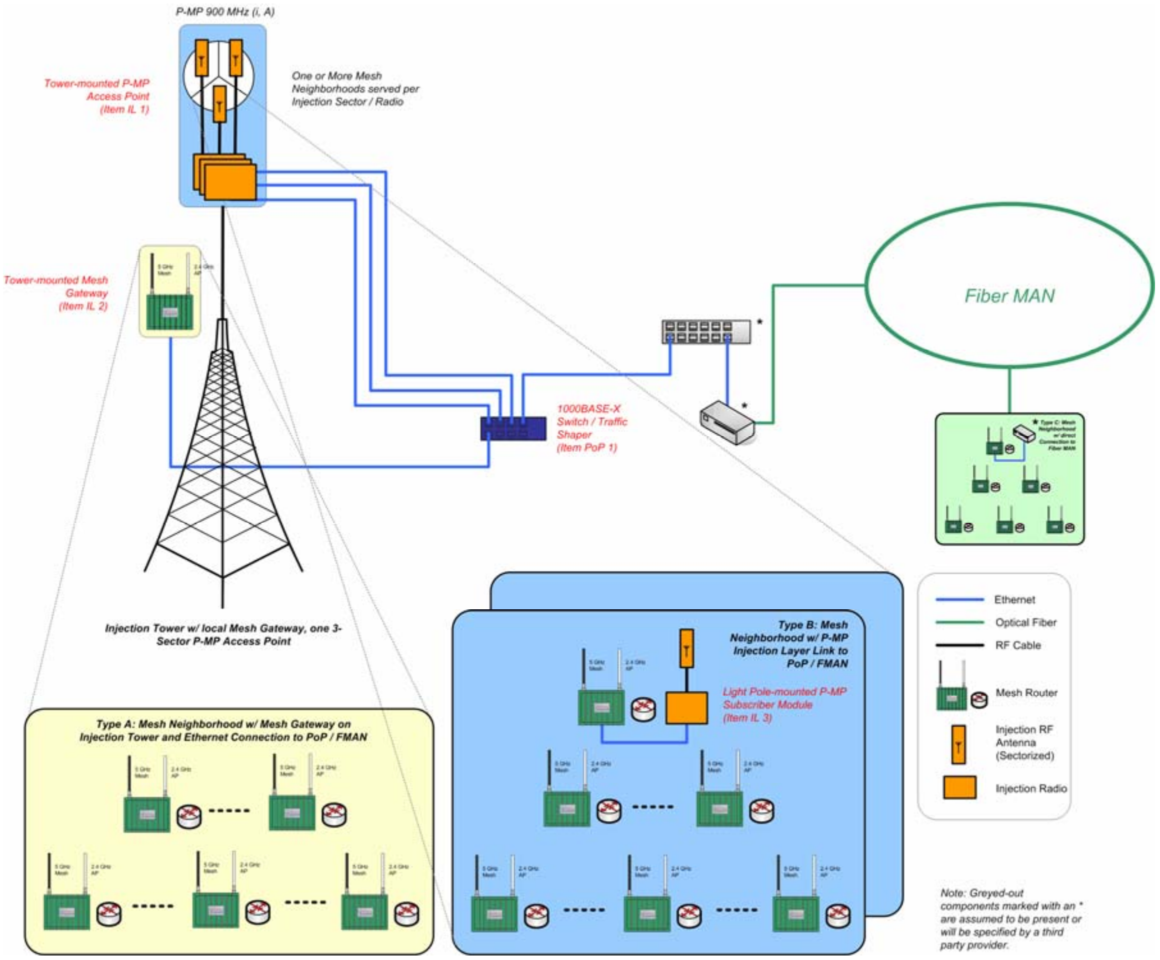


Figure 4. Injection layer view

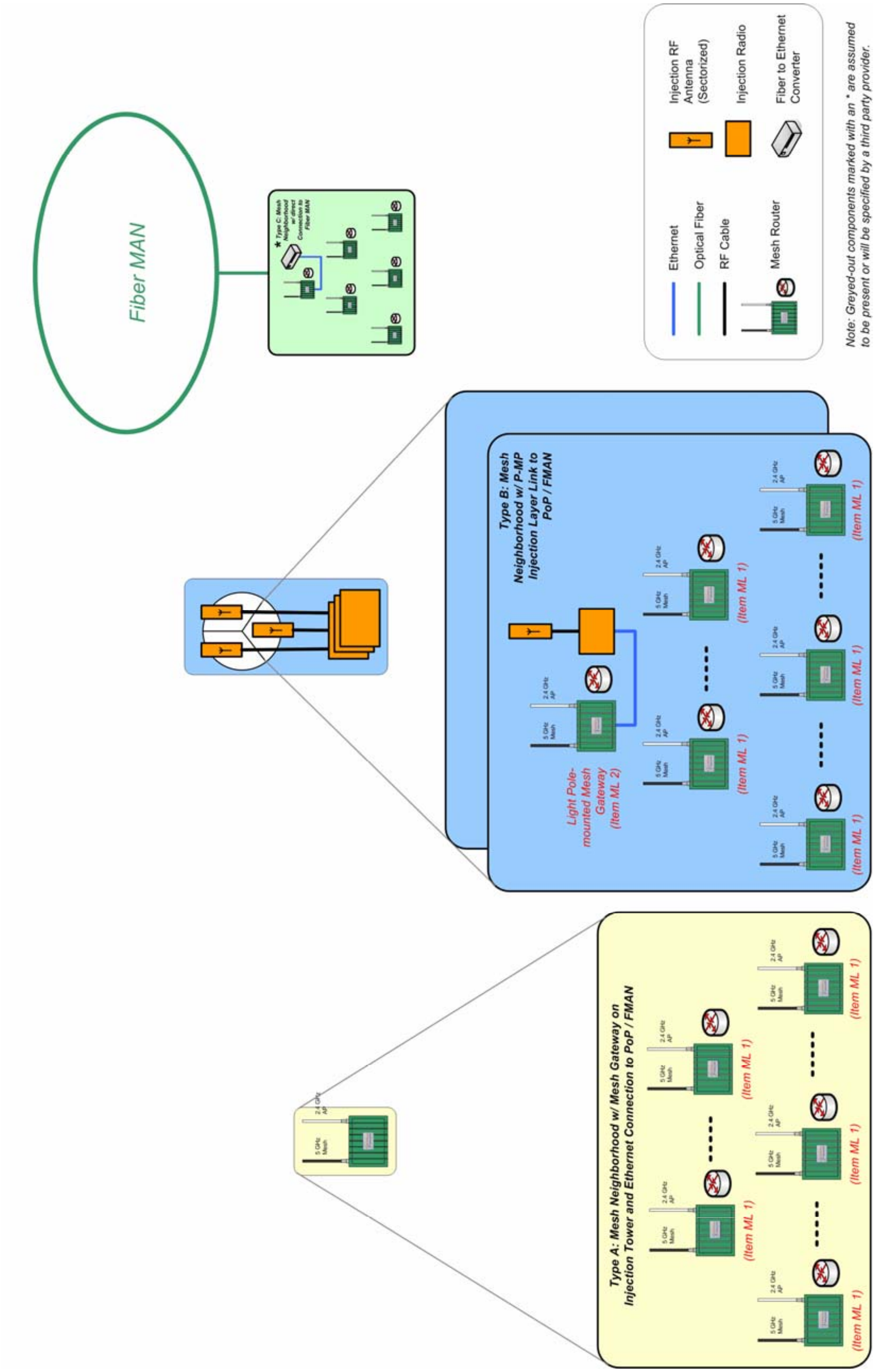


Figure 5. Mesh/AP view

4. Network Capacity

In order to dimension an access network[1], the following three pieces of information must be available:

- Available capacity of the network – Given the specific choice of technology, what is the actual available capacity of the links, switches and routers, available at each point of the network
- Required bandwidth per application – What is the application data model?
- User behavior – How do the users access the network?

We will provide an overview of assumptions used to arrive at models that describe user bandwidth requirements and user behavior. A review of the network topology that will provide the basis for assumed parameters that describe available capacity at various tiers/layers of the network will also be provided.

4.1. Topology Overview

The components of the infrastructure include:

- Access Layer – This layer consists of 802.11b/g mesh access points. As we will see later, the traffic model suggests that the access layer will be providing service to an average of 3 users per access point.
- Mesh layer – The mesh layer capacity is governed by the topology of each mesh neighborhood. The maximum hop count in a mesh neighborhood is limited to six for this design.
- Injection layer – The technology candidates at the injection layer provide aggregate data rates of 4 Mbps (2 Mbps in each direction) for the 900 MHz band.
- Fiber fabric bandwidth – The exact details of the fiber technology are not clear at this time. However it is assumed the fiber fabric will be able to support the voice and data requirements and thus will not be a bottleneck.

As was described in earlier sections, the injection layer is comprised of point-to-multipoint links between injection layer base stations and injection layer subscriber modules associated with the base stations. The injection layer base station has a direct wired link to the FMAN (or PoP) and thus acts as a traffic aggregation point for the mesh neighborhoods served by it. Each injection layer subscriber module is directly connected to a mesh gateway node. Ethernet frames will be transmitted over the point-to-point links of the injection layer. When operating in the 900 MHz band, there will be a total of 2 Mbps of bandwidth available that is shared amongst all subscriber modules attached to a single injection layer base station in the downlink direction (from the access point to the subscriber module). The actual bandwidth dedicated to a subscriber module is adjusted adaptively based on its instantaneous load. In the uplink direction a separate 2 Mbps of bandwidth is available. For our purposes, the entire injection layer may be modeled as an Ethernet segment. In each direction, the Ethernet segment provides 2 Mbps per sector. Note that a single sector is defined as a single 900MHz access point and the collection of all subscriber modules connected to the access point. The sector can use a single omni-directional antenna, in which case the entire capacity of the sector would be injected over a disk centered at the access

---

[1] An access network is one that sits at the edge of the larger internet, and directly reaches end users, by providing means of access to the network via edge access devices such as computers, VoIP phones, network appliances, cell phones, etc.

point. In the case of sectorization, the entire capacity of the access point would be injected only over the arc served by the antenna's foot print.

For the 900 MHz band, it is possible to use up to 6 non-overlapping sectors, with the corresponding access points co-located on the same pole. This allows injection of up to 12 Mbps (6 x 2 Mbps) at a single pole location.

4.2. Summary of Observations

Combining the available capacity at each point in the network, the required application bandwidth, and statistical modeling of user behavior combined with market penetration we will provide numbers for the total number of users supported by the network.

The capacity planning, as we will later see, indicates that in areas where injection layer links are used instead of connecting directly to the community fiber MAN, the injection layer is the bottle neck. The capacity planning will provide sufficient bandwidth for web traffic, including low-bit-rate multimedia streaming data, as well as enough dedicated bandwidth to support VoIP services. In other areas where direct connection to the high-speed fiber MAN is available to the mesh neighborhoods, data, voice and some broadcast video services can be supported. In this case the mesh capacity will limit the maximum available rate per user, and thus video services with low definition (i.e. non-HDTV broadcast) would be feasible[2]. We will see that the projected density of households (users) per mesh AP will be such that the access technology, 802.11b/g, will not be the bottleneck. The current maximum bandwidth that is sustainable with 802.11a technology will not be sufficient to support large market penetration of high-definition video service.

4.3. Data Model Overview

We now shift our focus to the traffic model. First we consider the Bursty Data Model (BDM) that will be used to model web traffic. The BDM takes advantage of statistical multiplexing, which is a technique commonly used in data communications to extract the maximum efficiency from a shared link. For example, the methods of BDM are used to dimension cable network access segments.

For constant bit rate (CBR) streams, a number of uncorrelated, bursty traffic sources are multiplexed together so that the sum of their peak rates exceeds the link capacity. Because the sources are uncorrelated, there is a low probability that the sum of their transmit rates will exceed the link capacity (i.e. all sources will initiate transmission at the peak rate simultaneously). However, although the multiplexing can be engineered so that periods of link oversubscription are rare, they will occur. In data communications networks, periods of oversubscription are accommodated by packet buffering and, in extreme cases, packet discard. The Internet is a prime example of an oversubscribed, statistically multiplexed network where packet delay and loss may be high during busy periods.

The concept of statistical multiplexing takes advantage of the fact that not all users of network service will be logged on at the same time. Of all the users that are logged on, not all will be using the network actively, and only a fraction of the active users will be running applications that require transmission and reception of packets at the peak rate.

---

[2] Note that the high speed video service requires non-random access at the MAC layer to allow fast delivery of TV signals to the end users. Currently only random MAC access is supported in the access and mesh layer radios.

We will provide a voice traffic model that takes into account VoIP encoding, typical voice call arrival rates in residential areas, and the concept of service market penetration rate, to arrive at a required bandwidth for VoIP traffic to support a given user density.

4.4. User Experience

Because of statistical multiplexing, a link with a given capacity may be shared between a number of users, where the sum of the peak data rates of users may be more than the line capacity.

To understand the concept, take the case of download data rates. The key here is that the likelihood that all users will initiate packet download at the same time is low, even in situations where the user sessions are ongoing simultaneously. In the unlikely event that all users will have simultaneous packet transmissions, the network infrastructure will queue the packets, and deliver them according to some order, based on the QoS policies of the network and requirements of the applications generating/requesting the packets. The store and forward nature of the IP network compensates for the occasional peaks in network access, or congestion, by introducing delay in packet delivery. In the extreme case where too much congestion is observed, packets may be dropped.

A means for users to characterize their line speed is to use line speed tests such as those provided by www.speakeasy.net. The speed test provided at this site allows a user to test the capacity of the link the ISP provides to the user. In almost all residential ISP situations, where the service is provided over phone lines with DSL or via a cable network, the link is a shared medium, and the result of the capacity test provides the instantaneous capacity available to the user, which is shared amongst all the users that share the given link.

4.5. Application Data Models

The applications that make use of a network connection can be grouped into three distinct categories:

- Variable Bit Rate data – This includes typical data applications such as web browsing, e-mail, file transfers, and low-speed, highly compressed, streaming audio and video.
- Voice – This is typically constant bit rate traffic that carries voice encapsulated in IP packets.
- Video – This is typically broadcast quality video, which is usually MPEG encoded. Since this service is out of the scope of deliverables for this network design, we will not discuss this category further.

4.5.1. Variable Bit Rate Data Traffic Model

Web traffic belongs to the variable bite rate (VBR) data category. There has been extensive analysis of such traffic. For the purposes of our network dimensioning we will combine the capacity planning methods used in cable data networks[3] and traffic data gathered for large scale public WLAN deployments.

The results of analysis of Internet traffic usage at a conference over a public WLAN are shown in Figure 6. These plots provide traffic breakdown by protocol and application type.

---

[3] John T. Chapman, “Multimedia Traffic Engineering: The Bursty Data Model”, SCTE Emerging Technologies 2002.

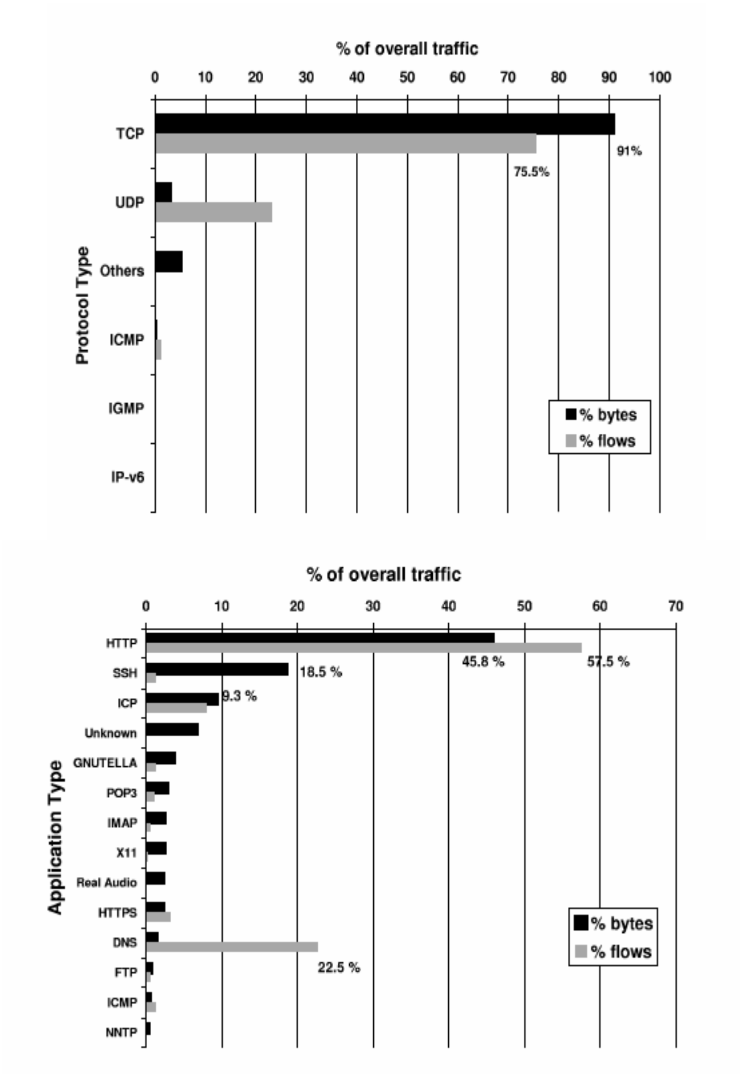


Figure 6. Traffic breakdown by protocol type and application type for a 3-day conference.

Recent studies suggest that more than 50 percent of Internet traffic is P2P file sharing. According to Time Warner Cable, 12 percent of users use 80 percent of capacity and on some ISPs up to 70 percent of upload traffic is P2P. However since P2P traffic is sent and received within HTTP messages for some applications such as KaZaA, and use TCP/IP in other proprietary mechanisms such as Bittorrent, the above results include the P2P traffic, even if the P2P traffic is not outlined separately.

As discussed above, a useful and simple model for representing the activity of a data user on an access network, such as the cable network providing DOCSIS services or the community mesh network, is the Bursty Data Model. This model is based on observed behavior of the users' network usage. It describes various levels of burstiness of data by categorizing traffic into different usage scenarios. Each scenario has an interval of time known as the measurement interval. During that interval, the number of users and their bandwidth usage is determined. The average per user data rate for that interval is then calculated by dividing the total measured data by the length of the measured interval and total number of users.

For our modeling purposes we define three different scenarios: ***average, peak***, and ***max***. The average scenario considers the network usage over relative long time periods and represents the performance seen by the user over a long time interval on a loaded network. The relationship between these time intervals is depicted in Figure 7.

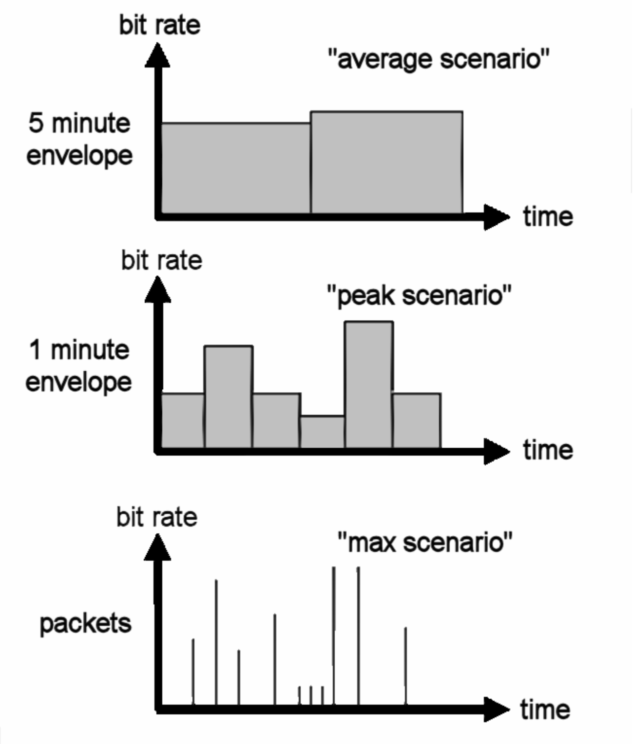


Figure 7. Relationship between average, peak, and max data rates of the BDM

We have taken the published results of public WLAN usage from [3] to arrive at average and peak data rate measurements for our system. A peak rate of 590 kbps and an average data rate of 80 kbps are given in this paper as representative rates for web traffic per user. Given that the mesh network will have a rate limit of 2 Mbps for individual users, taking into account packetization overhead, we have chosen the user's max data rate to be 1.9 Mbps. These rate assumptions are summarized in Table 1. The second row shows actual line rate, while the first row data indicates application layer data payload rate.

	Average one way data rate (kbps)	Peak one way data rate (kbps)	Max one way data rate (Mbps)
Application data rate	80	590	1.9
Line data rate	90.4	621	2.0

Table 1. Variable Bit Rate data model parameters

Assuming 1500-byte payload for Ethernet frames and 40-byte TCP/IP headers, for the peak and max scenarios, we will have an effective throughput of 95% for application payload over links that use Ethernet. As a result a data rate of 590 kbps of application goodput will have used an actual bandwidth of 621 kbps (590 kbps * 100/95) over the injection layer link. The average data scenario assumes a 400-byte data payload.

Injection Layer User Capacity – To answer the question of how many typical users can be supported by a collection of mesh neighborhoods that are served by a 2 Mbps (aggregate 4 Mbps bi-directional) injection layer sector, we will follow the computational model of [2]. Assuming a 2

Mbps raw injection layer bandwidth and an oversubscription factor of 20 (assuming over a one minute interval, only one out of twenty users will use the network at its peak rate), a single sector of an injection layer will be able to support 64 users as shown in the equations below:

$$S = \frac{LinkBW}{d \times BW_p}$$

$$S = \frac{2000000}{0.05 \times 621000}$$

$$S \approx 64$$

where *LinkBW* is the total available bandwidth over the injection layer, *d* is the inverse of the oversubscription factor for peak rate, also known as session density, and BW_p is the average peak rate of a single user, corrected for IP and Ethernet header overhead. For our system, a peak rate oversubscription factor of 20 is reasonable[4], effectively assuming one out of 20 active users will be receiving data at the peak rate, thus $d = 0.05$.

Mesh layer consideration – A market penetration of 2000 users over the entire community and a total number of 699 mesh access points in the area, corresponds to an average of approximately 3 users per mesh node. As a result, given the roughly 64 users per sectors calculated previously, we arrive at the general rule of 20 mesh nodes per injection layer sector.

4.5.2. Voice Data Model

Telephone systems have been very closely monitored for over 100 years. The public telephone systems incorporate statistical over-subscription of phone lines. In the United States, there are typically between four and eight phones per active (served) phone line in the network. POTS (plain old telephone system) networks are designed to have a specific probability that a call can be blocked from time to time. In the United States, call blocking is typically limited to 0.5 to 1% of total calls.

Typical residential users offer 0.15 Erlangs of voice traffic to the POTS network. One Erlang equals one active call hour (or 3,600 call seconds) of voice line use per active line. Since a single phone line will not be active all the time, it is possible to multiplex a larger number of phone lines, M, to a smaller number of trunks, N, which are connected to telephone switches at the telephone company central office, where M > N. Although not likely, with this arrangement it is possible that a call will be blocked at initiation time if all the trunks are already busy. The Erlang-B formula provides the probability of a call being blocked, for a typical offered load, and number of trunk lines as follows:

$$P_r = \frac{\frac{A^N}{N!}}{\sum_{j=0}^{N} \frac{A^j}{j!}}$$

With

---

[4] The oversubscription factor is a design choice driven by a number of factors, including observation of actual user behavior in the deployed area and the measure of acceptable delay (or buffer size) the provider is willing to impose on he users, for the worst case congestion scenario among other factors. Oversubscription factors of 4 to 100 have been reported for various ISPs.

- A = Offered traffic load in Erlangs
- N = Number of trunks
- P_r = Probability of blockage (GoS)

In the context of VoIP, we are interested in determining the amount of dedicated bandwidth that must be set aside to support a given number of simultaneous phone conversations. In that respect, a single trunk line of the above equation will be interpreted as a single active phone conversation. If the total number of users multiplexed is *S*, then the offered voice load to the network will be $A = 0.15S$. For a given blocking probability, then it is possible to solve the Erlang-B equation for N[5]. Thus it is possible to represent the number of trunk (or active) lines as a function of number of network users, N(S). This relationship is plotted in Figure 8. We see that for 60 users, we need to set aside the amount of bandwidth equivalent to 17 phone conversations to allow toll quality service.

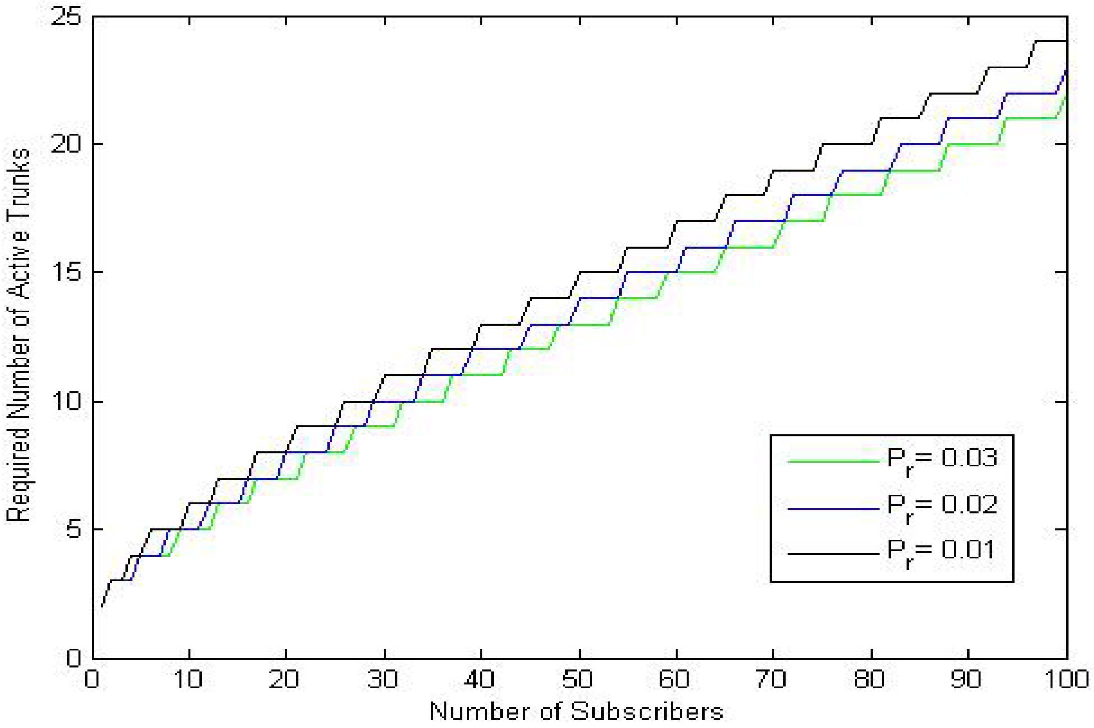


Figure 8. Required active trunks for VoIP operation as a function of user (subscriber) count

Next we need to determine the amount of required bandwidth for a single active call. The following table represents the required one-way bandwidth for various codecs used in VoIP [5].

---

[5] This equation would be solved iteratively to find N as a function of S.

Coding algorithm		Bandwidth (kbps)	Sample (ms)	Typical IP bandwidth (one way) (kbps)
G.711	PCM	64	0.125	80
G.723.1	ACELP	5.6	30	16.3
G.723.1	ACELP	6.4	30	17.1
G.726	ADPCM	32	0.125	48
G.728	LD-CELP	16	0.625	32
G.729(A)	CS-ACELP	8	10	24

Table 2. One-way bandwidth requirements for VoIP codecs

Following the methodology of [5], we use the average of 64 kbps as the required one-way bandwidth per call for our system.

Users per Sector – Assuming a VoIP market penetration factor of *p* – that is, a fraction *p* of wireless data users will subscribe to the VoIP service provided – we arrive at the following equation for the total required bandwidth for VoIP with S number of data users:

$$CB(S) = BW_v \times N(pS)$$

Assuming the same number of users have a session density of *d* for their peak rate we will have the following total consumed bandwidth for data

$$VB(S) = BW_p \times d \times S$$

Now we are ready to formulate the total consumed bandwidth of users that are served by a single injection layer sector. The total consumed bandwidth is:

$$BW = CB(S) + VB(S) + H$$

where *H* is the total amount of bandwidth needed for overhead to support network management functions. For the case of Tranzeo mesh technology, an assumption of 21 mesh nodes per sector is in order. A total of 30 bytes/sec of data payload per mesh node in each direction is the typical network overhead. After accounting for IP and Ethernet header overhead, this translates to 265 bps per mesh node. Thus in our case, $H = 21 \times 265$ bps is the network management overhead per sector. The following diagram shows the required amount of injection layer throughput for a sector serving 21 mesh nodes for various values of peak data session density, VoIP penetration factor, and call blocking probability.

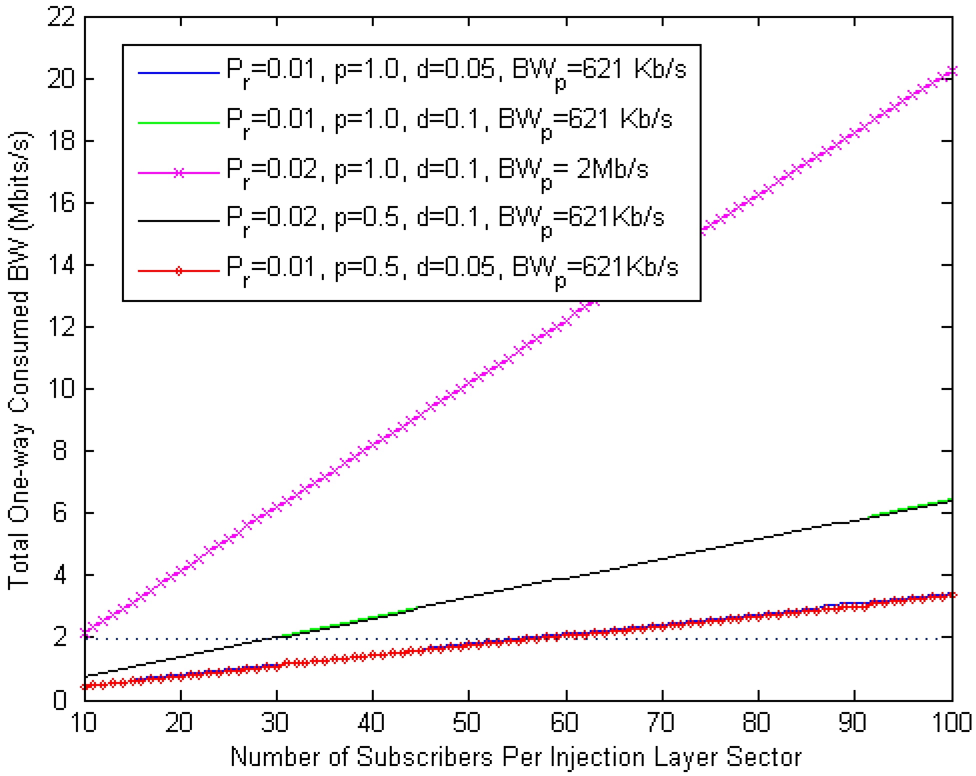


Figure 9. Bandwidth consumed per injection layer sector

Based on the results above, a number of interpretations for the final design of a network can be made. Of importance is understanding the relationship between the available bandwidth of the injection layer, and the number of supported users per injection points. We see that the expected peak rate of the users (BW) and the session density (d) are important factors in determining the number of users per injection layer PoP.

We thus see that an important issue for the community to consider is a usage model for VoIP traffic. Planning for VoIP traffic highlights the need for end-to-end QoS across the network. Also, a model for VoIP traffic will be an important input to the process of sizing of the injection layer.

4.6. Injection Layer Capacity Requirements

By applying the statistical multiplexing model to the network topology developed for this design, we can evaluate the ability of injection layer technologies to fulfill a 2 Mbps expectation when a user runs a bandwidth test. The two injection layer technologies under consideration are 900 MHz wireless and fiber. In the first table, the fiber injection bandwidth has been sized to provide the user with a 2 Mbps experience. The fiber rate required varies from between 2 Mbps and 7 Mbps:

Type	Location	Repeaters	Gateways	Total APs	Fiber Rate (Mbps)	Capacity Test (Mbps)
Traffic Lights	A	4	1	5	2	2.0
	B	5	1	6	2	2.0
	C	5	1	6	2	2.0
	D	9	1	10	3	2.0
	E	6	1	7	3	2.9
	F	14	1	15	5	2.2
	G	2	1	3	2	2.0
	H	3	1	4	2	2.0
	I	11	1	12	4	2.2
	J	13	1	14	5	2.4
	K	16	1	17	6	2.4
	L	15	1	16	5	2.1
	M	5	1	6	2	2.0
	N	8	1	9	3	2.2
	O	16	1	17	6	2.4
	P	6	1	7	3	2.9
	Q	0	1	1	2	2.0
Schools and Fire Stations	1	10	1	11	4	2.4
	2	11	1	12	4	2.2
	3	10	1	11	4	2.4
	4	20	1	21	7	2.2
	5	13	1	14	5	2.4
	6	18	1	19	6	2.1
	7	6	1	7	3	2.9
Parks and Open Space	N1	12	1	13	4	2.1
	N2	8	1	9	3	2.2
	N3	4	1	5	2	2.0
	N4	7	1	8	3	2.5
	N5	14	1	15	5	2.2
	Totals	**271**	**29**	**300**		

Table 3. Fiber rates required to meet 2 Mbps capacity test

Evaluating the 900 MHz injection technology in a similar manner shows that the user experience will fall short of expectation. In this case, a constant 2 Mbps is used to describe the available injection bandwidth. The user experience is observed to be in the range of 0.3 Mbps to 2 Mbps. There are several approaches which could be used to solve this problem:

- Break up the 900 MHz injection layer into smaller point-to-multipoint sectors
- Selectively employ point-to-point 900 MHz injection
- Use 900 MHz technology that provides more bandwidth (some vendor alternatives appear to exist)
- Selectively use 5 GHz injection
- Selectively employ more fiber points
- Utilize licensed band spectrum

Site Name	Height (ft)	Sector	Repeaters	Gateways	Total APs	900 MHz Rate (Mbps)	Capacity Test (Mbps)
1	150	SW	37	5	42	2	0.3
		NW	19	6	25	2	0.5
		SE	14	2	16	2	0.8
7	120	SE	16	3	19	2	0.7
4	120	E	8	3	11	2	1.2
		S-SW	0	3	3	2	2.0
2	120	NW	5	3	8	2	1.7
		SE	10	4	14	2	1.0
5	120	Omni	36	6	42	2	0.3
3	120	N-NW	11	4	15	2	0.9
N4	120	Omni	2	8	10	2	1.3
N2	120	N	8	6	14	2	1.0
		SE	6	2	8	2	1.7
N3	120	SE	6	3	9	2	1.5
		NW	32	6	38	2	0.4
N5	120	NW	10	4	14	2	1.0
Q	70	SW	20	5	25	2	0.5
		Totals	**240**	**73**	**313**		

Table 4. Predicted capacity test results using a 900MHz injection layer

4.7. Coverage

The community is broken down into the following areas:

- Exclusion Area: areas excluded from coverage due to land use (woods, fields, freeways, office parks, school grounds)
- Total Service Area: Community Area minus Exclusion Area
- Access Point Coverage: Access point coverage area using existing street lights for mounting assets
- Targeted Service Area: areas targeted for future service when mounting infrastructure becomes available

Please refer to the table below for a coverage summary.

Areas were calculated using image processing techniques applied to satellite maps of the community. Please refer to Exhibit TBD for a satellite view of the community depicting the coverage areas.

Area Description	Area (sq. mi)	Percent of Community	Percent of Total Service Area	Mesh Nodes
Entire Community	13.3	100 %	-	
Exclusion Area	2.7	20%	-	
Total Service Area	10.6	80%	100%	699
AP Coverage	9.3	70%	88%	613
Targeted Service Area	1.3	10%	12%	86

Table 5. Summary of community AP coverage

The AP Coverage Area in this design is serviced by 613 mesh nodes with WiFi access points, which results in an average density of 66 nodes per square mile. Applying this metric to the Targeted Service Area results in an additional 86 nodes to finish out the community. Therefore a projected number of 699 nodes will be required to service the Total Service Area of the community.

Another way to arrive at the required mesh node density is to calculate the areas of overlapping access point coverage. Some overlap is desirable and necessary to achieve continuous coverage, and further overlap is necessary when using mesh links to establish connectivity within the mesh layer in the presence of street corners or irregularly shaped streets. A positive result of the GIS survey is, using the street lights available, a minimal amount of AP coverage can be achieved. Referring to Table 6 below, one can see that 47% of the total AP coverage is covered by only one access point. Also, an additional 32% is covered by 2 overlapping access points. In summary, 93% of the AP coverage is achieved with 3 overlapping APs or less.

Number of Overlapping APs	Percent of AP Coverage
1	47%
2	32%
3	14%
4	5%
5	2%
6	<1%

Table 6. AP overlap

4.8. Multiple User Groups and Authentication Schemes

The network is capable of offering multiple network identities (ESSIDs) enabling the network operator to tailor security, bandwidth, quality of service and account management to the needs of users associated with each ESSID. Potential user groups identified so far include:

- Public Safety
- City Services
- School District
- Consumer Access

Once defined, the security, bandwidth, QoS and account management settings associated with each group may be configured at the NOC and dynamically adjusted if needed. For example, in emergency situations the group ‘Public Safety’ may be re-configured to receive all the available network bandwidth. Access point security may be handled in a way that is best suited for the user group and addresses their respective security needs. For example, public safety and city services will enjoy the highest available security offered by the 802.11i (WPA2) standard, while allowing for intra-group communication within the community Broadband Network. The available network bandwidth may be adjusted on a per-user or user group basis corresponding to the associated service level agreement.

4.9. Network Management

The network is designed to be managed and monitored from a single Network Operations Center (NOC) with a combination of generic and vendor-specific network management software tools and appliances widely known as the Element Management System / Network Management System (EMS/NMS). The EMS/NMS is used for the initial configuration of network elements at the access, mesh, injection and backhaul layer, as well as the configuration of network elements responsible for the enforcement of the service level parameters associated with each user group (access points and Wireless Internet Gateway). Furthermore, the EMS/NMS system is capable of dynamically adjusting service level parameters if needed. It provides the operator with a view into the network status and operations, with pre-defined error conditions raising an alarm. Finally, the NOC design provides for a secure connection from the Wireless Internet Gateway to an external OSS provider, such as Airpath / WiBoss, for the purpose of subscriber management.

4.10. Operations Support System (OSS)

An OSS, as offered by Airpath, enables WISPs to deploy and manage subscriber-related functions in a metro scale environment. These include user authentication, billing, customer service, trouble ticket generation and tracking, and roaming support for guest users. Subscriber usage tracking, as well as reporting of network-related issues experienced by individual subscribers, are also included in their service offering, allowing the network operator to adjust the network configuration and respond to network failure conditions.

4.11. Applications

- Public Safety – Using standard 802.11b/g WiFi cards, police vehicles may move throughout the community with access to the broadband network to enable applications which rely on broadband voice, video and data transfer. The Public Safety ESSID is secured with standards-based strong encryption.
- City Services – Members of mobile city service groups are given access to the network via a secured ESSID.
- School District – Students and faculty may access the network with their laptops, PDA's and WiFi-enabled phones.
- Consumer Access – Home subscribers may purchase an inexpensive CPE to supply the household with broadband access. Mobile subscribers may access the network from laptops, PDAs and WiFi-enabled phones.

5. RF Plan and Measurements Methods

The wireless mesh network designed for community uses radio frequency (RF) communication to connect three tiers of the communication system:

1. User access via 802.11b/g radios in the 2.4 GHz band,
2. 5.8GHz mesh links to relay user data with high communications capacity to aggregate user flows in the mesh,
3. Selected injection radio links to extend the mesh coverage across the community.

Each of these network layers is illustrated in the network diagrams in Figure 1, Figure 4, and Figure 5. To design each of those layers of our network we started with measurements using representative equipment for each network layer in the community in October 2006. These measurements were used in conjunction with simulation and analysis to prepare a set of design rules. The design rules were then used to create the mesh, AP, and injection layers of the community network design. The design rules included conservative margins for error at each layer in accounting for RF propagation obstruction, foliage loss, and the impact of interference in the unlicensed RF bands of interest. This section justifies the RF selection for each network segment, and in so doing discusses the design rules and methodology used to create our community network design. In each of the following three sections each layer of the municipal network RF options is considered in detail, prior to presenting an overview of the measurements supporting our design and analysis.

5.1. User Access Network Layer – RF Choice and Network Design Methodology

The access layer provides wireless network access to individual users. As a result the access layer radio frequency selection is limited by the equipment readily available to users, or equipment they may already have. The radio choice must also support adequate link closure capabilities to ensure each user can connect to a local municipal network access point (AP). In this section we discuss why we propose a 2.4GHz user access layer for the municipal network design. We also present our measurements and analysis that form our design methodology for this layer.

802.11b/g radios are currently the preeminent wireless local area network (WLAN) technology. Most laptops today incorporate client 802.11b/g radios as a standard feature, and a plethora of equipment is available to the user for choices of 802.11b/g client radios in the 2.4GHz ISM band, including a variety of high-power customer premise equipment (CPE) choices. Thus 802.11b/g radio technology was a natural first choice for the user access layer. As an example of the existing market penetration of these radios, the results of our 2.4 GHz-band RF survey of the community (available in section 5.7) showed that there is already widespread use of this technology throughout community. To verify the suitability of 802.11b/g radios for the access layer we considered whether most users would be able to leverage their current systems to close reliable communication links or whether the widespread existing usage of 802.11b/g would prevent effective throughput over the link. Thus a first step in evaluating the suitability of this radio choice was to measure the performance of access point links using representative mesh radios mounted in representative locations in the community. A complete discussion of those measurements is provided in section 5.5.

Our access layer measurements demonstrated reliable 802.11b/g links in the community within 500 feet of light pole-mounted access points. These measurements included propagation tests through dense trees and around buildings to adjoining streets. Along streets and across unobstructed areas serviceable communication links were tested at distances in excess of 1000 feet.

The results of these tests led to our AP design methodology: to consider an area covered if one wall of a house was within 500 feet of our access point. It was assumed that it was sufficient to reach one wall of a house since a CPE device with a 200 milliwatt transmit power (equal to our measurement equipment's transmit power) could be mounted at the house. While the circular coverage assumption is a very rough estimate, it includes significant fade margin as demonstrated in our measurements, and thus represents a worst-case coverage scenario for the access points. In addition, the significant circular overlap increases the network redundancy of the access point layer, so that 55% of the proposed community access coverage is within 500 feet of two or more access points.

Our measurements demonstrated that 2.4GHz would provide reasonable penetration within the community, given that a dense mesh network was deployed (see section 5.2 for more details on this topic). However, while using existing widely adopted radio minimizes user costs, it also means that each user access link is operating in a widely used spectrum. Thus link usage planning should allow for interference within this layer of the network.

The 802.11b/g radio and 2.4GHz RF spectrum was chosen for the community access network due to the following considerations:

- While a large number of existing 802.11b/g radios are operated in the community these are primarily located indoors and operated at low power. Thus the same link range limits on access point communication measured within the community will localize interference. As most commercial 802.11b/g radios on the market operate well below the FCC radiated power limits of 36dBm EIRP, the typical interference range of the existing radios will be significantly less than that of the proposed community Wireless Network.
- The 802.11b/g radio standard was developed to allow fair use of the radio spectrum between multiple radios all operating in the same local area. This sharing of the channel operates efficiently when the channel usage is less than 70% to 80% of channel capacity. Using 802.11b/g at the access layer for a single hop providing 2.0 Mbps uplink or downlink represents a fraction of the available capacity for each link to the access point. As a result, multiple users can be supported in each local frequency spectrum (for example using the highest 802.11g rate which provides an effective data rate of around 25Mbps). In addition this provides some margin for other interference, and particularly as any of the three non-overlapping 802.11b/g channels can be assigned to any access point in our proposed network design.
- Contention and collisions in the access layer are dictated not by the number of existing access links, but by the traffic over those access links. Even with a high density of existing 802.11b/g radios, many of these radios are likely to only see limited use. Even with dense deployments of the proposed access points in the community network design, interference and channel usage scales with the traffic the users transfer, not with the number of access points. This occurs since the control traffic sent by 802.11 radios is a very small fraction of the available capacity.
- The choice was made to use a mesh radio provider that does not operate in the same band as the user access radio (a two-radio mesh device). This localizes the interference observed between users at each access point, and allows more control and resilience in the mesh network, as discussed in more detail in the following section.

5.2. Mesh Layer – RF Choice and Network Design Methodology

The mesh layer of the network provides a resilient, flexible communication path between each access point and the injection layer or the community fiber MAN. The mesh may connect to the community fiber MAN either via a direct wired link (for example, the proposed fiber drop locations would also host a mesh gateway) or via the wireless injection layer, whose placement is optimized to enable a reliable wireless connection to the community fiber MAN. As a result, the properties of the mesh network affect the injection layer choices (discussed in section 5.3) as well as the density, available capacity, and redundancy provided in the mesh network. In this sub-section we discuss why we recommend 5.8GHz 802.11a radios in the municipal network mesh layer and discuss our analysis based on the measurements presented in section 5.4 to form our design methodology for this layer.

The mesh layer requires a radio choice that has similar propagation range to the access layer radio choice. The goal of the community wireless network is to provide ubiquitous access to each resident's home, as well as along main service roads. As a result the AP coverage should overlap to provide this extended wireless access "cloud". Since mesh nodes will generally be installed at elevated locations (for example on street lights) the link between mesh nodes will often be less cluttered than the access layer links from each of those nodes. As a result, even though the 5.8GHz band incurs more loss in penetrating foliage than the 2.4GHz band does, in general the mesh links penetrate less foliage than the access links. As a result, for continuous access layer coverage, the choice of the mesh radio is anticipated to require similar propagation range to that of the AP radio, or mesh links constrained to 1000 feet, since each node contains both a mesh and access radio.

Another consideration in choosing the mesh radio is that it should enable reliable end-to-end communication across the mesh that supports defined service standards. Extending the length of the end-to-end path (i.e. the number of mesh hops) enables flexibility for where injection radios are placed. To achieve end-to-end reliability, error margin must be incorporated into the system design by reducing the maximum mesh radio link range estimate. In addition, the mesh layer susceptibility to interference is more critical than at the access layer since the mesh relays traffic over multiple hops and each new hop is an opportunity for interference to degrade the end-to-end communication path. To eliminate self-interference from the access layer, which also has a negative effect on mesh capacity, we used a separate frequency band for the mesh layer in our network design.

In this design, five to six relay hops are needed to provide the greatest mesh design flexibility. Mesh neighborhoods that fall short of these hop counts while providing multi-megabit data rates would require a larger number of injection points. This is impractical and not cost effective as the injection locations are often much more restricted than the potential mesh locations. As demonstrated with our design, using a six-hop mesh criterion requires eleven injection towers, fifteen injection base stations and seventy-four injection radio subscriber modules. The large number of towers required results from the dense foliage in the community, while the large number of subscriber modules results from a high incidence of isolated street light in areas without any mesh neighbors; this will be discussed in detail in section 5.3.

The selection of the mesh radio technology was driven by the need to support the defined service standards over at least six hops (2Mbps uplink or downlink across the mesh) and a range comparable to the access point range. In addition, we required that these mesh radios be currently available, preferably from multiple vendors. 802.11a radios meet all these requirements when operating in the 5.8GHz bands. As discussed in section 5.4, we measured ranges in excess of 1000 feet along uncluttered paths in the community with 5.8GHz radios. The range was restricted to 400 feet if the link penetrated a single tree (approximately ten meters of foliage), and we could observe high variability in the ability to close links through more than one tree. This matches the behavior observed for the demonstration five-node mesh network currently in place around the community municipal buildings.

However, as demonstrated in our measurements, a concern when operating in the 5.8GHz band is the poor foliage penetration. According to the International Telecommunication Union Radio sector (ITU-R) the propagation loss per meter of foliage at 5.8GHz approaches 1dB/m. However, we still believe 802.11a is the best choice for the mesh due to the limited existence of other interferers at 5.8GHz, the elevated FCC radiated power options compared to the 5.2GHZ UNI band, and the demonstrated potential to close links in the community supporting tens of megabits (needed to maintain more than 2Mbps uplink or downlink over six mesh hops).

802.11a radios operating in the 5.8GHz ISM band provide the best radio option for use in the mesh layer. Following this choice as a mesh technology we established design rules we used to create our mesh network design. The design process for the mesh started with evaluating each inter-mesh path from a candidate mounting site using Google Earth's satellite photography, Microsoft Local Live's local aerial photography, and the recorded indication at each light pole (obtained in our GIS survey) of the street lights that are clearly visible from each street light location. This evaluation provides a street light separation and anticipated foliage blocking the individual links. Mesh links were allowed according to the following rules:

- Up to 1000 feet range if the direct path between mesh nodes was clear of obstruction.
- Up to 400 feet link range if one tree or approximately ten meters of foliage obstructed the path.
- Do not rely on any mesh links through paths with two trees or more in the direct path.

Based on the mesh and access guidelines, nodes were placed to reduce node densities when possible and maximize mesh link margins, while maintaining contiguous AP coverage within each neighborhood. The resulting mesh network connectivity using these mesh and access design guidelines are shown in our KML exhibit, within the directory "Mesh Neighbors". Anticipated mesh paths based on our conservative estimates are shown.

The mesh topology and the capacity funneling into each injection link through the mesh dictate the number of injection points that are needed and where they will have to be located. Given the multi-hop throughput capability of the mesh, we allowed at most six mesh hops from any node to the injection point, with a preference for five or fewer hops. To limit the bottleneck imposed by each injection link, we load balanced the mesh and collocated AP's to meet the capacity models discussed in the capacity plan section of this document. The considerations for the injection design, and method used to create our community network design are discussed in the following section.

5.3. Injection Layer – RF Selection and Design Discussion

The injection layer is designed to connect the mesh layer to the community fiber MAN. The most reliable approach to connect the mesh layer to the Internet would be to bypass the injection layer and provide a direct wired link from mesh gateway nodes to the fiber MAN. However, given the points at which fiber connections can be made and the constraints of the mesh layer topology, this is not cost effective for every mesh neighborhood in the community. We evaluated a number of wireless injection layer technologies to reach a balance between performance and cost for each of the coverage areas.

Our evaluation of radio technology options focused primarily on differentiating frequency bands. Since the FCC limits the radiated power primarily based on frequency band many technologies are often comparable in band, such as the 900 MHz Cascade radios and the radios provided by

Tranzeo. Similarly, most competitive radios provide comparable receive sensitivities and antenna gain options in each frequency band. Thus, instead of evaluating specific radio technologies, our injection layer propagation analysis focused on comparing frequency bands using representative radio specifications. The starting point in our evaluation was to select two candidate injection frequency bands, and collect measurements in the community around the municipal tower (described in detail in section 5.4). We augmented these measurements, which were only taken around the municipal tower at a 60 foot height, with analysis and simulation. We correlated the simulation results with our measured data to limit the high degree of predictive accuracy that often results from simulation of complex propagation environments. Using the correlated simulation tools we evaluated the locations for injection points throughout the community to conservatively assess the capability of each injection link. Specifically we selected points that could serve as injection clients of subscriber modules (SMs) within the proposed mesh locations. We simulated the links from these sites to multiple proposed injection tower locations. We designed the injection layer to support, rather than to dictate our mesh and access layers. This section first discusses the choice of frequency and required number of injection base stations, and proceeds with a discussion of the design method used with the chosen 900MHz injection technology to select appropriate locations in the community.

The measurements conducted around the municipal tower illustrated the difficulty of penetrating foliage at the injection layer. The furthest distance within the community from the two existing towers exceeds three kilometers and due to the ridges, the valleys, and the heavy foliage across the community additional injection towers were required. As an example of the difficulty we will consider a canonical case of the Fire Tower (36m tall) communicating to an injection SM on a street light at a height of 7.6m. This simplified example is shown in Figure 10. We will make the simplifying assumption that the community is flat and entirely covered by trees that are 15m tall (our GIS survey indicated that most of the canopy was estimated at 15m to 20m in areas of dense foliage). Using simple geometry at a radial distance from the injection tower to SM of d the path penetrating the foliage canopy is $0.26d$. Thus, for a path length of 1km any trees in the 260m of the path closest to the SM would block the signal. For much of the community, which has dense foliage near many of the residential locations at which mesh nodes are desired, this translates to over 150m of foliage penetration. This results in a path loss of around 100dB at 5.2GHz or 5.8GHz. Our measurements also showed that 150m of foliage penetration at 900 MHz, where the loss is approximately 0.2dB/m, meant closing links reliably was not possible in most cases. This simple example illustrates the difficulty that heavy foliage presents to the injection layer.

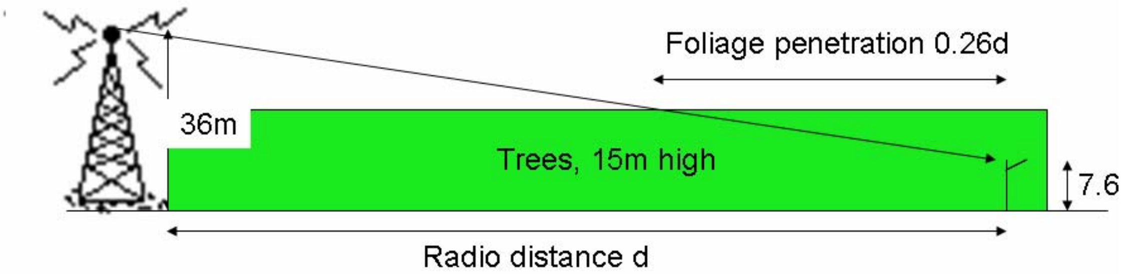


Figure 10. Simplified example illustrating injection link obstruction by foliage

To understand what frequency to use for the injection layer, we considered available technologies that could support more than 2Mbps uplink or downlink at low cost in the network. The resulting product evaluation led to our consideration of point-to-point and point-to-multipoint technology in the following three frequency bands:

- The 902-928MHz ISM band – Equipment is limited to a 36dBm EIRP by the FCC and antenna gains are limited to 10-15dB for reasonably-sized antennas. The radio system used in our measurements is representative of these systems. Of particular concern for 900MHz is the high level of interference due to adjacent paging bands (observed at the high end of the spectrum coming from the south of the community) and the transitory interference from other users in the band such as telemetry devices, lottery terminals, and power monitoring equipment. This interference is illustrated in section 5.7 presenting the noise background at each school and a number of the proposed parks.

- The 5.25 to 5.35GHz UNI band – Equipment is limited to a 30dBm EIRP by the FCC, although antenna sizes allow for higher gains. However, limited commercial choices for antennas and the limits by the FCC on the maximum EIRP for high gain antennas limit the utility of this band even though it would not interfere with either the mesh or access layer frequency choices. Very limited noise is observed in this band in the community as illustrated in our exhibit presenting the noise background at each school and a number of the proposed parks.
- The 5.725 to 5.875GHz ISM band – Equipment is limited to a 36dBm EIRP by the FCC and a wide variety of antenna options and gains are available. The FCC allows higher EIRP for point-to-point solutions using high gain antennas. Little noise is observed currently in the community in this band as illustrated in our exhibit presenting the noise background at each school and a number of the proposed parks. However, any injection system using this band would have to share the frequency band with the mesh layer.

In our injection design, a goal of the radio technology selection was to limit the injection towers required, while providing reliable links. Based on our measurements, the main concern with using the 900MHz band is the extent of existing interference in this band (as shown in detail in the figures in section 5.7) assuming reasonable levels of foliage penetration (up to 20dB of loss or less than 100m of foliage along links). Finding links that are predominantly free of foliage is the main constraint on the injection layer design if equipment that operates in the 5.2GHz or 5.8GHz band were to be used in the injection layer.

Prior to considering each technology, we first selected candidate injection tower locations. Using our injection layer measurements we estimated a reliable coverage area of half a mile from the municipal tower for the links that were closed at 900MHz with a 60-foot injection base station antenna height. Assuming ½ mile injection links were often plausible, we selected a variety of potential tower locations that would cover most of the community. In selecting these locations we considered potential sites at town parks, schools and town open space. To provide further flexibility on which towers were chosen we utilized the planned municipal tower height of 46 meters and the 36 meters of the fire station tower as a representative heights for all other towers. Increasing the tower heights well above the 18m used in our injection layer measurements reduces the potential foliage in each path and extends the viability for closing and comparing links at further distances than our simple ½ mile estimate. The resulting candidate locations are presented in Table 7. Our design did not use all of these locations, but these were the locations evaluated to support the network and evaluate the choice of 5 GHz or 900 MHz as the injection layer operating frequency.

Site Name	Longitude (°)	Latitude (°)	Projected Tower Height (m)
1	-X.20166	Y.15220	45
7	-X.15993	Y.13747	36
4	-X.17000	Y.12900	36
2	-X.18259	Y.16542	36
5	-X.17064	Y.15140	36
3	-X.14720	Y.14087	36
8	-X.20799	Y.13964	36
N4	-X.20153	Y.17606	36
N2	-X.17671	Y.17120	36
N1	-X.15798	Y.16209	36
N3	-X.18464	Y.13701	36
N5	-X.17322	Y.11691	36

Table 7. Tower locations evaluated based on a 1/2 mile injection range estimate.

The next step in our injection frequency comparison was to use these candidate tower locations to establish what line-of-sight (LOS) views existed from each tower within the community to at least the top of the surrounding trees or structures in the community. LOS plots allow us to quickly eliminate regions that are completely obstructed and should not be considered as candidate links to each tower. As Figure 11 and the LOS-simulation KML exhibit illustrates the LOS extensive coverage regions from the top of each tower to the top of the local canopy. This illustrates that if each injection SM were raised to the height of the canopy (usually 15 to 20 meters in areas with trees), then foliage free links are possible, and operating in the 5GHz band would be a viable option. To create these plots the absolute elevation of each tower height was computed using 10m resolution ground truth data available from the publicly-available US Geological Survey. Then the top of the canopy and surrounding building heights was determined using the publicly-available shuttle radar topography mission (SRTM) data. To determine the canopy height, the SRTM data used a combination of radar and lidar to measure elevation from the space shuttle. The absolute tower heights were then used in the Radio Mobile Deluxe propagation simulation tool to plot the LOS between each pole height and the top of the canopy, or first return echo from the SRTM data. From the KML file in the attached exhibit, a screen shot of which is shown in Figure 11, the proposed pole locations can be seen to cover the top of the canopy across the community. The LOS plot also allows us to quickly determine locations that should be considered based on the perspective of each potential tower location. In the KML exhibit, the LOS coverage from any individual tower is selectable.

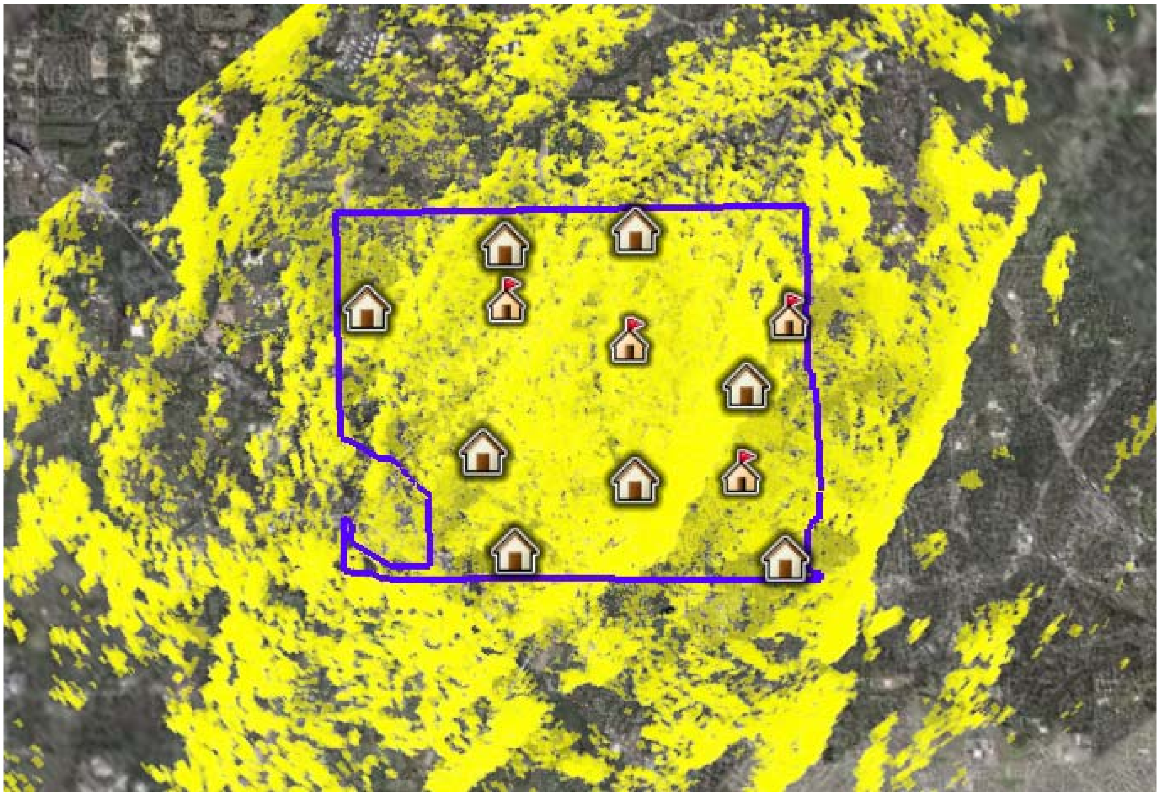
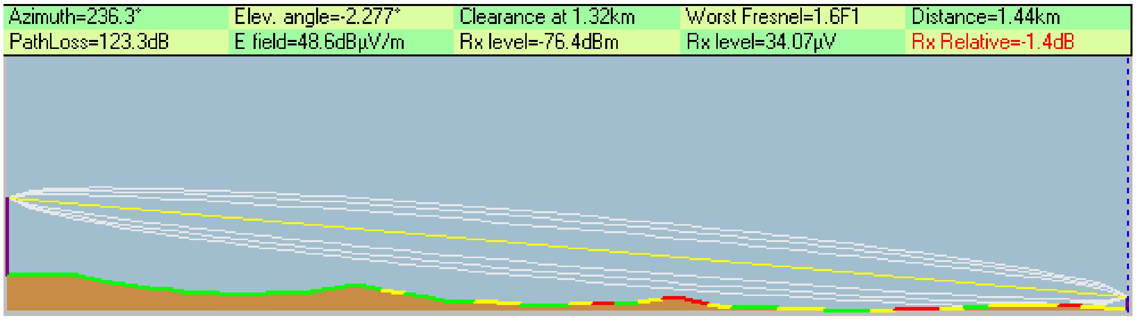


Figure 11. Illustration of LOS coverage to the top of the canopy from the potential injection towers.

To select between the 5.8GHz, 5.2GHz, and the 900MHz injection technologies for the injection layer (or to recommend a combination of them) we must determine the prevalence of foliage along each link between the SM and each surrounding tower. Our design assumed that injection layer SMs would not be mounted above the canopy, but co-located with certain mesh nodes at the height of the street lights considered for mounting the mesh node. The street light height in the community is approximately 7.6 meters for a luminary street light and 4 meters for an ornamental street light. To evaluate the potential of each injection frequency band we chose a number of mesh nodes whose top canopy, based on the LOS plots, appeared to have a clear link to one or more injection towers. Then for these links we estimate the propagation loss and the foliage loss to penetrate the canopy. For each of potential injection SM locations we first evaluated the link elevation profile, in the Radio Mobile Deluxe tool. An example of an elevation profile between the Municipal Tower and mesh node 30 is shown in Figure 12. This figure illustrates that assuming 100m of foliage in the 1.44 km path (19.5dB loss at 915MHz) the Radio Mobile Deluxe tool estimates a signal level of -76.4dBm for the 900MHz Cascade injection equipment with omni-directional antennas on the tower. However as can be seen from the figure, the amount of foliage in the link depends on how many trees are in the right-most 20% of the path, as the rest of the link clears the observed tree heights. Assuming tree heights of 20 meters, we consider a tree to obstruct the path if part of the tree blocks the yellow line. This elevation profile is based on the 10m elevation data provided by the USGS and is thus the actual ground height, not the canopy height. To determine the amount of foliage in the first fifth of the path we use the aerial photographs available in Google Earth, and measure the length of the path in that foliage. For the link between node 30 and the 45 meter Municipal Tower we calculated that only 30m (approximately three trees) obstruct the 20% of the direct path nearest the street light-mounted SM. Thus this link would be a candidate for 900MHz injection as the foliage penetration is well below the 100m estimate in our path loss calculation. However, this link would require

30dB of foliage margin at 5.2GHz and potentially even more foliage penetration margin at 5.8GHz.



Azimuth=236.3°	Elev. angle=-2.277°	Clearance at 1.32km	Worst Fresnel=1.6F1	Distance=1.44km
PathLoss=123.3dB	E field=48.6dBµV/m	Rx level=-76.4dBm	Rx level=34.07µV	Rx Relative=-1.4dB

Figure 12. Elevation profile of the link between the 150ft Municipal tower and node 30 mounted at 30ft on a street light.

Our method of considering the path profile, viewing the Radio Mobile Deluxe simulated path loss, and estimating the foliage penetration based on the path profile was used to evaluate every injection link included in our network design. To illustrate the difficulty of closing these links at either 5.2GHz or 5.8GHz, and the need for the large number of injection towers chosen, we present a list of the injection links in our design in Table 8. In addition to the links listed in this table, a variety of other links were also evaluated and considered to be too high risk, due to long paths through foliage and the low signal levels predicted by Radio Mobile Deluxe in each frequency band considered. As illustrated by the median of 40m of foliage obstruction, closing these links is feasible at 900MHz, however the use of a 5.2GHz or 5.8GHz injection layer is not viable. In the 5.8 GHz band, equipment that adapts links using adaptive antenna arrays is allowed by the FCC to emit up to 48dBm EIRP, with the option to use high-gain antennas to further improve link closure capability. An example of this type of equipment is provided by SkyPilot. However, to be comparable to the 900MHz equipment, these 5.8 GHz-based systems would require at least 30dB of additional link margin to be a viable option, and even with this margin could not close a large portion of the links specified. Thus we have concluded in our injection design that a 900MHz injection layer solution is required, with the potential to address individual links with different radio technologies.

Injection Base Station	Link distance (km)	Estimated Foliage along Link (m)	Simulated 915MHz Signal, 20dB foliage and 10dB fading (dBm)
Q	0.26	25	-59.8
Q	0.45	5	-71.7
Q	0.16	20	-53.8
Q	0.46	40	-64.7
Q	0.84	40	-67.8
N3	1.24	40	-71.7
N3	0.62	15	-74.0
N3	0.74	40	-78.0
N3	1.47	40	-81.2
N3	0.85	15	-80.9
N3	0.93	10	-81.8
N3	0.76	150	-58.9
N3	1.03	75	-80.7
N3	1.26	110	-79.3

Injection Base Station	Link distance (km)	Estimated Foliage along Link (m)	Simulated 915MHz Signal, 20dB foliage and 10dB fading (dBm)
7	0.29	60	-70.6
7	0.58	80	-81.9
7	0.36	100	-67.1
N2	0.79	20	-78.5
N2	1.11	20	-73.5
N2	1.03	110	-72.5
N2	1.21	90	-71.8
N2	0.72	5	-78.5
N2	0.51	20	-65.0
N2	0.6	30	-67.3
N2	0.86	40	-68.9
5	0.38	100	-60.3
5	0.28	40	-67.0
5	0.76	60	-69.6
5	1.18	10	-71.3
5	1.39	70	-69.9
5	1.19	75	-66.9
2	1.21	50	-72.6
2	0.73	40	-74.0
2	1.65	60	-71.7
2	0.29	40	-81.2
2	0.59	25	-74.3
2	0.34	50	-69.6
2	0.96	5	-76.4
2	1.15	10	-70.3
1	0.29	20	-66.9
1	0.68	10	-71.3
1	0.74	75	-64.7
1	1.19	60	-69.9
1	1.03	110	-59.2
1	1.54	60	-81.1
1	1.44	30	-83.0
1	1.02	50	-70.0
1	0.62	100	-76.7
1	0.81	75	-65.1
1	0.18	15	-71.8
1	0.55	50	-68.4
1	0.76	20	-75.0
N5	0.64	15	-70.3
N5	0.87	25	-70.5
N5	0.7	20	-72.0
N5	1.58	50	-56.6
4	0.75	5	-71.9
4	0.45	10	-74.9
4	0.72	30	-74.6
4	1.23	10	-74.0
4	1.21	15	-71.7

Injection Base Station	Link distance (km)	Estimated Foliage along Link (m)	Simulated 915MHz Signal, 20dB foliage and 10dB fading (dBm)
4	0.63	100	-65.3
3	0.7	5	-66.5
3	0.73	40	-71.6
3	1.16	50	-72.7
3	0.24	60	-57.8
N4	0.42	30	-75.5
N4	0.64	90	-71.1
N4	0.29	30	-68.2
N4	0.42	25	-65.2
N4	0.59	70	-65.1
N4	0.43	70	113.4
N4	0.61	80	-66.3
N4	0.55	110	-68.8
Median	**0.75**	**40**	**-71.7**

Table 8. Designed injection links illustrating the foliage penetration estimated for each link.

In our injection layer analysis we have specified twelve potential injection towers. These tower locations were selected using a simple 3/4 km community coverage estimate. Each potential injection link was then considered. In our analysis we used a conservative estimate of the foliage in the injection link path and a minimum link sensitivity of -75dBm, although most 900MHz radios specify sensitivities of -80dBm or less. This -75dBm conservative sensitivity estimate was used to account for the some of the impact of the background interference. In our injection link measurements in excess of 2Mbps uplink or downlink capacity was measured for signal levels down to -80dBm. However, transitory interference, particularly at signal levels close to -80dBm, would often restrict throughput over the injection layer at the lowest signal levels. Our link analysis also used a conservative antenna gain by assuming omnidirectional antennas at each tower. In our design we specify predominantly sector antennas which provide a few dB of additional gain in the path loss calculation in comparison to the available omnidirectional antennas.

Although our analysis started with a large number of candidate tower locations, we made an effort to limit the number of poles utilized in our final design. Unfortunately due to the heavy foliage and topology we were not able to significantly reduce the number of towers. The recommended eleven tower locations are listed in Table 9. This includes ten of the original twelve sites and one additional 70-foot pole near the traffic light at Butler Pike and Welsh Rd. While this is a large amount of infrastructure to support the injection layer, based on our measurements and our analysis of over one hundred potential injection SM locations we believe this level of coverage is required for a reliable injection layer. Even with the eleven tower locations, our network design assumes many mesh gateways are directly connected to the community fiber MAN, bypassing the lower-bandwidth 900MHz injection layer. At seventeen traffic lights, as well as at each of the towers, it is assumed that direct connections will be made to the MAN. A list of the locations of the mesh gateways that connect directly to the community fiber MAN, the intended minimum height of those gateways, and the number of mesh repeaters estimated to connect to the Fiber MAN through each gateway is shown in Table 10. Direct injection points were used when possible to support the mesh in order to limit the required number of injection towers.

Our design calls for nine additional injection towers and an increase in height of the Municipal tower as shown in Table 9. In addition, our design, assumes available connection to the community fiber MAN at each of the locations listed in Table 10. Our understanding is that at each of the locations listed under “Schools and Fire Stations” connections to the community fiber MAN are currently planned. Additionally, the design requires CT Fiber MAN connections at each of the tower locations, the listed traffic lights, and parks. Each of the locations at which a tower is assumed in our design also has a connection the community fiber MAN. At each of the locations where a connection is made to the fiber MAN, a mesh gateway is placed to serve multiple mesh repeaters or, as in the case of the tower at the traffic light at Butler Pike and Welsh, only serves as an access point for the access layer.

Site Name	Latitude	Longitude	Antenna Type and Direction	Projected Tower Height (m)
1	Y.1522	-X.20166	3 sectors: SW, NW, SE	45
7	Y.13747	-X.15992833	1 sector: SE	36
4	Y.129	-X.17	2 sectors: E and S-SW	36
2	Y.16542	-X.18259	2 sectors: NW and SE	36
5	Y.15140307	-X.17064134	Omnidirectional	36
3	Y.14087	-X.1472	1 sector: N-NW	36
N4	Y.1760574	-X.20153328	Omnidirectional	36
N2	Y.1712	-X.17671	2 sectors: N and SE	36
N3	Y.13701	-X.18464	2 sectors: SE and NW	36
N5	Y.11691	-X.17322	1 sector NW	36
Q	Y.1836317	-X.18804	1 sector: SW	21

Table 9. Proposed locations for the injection towers in the network design

	Direct Mesh sizes	Mesh Gateway Height (m)	Number of mesh repeaters served
Traffic Lights	A	7.6	4
	B	7.6	5
	C	7.6	5
	D	7.6	9
	E	7.6	6
	F	7.6	14
	G	7.6	2
	H	7.6	3
	I	7.6	11
	J	7.6	13
	K	7.6	16
	L	7.6	15
	M	7.6	5
	N	7.6	8
	O	7.6	16
	P	7.6	6
	Q	7.6	0

	Direct Mesh sizes	Mesh Gateway Height (m)	Number of mesh repeaters served
Schools and Fire stations	1	7.6	10
	2	7.6	11
	3	7.6	10
	4	7.6	20
	5	7.6	13
	6	7.6	18
	7	7.6	6
Parks and Open Space	N1	7.6	12
	N2	7.6	8
	N3	7.6	4
	N4	7.6	7
	N5	7.6	14

Table 10. Mesh gateways directly connected to the community fiber MAN

One of the reasons our design used conservative margin estimates, such as 20dB of foliage penetration and 10dB of fade margin coupled with a -75dBm receiver sensitivity, is the high levels of transient interference in the 900 MHz ISM band. As shown in our attached exhibit on noise measurement, a large amount of interference is present in the 902-928 MHz band. While much of this interference is transitory, constant interference is particularly prevalent in the upper portion of the band for south-facing antennas in the southern portion of the community. In general, each area has a different noise picture, as illustrated in the exhibit in section 5.7.

To limit the impact of this interference, as well as to increase our 900 MHz channel capacity, our design calls for injection layer base-station antennas to cover 120 degree sectors, with 9dBm or greater panel antenna gain on the SMs. In conjunction with our use of directional sectors to localize interference at each tower, emphasis was made in the design to use links for which the 900 MHz base station antenna faced north if multiple reliable links were available. The direction of each sector utilized is listed in Table 9. In our design, two locations were indicated for omnidirectional 900MHz antenna installations, and as a result have a slightly lower path loss margin since sector antennas generally provide higher gain than omnidirectional antennas. However, in each of these locations an additional level of scrutiny was used to validate links. Our use of directional antennas will mitigate noise and increase flexibility for which part of the 900 MHz band an injection radio uses. For example, the 900MHz Access Point used in testing could dwell in three non-overlapping parts of the band, allowing frequency reuse in the network design. In most locations the use of less than three sectors allows the best choice of spectrum to enable these locations to work together and avoid the more interference-prone parts of the frequency band. Particularly this use of limited sectors allow flexibility in time sharing between towers reducing tower to tower interference in the injection layer.

Our injection network design focuses on links supporting mesh nodes mounted on street and traffic lights within the community. However, not all of the community can be covered by mounting on the available lights. As a result, some areas of the community would require additional mounting infrastructure. To evaluate if our current injection design, using only 900 MHz radios and eleven towers, would cover the additional areas of the community, a Radio Mobile Deluxe coverage simulation was carried out. The results of this simulation are shown in Figure 13 and are available in the included KML exhibit. This simulation assumes omnidirectional antennas (a few dB lower antenna gain than the sector antennas) and the resulting coverage to a level of -75dBm from the eleven proposed towers is shown in Figure 13. In this figure any location in red which passes through less than 100m of foliage in its path to the nearby towers, should support an injection link to an injection layer SM at a height of 7.6m.

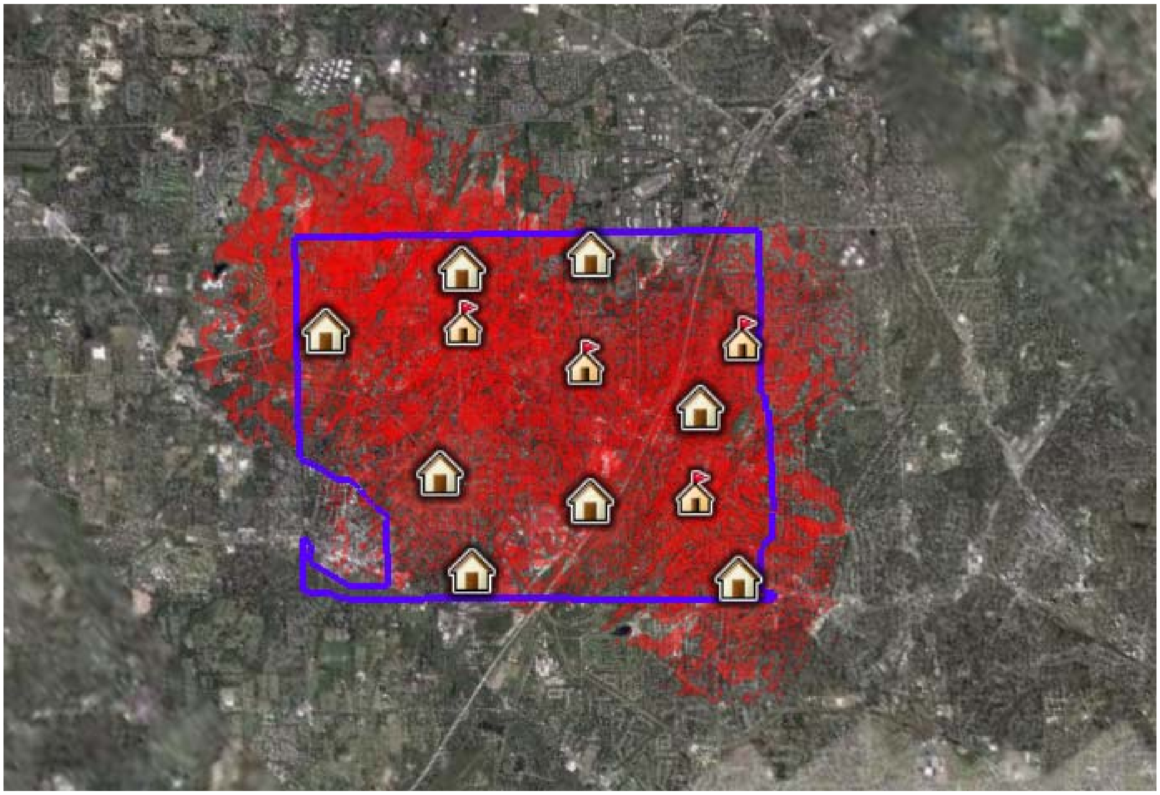


Figure 13. Simulation of the 900 MHz injection layer coverage from the eleven 36 meter and taller towers.

Uncertainties exist whenever simulation and analysis are used to design a network, instead of iterative installations. To minimize these uncertainties in our proposed design we focused on conservative estimates for link margin, and our accounting of the dominant propagation mechanisms (foliage and topography for the suburban community). Thus our conservative use of error margins and our combination of empirical measurement at representative locations, simulation, and analysis of each individual injection path leads to our confidence in the proposed network. In deploying such a system we anticipate a fraction of the mesh node and injection SM placement choices may need to be moved, however we expect that the proposed injection towers, and the proposed first strike network will provide an extensive municipal wireless network to community, and that this design provides a starting point to minimize installation changes and costs.

5.4. Injection Layer Measurements

The intent of our network design activity was to provide an estimate of the type and quantity of equipment needed for municipal wireless access in the community. Due to the heavy foliage throughout the community, one aspect of the design that was not well understood at the outset was the wireless injection from the community fiber MAN. To assist in understanding, and particularly to provide empirical data points from which we could extrapolate with simulation, approximately one hundred injection links around the Municipal tower were measured. These injection layer measurements used representative radios in the 902 - 928 MHz ISM and the 5.25 - 5.35 GHz UNII frequency bands. The radios chosen for testing were operated at the FCC limits for point-to-multipoint radios in these two frequency bands, 36dBm EIRP and 30dBm EIRP respectively. These bands were chosen as they provide different responses in passing through foliage and neither would interfere with the mesh (5.8 GHz) and access point (2.4GHz) frequencies. Injection locations to be measured were selected based on a preliminary simulation of the RF coverage from the existing radio tower in the community municipal building complex. Differences between these measurements and the simulation provided a basis for iterating simulation parameters, used to compare coverage for all proposed tower locations, and provided an empirical error margin used for all injection point links. At 900 MHz this error margin included 10dB of fading margin and 20dB of foliage loss, corresponding to a 915 MHz link penetrating 100 meters of foliage. Specifically, the injection layer measurements illustrated the difficulty of closing injection radio links using 5.2GHz equipment (for which the ITU-R recommended foliage path loss approaches 1dB per meter) and the requirement that links using 5.8GHz (for which a higher EIRP may be designed in using directional antennas) still pass through a minimum amount of foliage. As an example of the foliage loss, a link penetrating the large maple tree in front of the community offices suffered 12dB of additional loss at 5.2GHz and only a few dB at 900MHz. The results of our measurements around the municipal tower, and our subsequent simulation (as discussed further in section 5.3), were a large influence on our selection of 900 MHz radio equipment for the injection layer, and our recommendations for additional towers to support this equipment.

5.5. Mesh Layer Measurements

Mesh radio measurements were taken in the community to supplement theoretical models used for mesh node placement calculations. The heavy foliage present in many parts of the community complicates node placement and required detailed understanding of RF propagation at 5.8GHz in such an environment. Since radio placement and spacing will be heavily influenced by available mounting locations, existing foliage, and mesh link margins, many factors must be considered in the placement of radios to ensure the robust mesh radio links that are essential to network reliability.

Tests were performed in four separate neighborhoods, each with unique properties. In the first neighborhood, trees were typically old-growth that encroached on the street, obscuring line-of-sight to adjacent street lights. In these neighborhoods, luminary style light fixtures were typical. The second neighborhood consisted of sparse old-growth trees on winding streets. In general, there was fair line-of-sight with one or two trees obstruction transmission paths. The third neighborhood consisted of Manhattan-grid streets with medium height trees. There was little foliage encroachment in these neighborhoods. The last neighborhood was a newer housing area with ornamental poles. These areas had few tall trees and good to great visibility between light poles. See Table 11 for details.

Mesh and AP test neighborhood type	Canopy Height (m)	# of trees between mesh nodes	# of trees between an AP and a client device	Street Light Type
Dense old-growth trees, typically poor line-of-sight between nodes	15+	2-3	0-10	Luminary
Sparse old-growth trees on meandering streets	15+	1-2	0-5	Luminary
Medium height trees on city grid style streets	10+	0-1	0-5	Luminary
New development, few trees	N/A	0-1	0-3	Ornamental

Table 11. Mesh and AP RF test sites

At each test site, the mesh radios were mounted to the light standard (typically at 7.6 meters for luminaries and at 4 meters for ornamental poles) and powered from the existing source. A second radio was then moved to numerous adjacent light pole locations and raised for testing.

Bandwidth and received-signal-quality measurements were recorded. The GPS locations of all radio measurement locations were also recorded. The 5.8vGHz radios used in the tests were set to transmit powers of 26dBm and 24dBm for OFDM data rates of 24 Mbps and 54 Mbps respectively. The receiver sensitivities were -86dBm and -74dBm for the respective data rates.

5.6. Access Layer

Access radio measurements were taken in the community to supplement theoretical models used for AP coverage estimations. As with the mesh radio, heavy foliage, buildings and terrain posed design challenges in extending ubiquitous AP coverage throughout the community. Since AP coverage will be governed by available mounting locations, design metrics were needed that properly modeled the 2.4 GHz RF propagation in the targeted neighborhoods.

Test locations were selected in conjunction with mesh testing sites. In tandem with the mesh RF data collection, more than 50 locations were randomly sampled around each node. Samples were collected in each of the four representative neighborhoods during testing. See Table 11 for details on the different neighborhoods. At each test site, the mesh radios were mounted to the light standard (typically at 7.6 meters for luminaries and at 4 meters for ornamental poles) and powered from the existing source. A laptop, outfitted with a 200mW 802.11b PCMCIA client radio was then moved to various locations, radially outward from the installation site, to sample SNR quality and channel bandwidth potential. The location (measured with GPS), the bandwidth, and signal quality levels were logged at each location. Locations were chosen on the installation street, on neighboring streets, in driveways, and in-between houses, to better understand the extent of the AP coverage. The 2.4GHz radios used in the AP's were set to a transmit power of 26dBm for all data rates used. The receiver sensitivities were -97dBm to -92dBm from 1 to 11 Mbps. The PCMCIA client card specifications were 23dBm transmit power with a -95dBm to -87dBm receive sensitivity for data rates from 1 to 11 Mbps.

5.7. Spectrum Analysis Results

Spectrum analysis was conducted at 12 locations within the community at 30 feet AGL. One additional measurement was taken at 70 feet AGL on the pole near the municipal building. Measurements were taken with Rhode and Schwartz FHS3 and FHS6 spectrum analyzers fitted with omni-directional antennas. Measurement soak time was 5 minutes with peak hold enabled.

5.7.1. 900 MHz Spectrum

The spectrum between 900 MHz and 940 MHz was measured, even though the injection layer equipment will only use the spectrum in the 902 – 928 MHz ISM band. This was done to observe the presence of any paging systems in the area, which occupy spectrum above 928 MHz but can produce interference below 928 MHz.

5.7.2. 5GHz Spectrum

The spectrum between 5.0 and 6.0 GHz was measured. The bands of interest in this spectrum are:

- U-NII Lower Band 5.25 – 5.35 GHz for potential use as an injection layer
- U-NII Middle Band 5.47 - 5.725 GHz for potential use as an injection layer
- U-NII Upper Band 5.725 – 5.825 GHz is used by the mesh layer
- ISM Band 5.725 – 5.875 GHz for potential use as an injection layer

5.7.3. Conclusion

All the bands surveyed are suitable for injection layer and mesh layer implementation. There is existing equipment installed by the community at 900 MHz and 5 GHz that contributed to observed interference, which can be considered replaced in the network design. There is also interference observed that may be attributed to other devices in the 900 MHz ISM band, such as lottery machines, SCADA systems or other transmitters associated with Turnpike operations. The use of directional, sector antennas and frequency separation will mitigate the effects of this interference.

Location	Longitude	Latitude
N3	-X.18464	Y.13701
N1	-X.15798	Y.16209
3	-X.14720	Y.14087
5	-X.17064	Y.15140
2	-X.18259	Y.16542
1	-X.20166	Y.15220
4	-X.17000	Y.12900
6	-X.20799	Y.13964
7	-X.15993	Y.13747
N4	-X.20153	Y.17606
N5	- X.20832	Y.15028
N6	-X.17322	Y.11691

Table 12. Spectrum analysis locations

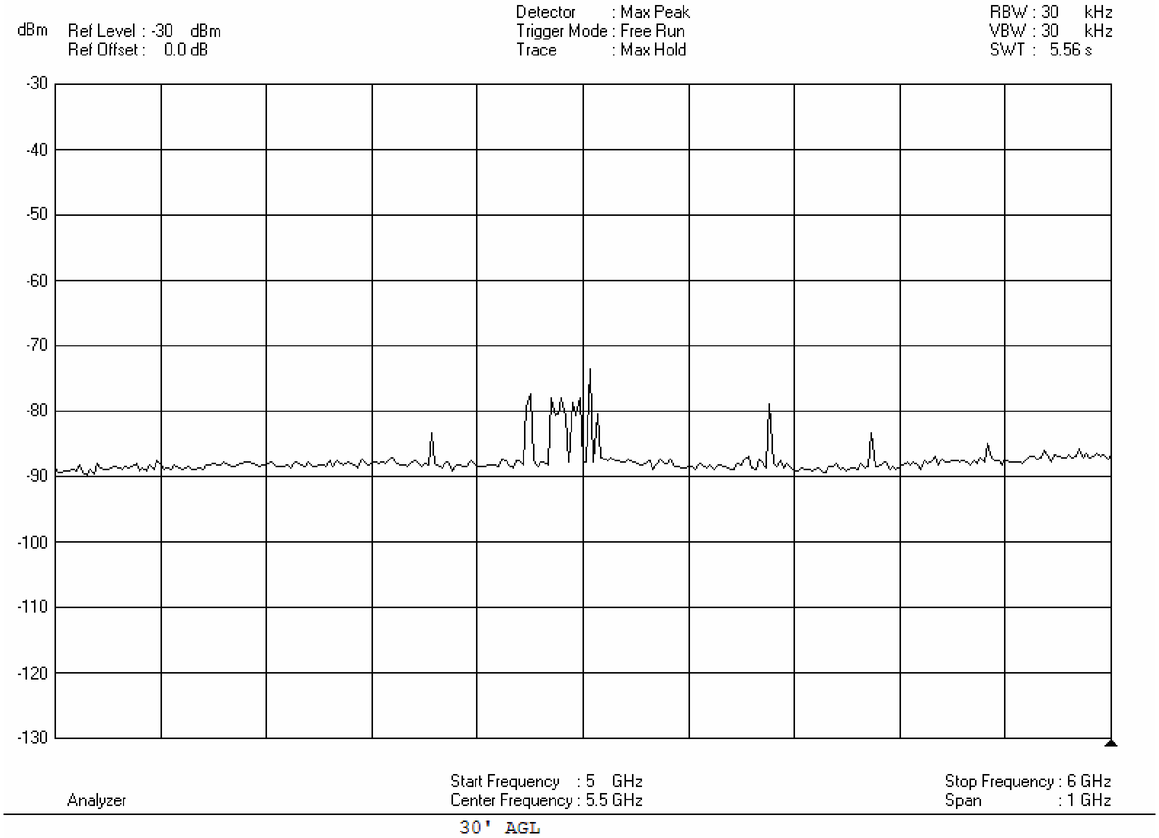


Figure 14. N3 location at 5-6GHz and 30' AGL

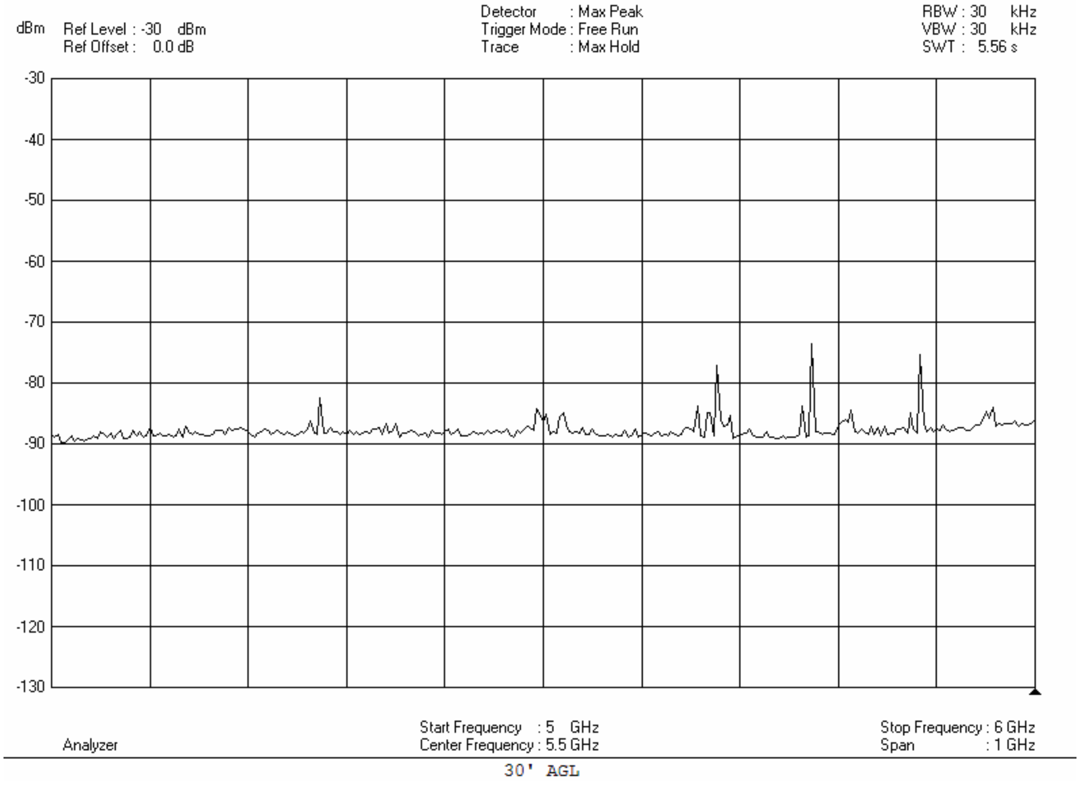


Figure 15. N1 location at 5-6GHz and 30' AGL

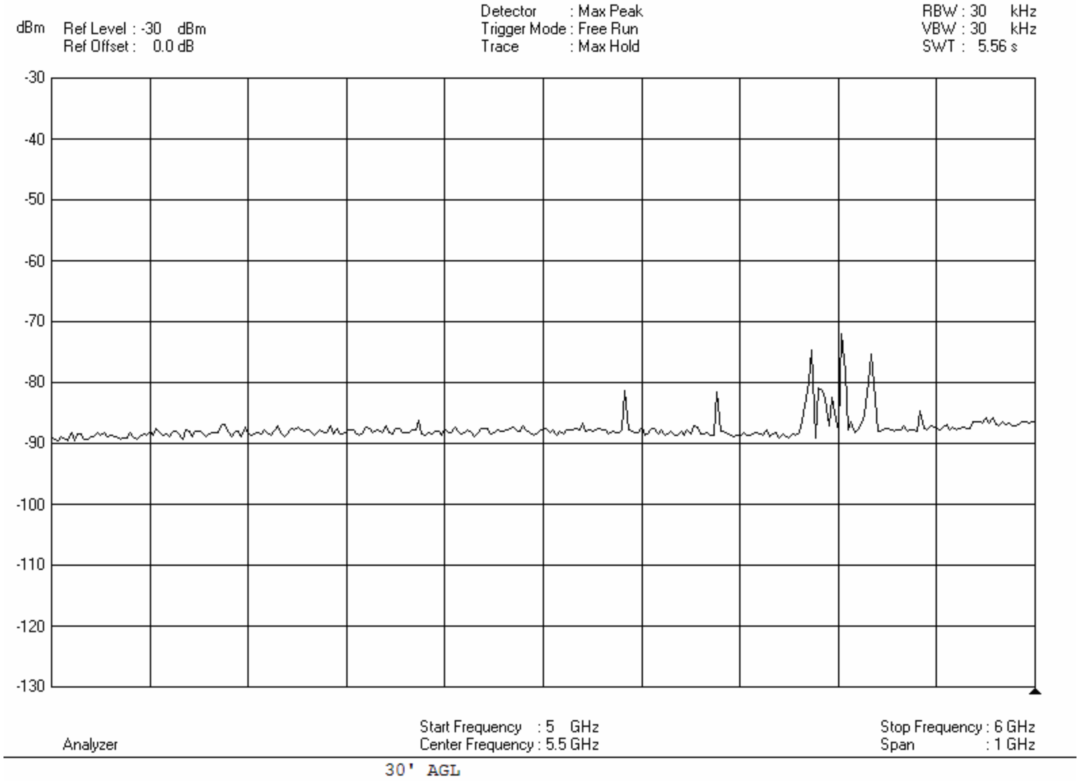


Figure 16. Location 3 at 5-6GHz and 30' AGL

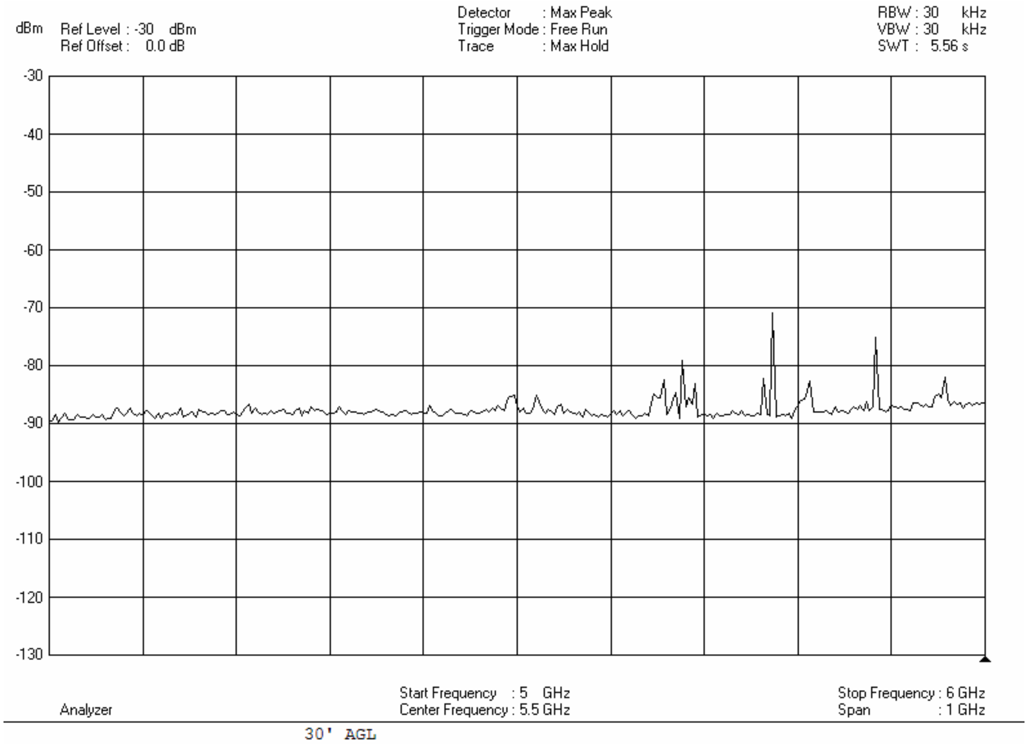


Figure 17. Location 5. at 5-6GHz and 30' AGL

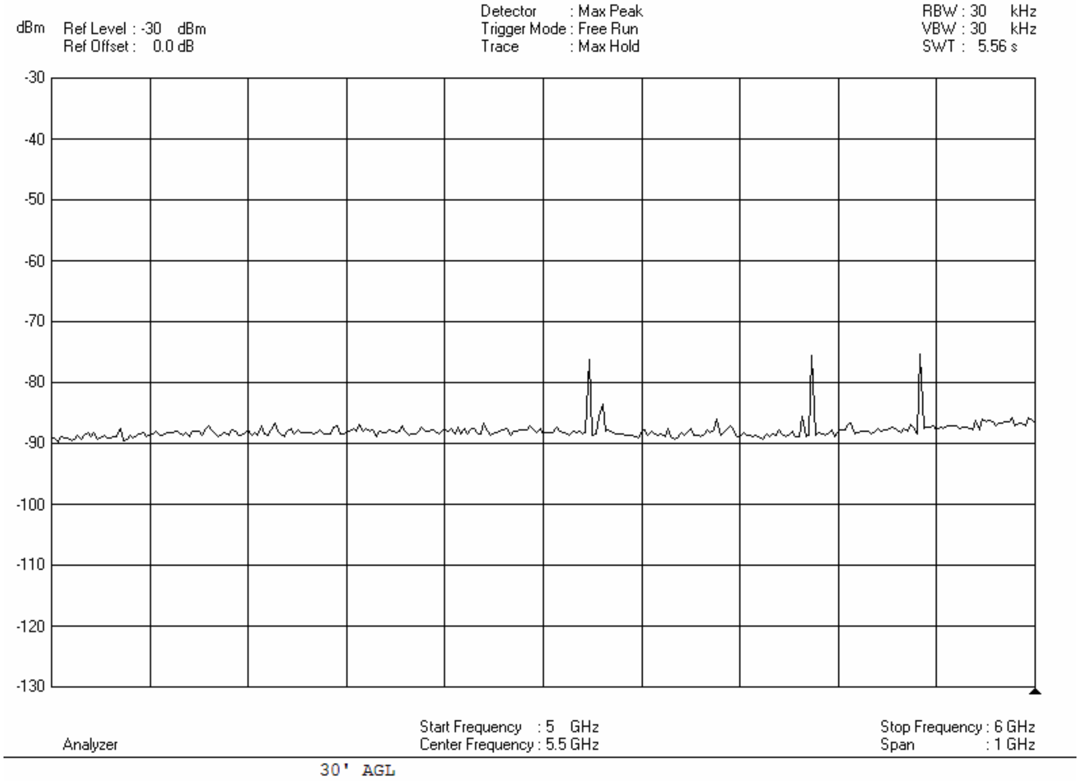


Figure 18. Location 2 at 5-6GHz and 30' AGL

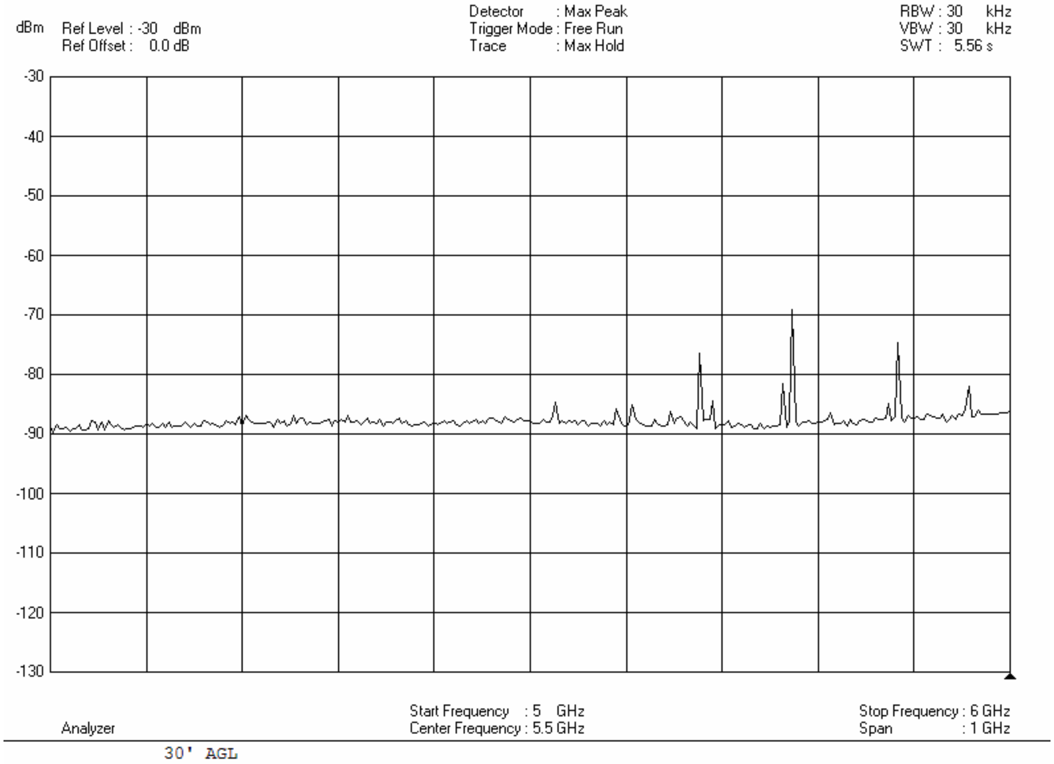


Figure 19. Location 1 at 5-6GHz and 30’ AGL

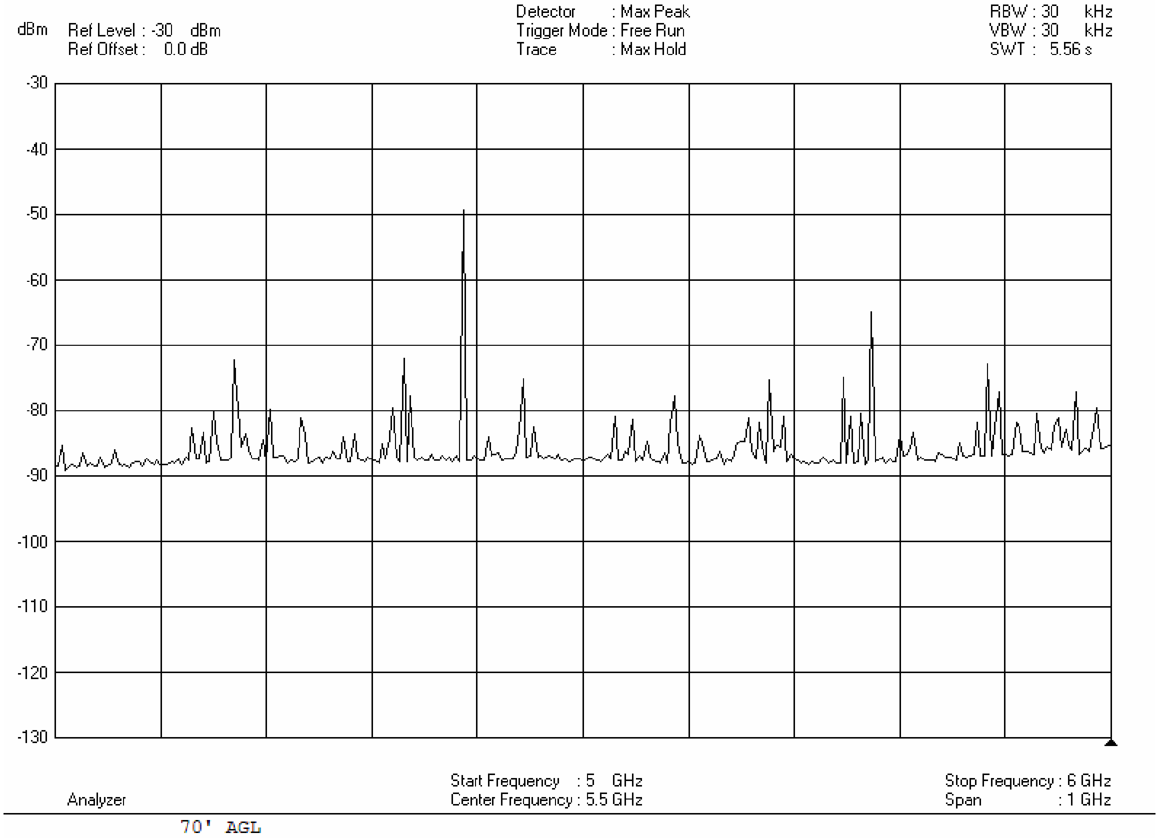


Figure 20. Location 1 at 5-6GHz and 70’ AGL

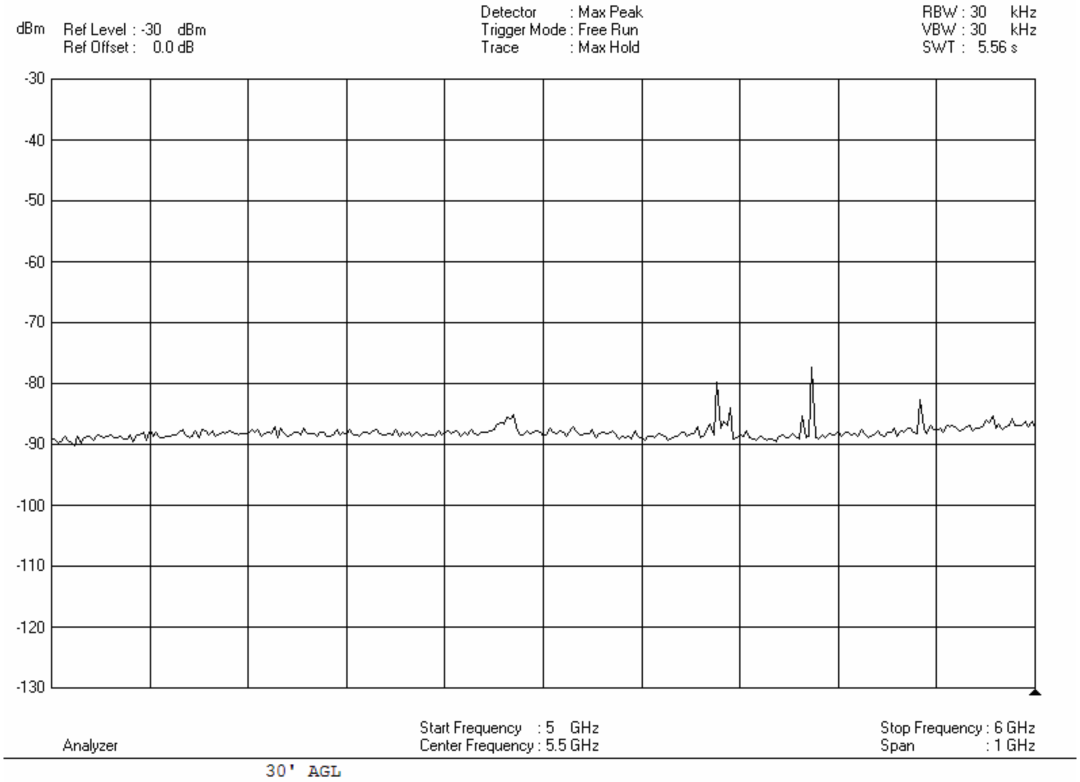


Figure 21. Location 4 at 5-6GHz and 30’ AGL

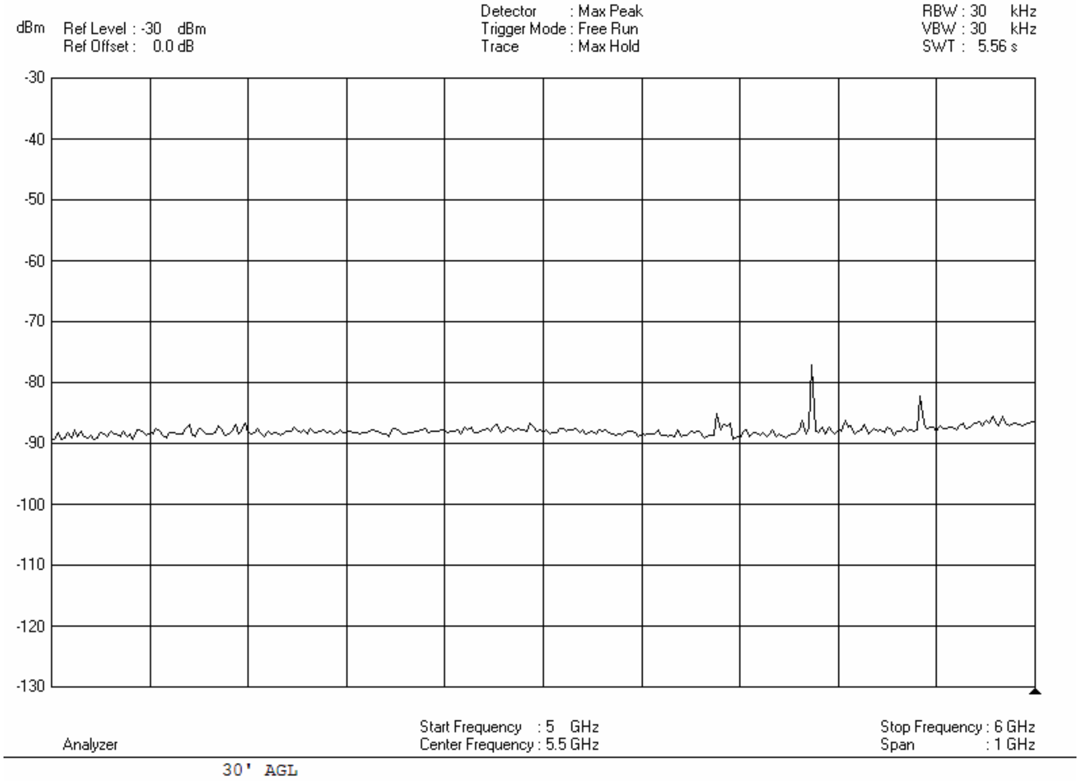


Figure 22. Location 6 at 5-6GHz and 30’ AGL

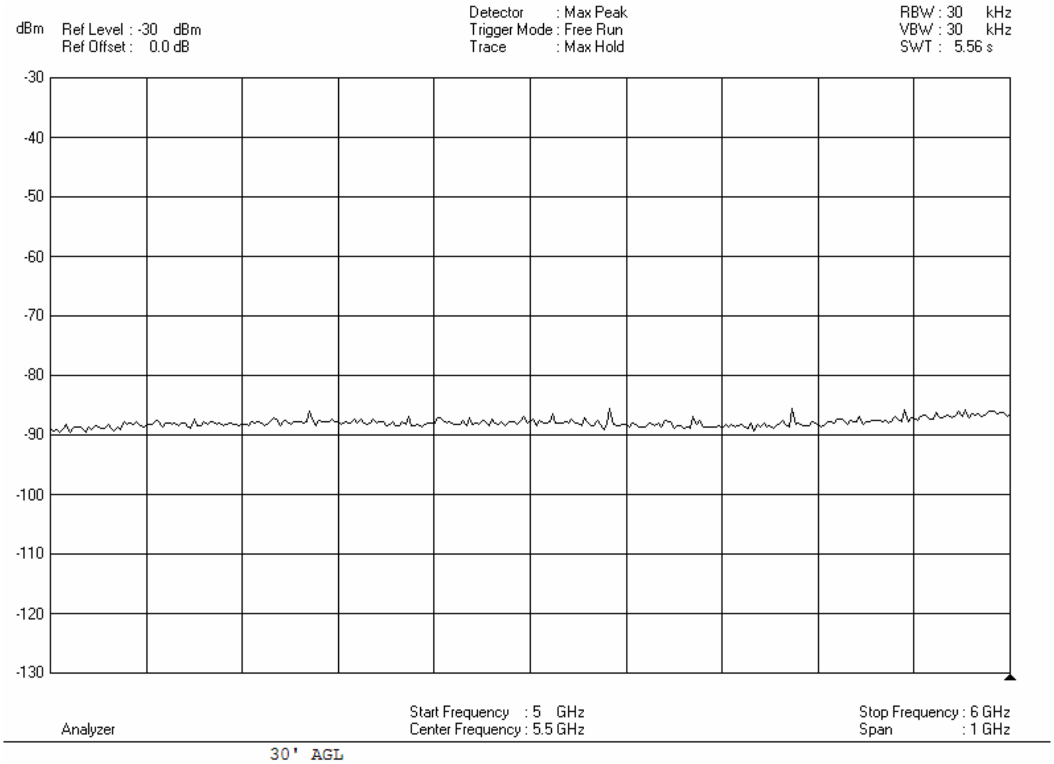


Figure 23. Location 7 at 5-6GHz and 30ft AGL.

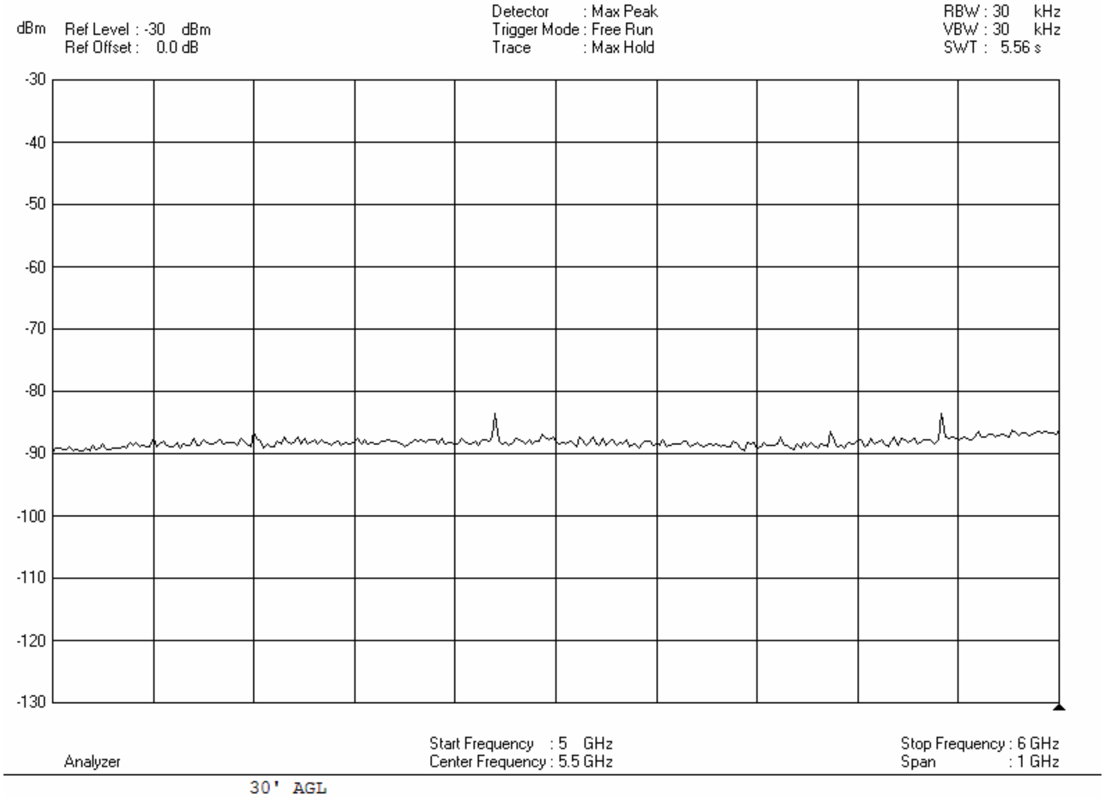


Figure 24. Location N4 at 5-6GHz and 30ft AGL.

dBm Ref Level : -30 dBm
Ref Offset : 0.0 dB

Detector : Max Peak
Trigger Mode : Free Run
Trace : Max Hold

RBW : 30 kHz
VBW : 30 kHz
SWT : 5.56 s

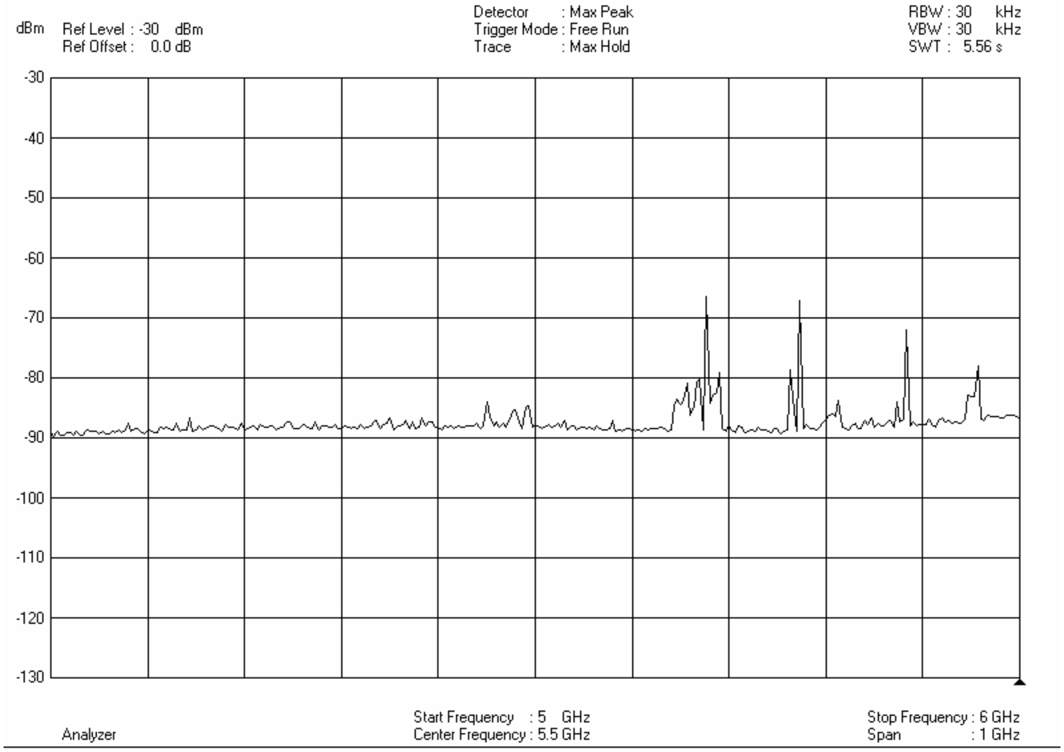
Analyzer

Start Frequency : 5 GHz
Center Frequency : 5.5 GHz

Stop Frequency : 6 GHz
Span : 1 GHz

30' AGL

Figure 25. Location N6 at 5-6GHz and 30ft AGL.



dBm Ref Level : -30 dBm
Ref Offset : 0.0 dB

Detector : Max Peak
Trigger Mode : Free Run
Trace : Max Hold

RBW : 30 kHz
VBW : 30 kHz
SWT : 5.56 s

Analyzer

Start Frequency : 5 GHz
Center Frequency : 5.5 GHz

Stop Frequency : 6 GHz
Span : 1 GHz

30' AGL

Figure 26. Location N7 at 5-6GHz and 30ft AGL.

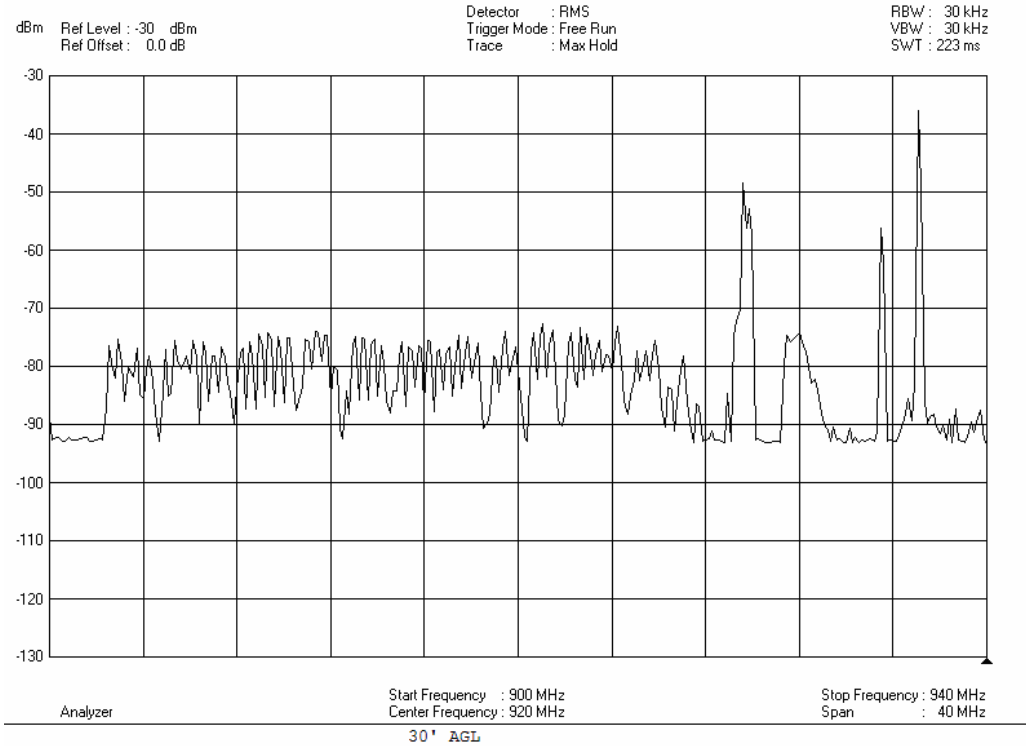


Figure 27. Location N3 at 900-940MHz and 30ft AGL.

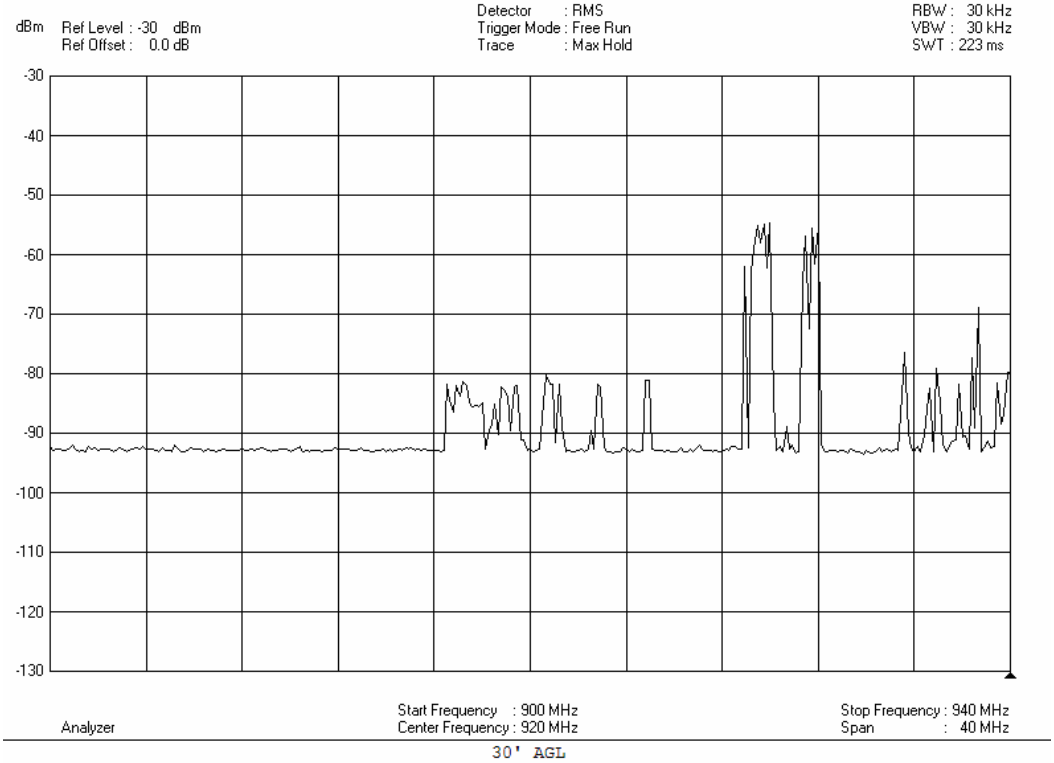


Figure 28. Location N1 at 900-940MHz and 30ft AGL.

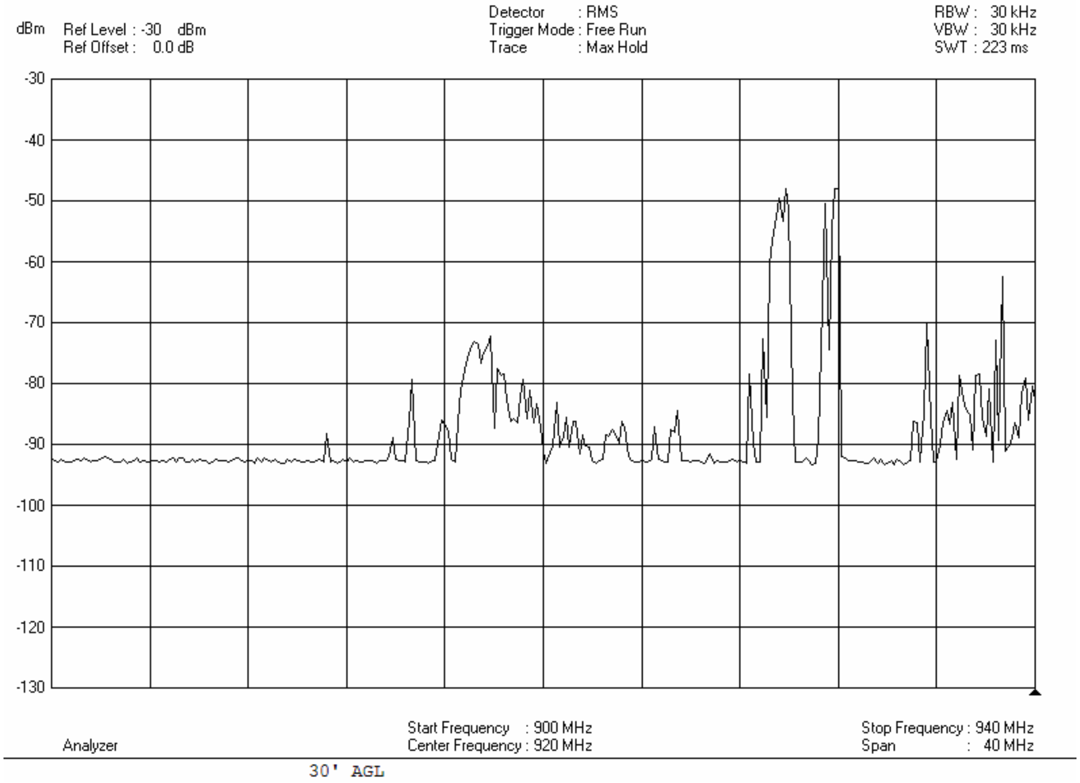


Figure 29. Location 3 at 900-940MHz and 30ft AGL.

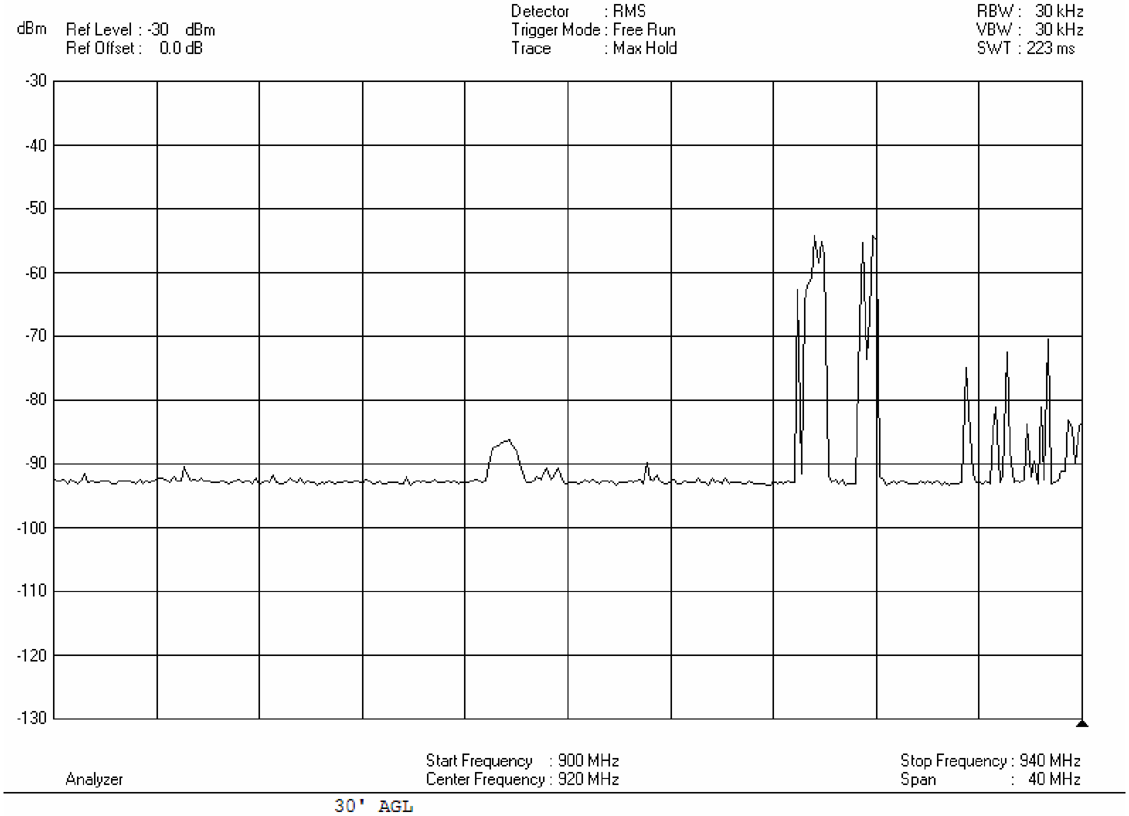
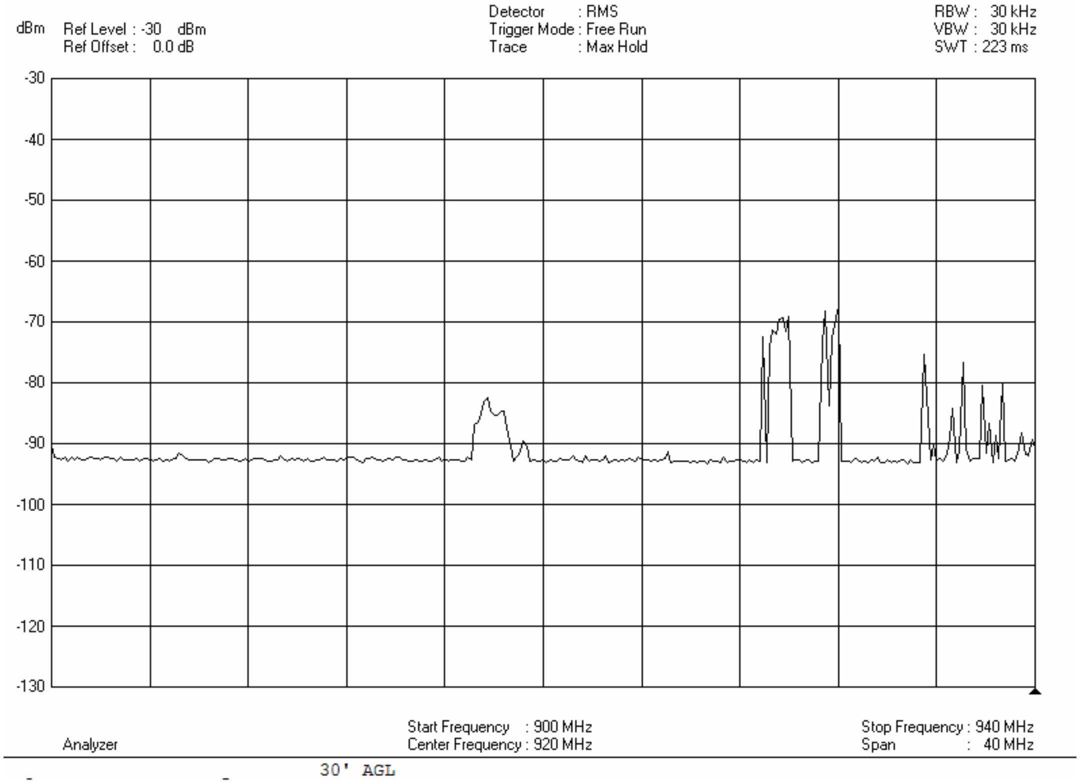
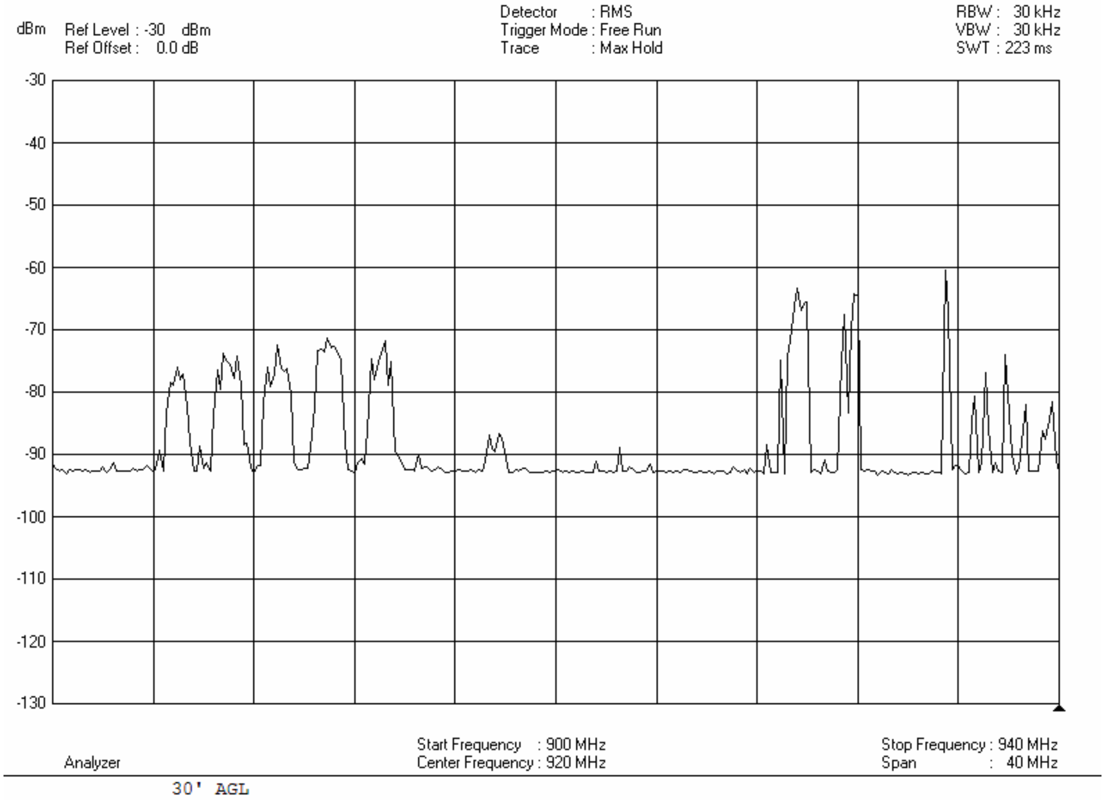


Figure 30. Location 5 at 900-940 MHz and 30ft AGL.



Ref Level : -30 dBm
Ref Offset : 0.0 dB
Detector : RMS
Trigger Mode : Free Run
Trace : Max Hold
RBW : 30 kHz
VBW : 30 kHz
SWT : 223 ms
Start Frequency : 900 MHz
Center Frequency : 920 MHz
Stop Frequency : 940 MHz
Span : 40 MHz

Figure 31. Location 2 at 900-940MHz and 30ft AGL.



Ref Level : -30 dBm
Ref Offset : 0.0 dB
Detector : RMS
Trigger Mode : Free Run
Trace : Max Hold
RBW : 30 kHz
VBW : 30 kHz
SWT : 223 ms
Start Frequency : 900 MHz
Center Frequency : 920 MHz
Stop Frequency : 940 MHz
Span : 40 MHz

Figure 32. Location 1 at 900-940 MHz and 30’ AGL

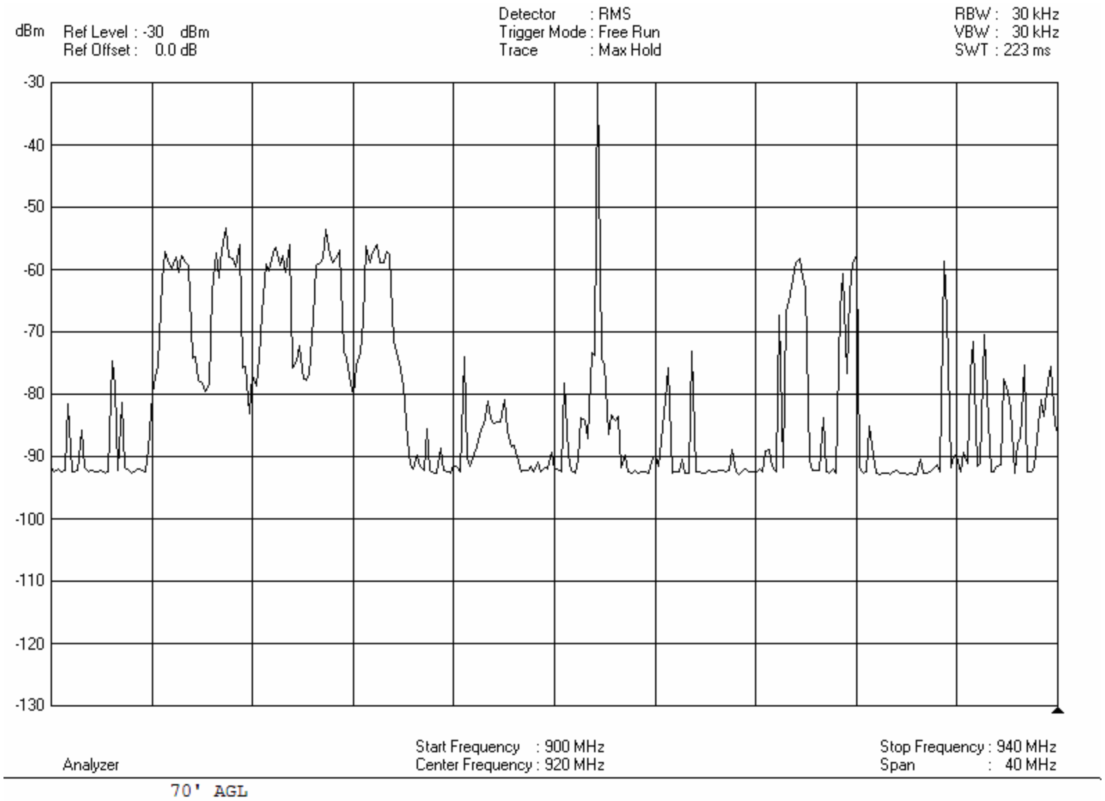


Figure 33. Location 1 at 900-940 MHz and 70’ AGL

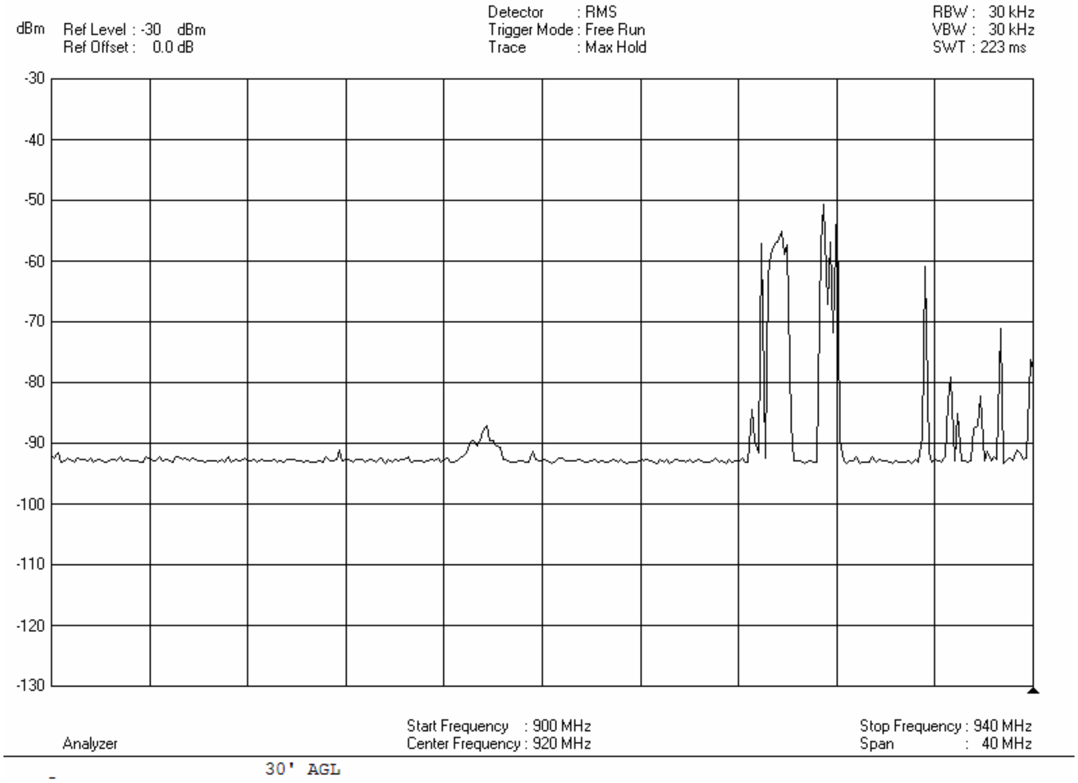


Figure 34. Location 4 at 900-940 MHz and 30ft AGL.

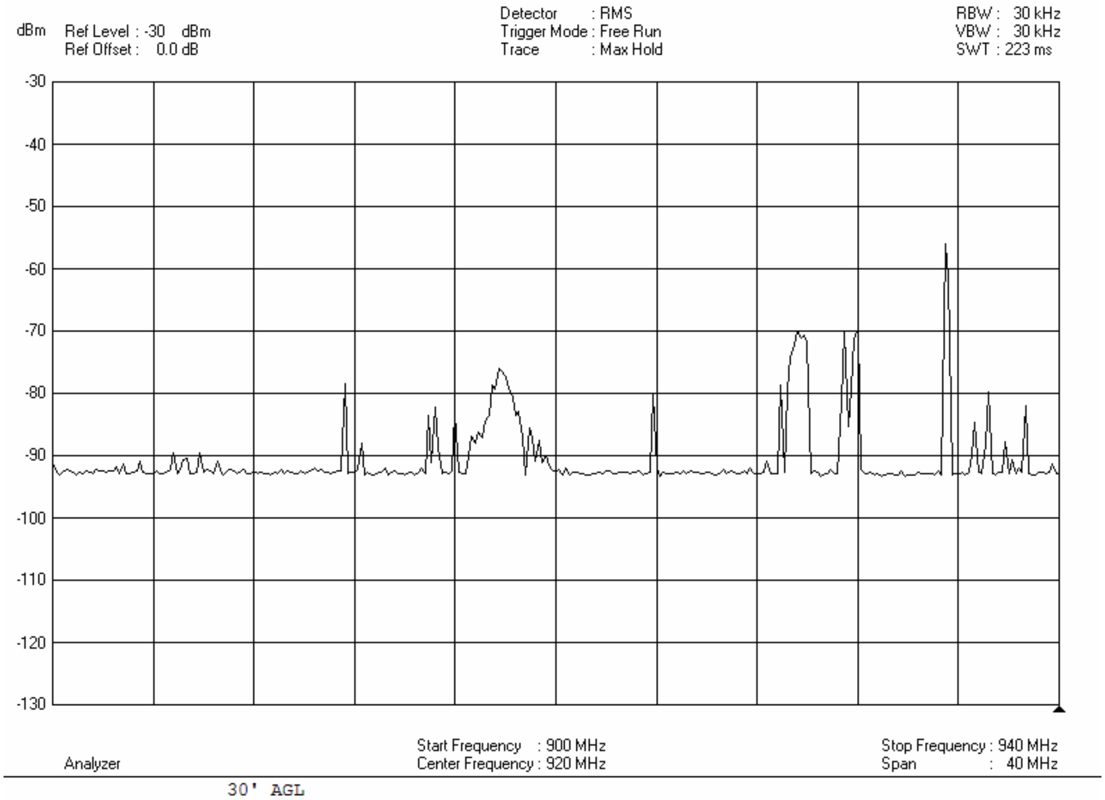


Figure 35. Location 6 at 900-940 MHz and 30ft AGL.

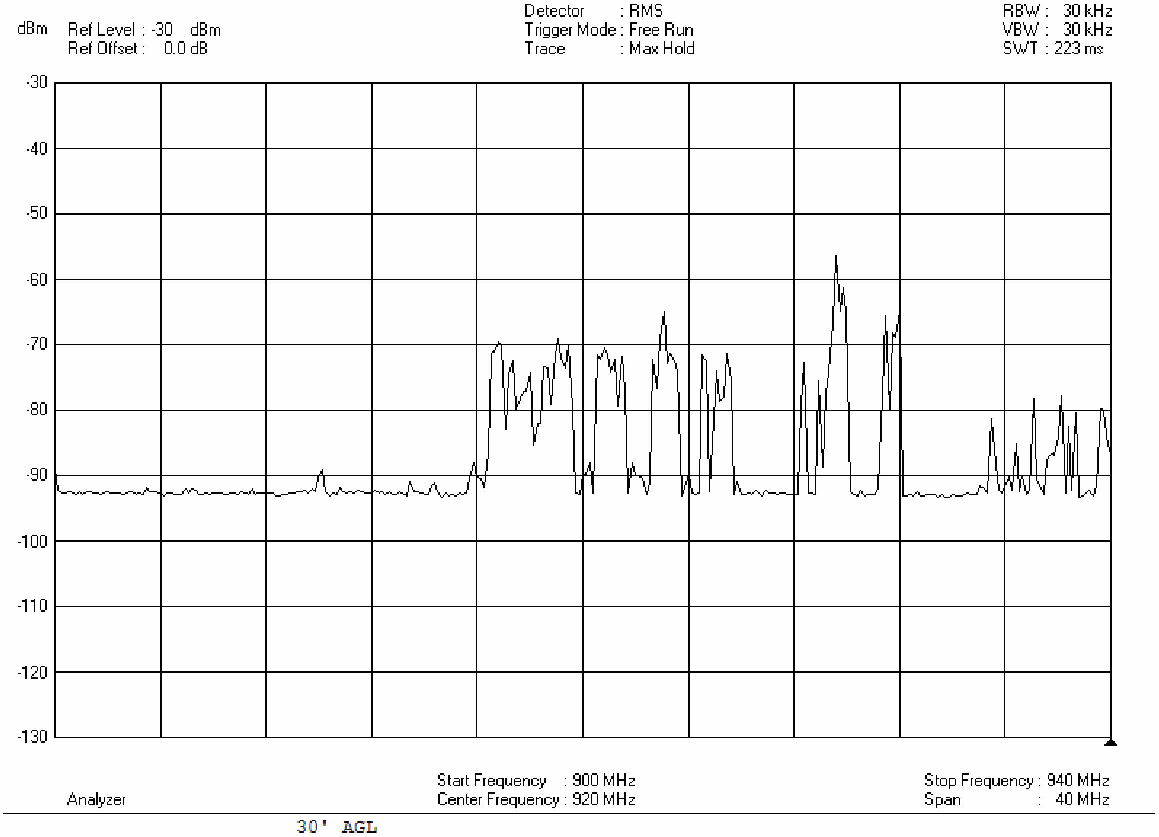
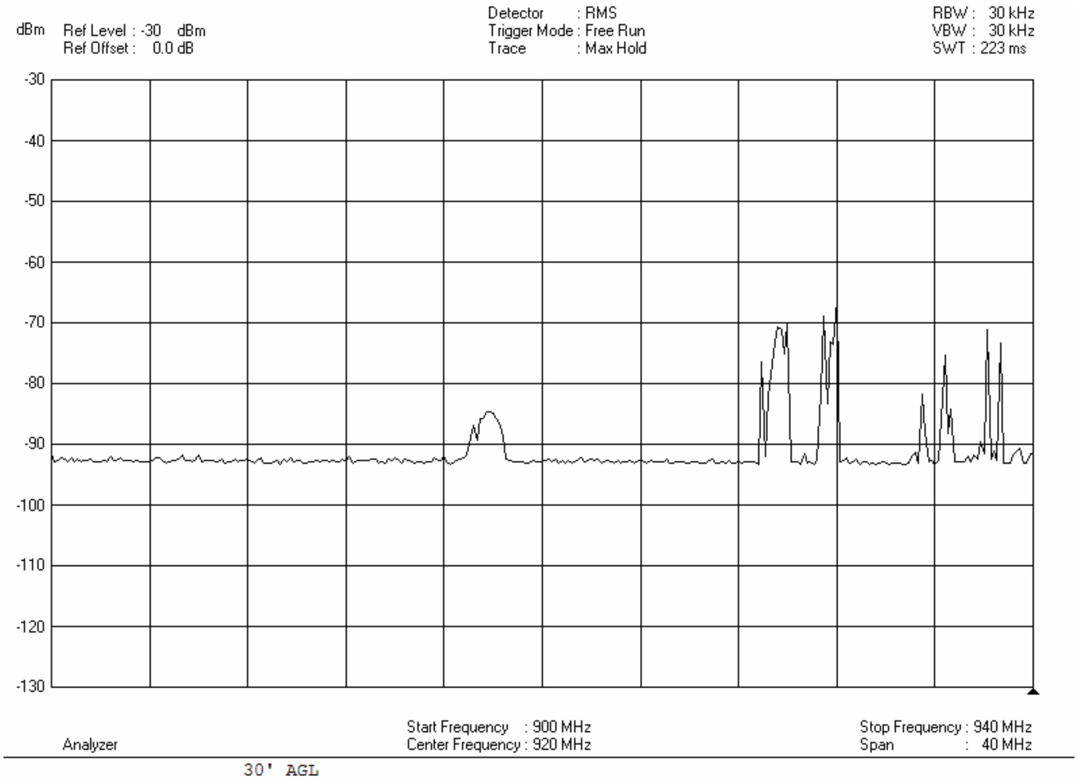
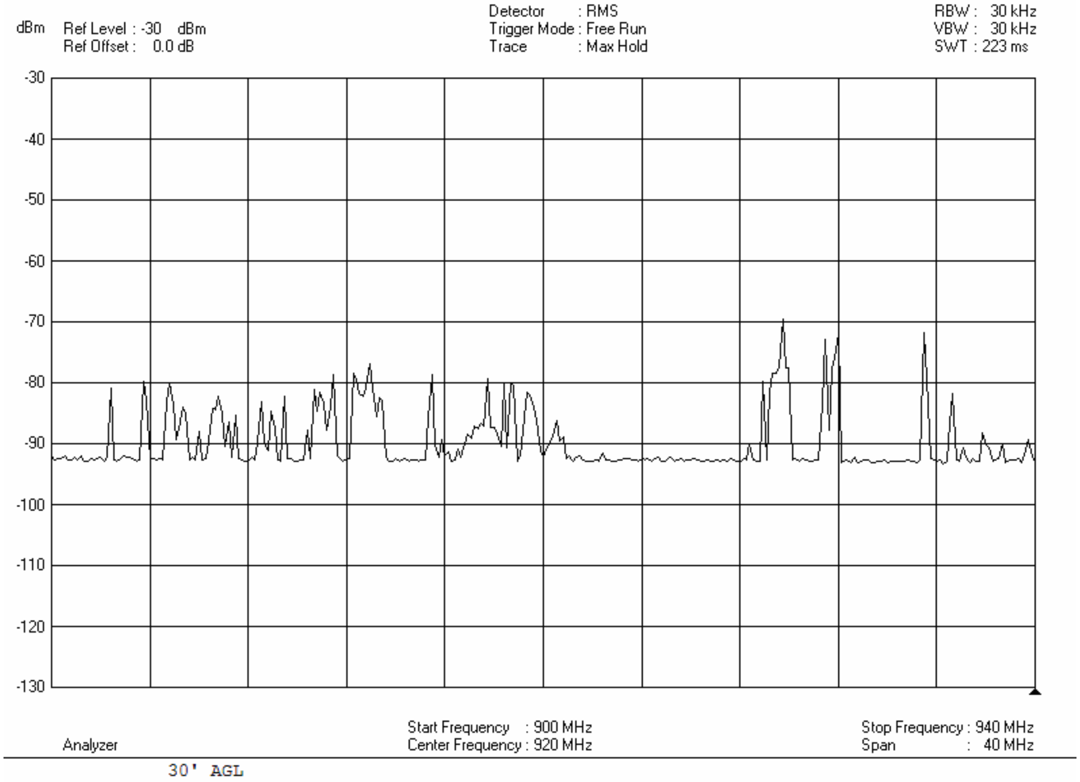


Figure 36. Location 7 at 900-940 MHz and 30ft AGL.



Ref Level : -30 dBm
Ref Offset : 0.0 dB
Detector : RMS
Trigger Mode : Free Run
Trace : Max Hold
RBW : 30 kHz
VBW : 30 kHz
SWT : 223 ms
Start Frequency : 900 MHz
Center Frequency : 920 MHz
Stop Frequency : 940 MHz
Span : 40 MHz

Figure 37. Location N4 at 900-940 MHz and 30ft AGL.



Ref Level : -30 dBm
Ref Offset : 0.0 dB
Detector : RMS
Trigger Mode : Free Run
Trace : Max Hold
RBW : 30 kHz
VBW : 30 kHz
SWT : 223 ms
Start Frequency : 900 MHz
Center Frequency : 920 MHz
Stop Frequency : 940 MHz
Span : 40 MHz

Figure 38. Location N6 at 900-940 MHz and 30ft AGL.

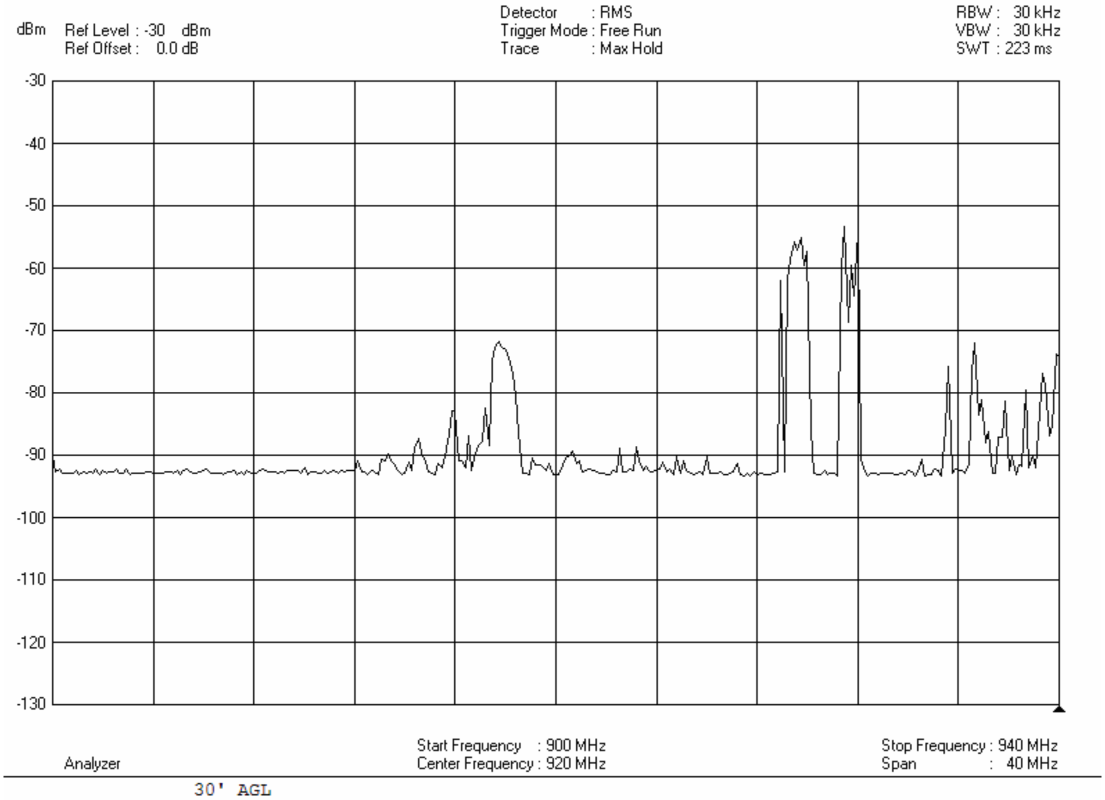


Figure 39. Location N7 at 900-940 MHz and 30ft AGL.

6. Equipment / Component Table

Item	Description	Total Number
Injection Layer		
IL 1	Tranzeo TR902-11f 900 MHz Access Point (tower-mounted)	17
IL 2	Tranzeo EnRoute500 Neighborhood Gateway (tower-mounted)	11
IL 3	Tranzeo TR902-11f 900 MHz Subscriber Module (light pole-mounted)	74
Mesh and AP Layer		
ML 1	Tranzeo EnRoute500 Neighborhood Router (light pole-mounted)	511
ML 2	Tranzeo EnRoute500 Neighborhood Gateway (light pole-mounted)	91
PoP		

PoP 1	Ellacoya e30 8-Port Gb Ethernet Switch w/ per-user and/or per-flow traffic characterization and prioritization capability, and centralized management support	17
NOC		
NOC 1	Bluesocket WG5000 Controller Array in load sharing and failover configuration; 1000 subscribers per controller; Provides client DHCP IP address configuration, as well as AAA relay and per-Client BW control functions; routes client and EMS/NMS traffic between MuniWiFi and EMS/NMS Subnet / Internet; interfaces to AAA provider for subscriber management.	2
	Alternate: Nomadix AG5000 Metro	
NOC 2	Cisco Catalyst 3750G 12S 12 Port Gb Ethernet Managed Switch.	1
NOC 3	Tranzeo EMS Element Management Software, openNMS Network Management Software, Ellacoya Service Control Software for traffic shaper, web browser for Cascade AP & SM components; deployed on Dell PowerEdge 6800 Series server.	1

6.1. Fiber Point Listing

Type	Location	Number
Traffic Lights	A	1
	B	1
	C	1
	D	1
	E	1
	F	1
	G	1
	H	1
	I	1
	J	1
	K	1
	L	1
	M	1
	N	1
	O	1
	P	1
	Q	1

Type	Location	Number
Schools and Fire stations	1	1
	2	1
	3	1
	4	1
	5	1
	6	1
	7	1
Parks and Open Space	N1	1
	N2	1
	N3	1
	N4	1
	N5	1
	Total	**29**

6.2. Tower Listing

Site Name	Latitude (°)	Longitude (°)	Projected Tower Height (ft)	Projected Tower Height (m)
1	Y.15220	-X.20166	150	45
7	Y.13747	-X.15993	120	36
4	Y.12900	-X.17000	120	36
2	Y.16542	-X.18259	120	36
5	Y.15140	-X.17064	120	36
3	Y.14087	-X.14720	120	36
N4	Y.17606	-X.20153	120	36
N2	Y.17120	-X.17671	120	36
N3	Y.13701	-X.18464	120	36
N5	Y.11691	-X.17322	120	36
Q	Y.18363	-X.18804	70	21

7. Mounting Site Assumptions

The following assumptions have been made regarding equipment mounting locations.

- Un-switched power will be available at each location; 110-220VAC or 24VDC via PoE.
- Power stubs will need to be provided on ornamental poles to improve esthetics since the lighting sensor, the existing power tap, is at the very top of the light and the radios, in most cases, will be mounted below or to the side.
- Equipment mounted to ornamental poles may need custom brackets and pole mounts.
- Equipment may need to be painted to match ornamental pole color schemes.
- Mesh routers can be mounted at any point on the luminary arm.
- Heavier, injection layer equipment will be mounted closer to the pole or on the pole to satisfy wind load calculations.
- All luminary arms, metal ornamental poles, and back-haul towers have proper earth grounding.

References

[1] http://www.att.com/network/netfacts98.html

[2] John T. Chapman, “Multimedia Traffic Engineering: The Bursty Data Model”, SCTE Emerging Technologies 2002.

[3] D. Kotz, K. Ession, “Characterizing Usage of a Campus-wide Wireless Network”, Dartmouth Computer Science Technical Report TR2002-423, March 12, 2002.

[4] A. Balachandran, G. Voelker, P. Bahl, and P. V. Rangan, “Characterizing User Behavior and Network Performance in a Public Wireless LAN”, ACM SIGMETRICS'02, Marina Del Rey, June 2002.

[5] “Including VoIP over WLAN in a Seamless Next-Generation Wireless Environment”, http://www.iec.org/online/tutorials/ti_voip_wlan/.