ANDREWSEYBOLD

Andrew Seybold, Inc., 315 Meigs Road, A-267, Santa Barbara, CA 93109
805-898-2460 voice, 805-898-2466 fax, www.andrewseybold.com

East Bay Regional Communications System Authority (EBRCSA)

Project Cornerstone Network LTE Testing

Network Test Report

September 12, 2011

Prepared by:
Andrew M. Seybold and Robert O'Hara

With assistance from:
Barney L. Dewey and John J. Thornton

www.andrewseybold.com

Contents

Executive Summary

The public safety community is about to embark on the most important upgrade to its mission-critical communications systems ever. Today, police, sheriff, fire, and EMS personnel only have access to voice communications on dedicated public safety spectrum. However, since the Federal Government allocated this spectrum for public safety use over the course of many years, it is not contiguous in nature but available on six different portions of the wireless spectrum.

The voice channels on each of these portions of the spectrum allocated to public safety communications voice are not sufficient to provide communications for all of the agencies and, therefore, over the years, some agencies make use of one portion of the spectrum while other agencies are assigned channels on another portion of the spectrum. This has resulted in a lack of interoperability between agencies, even within the same jurisdiction. It is not unusual for the police department in a city to be on a different portion of the spectrum than the fire and EMS departments. The result of this is that when these agencies are working side-by-side on an incident they cannot directly communicate with each other.

In addition, since these channels are suitable for voice communications only, the public safety community has little or no access to data services, pictures, or video. In order to partially solve some of these problems, some departments have entered into service agreements with commercial wireless operators for wireless phone, messaging, and broadband services. However, during major incidents these commercial networks are jammed with news media and citizens trying to contact their offices or loved ones. At the time this capability is needed most by the first responder community, it becomes unavailable due to commercial network overload.

The lack of interoperability that has been an issue for public safety nationwide for more than three decades was brought to the nation’s attention during the terrorist attacks on 9/11 and again during Katrina. A number of different agencies all responded to provide services and were unable to coordinate with each other due to a lack of interoperable voice communications along with the lack of data and video communications. Since these incidents, many agencies have upgraded their voice communications systems and banded together to form regional and even statewide voice communications systems. However, because of the nature of their spectrum allocations they have not been able to address the issue of providing broadband communications services to those in the field.

Recently, Congress and the FCC allocated additional spectrum for public safety in what is known as the 700-MHz band. This band was occupied by TV stations above channel 53 that were relocated lower in the TV spectrum. The resulting band was divided into blocks. Public safety received two blocks of this spectrum: one for additional voice channels and one for a nationwide, fully interoperable broadband system that will add data, picture, and video capabilities for first responders. AT&T, Verizon, and others were then permitted to bid on other blocks within this band. The block adjacent to the public safety allocation known as the D Block was supposed to have been sold at auction with the condition that the winner would work with public safety to build out a nationwide private/public partnership system that would result in a shared network for both the private network operator and for public safety.

For a number of reasons, no bids were received for this spectrum, thus it was not auctioned. Today it sits idle. The public safety community quickly rallied and joined forces in order to convince both the FCC and Congress that the D Block should be reallocated to public safety so the amount of broadband spectrum available meets the needs of the public safety community on a daily basis. During the past two years, public safety has gained a lot of traction for this reallocation of the D Block but has also faced some stiff opposition from those who would like to see it re-auctioned for commercial purposes. Most of the discussions about who should gain access to the D Block have to do with how much broadband spectrum public safety really needs on a daily basis for local incidents. There have been many studies (all theoretical in nature) about the capacity of the existing public safety spectrum but until now there have been no real-world tests to validate whether the Public Safety Spectrum Trust (PSST) spectrum is really sufficient for public safety's daily requirements.

While this debate continues, the FCC issued waivers to 21 jurisdictions allowing them to start building their portion of the network. The San Francisco Bay Area applied for and received one of the waivers. The East Bay Regional Communications System Authority in partnership with the Bay Area Urban Area Security Initiative (UASI) developed Project Cornerstone as a proof of concept for the larger LTE network planned for the Bay Area. For the first time, we were able to conduct real-world testing of the first demonstration system of public safety broadband. The methodology and the test results are presented in the following report.

The conclusion reached by Andrew Seybold, Inc. as a result of this in-depth testing is that the presently allocated 10 MHz of spectrum (5 MHz by 5 MHz) for public safety's exclusive use is not sufficient to meet its needs on a daily basis. One of the prime advantages to implementing a nationwide broadband network is to enable first responders in the field to have access to video for the first time. Think of this as giving sight to the blind. For the first time, those responding to incidents will be able to see video from a fixed camera near the incident. For the first time, those in the command center in charge of an incident will be able to view, in real time, video sent back from the scene. The SWAT commander will be able to see exactly what his team's sharpshooters can see using their rifle scopes, and during a bomb incident, live video of the bomb can be made available to bomb experts anywhere in the world, one of whom might recognize it and be able to guide those at the scene as to the best way to disarm it and render it harmless.

In order to accomplish all of this and more, including having access to information regarding an incident, the history of the perpetrator, or perhaps still pictures of a suspect wanted for a crime, public safety needs sufficient bandwidth for this nationwide broadband system and as our test results conclusively show, the 10 MHz of spectrum presently allocated to public safety does not provide sufficient bandwidth for incidents that occur in cities and counties on a daily basis. Therefore, the 700-MHz spectrum known as the D Block needs to be reallocated to public safety to ensure it has the bandwidth it needs.

Andrew M. Seybold	Robert O'Hara
CEO and Principal Consultant	Partner
Andrew Seybold, Inc.	Andrew Seybold, Inc.

Introduction

Andrew Seybold, Inc. (ASI) was contracted by the East Bay Regional Communications System Authority (EBRCSA) to undertake a series of network capacity tests for the first 700-MHz system in the United States to deploy LTE. This network operates in 10 MHz (5 MHz by 5 MHz) of spectrum licensed to the Public Safety Spectrum Trust (PSST) and under a waiver granted to EBRCSA by the FCC.

EBRCSA, in turn, will be integrated with the planned nationwide fully interoperable broadband network dedicated to public safety and providing, for the first time, a nationwide public safety network based on commercial standards that will enable the first responder community to move equipment and manpower anywhere in the nation and be able to communicate with all of the other agencies involved in a major incident. The lack of interoperability for public safety agencies has created problems during major incidents for more than thirty years but was brought to the attention of the public during the Oklahoma City bombing, the 9/11 tragedy, and major hurricanes such as Katrina.

The reason for the engagement of ASI to perform capacity tests on this system was many fold: First, it is important for network planning purposes to understand both the capacity and the limitations of the network. Next, there are ongoing discussions about the amount of spectrum, and therefore the amount of capacity the public safety community needs on a daily basis. The public safety community and its supporters believe that 10 MHz of broadband spectrum is not sufficient for the types of broadband services that will be required on a daily basis, especially in major metropolitan areas. There are also those who believe that the D Block, the additional 10 MHz of spectrum being requested, should instead be auctioned for use by a commercial network operator.

Up to this point, all of the capacity models that have been run by those involved with the public safety community have indicated that 10 MHz of spectrum is not sufficient for normal daily data and video requirements while those who are in favor of auctioning the D Block have presented their own capacity models that are designed to support their own position. These tests conducted on the Cornerstone system are the first real-world tests conducted on a live system, and simulating a variety of incidents that are commonplace and handled, on a daily basis, by police, fire and EMS agencies either acting alone or in combination with the other agencies.

ASI has been involved in these discussions and Andrew M. Seybold has filed numerous comments with the FCC based on our own computer-generated capacity studies. We found what we believe to be a major discrepancy in the way capacity was measured in the case of those who are proponents of the D Block auction. The capacity calculations used by these companies and the FCC were based on capacity models developed by the 3GPP and were based on a grid of 19 cells sites, each with 3 sectors, for a total of 57 cell sectors. Interference was assumed to be equal across all of these cell sectors and the capacity measurements were based on spreading a user base across all of the sectors. While this capacity

modeling method may in fact work for commercial network deployments, it is not germane when running capacity studies for a public safety broadband system.

The public safety community—police, fire, and EMS—responds to multiple incidents per day within their own jurisdictions that involve multiple public safety responders. These incidents, for the most part, are confined to a small geographic area that will usually be provided coverage by only one or at the most two cell sectors of the LTE broadband network. Therefore, the most important measure of capacity for a public safety broadband system needs to be focused on the capacity within a single cell sector rather than over a broader area. The testing methodology developed by ASI was based on self-contained incidents confined to a small geographic area and modeled based on real-world incidents that the public safety community responds to every day.

As an incident grows in complexity the number of first responders on the scene increases rapidly and the amount of video and data resources needed to manage the incident will increase exponentially. Incidents can grow in size and complexity quickly. During the early stages, while there is an incident commander on the scene, the demands that will be placed on the broadband network will continue to expand. If the incident needs to be managed for a longer period of time, additional resources such as command-and-control vehicles and incident management personnel will be put into place. At this point, it will be possible to manage the demand for voice, data, and video services, but in the early stages of an incident, those who are responding are occupied with sizing up the incident, deploying personnel, ensuring that the general public is out of harm's way, and coordinating resources that are either on the scene or responding to it.

As an incident builds, so too will the demand placed on the LTE broadband network, and since the vast majority of these incidents will occur within a small geographic area, the coverage of that area will, in most cases, be provided by a single cell sector or two overlapping cell sectors. Further, it is important to understand that a blocked call or lack of available bandwidth during the incident as it grows in size and complexity is not an option for public safety. Therefore, the total amount of bandwidth available within a single cell sector is of paramount importance when designing the public safety broadband network and the amount of capacity available within each cell sector is directly proportional to the amount of bandwidth available within the cell sector. It is imperative that there be enough bandwidth available to handle the increased demand in service on a daily basis.

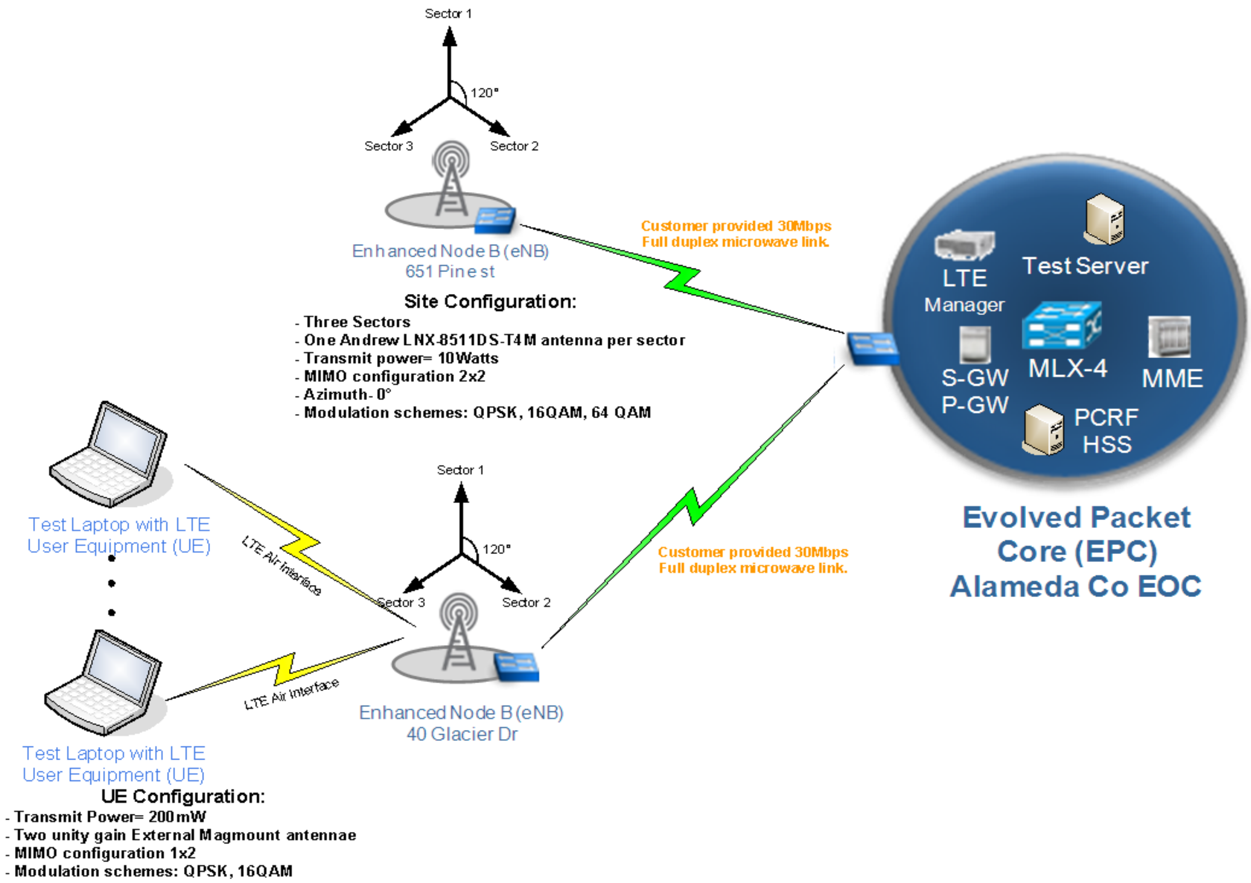
Based on our testing and the resources public safety agencies have identified as required for these types of incidents, ASI has concluded that 10 MHz of broadband spectrum (5 MHz X 5 MHz) is not sufficient to meet the needs of the public safety community on a daily basis in metropolitan and suburban areas of the United States.

The Network Under Test

The LTE network under test is located in Alameda County, California. The Evolved Packet Core (EPC) that is used to manage the network, identify units on the network, and for all command-and-control

functions is located in the Alameda County Emergency Operations Center (EOC). The EPC is connected to the two cell sites via County Microwave with a total per cell site capacity of 30 Mbits per second. For the purposes of these tests, the test server was co-located at the Core in order to ensure that there were no network bottlenecks between the test server and the network under test.

This is a diagram of the Alameda County test network:



Each of the two active cell sites is divided into three sectors, which is the standard cell site configuration for all commercial cellular networks. For the purposes of these tests, all were conducted within the coverage of a single cell sector for each of the two sites and it was verified that there was no network traffic on the other two sectors. The total backhaul of 30 Mbits per second provided by the County Microwave system was available for the single sector under test.

The field devices we used were Panasonic Toughbook computers of the same variety that are in daily use within the public safety community, and the LTE field devices were standard LTE USB modems that were connected to the Toughbooks with USB cables. These USB modems were connected to two unity gain antennas mounted on the roofs of the test vehicles, providing the best case connectivity between the user device and the network (units with internal antennas such as handheld LTE devices when available will have degraded coverage and capabilities).

Additional network details may be found in Appendix A. The network was functional and fully operational and drive tests were conducted both by Motorola and Anritsu prior to beginning the testing. Stationary tests were conducted at multiple locations, run multiple times for verification, and the results are presented later in this report.

The Test Procedures

The test methodology developed by ASI for these capacity tests are based on real-world scenarios. That is, typical incidents that require public safety response on a daily basis. The incidents were created by ASI with the assistance of public safety officials from various police, fire, and EMS departments across the nation. They are based first on the amount of manpower and the number of units needed to respond to each of the various types of incidents and then the stated requirements in terms of video and data traffic public safety officials believe would be required for each incident. The incidents were developed using the Incident Command Structure (ICS), which is almost universally used by all public safety agencies.

The resulting scenarios included:

1. Bank robbery with potential hostage situation
   a. First responders on the scene: police
   b. Additional police response
   c. Fire and EMS staged near the scene
   d. SWAT team deployment
   e. Perimeter units to seal off the incident area
2. Multi-story building fire
   a. First responders on the scene: fire
   b. Additional fire units and EMS responding
   c. Police response for street and crowd control
3. Multi-vehicle accident, multiple injuries and extensive damage to vehicles
   a. First responders on the scene: police
   b. Fire and EMS response
   c. Additional police for traffic control
   d. Tow trucks (secondary responders)

The tests were designed around each of these incidents and the number of personnel from each agency was vetted by several departments across the country. The data and video requirements for each incident were calculated to provide uplink video to the dispatch center from the first unit on scene. This would then be retransmitted down to additional incoming resources including the ranking officer who responds to take command of the scene.

A video was recorded in the test area, streaming at a resolution and data rate comparable to those used in police patrol cars. Streaming software and measurement software were loaded onto both the server computer and each of the client computers. Scripts were written to calculate actual throughput, accuracy of reception, and other factors. Video files were created for both uplink (from the scene) and

downlink (to the scene and responding units) and were varied in capacity requirements based on the resolution of the video required by public safety.

Prior to and during the stationary tests, both Motorola and Anritsu personnel conducted drive tests of the cell sector coverage area to verify coverage of the cell sector in use during the tests. During the actual tests, Anritsu America personnel equipped with state-of-the-art network monitoring equipment were monitoring and recording the amount of both the uplink and downlink traffic being generated during the tests.

More details of the testing methodology and the testing software used are provided in Appendix B.

The Actual Tests

The main objective of the tests was to measure network capacity in both the uplink and downlink directions from the scene of an incident and at various distances from the center of the cell sector under test. Four locations were chosen for each cell sector under test:

1. Near the cell center (highest possible data rates) location was 0.5 miles from the cell center
2. Mid-coverage (lower average data rates) location was 1.5 miles from cell center
3. Edge of cell (lowest average data rates) location was 3.8 miles from the cell center
4. A final location at the very edge of the cell coverage, in this case 4.2 miles from the cell center
5. The terrain varied for the two cell sectors under test
    a. One cell sector was located within the City of Martinez in a semi-dense building environment, but most of the buildings while multi-story were not more than six to eight floors tall
    b. The second location was more suburban in nature on the edge of Martinez with sparse housing, large trees, and in one case in the parking lot of a large shopping center.

It should be noted that LTE broadband networks are designed to provide three different data speeds down to the devices and two different data rates from the devices up to the network. Basically, those closest to the cell site will have the fastest data speeds to and from the network, those located in the middle of the cell sector coverage will have the next fastest data speed down from the network and, depending upon their location, either of the two up-to-the-network data speeds. Those toward the edge of the cell sector will have access to the slowest outbound data speed and the slower of the two up-to-the-network data speeds.

Devices and Configurations

The devices used for field testing were USB LTE modems built and designed specifically to provide service within the public safety licensed spectrum. In most cases, during the actual tests these modems were connected via USB cables to the Panasonic Toughbooks and external unity gain antennas on magnetic mounts were placed on the roof and/or back deck of the test vehicles. Two antennas were connected to each modem.

Seven Panasonic Toughbooks with Windows XP were used for all of the testing

For several of the tests, the USB modems made use of external antennas but were located within the vehicle rather than roof-mounted. This provided us with a sample of lower performance devices as well as the optimum performance of the modems using external antennas.

One of the test modems

For the most part, the modems performed well. There were several times during the tests when the modems stopped working due to glitches within the modem and the tests were stopped and restarted multiple times to verify all of the results. However, as can be seen from the data in Appendices C and D, a few of the tests are reported using only a single test session. The test Toughbooks were placed in two

or three vehicles and the vehicles were placed within 50 to 300 feet of each other, simulating a number of devices within a confined location.

One of the test vehicles – note the antennas on the roof

The actual testing started with a single video or data stream from the vehicle up to the server at the Alameda County EOC, followed by a simulation of a retransmission of the video down to the scene. During each test, the number of video and/or data streams to and from the scene was increased. At the same time, Anritsu was monitoring the LTE channel in both directions and was recording the percentage of the capacity in use during each phase of the testing. This gave us a visual indication of the percentage of capacity that was being used during each phase of the testing. In addition, the other criteria measured included the quality of the video in both directions and any packet loss experienced during the up and down loading of the data files. Appendix C shows the test results as recorded for both data and video up and downloading as well as the capacity usage as measured by Anritsu during the tests. The tests were run multiple times except as noted above and the overall results are recapped in the next section of this report and in a detailed listing of the tests included in Appendices C and D.

The test results reported were collected over several multi-day test cycles, recorded on the server (uplink) and on each of the seven Panasonic Toughbooks used for testing (downlink). Anritsu's data was captured in real time. Some of this data is included in the next section and some is included in Appendix E as well. ASI is confident that these test results reflect real-world scenarios and that the results are based on best case network performance with no known chokepoints between the mobile devices and the test server located within the core of the network.

Test Results

We first measured the total capacity of the cell site by sending data from it to the mobile units (downlink or download). We measured sending data to a single mobile unit and to several mobile units at the same time. Note that when we used multiple mobile units they were all located in the same cell sector. These tests were made under what should be considered "ideal" conditions: We were the only users of the network during the tests; there was no other traffic.

As described in Appendix B, we tested at three different locations. The locations were selected to represent "best case" (near the cell tower), "typical case" (a midpoint in the cell coverage area), and "worst case" (at the cell edge) network coverage and performance. We sent random data to and from the mobile units using the same network protocols that streaming video cameras use. From these tests we arrived at the following measurements of the network's total available bandwidth for a single sector:

Test Site	Downlink Bandwidth	Uplink Bandwidth
Glacier Street (near cell)	16 to 19 Mbits / sec	6 to 7 Mbits / sec
Sunvalley Mall (mid cell)	11 to 15 Mbits / sec	2 Mbits / sec
John Muir House (cell edge)	6 to 8 Mbits / sec	0.2 to 0.3 Mbits / sec

These measurements were made streaming data to and from a single or at most a handful of mobile units. As more mobile units are present in the cell sector, more network bandwidth will be devoted to packet management and other network traffic.

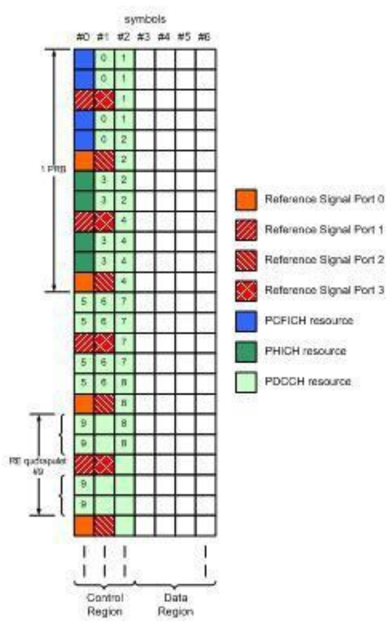
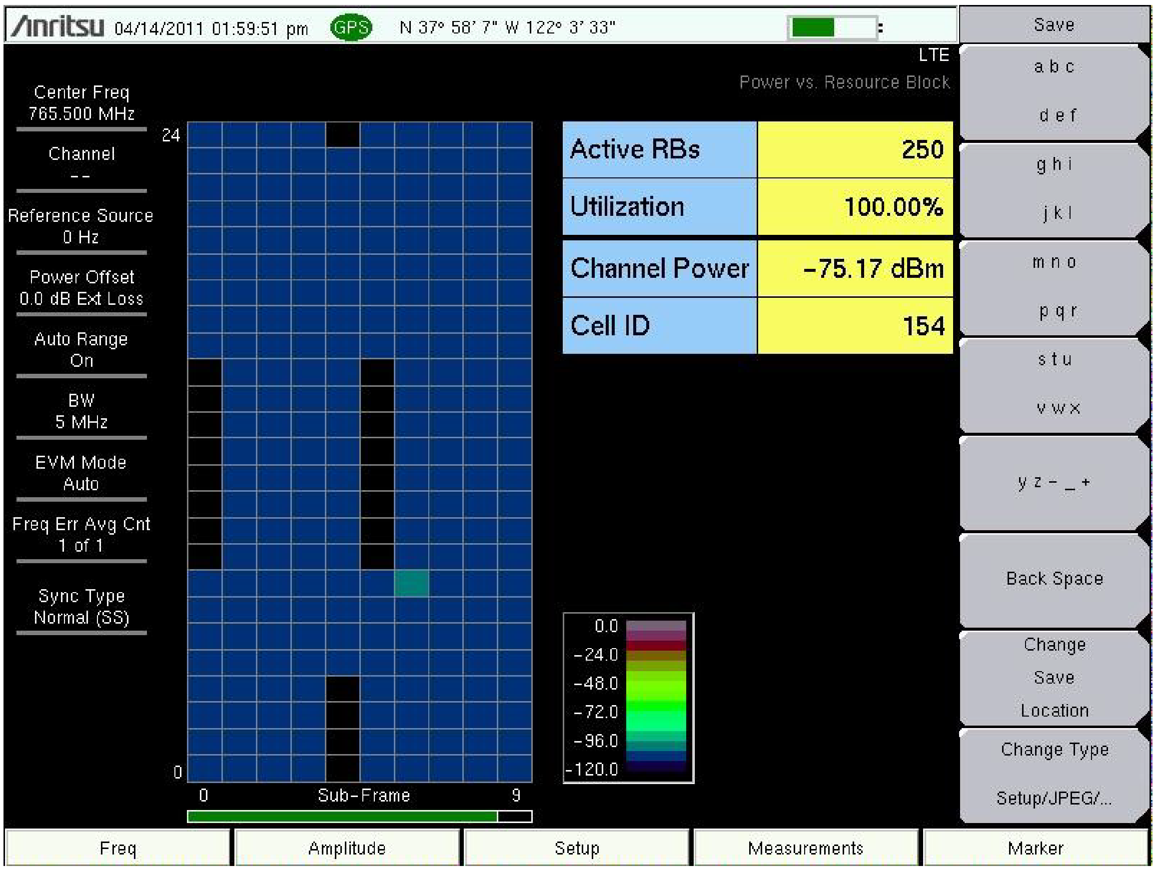


Diagram of LTE Resource Blocks

LTE assigns resource blocks to each user within a cell sector; in a 5 MHz by 5 MHz network the total number of resource blocks available is 520. Some of these blocks are reserved for signaling data (16

blocks) and network-to-device communications and are therefore not available for data communications.

The LTE carrier is made up of resource blocks. Some are reserved for signaling, but most of them are for data. Each user is assigned a number of resource blocks depending upon their priority on the system. The more data they are sending, the more resource blocks are required during their transmission. When sending a streaming video, the system allocates as many resource blocks as it can to that user.



Resource blocks in use during the network testing, courtesy of Anritsu America

Resource blocks that are not in use during these video transmissions are the signaling channel resource blocks that are used for the network and device to communicate with each other. In this particular case, 100% of the available resource blocks are being occupied with data. The signal level being reported is very good.

Besides streaming random data to and from the mobile units, we also streamed actual video using an MPEG4 codec. We recorded a VGA quality (640 x 480 pixels at about 15 frames per second) video while driving around the streets of Martinez near the test locations. This quality is typical of video cameras currently installed in police cars. The captured video enabled us to consistently stream a video with a known data rate of 1.91 Mbits per second.

At each of the test locations we simultaneously streamed videos to and from multiple mobile units while recording the received videos. Below is an image from the test video:

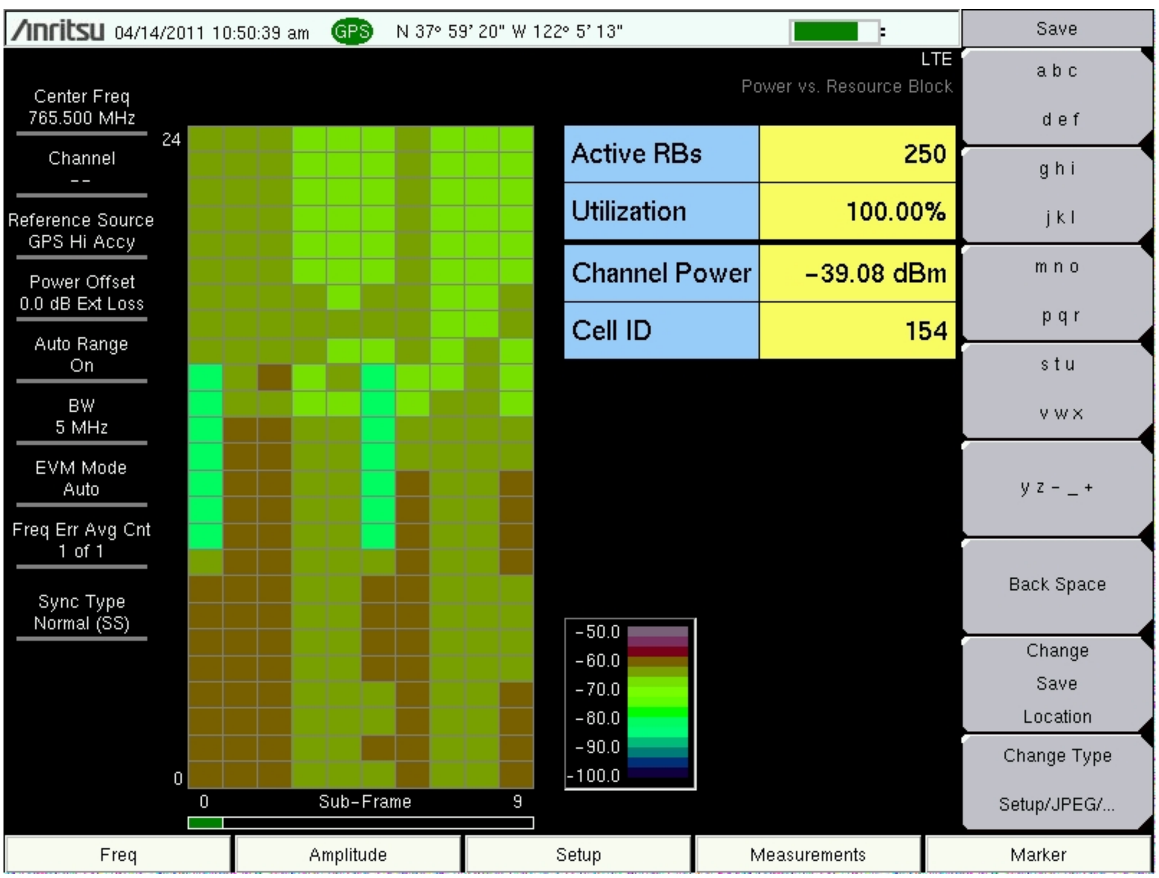
It became very obvious when there was insufficient bandwidth for a video to display, as the image quickly froze and broke up as shown below:

Actual video playbacks will be available in the PowerPoint presentation that will accompany this report and at www.andrewseybold.com.

The table below shows the number of simultaneous videos we were able to successfully stream to or from the cell site. Note that at the John Muir House location, which is at the edge of cell coverage, we were unable to stream a single video from the mobile unit to the cell site. This confirms the data measurements presented above, as we only measured an uplink bandwidth of 0.2 to 0.3 Mbits per second at that location, which is clearly below the 1.91 Mbits per second needed for the test video to successfully stream.

Test Site	Downlink Video Streams	Uplink Video Streams
Glacier Street (near cell)	5	3
Sunvalley Mall (mid cell)	3	2
John Muir House (cell edge)	2	0

More information on the data test results can be found in Appendix C. More information on the video test results can be found in Appendix D. We interpret the above numbers in the next section.



Anritsu Network Monitor showing very strong signal strength and 100% network utilization

What the Test Results Mean

Perhaps the best way to interpret the test results is to walk through two scenarios where first responders are reacting to an incident. We are not describing these incidents as they happen today, but as we project they will occur in the future when public safety LTE networks are widely deployed. The obvious change from today will be a significant increase in the use of live video feeds as a real-time information gathering tool for the first responders. The two scenarios are:

- "Barricaded Hostage": a gunman holds one or more hostages in a building
- "Suspected Bomb": a suspicious package turns out to be a bomb and must be deactivated

In each of these scenarios there will be a variety of data traffic both up to and down from the LTE network. Not every source will be active at all times. Data traffic will be transmitted from devices such as these in the field:

- Sniper scope (3.1 Mbits per second)
- Police car dashboard camera (1.9 Mbits per second)
- Helicopter-mounted camera (3.1 Mbits per second, typically via microwave link, not LTE network)
- Video feed from bomb / hazardous situation robot (3.1 Mbits per second)
- Additional handheld video feed (1.9 Mbits per second)
- Uploaded data from EMS response units (EKGs, scans, etc. at 0.1 Mbits per second)

Typically, all video feeds from the field are transmitted to the central dispatch center where the dispatcher relays one or more selected feeds to the police incident commander, the SWAT commander, and the fire chief. Therefore, in addition to the above traffic, the following data traffic will be transmitted down to devices in the field from the LTE network:

- Video feeds from any of the sources listed above, in either high resolution or converted down to a lower resolution
- Video feeds from existing wired street or highway cameras
- Video feeds from third-party cameras such as news helicopters
- Downloads of building plans, utility network plans, photographs, or other data

Beyond the above traffic related to the incident, there will be ongoing data traffic (both up and down) related to normal police activity in the same cell sector. An example of this would be a license check arising from a traffic stop.

What is important to this report is the estimated data traffic at the peak of the incident. Of course, in real life such incidents unfold over time. We are interested in projecting whether the LTE network can handle the maximum data load each scenario will generate.

Barricaded Hostage

A gunman holds one or more hostages in a building for a period of hours. The police respond with the following mobile units:

- 2 snipers
- 1 helicopter
- 1 police incident commander
- 1 SWAT commander
- 1 police car camera
- 2 police vehicles receiving video feed

At the peak of the incident, we have the following data being uploaded to the LTE network:

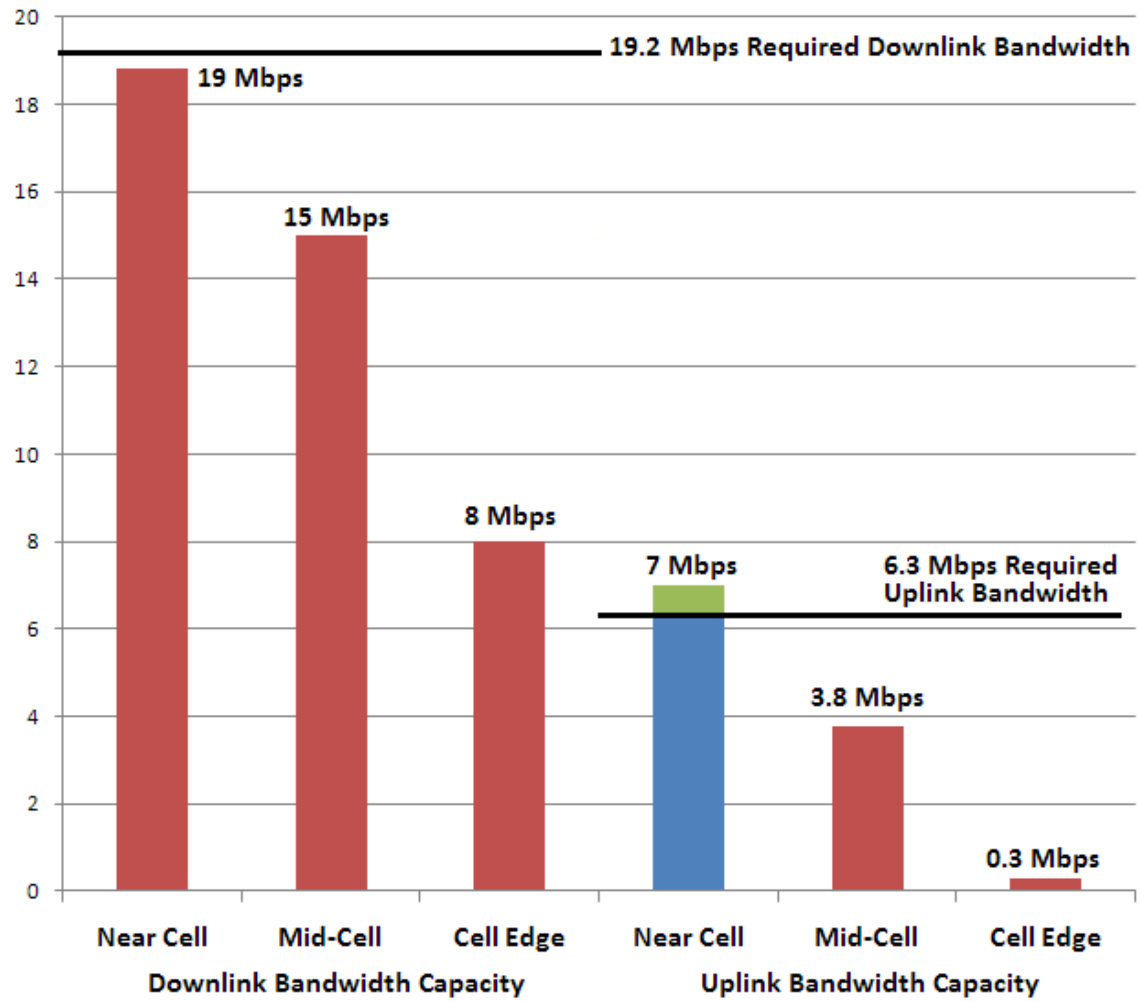
- Sniper 1 high-resolution streaming video: 3.1Mbits per second
- Sniper 2 low-resolution streaming video: 1.2 Mbits per second
- Police car camera streaming video: 1.9 Mbits per second
- "Background" ongoing police activity: 0.1 Mbits per second

This gives us a 6.3 Mbits per second uplink data stream to the LTE network and over the backhaul to the command center. We assume that the command center relays the sniper streams (one at high resolution and one at low resolution) and the helicopter stream to both the police and SWAT commanders, and the police car video stream to each of two close-in police vehicles. This means the following data are downloaded over the LTE network:

- Sniper 1 high-resolution streaming video to police commander: 3.1Mbits per second
- Sniper 1 high-resolution streaming video to SWAT commander: 3.1Mbits per second
- Sniper 2 low-resolution streaming video to police commander: 1.2Mbits per second
- Sniper 2 low-resolution streaming video to SWAT commander: 1.2Mbits per second
- Police car low-resolution streaming video to police vehicle1: 1.9Mbits per second
- Police car low-resolution streaming video to police vehicle2: 1.9Mbits per second
- Helicopter high-resolution streaming video to police commander: 3.1 Mbits per second
- Helicopter high-resolution streaming video to SWAT commander: 3.1 Mbits per second
- Download of floor plans: 0.5 Mbits per second
- "Background" ongoing police activity: 0.1 Mbits per second

This gives us a 19.2 Mbits per second downlink data stream from the command center over the backhaul and down the LTE network. The total backhaul load imposed by these streaming video feeds is 25.5 Mbits per second. Note that the downloads of floor plans or other data requests are probably only a few megabytes each and would only last 10 or 20 seconds.

The following diagram illustrates both the projected bandwidth required for the incident and the bandwidth that is available on a 10 MHz (5 MHz by 5 MHz) system. Where the available bandwidth is inadequate it is highlighted in red (below the line indicating required bandwidth):



Barricaded hostage scenario bandwidth as measured and required

It should be obvious that this scenario exceeds the capabilities of the network we tested in almost every situation.

Suspected Bomb

A suspicious package turns out to be a bomb and must be deactivated. The bomb squad uses a remote-controlled robot to open the package and deactivate the explosive device. Civilian cellular telephone service is turned off in the area to foil remote activation. The police respond with the following mobile units:

- 1 helicopter
- 1 police incident commander
- 1 bomb squad commander
- 1 bomb squad remote control camera
- 1 police car camera
- 1 police vehicle receiving video feed

At the peak of the incident, we have the following data being uploaded to the LTE network:

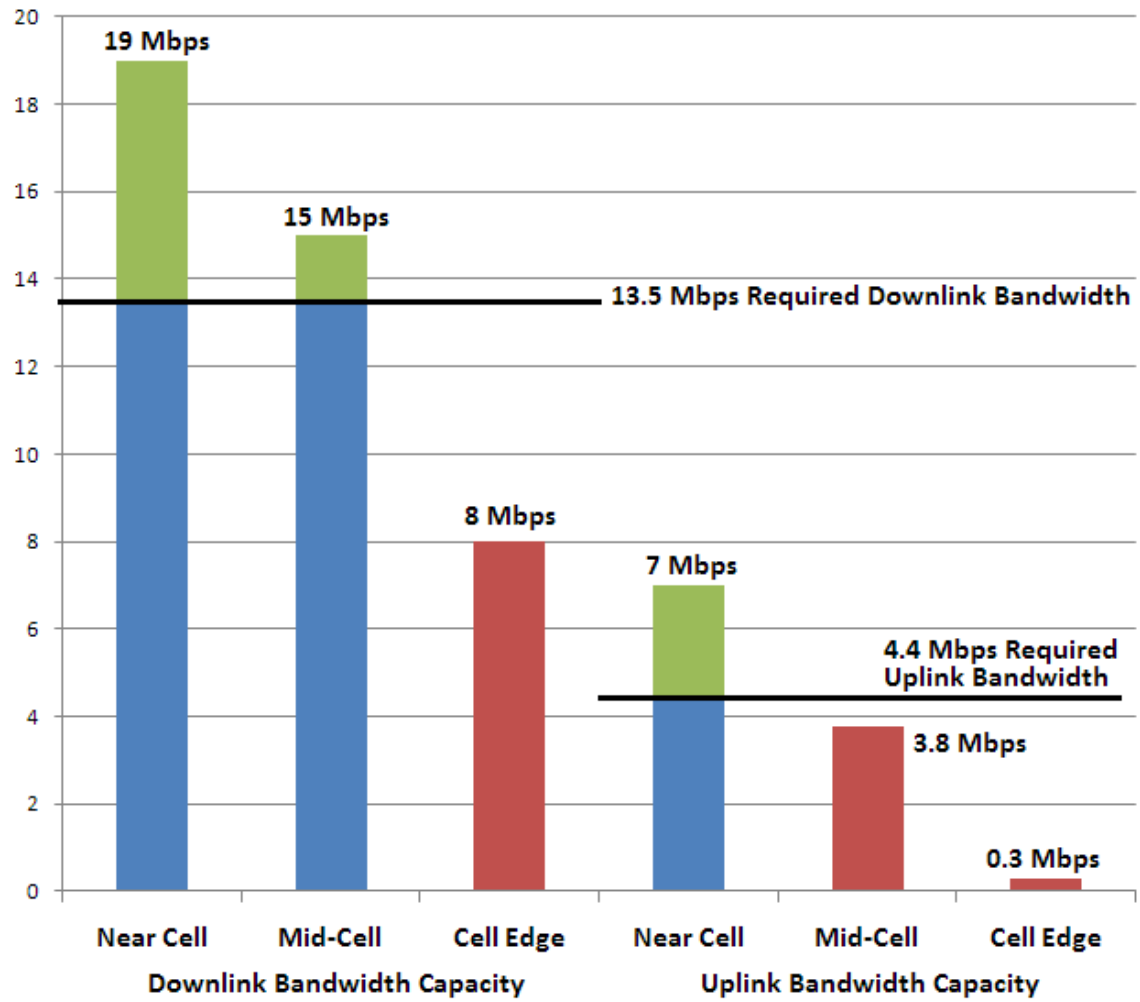
- Bomb squad remote control high-resolution streaming video: 3.1 Mbits per second
- Police car low-resolution streaming video: 1.2 Mbits per second
- “Background” ongoing police activity: 0.1 Mbits per second

This gives us a 4.4 Mbits per second uplink data stream to the LTE network and over the backhaul to the command center. We assume that the command center relays the helicopter stream, bomb squad remote control camera stream, and police vehicle stream to the bomb squad commander; the helicopter and squad car stream to the police commander; and the helicopter stream to a close-in police vehicle. This means the following data are downloaded over the LTE network:

- Helicopter high-resolution streaming video to police commander: 3.1 Mbits per second
- Helicopter high-resolution streaming video to bomb squad commander: 3.1 Mbits per second
- Bomb remote control camera high-resolution streaming video to bomb squad commander: 3.1 Mbits per second
- Police vehicle low-resolution streaming video: to police commander: 1.2 Mbits per second
- Police vehicle low-resolution streaming video: to bomb squad commander: 1.2 Mbits per second
- Helicopter high-resolution streaming video to police vehicle: 1.2 Mbits per second
- Download of utility plans of the neighborhood: 0.5 Mbits per second
- “Background” ongoing police activity: 0.1 Mbits per second

This gives us a 13.5 Mbits per second downlink data stream from the command center over the backhaul and down the LTE network. The total backhaul load imposed by these streaming video feeds is 17.9 Mbits per second. Note that the downloads of utility plans or other data requests are probably only a few megabytes each and would only last 10 or 20 seconds.

The following diagram illustrates both the projected bandwidth required for the incident and the bandwidth that is available on a 10 MHz (5 MHz by 5 MHz) system. Again, where the available bandwidth is inadequate it is highlighted in red (below the line indicating required bandwidth):



Suspected bomb scenario bandwidth as measured and required

It is clear that the test network can only support this scenario if it occurs very close to the cell site.

Public Safety Video and Data Requirements

The above scenarios do not account for any other types of applications that may be used or needed during these incidents but they clearly show that even under these conditions the 10 MHz of spectrum allocated to public safety is not sufficient to provide the video and data services that will be required during these types of incidents. These incidents are not events that happen once in a while within a given jurisdiction, these and other incidents that require multiple-unit response and the use of video and data for extended periods of time occur on a daily basis.

Note that the above scenarios do not include any voice service over LTE. If and when mission-critical voice does become available over LTE it will put additional stress on the broadband network, especially in confined areas, which is the case for most incidents. If we had added the bandwidth required for 30 push-to-talk devices into our testing scenarios, the amount of available bandwidth for video and data services would be reduced by 15-20% (based on current estimates within the LTE technology community). Thus the public safety network needs to have enough spectrum available to be able to provide the types of video and data services required as well as to be able to add mission-critical voice services if they become available.

Public demand for broadband services has grown more than 75% each year for the past three years, yet if you had asked prior to commercial broadband being available what the demand for wireless broadband services would be, the answer, three years ago, would not have anticipated this huge rate of growth due to the advancement of smartphones and tablets as well as the proliferation of applications. This same growth curve will apply to the public safety community as well. Until the network is built and placed into operation we can only identify the most obvious of applications and services. However, once the network is online, just as in the commercial world, public safety will find additional uses and applications for the broadband network that will not only drive up daily demand and usage but also drive up the amount of bandwidth that will be consumed during these types of incidents. Therefore, to limit the public safety community to 10 MHz of broadband spectrum will not meet its needs on a daily basis nor will it allow for new and innovative applications that can be used to better serve the pubic and protect the lives of first responders as well.

What Public Safety Can Count On in 10 MHz of Spectrum

As described above, the tests were conducted with the minimum expected response to an incident. As incidents escalate, response levels will increase and the demand for data and video services will increase as well. As can be seen by the test results, additional demand would create network overload in every condition and at every location within a cell sector.

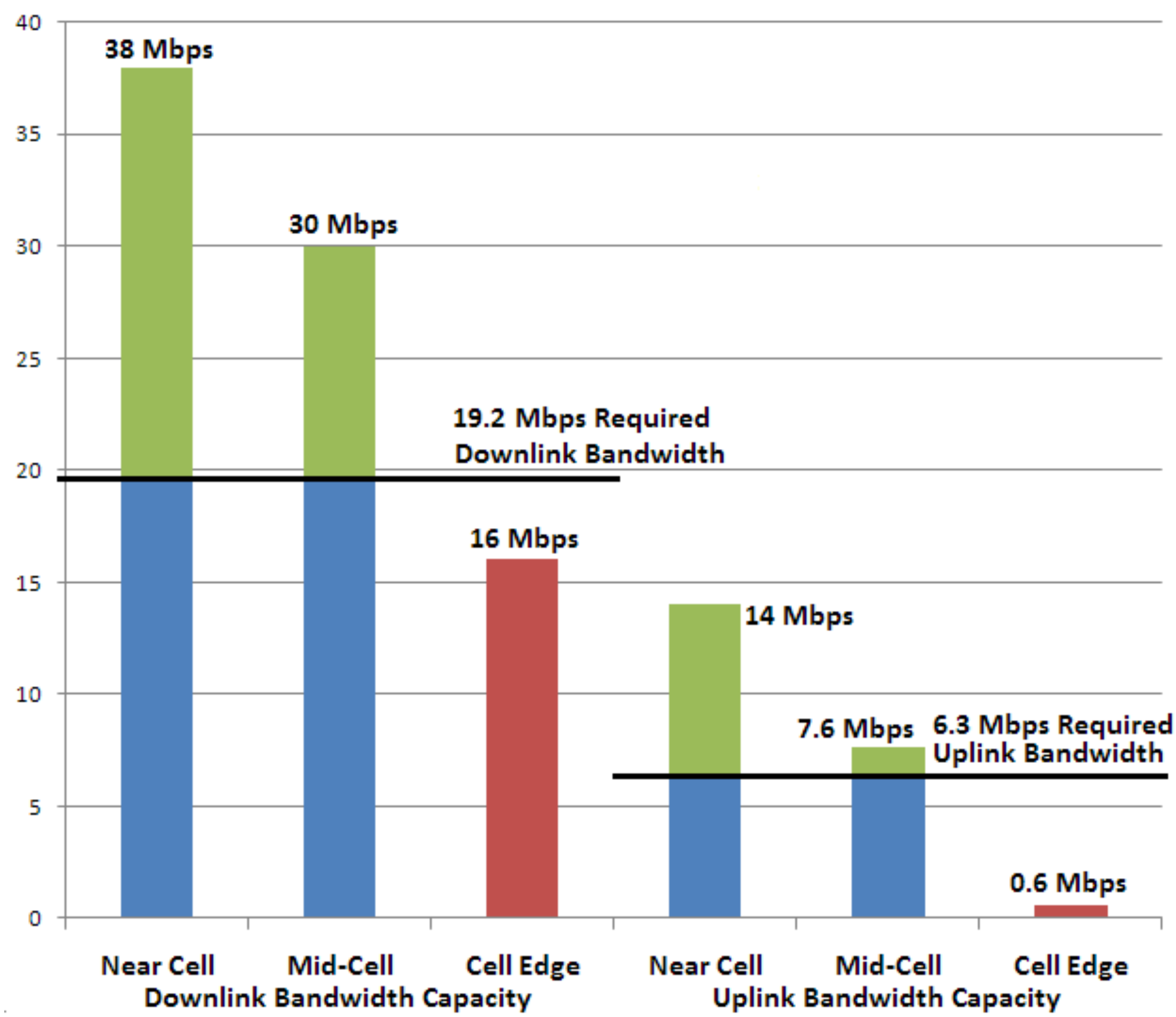
During a major incident, once an incident command center has been established it will be possible to interactively manage the demand for data and video, but the demand will outstrip the network's ability to meet that demand. Well before an incident command post is established at the scene, the demand for data services will be such that the network will quickly reach saturation and become non-functional. As we observed, when the network is overloaded, the impact of the overload was not only to block the subsequent video or data stream but also to cause the videos or data streams that had been usable to become unusable.

Public safety will be able to rely on a 10-MHz network during the initial phase of the incident and perhaps again once a command structure has been established. However, during the most critical portion of the response as more first responders arrive on the scene and when the agency's command center is in an information gathering mode, the system will reach saturation and not be able to provide the critical data needed to contain the incident. Incidents can and do grow rapidly in size and

complexity, and it is crucial to those in the field as well as those within the command structure to have real-time video and data services available to them during the entire incident, not only at the beginning.

How Much Spectrum Is Required?

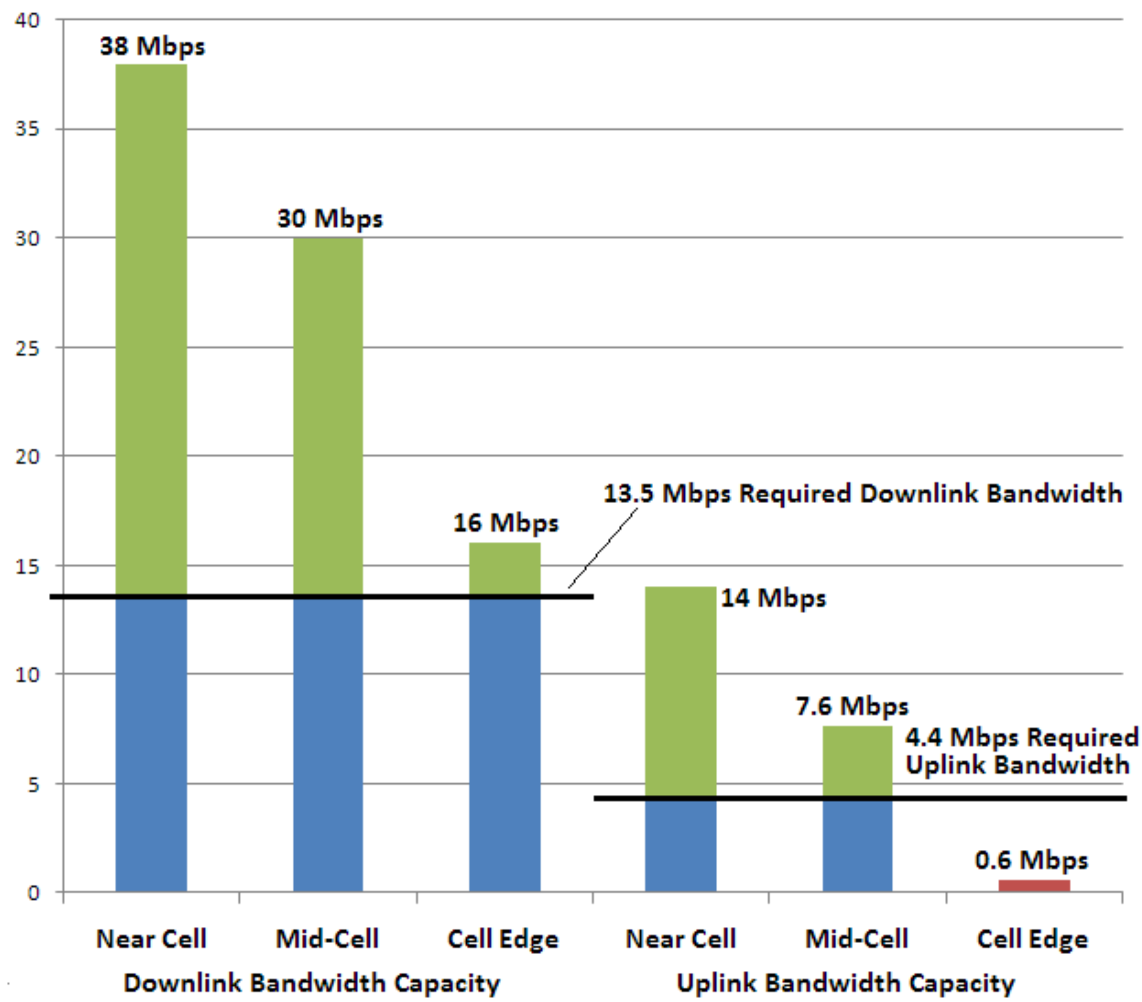
As described above, the tests demonstrate that 10 MHz of spectrum is inadequate to support the needs of the public safety community. The obvious question then is if 10 MHz is too little, how much is enough? While we do not have a 20-MHz network to test, we can project its performance. The following diagram illustrates how 20 MHz of contiguous spectrum would perform in the barricaded hostage scenario. Again, where the available bandwidth is inadequate it is highlighted in red (below the line indicating required bandwidth):



Barricaded hostage scenario bandwidth as projected and required

The projected 20 MHz (10 MHz by 10 MHz) network has sufficient capacity for this demanding scenario in all locations except at the very edge of the cell sector coverage. Edge of cell communications is an issue with both commercial and public safety networks. It will be critical for the network to be designed to minimize the edge of cell situations within a given coverage area. This can be accomplished with overlapping cell coverage but at the same time care must be taken to minimize the interference between overlapping cells. After the initial network completion it will be necessary to drive test the network to ensure that sufficient bandwidth is available, especially within major metro areas. Ensuring that there is sufficient bandwidth could add to the overall cost of this network.

The following diagram illustrates how 20 MHz of contiguous spectrum would perform in the suspected bomb scenario:



Suspected bomb scenario bandwidth as projected and required

The 20 MHz (10 MHz by 10 MHz) network has sufficient capacity for this demanding scenario in all locations except at the very edge of the cell sector coverage, and that for uplink only. Again, system design will be critical to ensure that edge of cell situations are minimized whenever possible.

Conclusions

We believe that the tests conducted using the Cornerstone network provide the first real-world results for a 10-MHz public safety broadband system. After vetting the incidents chosen prior to the testing and vetting the results of the testing with seasoned first responders and commanders, it is clear to us that 10 MHz of spectrum will not meet the daily incident requirements of the public safety community.

Some detractors might try to point out that some broadband is better than none. However, this is not the case since at the most crucial times network overload can and does result in the entire system not being available for use. During the recent earthquake on the east coast, the commercial networks were fully operational but they were overloaded. The result was not only that those who wanted to make a call or send video were denied access to the network, but many who had network connectivity lost that connectivity—a situation that is intolerable for public safety.

The public safety voice networks are built to meet harsh standards, and the broadband network must be designed and built to those same mission-critical standards. Not having enough capacity available for the network is not an acceptable option. Neither is expecting the commercial operators to provide priority access to the first responder community. Again, during the east coast earthquake not only were the networks overloaded, the signaling channel used by devices to communicate their requests for service was overloaded. In that circumstance, even if priority had been granted to public safety, the devices would not have been able to communicate that priority status with the network and would not have had access to the network.

Public safety needs a dedicated, nationwide broadband network. The network must be robust and it must have sufficient bandwidth available within a single cell sector. Our findings clearly show that 10 MHz of spectrum and the bandwidth it provides does not meet these criteria. More spectrum is needed and it must be contiguous to the existing public safety broadband spectrum, not in some other portion of the spectrum and not allocated after the public safety broadband network is in operation. To add spectrum that is not adjacent to the existing broadband spectrum would more than double the cost of the network and would increase the cost of the devices used on the network.

Based on these real-world tests, we strongly recommend that public safety be provided with at least 20 MHz of contiguous spectrum (10 MHz by 10 MHz). The only way to accomplish this is to reallocate the 700-MHz D Block to public safety and this should be done prior to the build-out of the waiver recipients' portion of the nationwide network. The cost to build out 10 MHz of spectrum and 20 MHz of spectrum is identical at the time of construction. Later, the addition of this spectrum would add to the cost of the network and require device redesign, adding to the cost of the user equipment. The entire premise of providing public safety with broadband spectrum using a commercial technology is to provide public safety personnel with capabilities they do not have presently at a lower cost than its existing voice communications equipment.

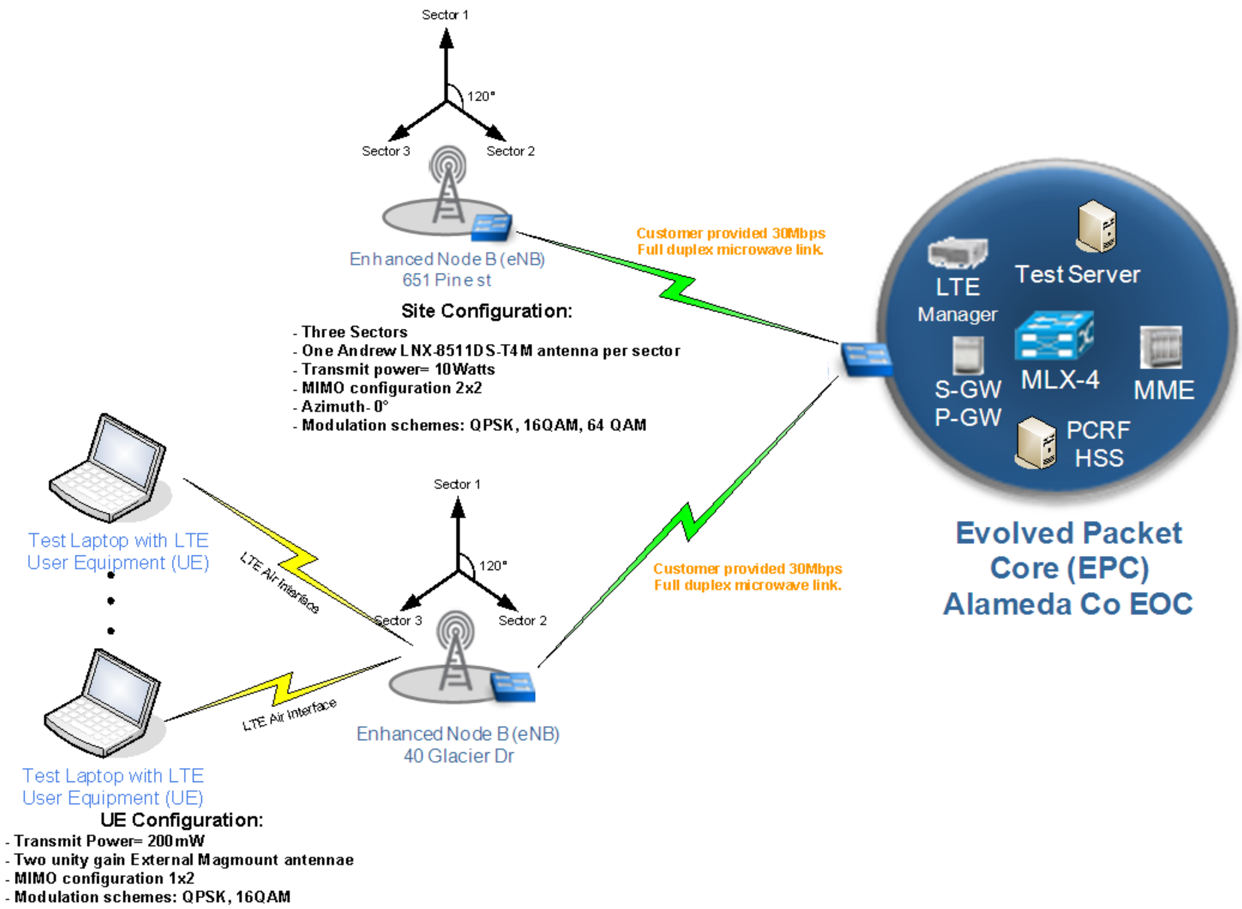
The public safety nationwide interoperable broadband network based on 10 MHz of spectrum that is currently available will not meet the needs of the public safety community. Rather it will, on a daily

basis, end up congested at incident locations and fail to provide the public safety community with the bandwidth that is needed for data, pictures, and video. Most emergency incidents are confined to a small geographic area and, as noted above, our testing results conclude that the current bandwidth assigned to public safety is not sufficient even for incidents that occur on a daily basis.

If, in the future, mission-critical voice is added to this network, it will further degrade the amount of available bandwidth. The demand for voice, data, and video all within the same cell sector will swamp the network's capacity and even with Quality of Service and priority status enabled, the public safety community will not have enough bandwidth to provide the mission-critical level of service required. Public safety cannot afford to rely on a network that will not provide the amount of bandwidth it needs when it needs it. We therefore recommend that the additional 10 MHz of bandwidth that is adjacent to the public safety spectrum be reallocated to public safety in a timely manner.

Appendix A: Network Details

The network under test was configured in this manner:



Motorola, the network system supplier, stated that the network was configured with a 30-Mbps backhaul bandwidth:

- Not limited to eNodeB sector or user device
- Available on a first come, first served basis
- Full 30 Mbps can be assigned to a single user device

The bottom line is that the backhaul did not create a network chokepoint. Also, note that none of the tests transmitted data over the Internet.

The cell site power output and effective radiated power are as follows:

- Full power output of the system is 80 Watts (2 x 40 Watts max) and the corresponding ERP (with conservative estimates on line losses) is 56.9dBm

- FCC Experimental License limits to 59.4 Watts max ERP. To abide by this limitation, the power on the eNb has been turned down to 10 Watts total, which corresponds to about 59.4 Watts ERP.

To explain further:

Tx Power = 10W = 40 dBm
Antenna Gain = 14 dBi
Cable + Connectors Loss = 4 dB*
EIRP = 40 + 14 – 4 = 50 dBm
ERP = EIRP – 2.1dB = 47.9 dBm

This is almost right at the FCC Experimental License ERP limit of 59.4W = 10*log10(59.4x1000) = 47.7dBm.

At the Glacier Street site, pictured below, the LTE antennas (circled) are co-located on a tower hosting public cellular antennas as well as microwave antennas:

LTE Antenna location at the Glacier Street site

In downtown Martinez at 651 Pine Street the LTE antennas are located on top of the tallest building in the area:

LTE Antennas at 651 Pine Street

The network core and our test server were located at the Contra County Emergency Operations Center:

Microwave dishes at EOC network core and test server location

Appendix B: Testing Methodology

Test Locations

We tested at three different sites in the Martinez, California area. The Glacier Street site was adjacent to the LTE base station at the center of the cell sector; our test location was 0.1 miles from the base station. This gave us the best possible signal strength, and thus the maximum data throughput over the air. In other words, this was the "best case" network performance.

Below is a photograph of the Glacier Street site, showing the location of the cell tower and the test site:

The Sunvalley Mall is located in the center of the cell sector at the midpoint of the base station's coverage map, 2.23 miles from the tower. We characterize this site as giving us "typical" network performance.

Below is a photograph showing the cell tower in the upper left corner and the Sunvalley Mall test site in the lower right corner:

The final site is at the John Muir House National Monument, 2.35 miles from the tower. Even though this location is only slightly farther from the tower than the Sunvalley Mall site, intervening hills place it at the edge of the base station's coverage area. Therefore this site gives us a measure of "worst case" performance.

Below is a photograph showing the cell tower at the right and the test location at the left. The area in the center contains hills that block line of sight between the tower and the test location:

Test Procedures and Tools

At each site we streamed data from the network core to the client computers ("download" tests) and streamed data from the client computers to the core ("upload" tests). We also streamed test videos in each direction. For both data and video we streamed to a single client and simultaneously to multiple clients. Likewise, we performed upload tests to the server from both single and multiple clients.

We used seven client computers during the tests. Each was a Panasonic Toughbook CF-30 with a 1.6-GHZ Intel Core 2 Duo CPU and 2 GB of memory running Microsoft Windows XP with Service Pack 3. Attached to the client computers was a pre-production external USB LTE modem. At the network core we installed a server computer that was powered by a 2.66-GHZ Intel Core i5 processor and 4 GB of memory, running Windows 7 Professional 32-bit. Since the server was located at the network core, we never relied on an Internet connection for any of the data traffic.

Several different software packages were used to conduct the tests:

VLC media player, available at videolan.org, was used to stream and display the test videos. VLC is a free and open source cross-platform multimedia player and framework that plays most multimedia files as well as DVD, audio CD, VCD, and various streaming protocols.

Wireshark, available at wireshark.org, was used to measure the data traffic generated by streaming the test videos. Wireshark is the world's foremost network protocol analyzer. It captures and allows interactive browsing of traffic running on a computer network. It is the *de facto* (and often *de jure*) standard across many industries and educational institutions.

Iperf, available at sourceforge.net/projects/iperf, was used to stream and measure data traffic. Iperf was developed by NLANR/DAST as a modern alternative for measuring maximum TCP and UDP bandwidth performance. Iperf allows the tuning of various parameters and UDP characteristics and reports bandwidth, delay jitter, and datagram loss.

We ran two types of tests: data streaming and video streaming.

In the data streaming tests we used Iperf to stream random data via UDP, sending 1470-byte data packets. As explained above, UDP is the carrier protocol for streaming video, so streaming UDP packets is a valid stand-in for streaming video. As well as performing the streaming, Iperf generated comprehensive logs that enabled us to accurately characterize the end-to-end network performance.

We used a webcam to record a video while driving through Martinez, California. The video was recorded on one of the Panasonic Toughbooks with VGA resolution (640 by 480 pixels). Because of the limited processing power of the Toughbook, the recorded video was captured at about 15 to 20 frames per second and exhibited the occasional dropped frame on playback. Streaming the test video on a computer with a 2.3-GHz Intel Core i5 processor produces an outbound bit rate of 1.91 Mbits per second.

In the video streaming tests we used VLC to stream a test video to a particular client computer using the Real-time Transport Protocol (RTP), which defines a standardized packet format for delivering audio and video over IP networks. RTP is used extensively in communication and entertainment systems that involve streaming media and it is designed for end-to-end, real-time transfer of streaming data. The protocol provides facility for jitter compensation and detection of out of sequence arrival in data that are common during transmissions on an IP network. RTP is regarded as the primary standard for audio/video transport in IP networks.

Real-time multimedia streaming applications require timely delivery of information and can tolerate some packet loss to achieve this goal. Thus the majority of the RTP implementations are built on the User Datagram Protocol (UDP) rather than on the Transmission Control Protocol (TCP), commonly used for email, file transfer, and web browsing. However, too many lost packets result in dropped video frames, lost pixels, and image freezing.

Appendix C: Data Test Results

The following tables present the raw data from the field tests. The columns display the following information:

Mbits/sec is the rate at which data was received by the target computer (client computer on downloads, server computer on uploads) measured in megabytes (not megabits) per second of data delivered.

Jitter is the average of the deviation from the network mean packet latency across the network, measured in milliseconds.

Lost Data is the percentage of sent data that was not received by the target computer.

Antenna indicates whether the field computer's LTE modem is connected to an external antenna or is relying on an antenna internal to the modem. During the tests we found the modems with external antennas to perform significantly better than those with internal antennas.

Test summarizes the particular test for which the results are displayed. If the test mentions more than one client, it means that data was being sent to or received from multiple computers at the same time.

Glacier Street (near cell) Downlink Tests

The first test set below demonstrates the maximum capacity of the network at the "best case" location. We streamed data to a mobile unit at a rate of 50 Mbits per second, well above the network capacity. As expected, only a fraction of the packets were received. We repeated the test twice more at a lower rate of 20 Mbits per second, for an average capacity of slightly less than 16 Mbits per second.

The next two test sets demonstrate that at 10 Mbits per second the network is highly reliable with very few lost packets, and at 5 Mbits per second no packets are lost.

Following that, the next two tests show the limits of the network: Streaming to three mobile units at 5 Mbits per second shows that more than 25% of the data packets are lost. The final test shows that performance will vary, as we were able to stream data to four mobile clients at 5 Mbits per second with negligible packet loss.

Mbits/sec	Jitter (ms)	Lost Data	Antenna	Test
15.40	2.77	69%	External	Download at 50 Mbits/sec to 1 client
14.60	1.78	3%	External	Download at 20 Mbits/sec to 1 client
17.00	1.86	15%	External	Download at 20 Mbits/sec to 1 client
15.67	1.82	9%	External	Average Mbits/sec
9.97	1.39	0%	External	Download at 10 Mbits/sec to 1 client
9.83	2.32	2%	External	Download at 10 Mbits/sec to 1 client
9.90	1.85	1%	External	Average Mbits/sec
5.00	2.03	0%	External	Download at 5 Mbits/sec to 1 client
4.99	1.99	0%	Internal	Download at 5 Mbits/sec to 2 clients
4.99	3.96	0%	External	
9.98				Total Mbits/sec
3.56	9.73	28%	External	Download at 5 Mbits/sec to 3 clients
4.49	1.61	10%	External	
4.82	3.90	4%	Internal	
12.87				Total Mbits/sec
7.73	2.37	23%	External	Download at 10 Mbits/sec to 2 clients
7.12	2.43	29%	Internal	
14.85				Total Mbits/sec
4.82	5.34	2%	Internal	Download at 5 Mbits/sec to 4 clients
4.69	3.68	2%	External	
4.74	3.79	1%	External	
4.74	2.13	1%	Internal	
18.99				Total Mbits/sec

Eleven attempts were made to simultaneously download data at 5 Mbits/sec to four clients. Unfortunately, only one of these tests completed (and as noted above, with almost no dropped packets). During the other ten tries one or more of the modems dropped the network connection.

Glacier Street (near cell) Uplink Tests

In the first test set below we streamed data to from a mobile unit at a rate of 100 Mbits per second, well above the network capacity. As expected, only a fraction of the packets were received. The average capacity of the network was somewhat less than 6 Mbits per second.

The second test set shows that at an upload rate of 5 Mbits per second the network is highly reliable with no lost packets.

The next two test sets demonstrate the difference between a modem with an internal antenna and one connected to an external antennal. The mobile units with external antennas were able to stream data to the server at a higher data rate, with fewer lost packets.

The final two tests show the limits of the network: Streaming from multiple mobile units at 5 Mbits per second each resulted in significant packet loss.

Mbits/sec	Jitter (ms)	Lost Data	Antenna	Test
6.25	8.52	90%	External	Upload at 100 Mbits/sec from 1 client
5.44	3.68	92%	External	Upload at 100 Mbits/sec from 1 client
5.85	6.10	91%	External	Average Mbits/sec
5.00	4.31	0%	External	Upload at 5 Mbits/sec from 1 client
4.99	3.72	0%	External	Upload at 5 Mbits/sec from 1 client
5.00	4.01	0%	External	Average Mbits/sec
5.75	3.57	42%	External	Upload at 10 Mbits/sec from 1 client
5.70	5.92	43%	External	Upload at 10 Mbits/sec from 1 client
5.49	3.82	8%	External	Upload at 10 Mbits/sec from 1 client
5.65	4.44	31%	External	Average Mbits/sec
2.20	6.07	78%	Internal	Upload at 10 Mbits/sec from 1 client
4.40	7.62	56%	Internal	Upload at 10 Mbits/sec from 1 client
4.21	5.16	58%	Internal	Upload at 10 Mbits/sec from 1 client
4.35	3.37	27%	Internal	Upload at 10 Mbits/sec from 1 client
3.79	5.55	55%	Internal	Average Mbits/sec
2.98	9.02	40%	External	Upload at 5 Mbits/sec from 2 clients
3.57	4.17	29%	External	
6.55				Total Mbits/sec
2.12	11.13	57%	External	Upload at 5 Mbits/sec from 3 clients
2.52	5.54	49%	External	
2.44	4.67	51%	External	
7.08				Total Mbits/sec

As with the download tests reported above, we were unable to upload data from more than three clients simultaneously since none of these tests completed. One or more of the modems dropped the network connection.

Glacier Street (near cell) Simultaneous Downlink / Uplink Tests

These tests confirm what we observed in the separate download and upload tests above. Since the downlink and uplink operate on different frequencies, they are independent of each other, and that is what we measured. Also, these tests show the lower performance of the modems with internal antennas.

Mbits/sec	Jitter (ms)	Lost Data	Antenna	Test
5.00	1.60	0%	External	Download at 5 Mbits/sec to 2 clients, upload at 5 Mbits/sec from 2 clients
4.97	2.98	1%	External	
9.97				Total Download Mbits/sec
1.00	5.95	0%	Internal	
2.87	8.04	42%	Internal	
3.87				Total upload Mbits/sec
4.99	3.21	0%	External	Download at 5 Mbits/sec to 3 clients, upload at 5 Mbits/sec from 2 clients
4.97	2.98	1%	External	
4.99	3.15	0%	External	
14.95				Total Download Mbits/sec
1.00	8.86	0%	Internal	
1.94	5.53	61%	Internal	
2.94				Total upload Mbits/sec

Beyond these tests, five attempts were made to simultaneously download data to four clients while uploading from two others. Unfortunately, none of these tests completed. One or more of the modems dropped the network connection.

Sunvalley Mall (mid cell) Downlink Tests

The first test set below demonstrates the maximum capacity of the network at the “typical case” location. We streamed data to a mobile unit at data rates ranging from 20 Mbits per second, well above the network capacity, down to 10 Mbits per second. The average capacity measured was slightly less than 11 Mbits per second. Note that at a streaming rate of 10 Mbits per second, only 1% of the data packets were lost.

The next two test sets demonstrate the difference between a modem with an internal antenna and one connected to an external antennal. The mobile units with external antennas were able to receive data from the server at a higher data rate, with fewer lost packets.

The final two test sets demonstrate that at 5 Mbits per second the network is highly reliable and able to stream to three clients simultaneously with few if any lost packets.

Mbits/sec	Jitter (ms)	Lost Data	Antenna	Test
11.10	2.23	44%	External	Download at 20 Mbits/sec to 1 client
11.10	2.20	26%	External	Download at 15 Mbits/sec to 1 client
9.76	2.03	35%	External	Download at 15 Mbits/sec to 1 client
11.10	2.30	21%	External	Download at 14 Mbits/sec to 1 client
12.50	5.04	4%	External	Download at 13 Mbits/sec to 1 client
11.30	1.57	6%	External	Download at 12 Mbits/sec to 1 client
9.89	0.70	1%	External	Download at 10 Mbits/sec to 1 client
10.96				Average Mbits/sec
4.60	4.29	7%	Internal	Download at 5 Mbits/sec to 1 client
4.96	4.88	1%	External	Download at 5 Mbits/sec to 2 clients
2.45	5.16	51%	Internal	
7.41				Total download Mbits/sec
4.97	2.50	1%	External	Download at 5 Mbits/sec to 2 clients
4.98	0.55	0%	External	
9.95				Total download Mbits/sec
4.97	4.44	1%	External	Download at 5 Mbits/sec to 3 clients
4.97	4.62	1%	External	
4.98	0.83	0%	External	
14.92				Total download Mbits/sec

Two attempts were made to simultaneously download data at 5 Mbits/sec to four clients. Unfortunately, none of these tests completed. One or more of the modems dropped the network connection.

Sunvalley Mall (mid cell) Uplink Tests

In these tests we streamed data from one and then two mobile units at a rate of 5 Mbits per second, which turned out to be well above the network capacity. Thus only a fraction of the packets were received. The measured capacity of the network was slightly more than 2 Mbits per second.

Mbits/sec	Jitter (ms)	Lost Data	Antenna	Test
0.85	27.76	83%	External	Upload at 5 Mbits/sec from 1 client
0.75	36.15	85%	External	Upload at 5 Mbits/sec from 2 clients
1.36	8.22	72%	External	
2.11				Total upload Mbits/sec

Three additional attempts were made to stream data to the host, but the modems disconnected before the tests could be completed.

Sunvalley Mall (mid cell) Simultaneous Downlink / Uplink Tests

These tests confirm what we observed in the separate download and upload tests above. We were able to stream from the server to the mobile units at a total rate of almost 10 Mbits per second while simultaneously uploading at 1 Mbit per second.

Mbits/sec	Jitter (ms)	Lost Data	Antenna	Test
4.98	5.18	5%	External	Download at 5 Mbits/sec to 2 clients, upload at 5 Mbits/sec from 1 client
4.98	0.00	2%	External	
9.96				Total download Mbits/sec
1.02	21.11	79%	External	Total upload Mbits/sec

John Muir House (cell edge) Download Tests

Because this location is at the edge of the LTE cell coverage, the modems with internal antennas were unable to make a connection to the network, thus we were unable to run all of the planned tests.

The first two test sets below demonstrate the maximum capacity of the network at the “worst case” location. We streamed data to a mobile unit at data rates ranging from 15 Mbits per second, well above the network capacity, down to 10 Mbits per second. The average capacity measured was slightly less than 11 Mbits per second. Note that at a streaming rate of 5 Mbits per second, only 4% of the data packets were lost.

The last two test sets demonstrate that the network cannot support streaming to more than one mobile client at 5 Mbits per second without suffering significant data packet loss.

Mbits/sec	Jitter (ms)	Lost Data	Antenna	Test
6.08	3.19	59%	External	Download at 15 Mbits/sec to 1 client
6.05	3.21	49%	External	Download at 12 Mbits/sec to 1 client
5.99	3.53	40%	External	Download at 10 Mbits/sec to 1 client
6.04				Average Mbits/sec
4.88	3.59	4%	External	Download at 5 Mbits/sec to 1 client
3.26	6.79	35%	External	Download at 5 Mbits/sec to 2 clients
4.32	0.58	14%	External	
7.58				Total download Mbits/sec
2.13	4.22	57%	External	Download at 5 Mbits/sec to 3 clients
2.84	7.66	43%	External	
3.14	3.44	37%	External	
8.11				Total download Mbits/sec

Two attempts were made to simultaneously download data at 5 Mbits/sec to four clients. Unfortunately, none of these tests completed. One or more of the modems dropped the network connection.

John Muir House (cell edge) Upload Tests

In these tests we streamed data from a mobile unit at a rate of 10 and then 5 Mbits per second, which turned out to be well above the network capacity, thus only a fraction of the packets were received. The measured capacity of the network was slightly more than 0.2 Mbits per second.

Mbits/sec	Jitter (ms)	Lost Data	Antenna	Test
0.19	67.35	98%	External	Upload at 10 Mbits/sec from 1 client
0.19	70.20	96%	External	Upload at 5 Mbits/sec from 1 client
0.27	47.86	95%	External	Upload at 5 Mbits/sec from 1 client
0.22				Average Mbits/sec

Appendix D: Video Test Results

The following tables present the raw data from the field tests. The columns display the following information:

Mbits/sec	is the rate at which data was received by the target computer (client computer on downloads, server computer on uploads) measured in megabytes (not megabits) per second of data delivered.
Jitter	is the average of the deviation from the network mean packet latency across the network measured in milliseconds.
Lost Data	is the percentage of sent data that was not received by the target computer.
Antenna	indicates whether the field computer's LTE modem is connected to an external antenna or is relying on an antenna internal to the modem. During the tests we found the modems with external antennas to perform significantly better than those with internal antennas.
Test	summarizes the particular test for which the results are displayed. If the test mentions more than one client, it means that data was being sent to or received from multiple computers at the same time.

Note that some of the tests do not have the data rates recorded due to a software failure on the mobile units.

Downlink Tests

In these tests we streamed our test video to one or more mobile units. We recorded the received video image and later checked it for quality. When the received video is labeled "good quality" it means a reasonable image is displayed, although some dropped frames are noticeable.

Location	Mbits/sec	Lost Data	Antenna	Test
Glacier Street	1.86	3%	External	Stream to client – good quality
	5.73			Stream to 3 clients – good quality
	7.64			Stream to 4 clients – good quality
	9.55			Stream to 5 clients – good quality
				Stream to 6 clients – modems disconnect
Sunvalley Mall	5.73			Stream to 3 clients – good quality
				Stream to 4 clients – modems disconnect
John Muir House	1.76	8%	External	Stream to client – good quality
John Muir House	1.60	16%	External	Stream to 2 clients – good quality
	1.42	26%	External	
	3.02		External	Total Mbits/sec
John Muir House	1.71	10%	External	Stream to 3 clients – good quality
	1.28	33%	External	
	1.81	5%	External	
	4.80			Total Mbits/sec
John Muir House				Stream to 4 clients – modems disconnect

Uplink Tests

In these tests we streamed our test video from one or more mobile units to the server. We recorded the received video image and later checked it for quality. When the received video is labeled "good quality" it means a reasonable image is displayed, although some dropped frames are noticeable.

Location	Mbits/sec	Lost Data	Antenna	Test
Glacier Street	1.67	13%	External	Stream from client – good quality
Sunvalley Mall	0.93	51%	External	Stream from client – image breakup
	3.82			Stream from 2 clients – good quality
				Stream from 3 clients – image breakup

Several attempts were made to stream more than one video simultaneously to the server at the Glacier Street test location, but none were successful. We were unable to successfully stream any videos from the mobile units to the server at the "worst case" John Muir House test site. The available network bandwidth was inadequate.

Appendix E: Anritsu Test Data

The following are images taken off the screen of the Anritsu LTE broadband test sets used during the tests. Each of these represents a snapshot in time and each includes a total of 520 Resource Blocks, 16 of which are used for signaling between the network and the device, leaving a total of 504 resource blocks allocated for data transfer.

The downlink and uplink each contain the same number of resource blocks; these screen shots are for the downlink only. The color of the resource block indicates the signal strength of the received signal. The lower numbers (i.e., closer to -0) indicate a stronger signal. As the signal weakens the numbers will move lower, i.e., -50, -89, etc. See the color grid within each screen shot to indicate the signal strength for each resource block. Black indicates that that resource block is empty and therefore available.

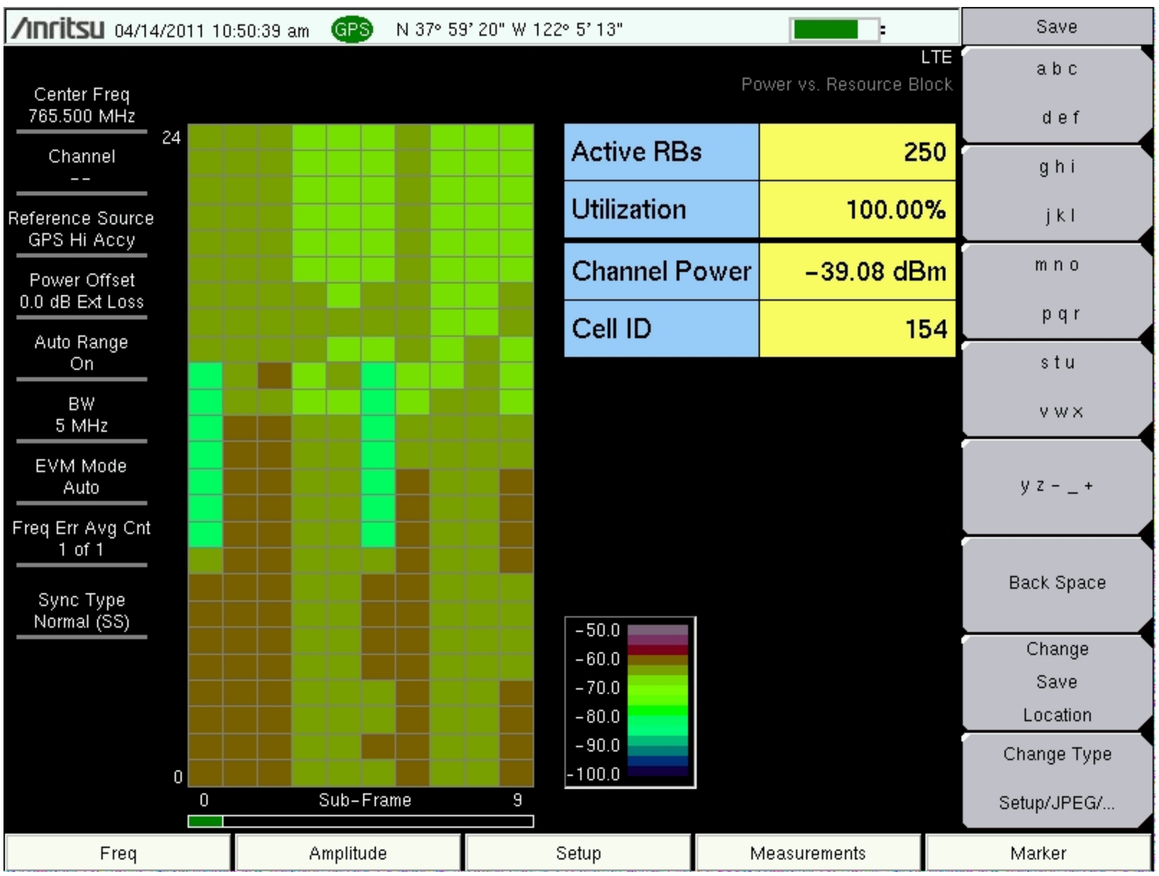


Diagram 1: Closest to the cell center, very strong signal, network is operating at 100% of its capacity

Notice in this diagram that the 16 signaling channel resource blocks as well as a few others in this frame are not in use.

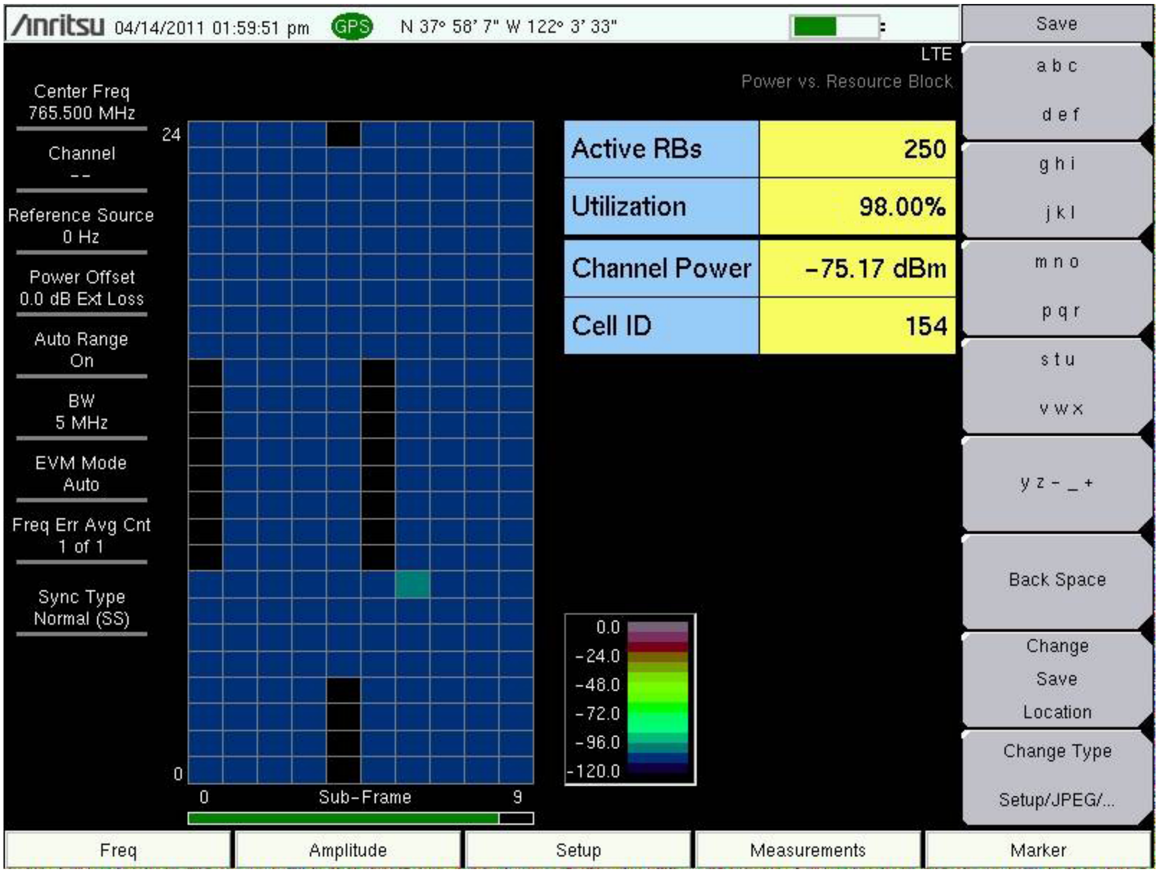


Diagram 2: Middle of cell coverage, signal level weaker, 98% network utilization

In the next diagram, notice that signal strength is much weaker and unevenly distributed within the resource block.

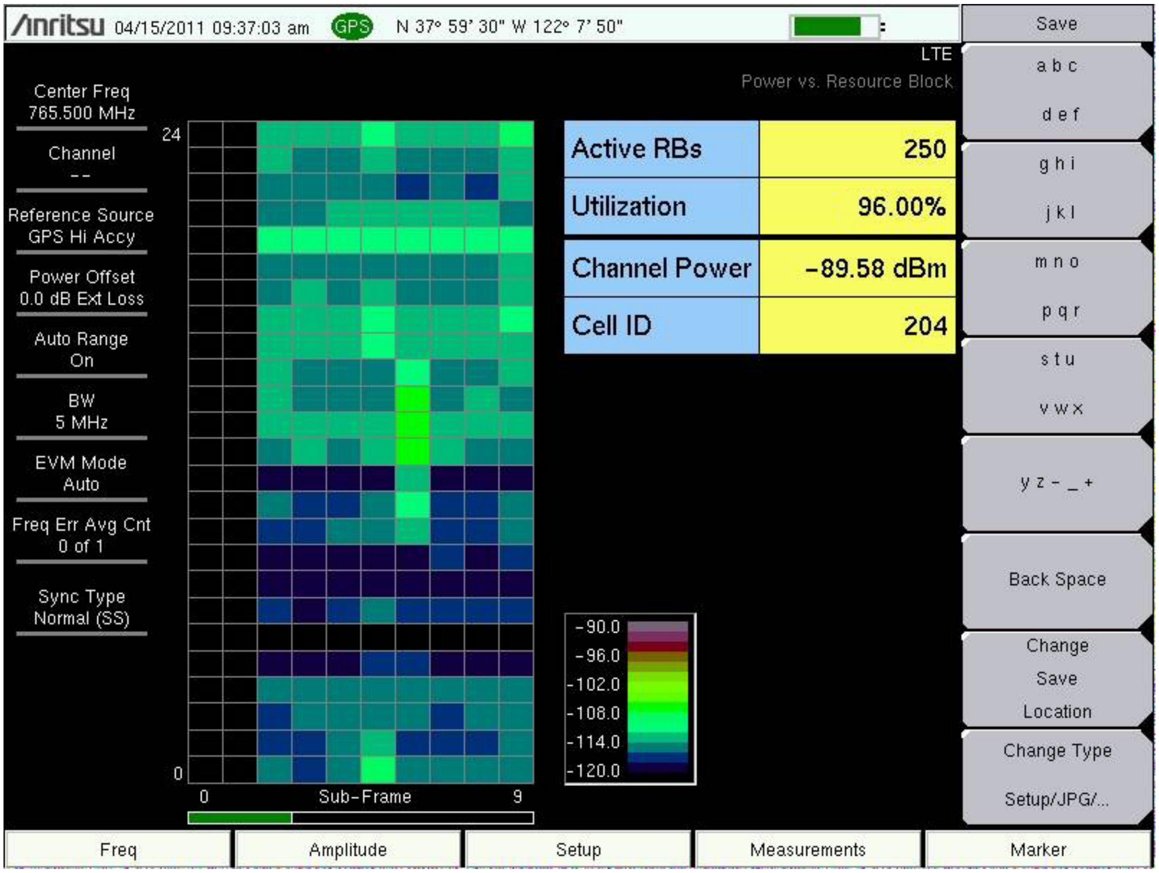


Diagram 3: Edge of cell, 96% system utilization

Appendix F: Test Logs

In this section we list a sample Iperf report from each of the three test sites.

Glacier Street (near cell)

This log documents the server sending data to a single client at the rate of 20 megabits per second:

```
------------------------------------------------------------
Server listening on UDP port 5001
Receiving 1470 byte datagrams
UDP buffer size: 8.00 KByte (default)
------------------------------------------------------------
[1908] local 10.170.2.224 port 5001 connected with 10.171.96.6 port 51051
[ ID] Interval      Transfer     Bandwidth       Jitter   Lost/Total Datagrams
[1908] 0.0- 1.0 sec 1.15 MBytes 9.68 Mbits/sec 1.740 ms 1313429363/ 846 (1.6e+008%)
[1908] 1.0- 2.0 sec 1.17 MBytes 9.85 Mbits/sec 0.920 ms  3/ 841 (0.36%)
[1908] 2.0- 3.0 sec 1.19 MBytes 9.96 Mbits/sec 1.689 ms  11/ 858 (1.3%)
[1908] 3.0- 4.0 sec 1.16 MBytes 9.76 Mbits/sec 1.826 ms  13/ 843 (1.5%)
[1908] 4.0- 5.0 sec 1.16 MBytes 9.73 Mbits/sec 2.240 ms  19/ 846 (2.2%)
[1908] 5.0- 6.0 sec 1.19 MBytes 9.97 Mbits/sec 1.699 ms  15/ 863 (1.7%)
[1908] 6.0- 7.0 sec 1.19 MBytes 9.95 Mbits/sec 1.616 ms  5/ 851 (0.59%)
[1908] 7.0- 8.0 sec 1.18 MBytes 9.87 Mbits/sec 1.801 ms  2/ 841 (0.24%)
[1908] 8.0- 9.0 sec 1.19 MBytes 9.98 Mbits/sec 1.082 ms  9/ 858 (1%)
[1908] 9.0-10.0 sec 1.16 MBytes 9.73 Mbits/sec 1.552 ms  23/ 850 (2.7%)
[1908] 10.0-11.0 sec 1.18 MBytes 9.91 Mbits/sec 1.395 ms  2/ 845 (0.24%)
[1908] 11.0-12.0 sec 1.14 MBytes 9.57 Mbits/sec 1.914 ms  34/ 848 (4%)
[1908] 12.0-13.0 sec 1.18 MBytes 9.94 Mbits/sec 0.747 ms  6/ 851 (0.71%)
[1908] 13.0-14.0 sec 1.16 MBytes 9.76 Mbits/sec 0.918 ms  20/ 850 (2.4%)
[1908] 14.0-15.0 sec 1.17 MBytes 9.85 Mbits/sec 2.511 ms  15/ 853 (1.8%)
[1908] 15.0-16.0 sec 1.19 MBytes 9.95 Mbits/sec 1.104 ms  11/ 857 (1.3%)
[1908] 16.0-17.0 sec 1.15 MBytes 9.67 Mbits/sec 2.070 ms  19/ 841 (2.3%)
[1908] 17.0-18.0 sec 1.17 MBytes 9.80 Mbits/sec 1.721 ms  25/ 858 (2.9%)
[1908] 18.0-19.0 sec 1.19 MBytes 9.98 Mbits/sec 1.818 ms  1/ 850 (0.12%)
[1908] 19.0-20.0 sec 1.16 MBytes 9.77 Mbits/sec 1.708 ms  19/ 850 (2.2%)
[ ID] Interval      Transfer     Bandwidth       Jitter   Lost/Total Datagrams
[1908] 20.0-21.0 sec 1.18 MBytes 9.90 Mbits/sec 2.894 ms  2/ 844 (0.24%)
[1908] 21.0-22.0 sec 1.18 MBytes 9.89 Mbits/sec 1.631 ms  17/ 858 (2%)
[1908] 22.0-23.0 sec 1.16 MBytes 9.76 Mbits/sec 1.943 ms  12/ 842 (1.4%)
[1908] 23.0-24.0 sec 1.18 MBytes 9.93 Mbits/sec 1.828 ms  6/ 850 (0.71%)
[1908] 24.0-25.0 sec 1.17 MBytes 9.81 Mbits/sec 0.764 ms  17/ 851 (2%)
[1908] 25.0-26.0 sec 1.19 MBytes 9.98 Mbits/sec 1.861 ms  8/ 857 (0.93%)
[1908] 26.0-27.0 sec 1.16 MBytes 9.73 Mbits/sec 1.721 ms  16/ 843 (1.9%)
[1908] 27.0-28.0 sec 1.17 MBytes 9.82 Mbits/sec 1.550 ms  24/ 859 (2.8%)
[1908] 28.0-29.0 sec 1.17 MBytes 9.85 Mbits/sec 1.964 ms  4/ 842 (0.48%)
[1908] 29.0-30.0 sec 1.17 MBytes 9.85 Mbits/sec 1.992 ms  12/ 850 (1.4%)
[1908] 30.0-31.0 sec 1.16 MBytes 9.71 Mbits/sec 1.840 ms  25/ 851 (2.9%)
[1908] 31.0-32.0 sec 1.20 MBytes 10.0 Mbits/sec 1.758 ms  4/ 857 (0.47%)
[1908] 32.0-33.0 sec 1.16 MBytes 9.70 Mbits/sec 1.639 ms  27/ 852 (3.2%)
[1908] 33.0-34.0 sec 1.18 MBytes 9.89 Mbits/sec 2.303 ms  11/ 852 (1.3%)
[1908] 34.0-35.0 sec 1.17 MBytes 9.85 Mbits/sec 0.480 ms  10/ 848 (1.2%)
[1908] 35.0-36.0 sec 1.12 MBytes 9.37 Mbits/sec 2.190 ms  38/ 835 (4.6%)
[1908] 36.0-37.0 sec 1.21 MBytes 10.1 Mbits/sec 0.746 ms  2/ 865 (0.23%)
[1908] 37.0-38.0 sec 1.06 MBytes 8.87 Mbits/sec 1.159 ms  11/ 765 (1.4%)
[1908] 38.0-39.0 sec 1.27 MBytes 10.6 Mbits/sec 0.842 ms  27/ 931 (2.9%)
[1908] 39.0-40.0 sec 1.19 MBytes 10.0 Mbits/sec 2.164 ms  8/ 859 (0.93%)
[ ID] Interval      Transfer     Bandwidth       Jitter   Lost/Total Datagrams
[1908] 40.0-41.0 sec 1.19 MBytes 10.0 Mbits/sec 1.674 ms  5/ 855 (0.58%)
[1908] 41.0-42.0 sec 1.04 MBytes 8.75 Mbits/sec 2.121 ms  15/ 759 (2%)
[1908] 42.0-43.0 sec 1.30 MBytes 10.9 Mbits/sec 1.849 ms  15/ 940 (1.6%)
[1908] 43.0-44.0 sec 1.17 MBytes 9.78 Mbits/sec 1.658 ms  12/ 844 (1.4%)
[1908] 44.0-45.0 sec 1.16 MBytes 9.73 Mbits/sec 0.780 ms  23/ 850 (2.7%)
[1908] 45.0-46.0 sec 1.17 MBytes 9.84 Mbits/sec 1.998 ms  13/ 850 (1.5%)
[1908] 46.0-47.0 sec 1.18 MBytes 9.87 Mbits/sec 1.709 ms  20/ 859 (2.3%)
[1908] 47.0-48.0 sec 1.18 MBytes 9.90 Mbits/sec 1.903 ms  0/ 842 (0%)
[1908] 48.0-49.0 sec 1.18 MBytes 9.93 Mbits/sec 1.780 ms  14/ 858 (1.6%)
[1908] 49.0-50.0 sec 1.16 MBytes 9.69 Mbits/sec 1.668 ms  19/ 843 (2.3%)
[1908] 50.0-51.0 sec 1.17 MBytes 9.85 Mbits/sec 1.832 ms  12/ 850 (1.4%)
[1908] 51.0-52.0 sec 1.17 MBytes 9.78 Mbits/sec 1.773 ms  26/ 858 (3%)
[1908] 52.0-53.0 sec 1.15 MBytes 9.62 Mbits/sec 1.670 ms  25/ 843 (3%)
[1908] 53.0-54.0 sec 1.20 MBytes 10.1 Mbits/sec 2.312 ms  9/ 868 (1%)
[1908] 54.0-55.0 sec 1.16 MBytes 9.71 Mbits/sec 1.863 ms  21/ 847 (2.5%)
[1908] 55.0-56.0 sec 1.15 MBytes 9.61 Mbits/sec 2.370 ms  36/ 853 (4.2%)
[1908] 56.0-57.0 sec 1.18 MBytes 9.88 Mbits/sec 1.775 ms  16/ 856 (1.9%)
```

```
[1908] 57.0-58.0 sec 1.17 MBytes 9.78 Mbits/sec 1.681 ms  10/ 842 (1.2%)
[1908] 58.0-59.0 sec 1.12 MBytes 9.41 Mbits/sec 1.228 ms  50/ 850 (5.9%)
[1908] 59.0-60.0 sec 1.18 MBytes 9.91 Mbits/sec 1.521 ms  14/ 857 (1.6%)
[ ID] Interval      Transfer     Bandwidth       Jitter   Lost/Total Datagrams
[1908] 60.0-61.0 sec 1.18 MBytes 9.90 Mbits/sec 0.990 ms  11/ 853 (1.3%)
[1908] 61.0-62.0 sec 1.17 MBytes 9.81 Mbits/sec 1.677 ms  16/ 850 (1.9%)
[1908] 62.0-63.0 sec 1.16 MBytes 9.77 Mbits/sec 0.924 ms  19/ 850 (2.2%)
[1908] 63.0-64.0 sec 1.12 MBytes 9.41 Mbits/sec 1.609 ms  48/ 848 (5.7%)
[1908] 64.0-65.0 sec 1.19 MBytes 10.0 Mbits/sec 1.780 ms  0/ 852 (0%)
[1908] 65.0-66.0 sec 1.19 MBytes 9.97 Mbits/sec 1.976 ms  0/ 848 (0%)
[1908] 66.0-67.0 sec 1.18 MBytes 9.94 Mbits/sec 1.556 ms  0/ 845 (0%)
[1908] 67.0-68.0 sec 1.17 MBytes 9.82 Mbits/sec 1.807 ms  15/ 850 (1.8%)
[1908] 68.0-69.0 sec 1.19 MBytes 10.0 Mbits/sec 1.377 ms  9/ 859 (1%)
[1908] 69.0-70.0 sec 1.18 MBytes 9.89 Mbits/sec 1.884 ms  7/ 848 (0.83%)
[1908] 70.0-71.0 sec 1.19 MBytes 10.0 Mbits/sec 1.634 ms  2/ 852 (0.23%)
[1908] 71.0-72.0 sec 1.18 MBytes 9.90 Mbits/sec 1.798 ms  0/ 842 (0%)
[1908] 72.0-73.0 sec 1.17 MBytes 9.81 Mbits/sec 0.653 ms  17/ 851 (2%)
[1908] 73.0-74.0 sec 1.18 MBytes 9.88 Mbits/sec 1.820 ms  17/ 857 (2%)
[1908] 74.0-75.0 sec 1.18 MBytes 9.91 Mbits/sec 1.106 ms  6/ 849 (0.71%)
[1908] 75.0-76.0 sec 1.18 MBytes 9.94 Mbits/sec 1.844 ms  6/ 851 (0.71%)
[1908] 76.0-77.0 sec 1.18 MBytes 9.93 Mbits/sec 1.717 ms  7/ 851 (0.82%)
[1908] 77.0-78.0 sec 1.18 MBytes 9.93 Mbits/sec 1.734 ms  7/ 851 (0.82%)
[1908] 78.0-79.0 sec 1.18 MBytes 9.91 Mbits/sec 1.805 ms  0/ 843 (0%)
[1908] 79.0-80.0 sec 1.08 MBytes 9.06 Mbits/sec 1.792 ms  87/ 857 (10%)
[ ID] Interval      Transfer     Bandwidth       Jitter   Lost/Total Datagrams
[1908] 80.0-81.0 sec 1.12 MBytes 9.36 Mbits/sec 0.770 ms  55/ 851 (6.5%)
[1908] 81.0-82.0 sec 1.18 MBytes 9.91 Mbits/sec 1.886 ms  6/ 849 (0.71%)
[1908] 82.0-83.0 sec 1.19 MBytes 9.98 Mbits/sec 1.619 ms  1/ 850 (0.12%)
[1908] 83.0-84.0 sec 1.19 MBytes 10.0 Mbits/sec 1.746 ms  0/ 851 (0%)
[1908] 84.0-85.0 sec 1.15 MBytes 9.65 Mbits/sec 1.770 ms  30/ 851 (3.5%)
[1908] 85.0-86.0 sec 1.05 MBytes 8.81 Mbits/sec 0.858 ms  9/ 758 (1.2%)
[1908] 86.0-87.0 sec 1.28 MBytes 10.7 Mbits/sec 1.020 ms  31/ 942 (3.3%)
[1908] 87.0-88.0 sec 1.19 MBytes 9.95 Mbits/sec 2.225 ms  0/ 846 (0%)
[1908] 88.0-89.0 sec 1.15 MBytes 9.61 Mbits/sec 0.514 ms  31/ 848 (3.7%)
[1908] 89.0-90.0 sec 1.19 MBytes 9.98 Mbits/sec 2.083 ms  6/ 855 (0.7%)
[1908] 90.0-91.0 sec 1.17 MBytes 9.84 Mbits/sec 1.815 ms  15/ 852 (1.8%)
[1908] 91.0-92.0 sec 1.16 MBytes 9.74 Mbits/sec 2.205 ms  0/ 828 (0%)
[1908] 92.0-93.0 sec 1.21 MBytes 10.1 Mbits/sec 2.642 ms  7/ 867 (0.81%)
[1908] 93.0-94.0 sec 1.19 MBytes 9.98 Mbits/sec 1.521 ms  7/ 856 (0.82%)
[1908] 94.0-95.0 sec 1.19 MBytes 9.95 Mbits/sec 1.771 ms  5/ 851 (0.59%)
[1908] 95.0-96.0 sec 1.15 MBytes 9.61 Mbits/sec 1.711 ms  32/ 849 (3.8%)
[1908] 96.0-97.0 sec 1.16 MBytes 9.71 Mbits/sec 1.688 ms  27/ 853 (3.2%)
[1908] 97.0-98.0 sec 1.17 MBytes 9.84 Mbits/sec 1.632 ms  5/ 842 (0.59%)
[1908] 98.0-99.0 sec 1.18 MBytes 9.90 Mbits/sec 1.709 ms  16/ 858 (1.9%)
[1908] 0.0-100.0 sec  117 MBytes 9.83 Mbits/sec 2.323 ms 1485/85031 (1.7%)
```

Sunvalley Mall (mid cell)

This log documents the server sending data to a single client at the rate of 20 megabits per second:

```
------------------------------------------------------------
Server listening on UDP port 5001
Receiving 1470 byte datagrams
UDP buffer size: 8.00 KByte (default)
------------------------------------------------------------
[1908] local 10.170.2.207 port 5001 connected with 10.171.96.6 port 51726
[ ID] Interval      Transfer     Bandwidth       Jitter   Lost/Total Datagrams
[1908] 0.0- 1.0 sec 1.17 MBytes 9.80 Mbits/sec 0.849 ms 1547322235/ 897 (1.7e+008%)
[1908] 1.0- 2.0 sec 1.29 MBytes 10.8 Mbits/sec 1.077 ms 782/ 1699 (46%)
[1908] 2.0- 3.0 sec 1.47 MBytes 12.4 Mbits/sec 1.683 ms 535/ 1586 (34%)
[1908] 3.0- 4.0 sec 1.63 MBytes 13.7 Mbits/sec 2.016 ms 637/ 1802 (35%)
[1908] 4.0- 5.0 sec 1.27 MBytes 10.7 Mbits/sec 1.802 ms 806/ 1715 (47%)
[1908] 5.0- 6.0 sec 1.30 MBytes 10.9 Mbits/sec 1.718 ms 765/ 1692 (45%)
[1908] 6.0- 7.0 sec 1.39 MBytes 11.6 Mbits/sec 1.748 ms 710/ 1698 (42%)
[1908] 7.0- 8.0 sec 1.52 MBytes 12.7 Mbits/sec 0.963 ms 635/ 1718 (37%)
[1908] 8.0- 9.0 sec 1.56 MBytes 13.1 Mbits/sec 1.473 ms 565/ 1681 (34%)
[1908] 9.0-10.0 sec 1.54 MBytes 12.9 Mbits/sec 1.879 ms 621/ 1722 (36%)
[1908] 10.0-11.0 sec 1.29 MBytes 10.8 Mbits/sec 1.765 ms 734/ 1655 (44%)
[1908] 11.0-12.0 sec 1.28 MBytes 10.8 Mbits/sec 1.491 ms 806/ 1721 (47%)
[1908] 12.0-13.0 sec 1.30 MBytes 10.9 Mbits/sec 1.776 ms 756/ 1680 (45%)
[1908] 13.0-14.0 sec 1.30 MBytes 10.9 Mbits/sec 1.558 ms 793/ 1720 (46%)
[1908] 14.0-15.0 sec 1.27 MBytes 10.6 Mbits/sec 1.953 ms 775/ 1679 (46%)
[1908] 15.0-16.0 sec 1.26 MBytes 10.5 Mbits/sec 2.138 ms 827/ 1723 (48%)
[1908] 16.0-17.0 sec 1.30 MBytes 10.9 Mbits/sec 1.190 ms 758/ 1688 (45%)
[1908] 17.0-18.0 sec 1.27 MBytes 10.7 Mbits/sec 1.258 ms 794/ 1702 (47%)
[1908] 18.0-19.0 sec 1.21 MBytes 10.2 Mbits/sec 0.629 ms 827/ 1693 (49%)
[1908] 19.0-20.0 sec 1.24 MBytes 10.4 Mbits/sec 2.483 ms 740/ 1624 (46%)
[ ID] Interval      Transfer     Bandwidth       Jitter   Lost/Total Datagrams
```

```
[1908] 20.0-21.0 sec 1.26 MBytes 10.6 Mbits/sec 2.101 ms 872/ 1772 (49%)
[1908] 21.0-22.0 sec 1.28 MBytes 10.8 Mbits/sec 1.155 ms 804/ 1720 (47%)
[1908] 22.0-23.0 sec 1.29 MBytes 10.8 Mbits/sec 1.444 ms 784/ 1702 (46%)
[1908] 23.0-24.0 sec 1.25 MBytes 10.5 Mbits/sec 1.344 ms 801/ 1694 (47%)
[1908] 24.0-25.0 sec 1.30 MBytes 10.9 Mbits/sec 1.655 ms 764/ 1692 (45%)
[1908] 25.0-26.0 sec 1.31 MBytes 10.9 Mbits/sec 2.123 ms 767/ 1698 (45%)
[1908] 26.0-27.0 sec 1.28 MBytes 10.8 Mbits/sec 2.047 ms 786/ 1701 (46%)
[1908] 27.0-28.0 sec 1.22 MBytes 10.2 Mbits/sec 1.304 ms 840/ 1711 (49%)
[1908] 28.0-29.0 sec 1.32 MBytes 11.1 Mbits/sec 0.350 ms 766/ 1709 (45%)
[1908] 29.0-30.0 sec 1.28 MBytes 10.7 Mbits/sec 1.372 ms 776/ 1690 (46%)
[1908] 30.0-31.0 sec 1.28 MBytes 10.7 Mbits/sec 1.277 ms 788/ 1699 (46%)
[1908] 31.0-32.0 sec 1.27 MBytes 10.7 Mbits/sec 1.283 ms 807/ 1714 (47%)
[1908] 32.0-33.0 sec 1.30 MBytes 10.9 Mbits/sec 1.257 ms 765/ 1689 (45%)
[1908] 33.0-34.0 sec 1.26 MBytes 10.5 Mbits/sec 1.657 ms 805/ 1702 (47%)
[1908] 34.0-35.0 sec 1.29 MBytes 10.8 Mbits/sec 1.390 ms 780/ 1702 (46%)
[1908] 35.0-36.0 sec 1.30 MBytes 10.9 Mbits/sec 1.432 ms 775/ 1699 (46%)
[1908] 36.0-37.0 sec 1.17 MBytes 9.80 Mbits/sec 2.081 ms 709/ 1542 (46%)
[1908] 37.0-38.0 sec 1.40 MBytes 11.7 Mbits/sec 1.287 ms 862/ 1858 (46%)
[1908] 38.0-39.0 sec 1.30 MBytes 10.9 Mbits/sec 1.336 ms 771/ 1699 (45%)
[1908] 39.0-40.0 sec 1.33 MBytes 11.2 Mbits/sec 1.323 ms 765/ 1715 (45%)
[ ID] Interval     Transfer    Bandwidth     Jitter   Lost/Total Datagrams
[1908] 40.0-41.0 sec 1.31 MBytes 11.0 Mbits/sec 1.195 ms 753/ 1688 (45%)
[1908] 41.0-42.0 sec 1.34 MBytes 11.2 Mbits/sec 1.437 ms 761/ 1714 (44%)
[1908] 42.0-43.0 sec 1.29 MBytes 10.9 Mbits/sec 2.117 ms 778/ 1701 (46%)
[1908] 43.0-44.0 sec 1.25 MBytes 10.5 Mbits/sec 1.408 ms 798/ 1690 (47%)
[1908] 44.0-45.0 sec 1.31 MBytes 11.0 Mbits/sec 1.361 ms 773/ 1709 (45%)
[1908] 45.0-46.0 sec 1.35 MBytes 11.3 Mbits/sec 2.029 ms 743/ 1703 (44%)
[1908] 46.0-47.0 sec 1.33 MBytes 11.1 Mbits/sec 1.426 ms 739/ 1685 (44%)
[1908] 47.0-48.0 sec 1.35 MBytes 11.3 Mbits/sec 2.176 ms 756/ 1716 (44%)
[1908] 48.0-49.0 sec 1.32 MBytes 11.1 Mbits/sec 1.217 ms 746/ 1686 (44%)
[1908] 49.0-50.0 sec 1.31 MBytes 11.0 Mbits/sec 1.209 ms 775/ 1713 (45%)
[1908] 50.0-51.0 sec 1.31 MBytes 11.0 Mbits/sec 1.973 ms 765/ 1703 (45%)
[1908] 51.0-52.0 sec 1.32 MBytes 11.1 Mbits/sec 1.542 ms 740/ 1685 (44%)
[1908] 52.0-53.0 sec 1.32 MBytes 11.1 Mbits/sec 0.117 ms 773/ 1715 (45%)
[1908] 53.0-54.0 sec 1.33 MBytes 11.2 Mbits/sec 1.326 ms 749/ 1699 (44%)
[1908] 54.0-55.0 sec 1.28 MBytes 10.7 Mbits/sec 1.002 ms 777/ 1689 (46%)
[1908] 55.0-56.0 sec 1.33 MBytes 11.2 Mbits/sec 1.267 ms 760/ 1710 (44%)
[1908] 56.0-57.0 sec 1.29 MBytes 10.9 Mbits/sec 2.294 ms 748/ 1671 (45%)
[1908] 57.0-58.0 sec 1.23 MBytes 10.3 Mbits/sec 1.127 ms 855/ 1732 (49%)
[1908] 58.0-59.0 sec 1.24 MBytes 10.4 Mbits/sec 1.547 ms 806/ 1688 (48%)
[1908] 59.0-60.0 sec 1.28 MBytes 10.7 Mbits/sec 1.049 ms 801/ 1712 (47%)
[ ID] Interval     Transfer    Bandwidth     Jitter   Lost/Total Datagrams
[1908] 60.0-61.0 sec 1.29 MBytes 10.8 Mbits/sec 1.310 ms 788/ 1706 (46%)
[1908] 61.0-62.0 sec 1.33 MBytes 11.1 Mbits/sec 1.218 ms 740/ 1687 (44%)
[1908] 62.0-63.0 sec 1.33 MBytes 11.1 Mbits/sec 0.289 ms 767/ 1713 (45%)
[1908] 63.0-64.0 sec 1.32 MBytes 11.1 Mbits/sec 1.457 ms 751/ 1692 (44%)
[1908] 64.0-65.0 sec 1.38 MBytes 11.6 Mbits/sec 0.825 ms 721/ 1704 (42%)
[1908] 65.0-66.0 sec 1.55 MBytes 13.0 Mbits/sec 0.931 ms 595/ 1704 (35%)
[1908] 66.0-67.0 sec 1.55 MBytes 13.0 Mbits/sec 0.898 ms 588/ 1695 (35%)
[1908] 67.0-68.0 sec 1.35 MBytes 11.3 Mbits/sec 1.775 ms 612/ 1572 (39%)
[1908] 68.0-69.0 sec 1.45 MBytes 12.1 Mbits/sec 1.026 ms 804/ 1835 (44%)
[1908] 69.0-70.0 sec 1.39 MBytes 11.7 Mbits/sec 1.826 ms 690/ 1685 (41%)
[1908] 70.0-71.0 sec 1.33 MBytes 11.2 Mbits/sec 1.199 ms 756/ 1707 (44%)
[1908] 71.0-72.0 sec 1.31 MBytes 11.0 Mbits/sec 1.229 ms 766/ 1701 (45%)
[1908] 72.0-73.0 sec 1.36 MBytes 11.4 Mbits/sec 1.003 ms 726/ 1695 (43%)
[1908] 73.0-74.0 sec 1.26 MBytes 10.6 Mbits/sec 1.056 ms 817/ 1717 (48%)
[1908] 74.0-75.0 sec 1.33 MBytes 11.2 Mbits/sec 1.146 ms 748/ 1700 (44%)
[1908] 75.0-76.0 sec 1.32 MBytes 11.1 Mbits/sec 1.294 ms 755/ 1697 (44%)
[1908] 76.0-77.0 sec 1.31 MBytes 11.0 Mbits/sec 1.711 ms 755/ 1693 (45%)
[1908] 77.0-78.0 sec 1.33 MBytes 11.1 Mbits/sec 0.581 ms 764/ 1711 (45%)
[1908] 78.0-79.0 sec 1.29 MBytes 10.9 Mbits/sec 2.153 ms 781/ 1704 (46%)
[1908] 79.0-80.0 sec 1.31 MBytes 11.0 Mbits/sec 1.263 ms 764/ 1698 (45%)
[ ID] Interval     Transfer    Bandwidth     Jitter   Lost/Total Datagrams
[1908] 80.0-81.0 sec 1.26 MBytes 10.5 Mbits/sec 2.077 ms 787/ 1684 (47%)
[1908] 81.0-82.0 sec 1.29 MBytes 10.8 Mbits/sec 1.429 ms 800/ 1720 (47%)
[1908] 82.0-83.0 sec 1.34 MBytes 11.2 Mbits/sec 0.952 ms 746/ 1699 (44%)
[1908] 83.0-84.0 sec 1.29 MBytes 10.8 Mbits/sec 0.612 ms 778/ 1697 (46%)
[1908] 84.0-85.0 sec 1.28 MBytes 10.8 Mbits/sec 1.303 ms 777/ 1692 (46%)
[1908] 85.0-86.0 sec 1.29 MBytes 10.9 Mbits/sec 1.314 ms 777/ 1700 (46%)
[1908] 86.0-87.0 sec 1.28 MBytes 10.8 Mbits/sec 1.179 ms 787/ 1703 (46%)
[1908] 87.0-88.0 sec 1.33 MBytes 11.2 Mbits/sec 1.825 ms 756/ 1706 (44%)
[1908] 88.0-89.0 sec 1.29 MBytes 10.8 Mbits/sec 1.857 ms 748/ 1670 (45%)
[1908] 89.0-90.0 sec 1.30 MBytes 10.9 Mbits/sec 1.547 ms 799/ 1724 (46%)
[1908] 90.0-91.0 sec 1.30 MBytes 10.9 Mbits/sec 1.155 ms 786/ 1711 (46%)
[1908] 91.0-92.0 sec 1.34 MBytes 11.2 Mbits/sec 1.221 ms 748/ 1701 (44%)
[1908] 92.0-93.0 sec 1.30 MBytes 10.9 Mbits/sec 1.401 ms 762/ 1688 (45%)
[1908] 93.0-94.0 sec 1.27 MBytes 10.7 Mbits/sec 1.296 ms 795/ 1704 (47%)
[1908] 94.0-95.0 sec 1.31 MBytes 10.9 Mbits/sec 1.209 ms 768/ 1699 (45%)
[1908] 95.0-96.0 sec 1.20 MBytes 10.0 Mbits/sec 2.489 ms 841/ 1695 (50%)
[1908] 96.0-97.0 sec 1.19 MBytes 9.97 Mbits/sec 1.256 ms 860/ 1708 (50%)
[1908] 97.0-98.0 sec 1.34 MBytes 11.2 Mbits/sec 1.271 ms 754/ 1709 (44%)
```

```
[1908] 98.0-99.0 sec 1.35 MBytes 11.3 Mbits/sec 1.804 ms 723/ 1687 (43%)
[1908] 99.0-100.0 sec 1.35 MBytes 11.3 Mbits/sec 1.279 ms 740/ 1704 (43%)
[ ID] Interval     Transfer    Bandwidth     Jitter   Lost/Total Datagrams
[1908] 0.0-100.5 sec  132 MBytes 11.1 Mbits/sec 2.228 ms 75636/170043 (44%)
```

John Muir House (cell edge)

This log documents the server sending data to a single client at the rate of 15 megabits per second:

```
------------------------------------------------------------
Server listening on UDP port 5001
Receiving 1470 byte datagrams
UDP buffer size: 8.00 KByte (default)
------------------------------------------------------------
[1908] local 10.170.2.217 port 5001 connected with 10.171.96.6 port 62928
[ ID] Interval     Transfer    Bandwidth     Jitter   Lost/Total Datagrams
[1908] 0.0- 1.0 sec  659 KBytes 5.40 Mbits/sec 2.824 ms 1313429522/ 641 (2e+008%)
[1908] 1.0- 2.0 sec  689 KBytes 5.64 Mbits/sec 3.884 ms 795/ 1275 (62%)
[1908] 2.0- 3.0 sec  678 KBytes 5.55 Mbits/sec 4.422 ms 804/ 1276 (63%)
[1908] 3.0- 4.0 sec  614 KBytes 5.03 Mbits/sec 1.804 ms 703/ 1131 (62%)
[1908] 4.0- 5.0 sec  670 KBytes 5.49 Mbits/sec 2.681 ms 849/ 1316 (65%)
[1908] 5.0- 6.0 sec  797 KBytes 6.53 Mbits/sec 3.970 ms 822/ 1377 (60%)
[1908] 6.0- 7.0 sec  711 KBytes 5.82 Mbits/sec 3.302 ms 781/ 1276 (61%)
[1908] 7.0- 8.0 sec  708 KBytes 5.80 Mbits/sec 3.503 ms 742/ 1235 (60%)
[1908] 8.0- 9.0 sec  820 KBytes 6.71 Mbits/sec 2.970 ms 746/ 1317 (57%)
[1908] 9.0-10.0 sec  781 KBytes 6.40 Mbits/sec 3.810 ms 732/ 1276 (57%)
[1908] 10.0-11.0 sec  758 KBytes 6.21 Mbits/sec 3.236 ms 745/ 1273 (59%)
[1908] 11.0-12.0 sec  670 KBytes 5.49 Mbits/sec 2.835 ms 671/ 1138 (59%)
[1908] 12.0-13.0 sec  769 KBytes 6.30 Mbits/sec 2.869 ms 787/ 1323 (59%)
[1908] 13.0-14.0 sec  811 KBytes 6.64 Mbits/sec 4.073 ms 762/ 1327 (57%)
[1908] 14.0-15.0 sec  744 KBytes 6.09 Mbits/sec 2.071 ms 798/ 1316 (61%)
[1908] 15.0-16.0 sec  742 KBytes 6.08 Mbits/sec 3.361 ms 722/ 1239 (58%)
[1908] 16.0-17.0 sec  778 KBytes 6.37 Mbits/sec 2.705 ms 771/ 1313 (59%)
[1908] 17.0-18.0 sec  706 KBytes 5.79 Mbits/sec 2.398 ms 745/ 1237 (60%)
[1908] 18.0-19.0 sec  755 KBytes 6.19 Mbits/sec 3.400 ms 786/ 1312 (60%)
[1908] 19.0-20.0 sec  761 KBytes 6.23 Mbits/sec 3.696 ms 747/ 1277 (58%)
[ ID] Interval     Transfer    Bandwidth     Jitter   Lost/Total Datagrams
[1908] 20.0-21.0 sec  639 KBytes 5.23 Mbits/sec 2.544 ms 746/ 1191 (63%)
[1908] 21.0-22.0 sec  782 KBytes 6.41 Mbits/sec 3.652 ms 816/ 1361 (60%)
[1908] 22.0-23.0 sec  777 KBytes 6.36 Mbits/sec 2.506 ms 734/ 1275 (58%)
[1908] 23.0-24.0 sec  780 KBytes 6.39 Mbits/sec 3.338 ms 734/ 1277 (57%)
[1908] 24.0-25.0 sec  709 KBytes 5.81 Mbits/sec 3.416 ms 780/ 1274 (61%)
[1908] 25.0-26.0 sec  739 KBytes 6.06 Mbits/sec 2.579 ms 761/ 1276 (60%)
[1908] 26.0-27.0 sec  775 KBytes 6.35 Mbits/sec 2.690 ms 732/ 1272 (58%)
[1908] 27.0-28.0 sec  736 KBytes 6.03 Mbits/sec 4.687 ms 764/ 1277 (60%)
[1908] 28.0-29.0 sec  699 KBytes 5.73 Mbits/sec 3.907 ms 772/ 1259 (61%)
[1908] 29.0-30.0 sec  617 KBytes 5.06 Mbits/sec 2.906 ms 722/ 1152 (63%)
[1908] 30.0-31.0 sec  815 KBytes 6.68 Mbits/sec 3.041 ms 851/ 1419 (60%)
[1908] 31.0-32.0 sec  719 KBytes 5.89 Mbits/sec 2.697 ms 773/ 1274 (61%)
[1908] 32.0-33.0 sec  725 KBytes 5.94 Mbits/sec 3.704 ms 768/ 1273 (60%)
[1908] 33.0-34.0 sec  645 KBytes 5.28 Mbits/sec 3.915 ms 691/ 1140 (61%)
[1908] 34.0-35.0 sec  738 KBytes 6.04 Mbits/sec 3.445 ms 816/ 1330 (61%)
[1908] 35.0-36.0 sec  769 KBytes 6.30 Mbits/sec 3.691 ms 821/ 1357 (61%)
[1908] 36.0-37.0 sec  755 KBytes 6.19 Mbits/sec 2.926 ms 753/ 1279 (59%)
[1908] 37.0-38.0 sec  653 KBytes 5.35 Mbits/sec 3.600 ms 781/ 1236 (63%)
[1908] 38.0-39.0 sec  790 KBytes 6.47 Mbits/sec 3.151 ms 761/ 1311 (58%)
[1908] 39.0-40.0 sec  797 KBytes 6.53 Mbits/sec 3.896 ms 722/ 1277 (57%)
[ ID] Interval     Transfer    Bandwidth     Jitter   Lost/Total Datagrams
[1908] 40.0-41.0 sec  663 KBytes 5.43 Mbits/sec 2.196 ms 730/ 1192 (61%)
[1908] 41.0-42.0 sec  718 KBytes 5.88 Mbits/sec 1.910 ms 821/ 1321 (62%)
[1908] 42.0-43.0 sec  568 KBytes 4.66 Mbits/sec 1.789 ms 861/ 1257 (68%)
[1908] 43.0-44.0 sec  718 KBytes 5.88 Mbits/sec 4.188 ms 793/ 1293 (61%)
[1908] 44.0-45.0 sec  767 KBytes 6.28 Mbits/sec 5.151 ms 780/ 1314 (59%)
[1908] 45.0-46.0 sec  726 KBytes 5.95 Mbits/sec 3.054 ms 764/ 1270 (60%)
[1908] 46.0-47.0 sec  680 KBytes 5.57 Mbits/sec 2.438 ms 799/ 1273 (63%)
[1908] 47.0-48.0 sec  734 KBytes 6.01 Mbits/sec 2.577 ms 734/ 1245 (59%)
[1908] 48.0-49.0 sec  699 KBytes 5.73 Mbits/sec 4.033 ms 740/ 1227 (60%)
[1908] 49.0-50.0 sec  759 KBytes 6.22 Mbits/sec 2.169 ms 695/ 1224 (57%)
[1908] 50.0-51.0 sec  837 KBytes 6.86 Mbits/sec 2.250 ms 828/ 1411 (59%)
[1908] 51.0-52.0 sec  660 KBytes 5.41 Mbits/sec 2.745 ms 681/ 1141 (60%)
[1908] 52.0-53.0 sec  838 KBytes 6.87 Mbits/sec 2.629 ms 824/ 1408 (59%)
[1908] 53.0-54.0 sec  724 KBytes 5.93 Mbits/sec 1.911 ms 740/ 1244 (59%)
[1908] 54.0-55.0 sec  738 KBytes 6.04 Mbits/sec 2.482 ms 795/ 1309 (61%)
[1908] 55.0-56.0 sec  775 KBytes 6.35 Mbits/sec 3.381 ms 702/ 1242 (57%)
[1908] 56.0-57.0 sec  817 KBytes 6.69 Mbits/sec 3.044 ms 744/ 1313 (57%)
[1908] 57.0-58.0 sec  721 KBytes 5.90 Mbits/sec 2.446 ms 736/ 1238 (59%)
[1908] 58.0-59.0 sec  775 KBytes 6.35 Mbits/sec 1.565 ms 687/ 1227 (56%)
[1908] 59.0-60.0 sec  673 KBytes 5.52 Mbits/sec 3.071 ms 753/ 1222 (62%)
```

```
[ ID] Interval     Transfer    Bandwidth     Jitter  Lost/Total Datagrams
[1908] 60.0-61.0 sec  732 KBytes 6.00 Mbits/sec 2.747 ms 816/ 1326 (62%)
[1908] 61.0-62.0 sec  722 KBytes 5.92 Mbits/sec 3.865 ms 723/ 1226 (59%)
[1908] 62.0-63.0 sec  746 KBytes 6.12 Mbits/sec 1.895 ms 799/ 1319 (61%)
[1908] 63.0-64.0 sec  731 KBytes 5.99 Mbits/sec 3.163 ms 864/ 1373 (63%)
[1908] 64.0-65.0 sec  772 KBytes 6.33 Mbits/sec 1.967 ms 645/ 1183 (55%)
[1908] 65.0-66.0 sec  804 KBytes 6.59 Mbits/sec 3.280 ms 806/ 1366 (59%)
[1908] 66.0-67.0 sec  758 KBytes 6.21 Mbits/sec 2.383 ms 747/ 1275 (59%)
[1908] 67.0-68.0 sec  840 KBytes 6.88 Mbits/sec 3.723 ms 611/ 1196 (51%)
[1908] 68.0-69.0 sec  775 KBytes 6.35 Mbits/sec 2.352 ms 728/ 1268 (57%)
[1908] 69.0-70.0 sec  811 KBytes 6.64 Mbits/sec 2.755 ms 657/ 1222 (54%)
[1908] 70.0-71.0 sec  935 KBytes 7.66 Mbits/sec 2.667 ms 766/ 1417 (54%)
[1908] 71.0-72.0 sec  827 KBytes 6.77 Mbits/sec 2.501 ms 659/ 1235 (53%)
[1908] 72.0-73.0 sec  838 KBytes 6.87 Mbits/sec 2.934 ms 733/ 1317 (56%)
[1908] 73.0-74.0 sec  797 KBytes 6.53 Mbits/sec 3.487 ms 719/ 1274 (56%)
[1908] 74.0-75.0 sec  719 KBytes 5.89 Mbits/sec 3.314 ms 774/ 1275 (61%)
[1908] 75.0-76.0 sec  685 KBytes 5.61 Mbits/sec 1.155 ms 755/ 1232 (61%)
[1908] 76.0-77.0 sec  701 KBytes 5.74 Mbits/sec 1.657 ms 828/ 1316 (63%)
[1908] 77.0-78.0 sec  782 KBytes 6.41 Mbits/sec 3.438 ms 735/ 1280 (57%)
[1908] 78.0-79.0 sec  757 KBytes 6.20 Mbits/sec 3.932 ms 745/ 1272 (59%)
[1908] 79.0-80.0 sec  589 KBytes 4.82 Mbits/sec 2.623 ms 728/ 1138 (64%)
[ ID] Interval     Transfer    Bandwidth     Jitter  Lost/Total Datagrams
[1908] 80.0-81.0 sec  800 KBytes 6.55 Mbits/sec 3.499 ms 856/ 1413 (61%)
[1908] 81.0-82.0 sec  685 KBytes 5.61 Mbits/sec 2.536 ms 802/ 1279 (63%)
[1908] 82.0-83.0 sec  742 KBytes 6.08 Mbits/sec 3.178 ms 757/ 1274 (59%)
[1908] 83.0-84.0 sec  738 KBytes 6.04 Mbits/sec 3.019 ms 762/ 1276 (60%)
[1908] 84.0-85.0 sec  693 KBytes 5.68 Mbits/sec 1.791 ms 706/ 1189 (59%)
[1908] 85.0-86.0 sec  815 KBytes 6.68 Mbits/sec 3.448 ms 795/ 1363 (58%)
[1908] 86.0-87.0 sec  703 KBytes 5.76 Mbits/sec 3.035 ms 784/ 1274 (62%)
[1908] 87.0-88.0 sec  693 KBytes 5.68 Mbits/sec 3.725 ms 656/ 1139 (58%)
[1908] 88.0-89.0 sec  887 KBytes 7.27 Mbits/sec 3.433 ms 793/ 1411 (56%)
[1908] 89.0-90.0 sec  755 KBytes 6.19 Mbits/sec 3.604 ms 751/ 1277 (59%)
[1908] 90.0-91.0 sec  699 KBytes 5.73 Mbits/sec 2.895 ms 790/ 1277 (62%)
[1908] 91.0-92.0 sec  739 KBytes 6.06 Mbits/sec 2.864 ms 759/ 1274 (60%)
[1908] 92.0-93.0 sec  713 KBytes 5.84 Mbits/sec 3.650 ms 777/ 1274 (61%)
[1908] 93.0-94.0 sec  703 KBytes 5.76 Mbits/sec 3.870 ms 747/ 1237 (60%)
[1908] 94.0-95.0 sec  790 KBytes 6.47 Mbits/sec 3.490 ms 765/ 1315 (58%)
[1908] 95.0-96.0 sec  739 KBytes 6.06 Mbits/sec 3.727 ms 723/ 1238 (58%)
[1908] 96.0-97.0 sec  724 KBytes 5.93 Mbits/sec 2.933 ms 724/ 1228 (59%)
[1908] 97.0-98.0 sec  748 KBytes 6.13 Mbits/sec 4.365 ms 840/ 1361 (62%)
[1908] 98.0-99.0 sec  880 KBytes 7.21 Mbits/sec 3.940 ms 661/ 1274 (52%)
[1908] 99.0-100.0 sec  721 KBytes 5.90 Mbits/sec 3.243 ms 777/ 1279 (61%)
[ ID] Interval     Transfer    Bandwidth     Jitter  Lost/Total Datagrams
[1908] 0.0-100.5 sec 72.8 MBytes 6.08 Mbits/sec 3.189 ms 75602/127553 (59%)
```

Wireshark Download Log

This log documents the server streaming the video to a client. In two minutes of elapsed time, more than 20,000 packets will be transmitted. The first six, representing a little more than 1/100th of a second, are shown here:

```
No.    Time     Source         Destination       Protocol Length Info
   1 0.000000  10.171.96.6       10.170.2.218      UDP    1370  Source port: 58055 Destination port:
avt-profile-1

Frame 1: 1370 bytes on wire (10960 bits), 1370 bytes captured (10960 bits)
Ethernet II, Src: 11:22:33:44:55:66 (11:22:33:44:55:66), Dst: 02:50:f2:00:01:81
(02:50:f2:00:01:81)
Internet Protocol Version 4, Src: 10.171.96.6 (10.171.96.6), Dst: 10.170.2.218 (10.170.2.218)
User Datagram Protocol, Src Port: 58055 (58055), Dst Port: avt-profile-1 (5004)
Data (1328 bytes)

No.    Time     Source         Destination       Protocol Length Info
   2 0.002860  10.171.96.6       10.170.2.218      UDP    1370  Source port: 58055 Destination port:
avt-profile-1

Frame 2: 1370 bytes on wire (10960 bits), 1370 bytes captured (10960 bits)
Ethernet II, Src: 11:22:33:44:55:66 (11:22:33:44:55:66), Dst: 02:50:f2:00:01:81
(02:50:f2:00:01:81)
Internet Protocol Version 4, Src: 10.171.96.6 (10.171.96.6), Dst: 10.170.2.218 (10.170.2.218)
User Datagram Protocol, Src Port: 58055 (58055), Dst Port: avt-profile-1 (5004)
Data (1328 bytes)

No.    Time     Source         Destination       Protocol Length Info
   3 0.005993  10.171.96.6       10.170.2.218      UDP    1370  Source port: 58055 Destination port:
avt-profile-1
```

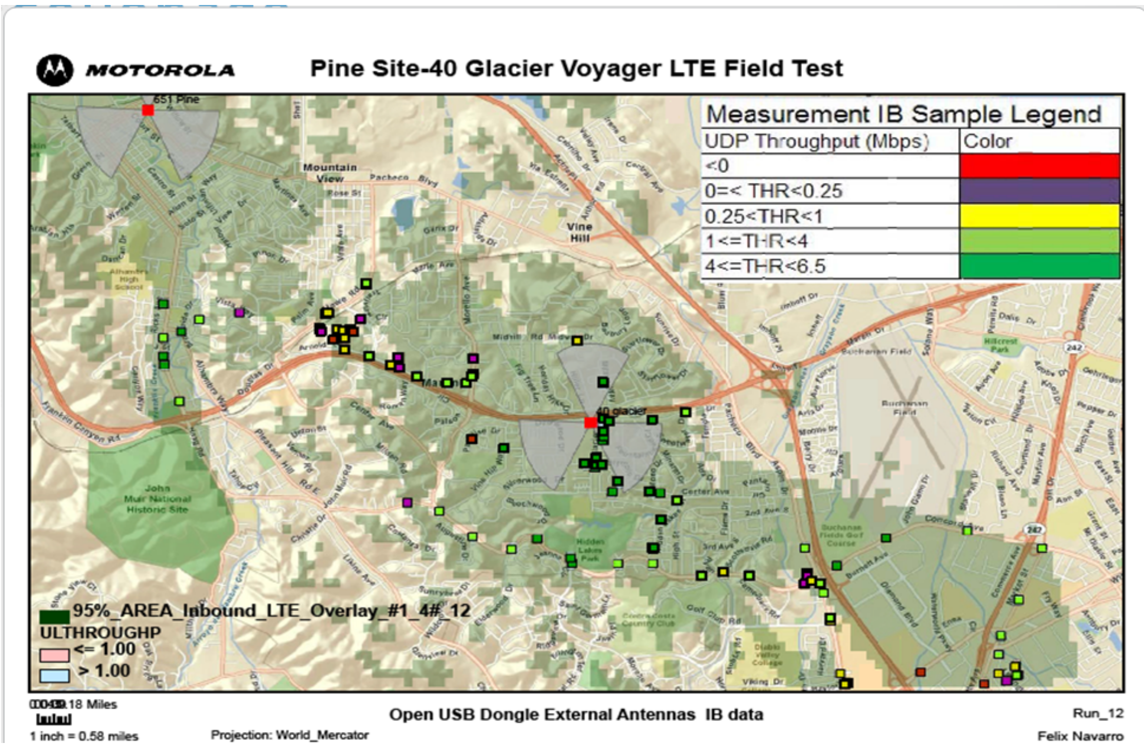
```
Frame 3: 1370 bytes on wire (10960 bits), 1370 bytes captured (10960 bits)
Ethernet II, Src: 11:22:33:44:55:66 (11:22:33:44:55:66), Dst: 02:50:f2:00:01:81
(02:50:f2:00:01:81)
Internet Protocol Version 4, Src: 10.171.96.6 (10.171.96.6), Dst: 10.170.2.218 (10.170.2.218)
User Datagram Protocol, Src Port: 58055 (58055), Dst Port: avt-profile-1 (5004)
Data (1328 bytes)

No.     Time     Source         Destination       Protocol Length Info
   4 0.008890  10.171.96.6      10.170.2.218      UDP    1370  Source port: 58055 Destination port:
avt-profile-1

Frame 4: 1370 bytes on wire (10960 bits), 1370 bytes captured (10960 bits)
Ethernet II, Src: 11:22:33:44:55:66 (11:22:33:44:55:66), Dst: 02:50:f2:00:01:81
(02:50:f2:00:01:81)
Internet Protocol Version 4, Src: 10.171.96.6 (10.171.96.6), Dst: 10.170.2.218 (10.170.2.218)
User Datagram Protocol, Src Port: 58055 (58055), Dst Port: avt-profile-1 (5004)
Data (1328 bytes)

No.     Time     Source         Destination       Protocol Length Info
   5 0.010870  10.171.96.6      10.170.2.218      UDP    1370  Source port: 58055 Destination port:
avt-profile-1

Frame 5: 1370 bytes on wire (10960 bits), 1370 bytes captured (10960 bits)
Ethernet II, Src: 11:22:33:44:55:66 (11:22:33:44:55:66), Dst: 02:50:f2:00:01:81
(02:50:f2:00:01:81)
Internet Protocol Version 4, Src: 10.171.96.6 (10.171.96.6), Dst: 10.170.2.218 (10.170.2.218)
User Datagram Protocol, Src Port: 58055 (58055), Dst Port: avt-profile-1 (5004)
Data (1328 bytes)

No.     Time     Source         Destination       Protocol Length Info
   6 0.013887  10.171.96.6      10.170.2.218      UDP    1370  Source port: 58055 Destination port:
avt-profile-1

Frame 6: 1370 bytes on wire (10960 bits), 1370 bytes captured (10960 bits)
Ethernet II, Src: 11:22:33:44:55:66 (11:22:33:44:55:66), Dst: 02:50:f2:00:01:81
(02:50:f2:00:01:81)
Internet Protocol Version 4, Src: 10.171.96.6 (10.171.96.6), Dst: 10.170.2.218 (10.170.2.218)
User Datagram Protocol, Src Port: 58055 (58055), Dst Port: avt-profile-1 (5004)
Data (1328 bytes)
```

Appendix G: Acknowledgements

The following companies and organizations provided support and/or equipment for these tests and we are grateful for their contribution:

Motorola Solutions

Motorola, which provided the system under test, was gracious in the time and personnel it provided before, during, and after the tests. In addition, its initial drive tests of the network enabled us to determine the best test locations within the cell sector.



Panasonic

Panasonic loaned us seven Toughbook computers (model CF 30) in order to provide a consistent set of test devices. Each of these notebooks was running the same version of Windows XP. These notebooks are the same as those used by many public safety agencies in the United States and around the world.

Two Toughbooks during the testing.

Toughbook displaying the test video.

Anritsu America

Anritsu America provided personnel, test equipment, and the latest version of its test software. Anritsu also verified our findings during the entire test period.

Anritsu America performing network measurements

The Anritsu America test equipment