
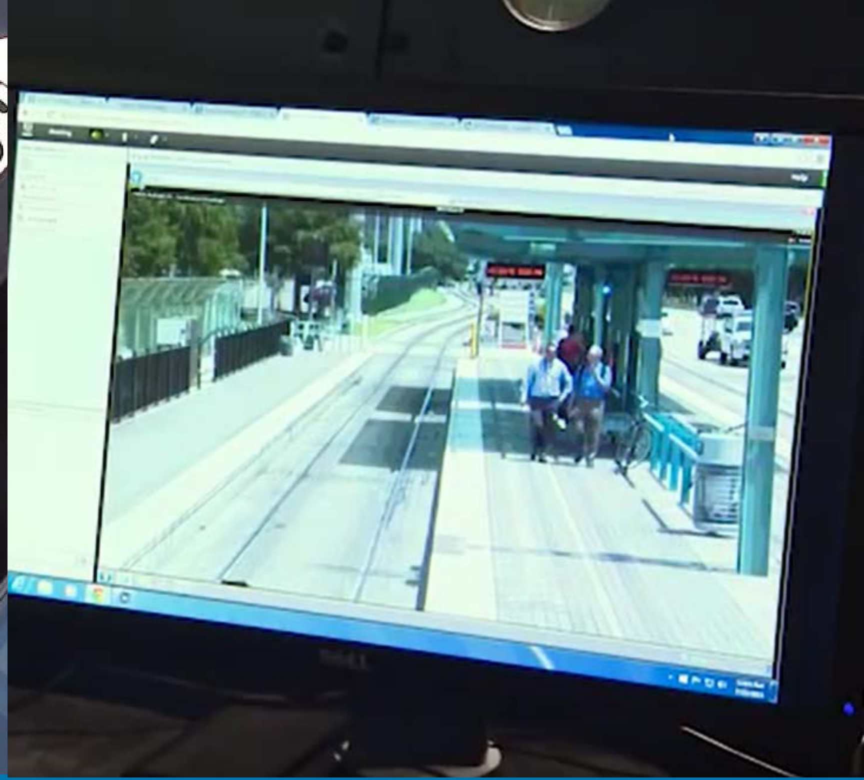

Datacasting:

Houston Datacasting Integration Pilot After Action Report

First Responders Group

July 2016

Homeland Security

Science and Technology

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Houston Datacasting Integration Pilot After Action Report

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Prepared for:	**The First Responders Group Office for Interoperability and Compatibility**
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Contents

Figures

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Executive Summary

The Johns Hopkins University Applied Physics Laboratory (JHU/APL), under the direction of the Department of Homeland Security (DHS) Science and Technology Directorate (S&T), recently tested a prototype datacasting system and a deployable cellular Long-Term Evolution (LTE) communications system. The datacasting system, developed by SpectraRep, was installed at the offices of Houston Public Media (Public Broadcasting Station KUHT). Parallel Wireless (PW) developed the deployable LTE communications system. Tests involved the technical aspects of both systems and emphasized the ability to integrate these systems into larger telecommunications architectures that could be used in support of public safety. The tests were conducted at various sites in Houston, Texas, on February 9-12, 2016. The National Geospatial-Intelligence Agency (NGA) acted as a partner for testing connectivity and the use of their apps on a mobile, deployable LTE system. The original objectives of these tests were to demonstrate the ability to feed data and video to the datacasting system from multiple sites and to connect the system to officers in the field via other networks. These objectives were expanded to include demonstration of an end-to-end solution in which a deployable LTE system could be used to extend access to areas without coverage.

Background

Datacasting is a technology that leverages available bandwidth in digital television signals to provide secure, targeted broadcasts of data, including voice, text, files, images and video. Data is encoded, encrypted, registered (for access control) and multiplexed with other streams into the digital television signal. Because it uses TV station infrastructure, datacasting is considered highly reliable, especially during emergencies. As long as the TV station has a source of power with an intact transmission tower and equipment, datacasting should be a reliable means of communicating emergency information to first responders.

LTE technology is an advanced fourth-generation (4G) wireless mobility standard maintained by the Third-Generation Partnership Project (3GPP), and deployed by major commercial wireless carriers throughout the world. As a result, support for advanced development in subsequent generations of the standard, reduced cost of network and user equipment, and other benefits are likely to be realized for carriers choosing the LTE technology path. Organized within the National Telecommunications and Information Administration (NTIA), the First Responder Network Authority (FirstNet) is an independent authority created to provide the first high-speed data network for emergency responders, called the Nationwide Public Safety Broadband Network (NPSBN). The wireless technology behind the NPSBN is the 4G LTE with spectrum specifically allocated for its use in the 700-MHz frequency band (Band 14) with 20 MHz of combined bandwidth (uplink and downlink[1]).

PW has developed a deployable Band 14 LTE solution that first responders can use to create ad hoc LTE networks in areas lacking commercial carrier or other wireless coverage. Using standard LTE Band 14 user equipment, first responders can use the PW solution in a

[1] Downlink is the frequency used for communication from the base station to the end user equipment. Uplink is the frequency used from communication from the end user equipment to the base state.

"disconnected" mode as a stand-alone system or in a mesh network configuration to locally communicate with one another. The deployable network can also be configured in a "connected" mode to allow connectivity to a commercial carrier's Evolved Packet Core (EPC), in conjunction with PW Heterogeneous Network Gateway (HNG), to extend the carrier's operational coverage and/or directly connect to external Internet Protocol (IP) networks to expand communication beyond the localized coverage area created by the PW eNodeB(s). The PW system can be used to support voice, video streaming or other applications within the disconnected network by using localized application servers or by accessing remote application servers when it is connected to an external IP network.

Testing Summary

Datacasting testing in February 2016 was built on an architecture originally configured in July 2015 to support operational testing of the system. The initial configuration supported the initiation of messages and transmission of data from a single point located within the University of Houston (UH) Office of Emergency Management (OEM). For the February test, this configuration was expanded to support control and data transmission from multiple sites, and to provide access to video streams from both the UH OEM and the City of Houston Emergency Operations Center (EOC). During the course of the week, transmissions were executed from the Houston City Hall Annex, KUHT, NRG Park and other locations around downtown Houston.

While this exercise was built upon the original 2015 datacasting test, it was expanded by introducing an LTE component into the overall architecture. In the nation's first-of-its-kind proof of concept, various FirstNet compatible Band 14 LTE network solutions were incorporated with the datacasting network to demonstrate interoperability between these two disparate systems, which were used to capture and deliver live video feeds from the field by means of an LTE network transmission to the datacasting network.

Three PW systems were field tested in Houston. Two were used by NGA and one was used by DHS. Six Sonim XP7 smartphones were provisioned to work on the PW network. One Sonim XP7 smartphone, provided by Harris County, was provisioned to work on the Harris County LTE network. These three systems were configured in various stand-alone and integrated architectures, some incorporating additional outside networks and backhaul connections through commercial LTE. Tests with PW equipment were performed in the parking lot and stadium at Houston's NRG Park.

Four sets of tests were performed:

1) Datacasting and the deployable LTE system were tested as *stand-alone networks*. For datacasting, this meant demonstrating the ability to initiate messages and data streams and to transmit data from a remote laptop connected to the datacasting system at KUHT via a Virtual Private Network (VPN). For the LTE system, NGA and JHU/APL/DHS each configured their PW equipment to create stand-alone enclaves as deployable mobile LTE networks used to characterize the coverage characteristics of the access and mesh networks.

2) Both systems were tested as *expanded interoperable networks*. Multiple deployable LTE systems were configured to form an expanded mesh network. The test team assessed the ability to use the datacasting system concurrently from different sites.

3) Tests were performed to assess the ability to *integrate the deployable LTE system and the datacasting system to local wireless networks*, with special emphasis placed on integration with the Harris County Band 14 Public Safety network.

4) An *end-to-end test*, using both the deployable LTE system and datacasting, was performed to evaluate the systems' ability to operate as part of a larger architecture composed of multiple and disparate networks.

Additional tests were conducted to assess the performance of the datacasting system under heavy loading conditions, and to evaluate the performance characteristics of the deployable LTE system configuration to support a range of applications.

Test Results

During the week, all test objectives were met. Accomplishments include:

1) The test team successfully configured the PWPW deployable LTE system in both stand-alone and mesh configurations. The test team captured data to construct a coverage characterization of the system.

2) The test team successfully initiated video streaming, sent text messages and transmitted data via datacasting from multiple locations across Houston. The team also demonstrated the ability to use LTE to backhaul data for subsequent datacasting from two different sites.

3) The test team successfully configured both systems to interoperate with multiple local networks, including the Harris County Band 14 Public Safety Network.

4) The test team demonstrated robust performance by the datacasting system under heavy loading conditions (e.g., sending multiple simultaneous data streams).

5) The test team successfully executed an end-to-end test using both the PWPW deployable LTE systems and the datacasting system integrated into architectures with other local networks, including the Harris County Band 14 Network.

6) The team assessed the video transmitted via datacasting, especially the quality of the video relative to the input video received. Because the test was conducted with a temporary input solution, there was some potential degradation in the input stream prior to transmission. As a result, the test team made efforts to compare system output to input.

The tests provided further validation of the capability and utility of datacasting for public safety entities. Datacasting efficiently uses the digital television spectrum's capacity to broadcast data to a wide area in a one-to-many fashion. The capability of the datacasting system can be further enhanced when used in combination with Band 14 LTE to provide a means for basic bi-directional data sharing from the field.

Datacasting equipment used in these tests will remain in place in Houston for the near future. The Houston Police Department (HPD) used this capability during the Republican Presidential Candidates' Debate held at the University of Houston on February 25, 2016 (see Appendix D for details). Datacasting provided three capabilities to enhance security at that event:

1) Datacasting was used to deliver video surveillance from cameras on the University of Houston campus to the HPD and Houston Fire Department (HFD) command vehicles at the scene. UH OEM personnel also viewed surveillance video, including HPD helicopter feeds pushed by HPD using datacasting technology.

2) Video surveillance was also accessed using the datacasting dashboard over an Internet connection. HPD and the UH Police both contributed video to the datacasting dashboard. Some users, including both command centers, accessed the other agency's video solely from that dashboard rather than over-the-air. We were informed that both HPD and UH OEM would not have had access to the other agency's video without this datacasting dashboard capability.

3) While it was not used operationally, HFD also tested the ability of LTE to feed live video to the datacasting system. HFD originated video from an LTE smartphone, which was viewed at the command center and then transmitted over the KUHT television signal to the HFD command vehicle at the scene of the Republican Presidential Candidates' Debate on the UH campus. HFD also tested video quality, datacast delivery, delivery time and other technical parameters during this event.

Datacasting was also used in support of security efforts associated with the NCAA Men's Basketball Championship Final Four and during excessive flooding in April 2016.

JHU/APL would like to thank the City of Houston, HPD, HFD, NRG Park, the University of Houston OEM and Police Department, KUHT Houston Public Media, Harris County Public Safety Technology Services, and the Harris County Sheriff's Office for their support of these tests.

1 Introduction

The U.S. Department of Homeland Security (DHS) is committed to using cutting-edge technologies and scientific talent in its efforts to make America safer. The DHS Science and Technology Directorate (S&T) is tasked with researching and organizing the scientific, engineering and technological resources of the United States and leveraging these existing resources into technological tools to help protect the nation. The DHS S&T First Responders Group (FRG) Office for Interoperability and Compatibility (OIC) administers a program entitled *"Video Quality in Public Safety"* (VQiPS) that is concerned with all facets of the use of video in the public safety field (i.e., law enforcement, fire, emergency medical technicians and associated entities). The VQiPS Vision, Mission and Goals are as follows:

VQiPS Vision

The VQiPS Working Group will create a collaborative environment that accelerates the ability of users to specify and deploy video technology solutions that meet user requirements and improve public safety and homeland security enterprise operations.

VQiPS Mission

The VQiPS Working Group creates knowledge products, fosters a knowledge-sharing environment, and supports research, development, testing and evaluation for enhanced video quality through measurable, objective and standards-based solutions across the full spectrum of video-use cases for the public safety community.

VQiPS Background and Goals

The VQiPS initiative, which started in 2008, is a multi-stakeholder partnership between DHS's Science and Technology Directorate, the U.S. Department of Commerce's Public Safety Communications Research Program (PSCR), public safety practitioners, the private sector, standards development organizations and the global research community. VQiPS gathers input from practitioners and video experts, and delivers unbiased guidance and educational resources that help the first responder community clearly define and communicate its video quality needs. In the beginning, the group sought to accomplish two tasks: educate end users about video system components and provide knowledge tools to help end users define their own use case requirements. VQiPS accomplished these goals with multiple technical reports, the development of the VQiPS Web Tool [1] and the Video Quality Standards Handbook [2].

Moving forward, VQiPS will support the build-out of the Nationwide Public Safety Broadband Network (NPSBN) by developing video-over-broadband materials and guides, as well as connect to First Responder Network Authority (FirstNet) to provide technical information and feedback regarding video over the Long-Term Evolution (LTE) communications system.

Identifying and supporting best practices in the efficient distribution of video is consistent with the VQiPS program goals. The DHS S&T FRG OIC is engaged in the execution of a series of tests and demonstrations of the use of datacasting technology to support public applications across the country. At the request of DHS S&T, the Johns Hopkins University

Applied Physics Laboratory (JHU/APL) has planned, designed and led the execution of three tests using a pilot datacasting system designed by SpectraRep. These tests are designed to evaluate both technical and operational aspects of datacasting. The first two tests were conducted in Houston in July 2015 [3] and in Chicago in August 2015 [4], respectively. This report documents the results of a third test conducted in Houston in February 2016.

The February tests, the third in a series of tests of datacasting capability, build upon the results of previous tests. In July 2015 and August 2015, tests were conducted in Houston and Chicago, respectively, to assess the operational capabilities of a datacasting system to support public safety applications. Scenarios were developed that reflected potential real-life operational events in which a datacasting system might be used to support public safety officers. End-users were invited to observe the tests, assess the data provided and evaluate the degree to which the system could be used to facilitate performance of their jobs. End users observing those tests were enthusiastic in their praise for the system and what they thought it could provide. While they saw datacasting as a potentially powerful tool for disseminating data and video from a command center or a dispatch to officers in the field, they also expressed a strong desire for a capability to transmit data from the field back to command centers. The February tests were designed to address this desired backhaul.

1.1 Datacasting Capabilities

The television (TV) broadcast industry recently completed an evolution from analog to digital signal transmission. The Advanced Television Systems Committee (ATSC) (www.ATSC.org) is the standards body for digital television (DTV) broadcasts in North America, South Korea and several other countries. The current standard uses eight-level Vestibule Sideband (8-VSB) Modulation in 6-MHz channels.

The digital broadcast signal is composed of time-division-multiplex (TDMC) or time-division-multiple-access (TDMA) slots, with each time slot containing a Moving Picture Experts Group (MPEG) packet that supports the delivery of MPEG-2 encoded video, Advanced Audio Coding (AAC) audio, and metadata at the entry and destination nodes (i.e., TV station and TV receiver). The signal is transmitted at a constant rate of approximately 19.39 Mbps. However, the TV signal does not consume the total bit rate. Null packets are transmitted to maintain the constant bit rate. Those null packets can be replaced with data content not intended for television viewing without degrading the received television signal.

The current ATSC standard is in the process of being updated to provide many enhancements, including improved bit density, mobility and bandwidth efficiency. This new standard is known as ATSC 3.0 [5]. ATSC 3.0 is currently a candidate standard, but full standard adoption is expected by the end of 2016.

Datacasting is a technique that takes advantage of available null packets in the bit rate to transmit Internet Protocol (IP) packets that may include various digital data types, such as voice, pictures, messaging, streaming video, documents, etc. For use in datacasting, these data may be encrypted to provide privacy, registered to enable targeting, and made highly reliable even in degraded reception environments by including forward-error correction and other techniques. The nature of datacasting is a one-way, wide-area broadcast to all receivers in the coverage area, but it allows the use of addressing to specific individuals,

groups of individuals, or every receiver for receiving and processing data. When incorporated into a communications ecosystem, datacasting can be used to enhance information sharing and improve bandwidth efficiency by offloading content destined for multiple recipients.

A multiplexer is used to integrate the various data types with the TV signal prior to transmission. The multiplexer input is typically provided via a data server that connects to various data sources [e.g., information repositories or databases, closed-circuit TV (CCTV) monitors, voice systems and messaging systems]. The datacasting server provides the ability to select the data source(s) for transmission over the air. At the receiver end, an antenna and an inexpensive dongle plugged into the Universal Serial Bus (USB) port enables any computer or laptop to receive the TV signal encoded data. Datacasting software installed on the computer extracts the datacasting information from the rest of the DTV signal and presents it in a form understandable by the end user.

As with other wireless capabilities, datacasting transmissions may be secured via encryption and access control. Compliance with Health Insurance Portability and Accountability Act (HIPAA) or other guidelines is achieved via encryption and access control, but this was not explicitly addressed in this exercise or in this report. Datacasting is amenable to a number of encryption and access control implementations.

Because it uses television station infrastructure, datacasting is more reliable than many other means of communication, especially during emergencies. For example, during the 2013 Boston Marathon, cellular and landline communications were saturated and largely unavailable for at least 90 minutes after the bombing [6]. Following the 2011 Mineral Virginia Earthquake, cell and landline communications were saturated for the first 30 minutes [7]. During 2005 Hurricane Katrina [8] and 2012 Superstorm Sandy [9], cellular and Internet communications were severely affected for an extended time (days). Television station downtime could result from damaged transmission towers, flooded transmission equipment or the loss of power for prolonged periods that exceeded back-up generator capabilities. However, as long as the TV station has a source of power with an intact transmission tower and equipment, datacasting should be a reliable means of communicating emergency information to first responders.

Datacasting has the potential to provide significant benefit to first responders, including law enforcement. Potential benefits include the following:

- Because broadcast TV signals are widely available in urban, suburban and rural environments, datacasting coverage typically exceeds that of cellular systems and land-mobile radio. TV broadcasts not only reach remote areas, but also urban "dead spots" not covered by existing public safety wireless telecommunications systems.

- Because datacasting uses the infrastructure provided by a broadcast TV station, it is a highly reliable and available method of telecommunication. In contrast, cellular coverage is often lost for significant periods of time following emergency events.

- Datacasting is not subject to congestion during emergencies. Unlike other public safety telecommunications systems, datacasting does not share infrastructure or capacity with open commercial communication networks.

- Datacasting can be used to multicast data to a large number of users for the same cost as the transmission of data to a single user. Datacasting can make more efficient use of available bandwidth and possibly reduce the cost of commercial service to the agency by reducing the overall demand for bandwidth.

- Datacasting is relatively inexpensive to implement and operate. Many public broadcasting TV stations are already configured to support datacasting. The existing digital TV transmission infrastructure (i.e., power, radio frequency equipment, antenna, tower) is used, so datacasting does not add a significant cost to the broadcaster. Thus, public safety users benefit from leveraging an existing operating broadcast network.

Datacasting is, however, a unidirectional capability. To achieve maximum effectiveness, it must be integrated with another transmission mechanism to provide backhaul and enable datacasting to operate as part of a robust two-way system. One way of doing this is to integrate datacasting with another network, such as an existing cellular public safety network. Houston/Harris County was selected as a test site because it has an existing public safety wireless network. The datacasting pilot simulated a projected architecture in which individual officers in the field could transmit information to a dispatch center using Harris County Band 14 LTE network as backhaul, and then widely disseminate that same information using the datacasting capability.

In addition, the actual throughput of a datacasting system is typically no more than 2.5 Mbps. Increasing the throughput beyond this would cause degradation in the television signal. Some stations, including KUHT in Houston, are willing to degrade their broadcast programming or even preempt some sub-channels to provide more capacity to public safety during emergencies.

For the pilot system in Houston, Houston Public Media (KUHT) has allotted approximately 1 Mbps for transmission of data via datacasting. Because datacasting is a true broadcast medium, it is capable of substantial and effective throughput even with only 1 Mbps, especially for widely disseminated information. For example, a 1-Mbps transmission broadcast simultaneously to 1,000 users has the same effective throughput as a unicast cellular system with a 1-Gbps throughput. However, there is the possibility of degradation if users attempt to use the system to simultaneously transmit extremely large amounts of data. Therefore, the datacasting pilot was constructed to simulate the potential for saturation with multiple users. An existing enclave, previously established to support an earlier datacasting exercise, was expanded to enable two users to transmit simultaneously. These test procedures were designed to examine the effects of heavy loading on the datacasting system.

Additional technical details of the datacasting process are provided in Appendix A.

1.2 LTE Capabilities

LTE is an advanced fourth-generation (4G) wireless mobile communications standard. The Third-Generation Partnership Project (3GPP) is developing and maintaining this cellular telecommunications network technology standard. LTE has been deployed by major wireless carriers throughout the world, including all major domestic commercial wireless

carriers, such as AT&T, Sprint, T-Mobile and Verizon. These carriers, Original Equipment Manufacturers and other participants have invested heavily in building and providing LTE service. As a result, carrier and end users are both likely to benefit from the continual advancements in the technology, including reduced cost for infrastructure and user equipment.

The First Responder Network Authority (FirstNet), organized within the National Telecommunications and Information Administration (NTIA), is an independent authority created to establish the Nationwide Public Safety Broadband Network (NPSBN). It is the first national high-speed data network of its kind that is designed and dedicated for emergency responders. The wireless technology behind the NPSBN is the 4G LTE standard with 10 MHz of dedicated spectrum in the 700-MHz frequency band (Band 14) consisting of a paired 10-MHz bandwidth. The Harris County (Texas) network is the nation's first LTE-based operational public safety broadband network using the Band 14 spectrum. This network consists of 14 on-air sites (as of August 2015), with plans to add additional sites in order to provide mobile LTE coverage throughout Harris County [10]. The network currently operates under a three-year spectrum manager lease agreement (SMLA) with FirstNet.

The February 2016 Houston datacasting pilot incorporated other LTE network architecture, including two deployable LTE systems from PWPW. One of the PW deployable LTE systems was operated by the National Geospatial-Intelligence Agency (NGA), and the other was operated by the DHS and JHU/APL. These PW systems were designed to be rapidly deployed and configured in areas without wireless coverage (e.g., rural or remote areas), or in areas where cellular service has recently been lost (e.g., following a natural disaster). These PW LTE enclaves can be operated independently or as a mesh network, and they are capable of providing connectivity to the Internet or to other Band 14 networks.

The PW system consists of two network nodes: the Converged Wireless System (CWS) and the Heterogeneous Network (HetNet) Gateway (HNG), which was previously called the LTE Access Controller (LAC). PW provides options to configure the LTE network in different ways. The CWS is a high-capacity, 3GPP-compliant, multi-Radio Access Technology (RAT) node available in outdoor or in-vehicle configurations. The CWS is able to establish a mesh network automatically when it is within the range of another CWS configured for mesh connectivity. The backhaul for meshing uses built-in 5-GHz Wi-Fi radios and allows a network of CWS nodes to provide expanded LTE coverage and service. The HNG is the central hub, which connects the CWS(s) to the Evolved Packet Core (EPC). The EPC uses IP to transport both voice and data on an LTE network. The HNG controls the CWS(s) and orchestrates the Self-Organizing Network (SON) functionality, such as interference mitigation or automatic neighbor relations (ANR).

The PW system can work independently as a "disconnected" LTE network to provide LTE coverage and custom services through local application servers. Disconnected in this context means that connection to an external packet data network (PDN) does not exist. The PW system works as a "connected" network by connecting directly to an external IP data network. Thus, in this context, there is a connection to an external PDN. The CWS can also be configured to anchor to a remote HNG, and thereby to the remote EPC and PDN, extending the carrier's operational LTE network to areas that may be underserved. The

backhaul connection between the CWS and the remote HNG is flexible. It can be Ethernet, commercial wireless or any connection that can provide a routable IP address.

Note that, for the remainder of this document, the term User Equipment (UE) will be used to refer to a smartphone, laptop equipped with a mobile broadband adapter or any device that an end user may use for LTE communications.

Additional technical details of the PW deployable LTE system are provided in Appendix B.

1.3 Goal of this Report

The goals of this Houston datacasting pilot demonstration (and of the 2015 exercises in Houston and Chicago) were to demonstrate the following:

1) The technical capabilities of datacasting;

2) Datacasting's utility to emergency management;

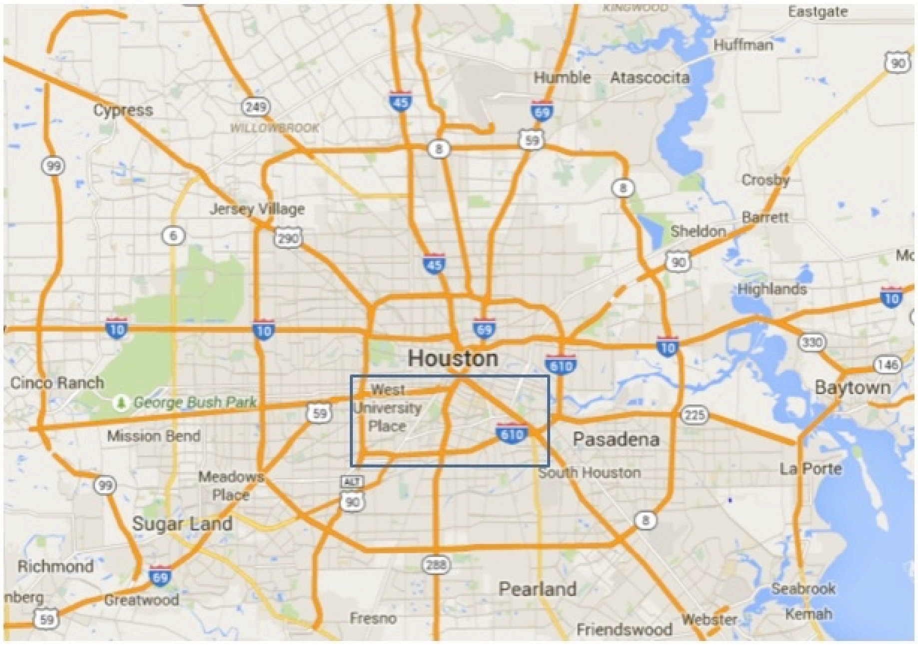
3) The ability to reliably broadcast large data files;

4) The ability to stream real-time video to multiple users; and

5) The ability to simultaneously broadcast data to multiple agencies. [11]

The main goal of this report is to provide an After Action Report for the datacasting pilot that took place in Houston, Texas, on February 8-12, 2016. This pilot involved several agencies, including the City of Houston, Harris County, Houston Public Media, the University of Houston (UH) Office of Emergency Management and Police Department, the City of Houston Police Department, and NRG Park (the sports and entertainment complex located at Reliant Pkwy, Houston, Texas).

Figure 1 shows the area in Houston where the testing took place. Harris County includes Houston and its surroundings. A detailed test plan is included as Appendix C to this report.



The blue rectangle contains the testing locations.

Figure 1: Map of Houston and Harris County

2 Houston Datacasting Pilot Demonstration with LTE: Test Planning

Formal planning for the February 8-12, 2016 test began in December 2015. Due to the number of systems and participants, planning for the tests required significant coordination. Multiple versions of the test plan, with each increment containing more detailed and better defined test procedures, were distributed to representatives of each participating organization. The final version of the test plan (including the test agenda) is provided in Appendix C.

2.1 Participants

The following organizations participated in the February Test in Houston:

1) DHS S&T: Test Sponsor;

2) NGA: Invited Government Agency;

3) City of Houston (stakeholder);

4) Harris County (stakeholder);

5) Houston Police Department (stakeholder);

6) UH OEM (test support);

7) JHU/APL (test design, execution, and analysis);

8) SpectraRep (datacasting equipment provider); and

9) PWPW (deployable LTE provider).

2.2 Training

Representatives of DHS S&T, JHU/APL and NGA were provided with a special training session on the PW deployable LTE system on January 12, 2016. PW technical staff provided training on how to configure and operate their system. This training covered configuring the system for standalone operations, operating multiple enclaves in a mesh architecture and connecting to a local Internet Provider's network. Due to time constraints, training did not include instruction in connecting the PW system to other Band 14 systems, such as the Harris County LTE Band 14 Public Safety Network.

3 Houston Datacasting Pilot Demonstration with LTE: Test Execution

Unlike the previous two tests in 2015, the 2016 February test emphasized technical aspects of datacasting over operational aspects. Primary objectives of the 2016 pilot test included the following:

1) Evaluate the ability of datacasting to function within a mixed architecture in which cellular LTE networks provide the backhaul for datacasting transmissions.

2) Evaluate the ability for datacasting to continue to function when provided substantial amounts of data simultaneously from multiple users, and for it to degrade gracefully when its limits have been surpassed.

Secondary objectives of the test centered on demonstrating the potential use of rapidly deployable and configurable cellular LTE networks and their ability to interoperate with the datacasting network. The deployable LTE Band 14 network would be used to demonstrate that an uplink path to provide input to the datacasting network could be established to share data from the field.

In support of the datacasting objective, the following were additional goals of the demonstration involving the LTE network:

1) Characterize the LTE coverage created by the PW system;

2) Measure the meshing distance established by two CWSs configured for this capability;

3) Perform basic performance validation of the LTE network created by meshing two CWS nodes; and

4) Stream live video from various LTE network architectures to demonstrate interoperability with the datacasting network.

To achieve these objectives, the 2016 datacasting exercise was executed in four stages:

1) Independent Enclave Tests: Conducted on February 9, 2016, these tests included establishing and verifying two independent deployable PWPW LTE enclaves, and verifying an expanded datacasting enclave.

2) Interconnected Enclave Tests: Conducted on February 10, 2016, these tests were intended to demonstrate the ability to connect two LTE enclaves as part of a mesh network, and to demonstrate the ability to simultaneously push data via the datacasting system from two independent sources.

3) Connectivity of Enclaves to External Networks Testing: On February 11, 2016, tests were conducted to demonstrate the ability to connect the PWPW LTE enclaves to a local network (Band 14 and/or Internet).

4) End-to-End Test: On February 11, 2016, an end-to-end test was conducted to demonstrate the ability to use various LTE network configurations as a backhaul for a datacasting system capable of wide dissemination of information.

3.1 Independent Enclave Testing

The following three sets of independent enclave testing were conducted:

1) NGA PW LTE Enclave Tests;

2) DHS PW LTE Enclave Tests; and

3) Datacasting Enclave Tests.

These tests are described in detail in the following subsections.

3.1.1 NGA PW LTE Enclave Tests

NGA performed LTE enclave testing to evaluate the ability of a deployable LTE system to provide LTE coverage in a mobile, distributed scenario without relying on any third-party service providers. NGA deployed a PW mobile prototype CWS-200 (203) device in a configuration similar to that described in Section 3.1.2. In addition, NGA planned to test some of their apps, including the Mobile Analytic geospatial intelligence (GEOINT) Environment (MAGE) app for situational awareness and the GLIMPSE app for use in video streaming. MAGE was used during functionality testing on the disconnected/meshed enclaves. GLIMPSE was tested on the UE connected to the CWS extending the Harris County wireless network. For further details, the reader is referred to the NGA test conductor, Chris Allen.

3.1.2 DHS PW LTE Enclave Tests

The DHS PW LTE enclave testing started on February 9, 2016 and continued through February 10, 2016 at NRG Park. There are various ways to configure the PW system, but it was delivered to DHS configured as illustrated in Figure 2.

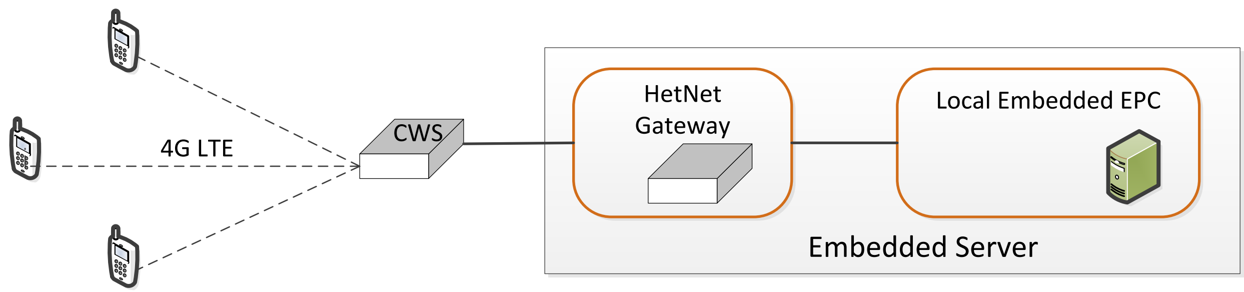


Figure 2: PW Deployable LTE System in the “Packaged” Configuration

The deployable LTE system consisted of a prototype CWS-200 (203) device designed for in-vehicle applications. This CWS operates in Band 14 with a maximum transmitter power of 1 W. The LTE package contained two LTE antennas with magnetic mounts, one GPS antenna and four generic Wi-Fi antennas for mesh connectivity. As shown in Figure 2, it also came with a Mintbox, which is a product line of miniature personal computers using the Linux Mint operating system. This Mintbox runs numerous virtual machines (VMs), including the Evolved Packet Core (EPC) and the HetNet Gateway (HNG), to create a fully functional LTE network in a small package. (For the remainder of this report, the Mintbox with EPC and HNG will be referred to as the “embedded server” so as not to create the impression that a specific product line is required.) As just described, this deployable LTE system is the configuration delivered by PWPW, and will henceforth be referred to as the “packaged” configuration.

Two test sites (locations shown in Figure 3) were selected to characterize the coverage footprint of various antennas at different elevations. Location 1 is situated at the southern-most portion of the NRG Park parking area, which is relatively flat and clear of any major obstructions. This location characterized the footprint of the PW configuration using the packaged antenna configuration. Location 2 is positioned at the southwest corner of the NRG stadium with access to higher ground clearance in the stadium for the antenna. This location (Figure 3) characterized the performance of a high-gain directional antenna with its radiation center (RC) at a higher elevation above ground.

Note: These two locations were also used to position Wi-Fi antennas to test meshing distance.

RC indicates the antenna radiation center.

Figure 3: Stationary CWS Transmitter Locations

3.1.2.1 Coverage Characterization with Packaged Antenna

Testing started at Location 1 on February 9, 2016. The goal of this phase of testing was to characterize the LTE network footprint created by a single PWPW eNodeB with the packaged configuration.

The CWS and embedded server were installed in the rear compartment of a Toyota Sienna vehicle (shown in Figure 4). The packaged LTE antennas were then mounted on the roof of this vehicle using magnetic mounts (Figure 5). Power to the system was supplied by a 12-VDC-to-120-VAC pure sine wave inverter capable of producing up to 300 W of power. A Dell laptop was connected to the embedded server to access the VMs required to operate the PWPW LTE network.

Figure 4: Installation of the Deployable PW LTE System

Figure 5: Installation of the Packaged Antenna at Location 1

All the components in the PWPW network were powered on to boot the LTE network. Once the VMs were loaded and became operational, the *lte-reference-signal-power* value was set to 2 dB below the 0-dB reference level. This was recommended by PWPW to safely provide the maximum possible transmit power and allow the greatest coverage range. The *admin-state* of the *access node* corresponding to the appropriate CWS was then "enabled" through the HNG to activate the eNodeB.

After the eNodeB became operational, a smartphone (UE) provisioned to work on the deployable network was powered on and mounted to the inside passenger side of the windshield. Once it was connected to the network, the UE was used to log and record the geocoded Reference Signal Received Power (RSRP) measurements for post-processing. RSRP is an indicator of received signal strength used to measure the downlink coverage of an LTE cell.

An extensive vehicle drive route was planned, but the initial drive revealed that the LTE coverage did not extend beyond the parking lot using this particular antenna configuration. As a result, the data collection for this part of the test was limited to the parking area of NRG Park.

The LTE antennas, which were attached to the eNodeB and the UE used to log the RSRP measurements, are described in Table 1.

Table 1: LTE Transmitting ("Packaged") and Receiving Antennas

LTE Transmit Antenna				LTE Receive Antenna		
Manufacturer	Model	Gain	RC	Manufacturer	Model	Mount Location
LAIRD	TRA6927M3NB-TS1	3.5 dBi	6 ft.	Sonim	XP7	Inside Windshield

In summary, the deployable LTE network with the packaged antenna configuration was characterized using the following components:

- PWPW CWS and an embedded server;
- Omnidirectional LTE antennas (manufactured by Laird Technologies);
- Global Positioning System (GPS) antenna;
- 12-VDC-to-120-VAC 300-W pure sine wave power inverter;
- Ruggedized Sonim XP7 Android smartphone;
- Dell Laptop to access and communicate with the VMs in the PWPW system; and
- Miscellaneous hardware and cables.

The results of this coverage characterization can be found in Section 4.1.2.1.

3.1.2.2 Coverage Characterization with a High-Gain Antenna

On February 10, 2016, testing was moved to Location 2. This location gave access to a higher elevation above ground, which allowed a more traditional base station installation. A high-gain directional antenna, brought to the exercise by PWPW personnel, was used to characterize the footprint created by this alternate configuration.

This configuration was not in the original test plan, but was added at the last minute to evaluate the benefits of using a high-gain directional antenna at a higher elevation above ground. The results of this test would then allow comparative assessment of the coverage improvement attributable to the difference in elevation combined with antenna type.

Both the eNodeB and the antenna were located on the fifth-level ramp of the NRG Park stadium. The directional antenna was 85 ft. above ground level and mounted on a tripod, as shown in Figure 6.

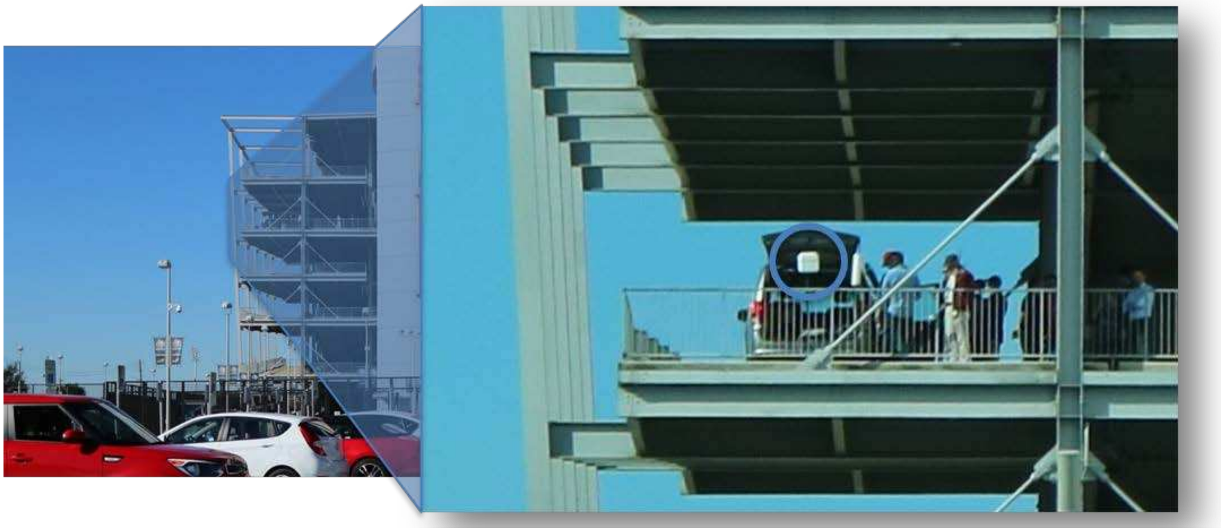


Figure 6: Installation of the High-gain LTE Antenna at Location 2

The antenna was then pointed due south (i.e., 180 degrees from true north) and parallel with Kirby Road in order to provide the best line of sight towards the intended coverage area, shown in Figure 7.

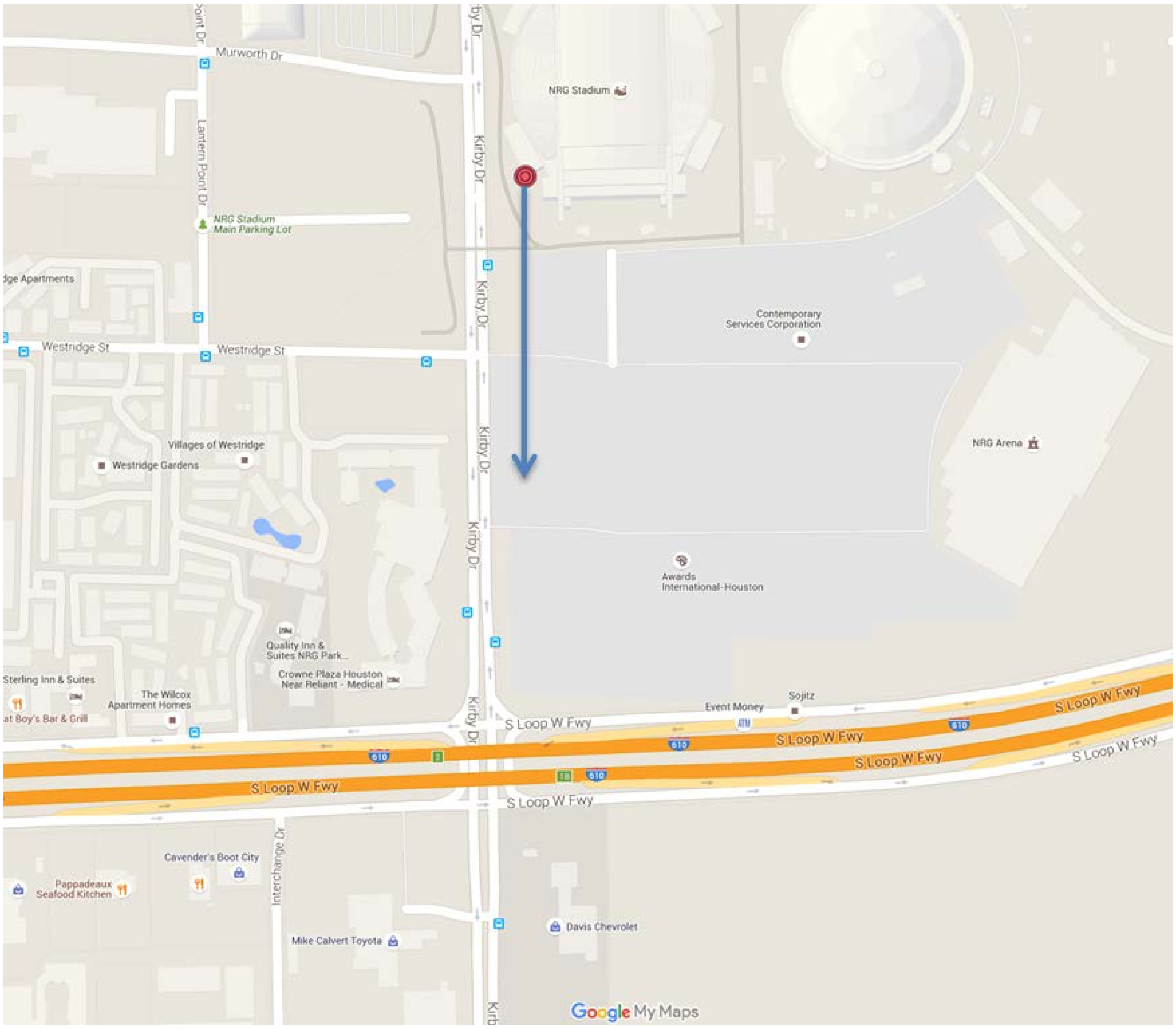


Figure 7: High-gain LTE Antenna Orientation at Location 2

For consistency, the eNodeB and the *lte-reference-signal-power* were set up with the same configuration and values as in the previous test at Location 1. Table 2 provides the details of the LTE antennas used to transmit the reference signal at Location 2 and the UE used to log and capture the RSRP measurements.

Table 2: LTE Transmitting (High-gain Directional) and Receiving Antennas

LTE Transmit Antenna				LTE Receive Antenna		
Manufacturer	Model	Gain	RC	Manufacturer	Model	Mount Location
LAIRD	PAS69278P-FNF	9.1 dBi	85 ft.	Sonim	XP7	Inside Windshield

Once all components were assembled and activated, the logging process started. In this configuration, LTE coverage appeared to extend beyond the parking lot. As a result, data

were collected using the predefined vehicle driving route, shown in Figure 8, and adjusted as coverage degraded.

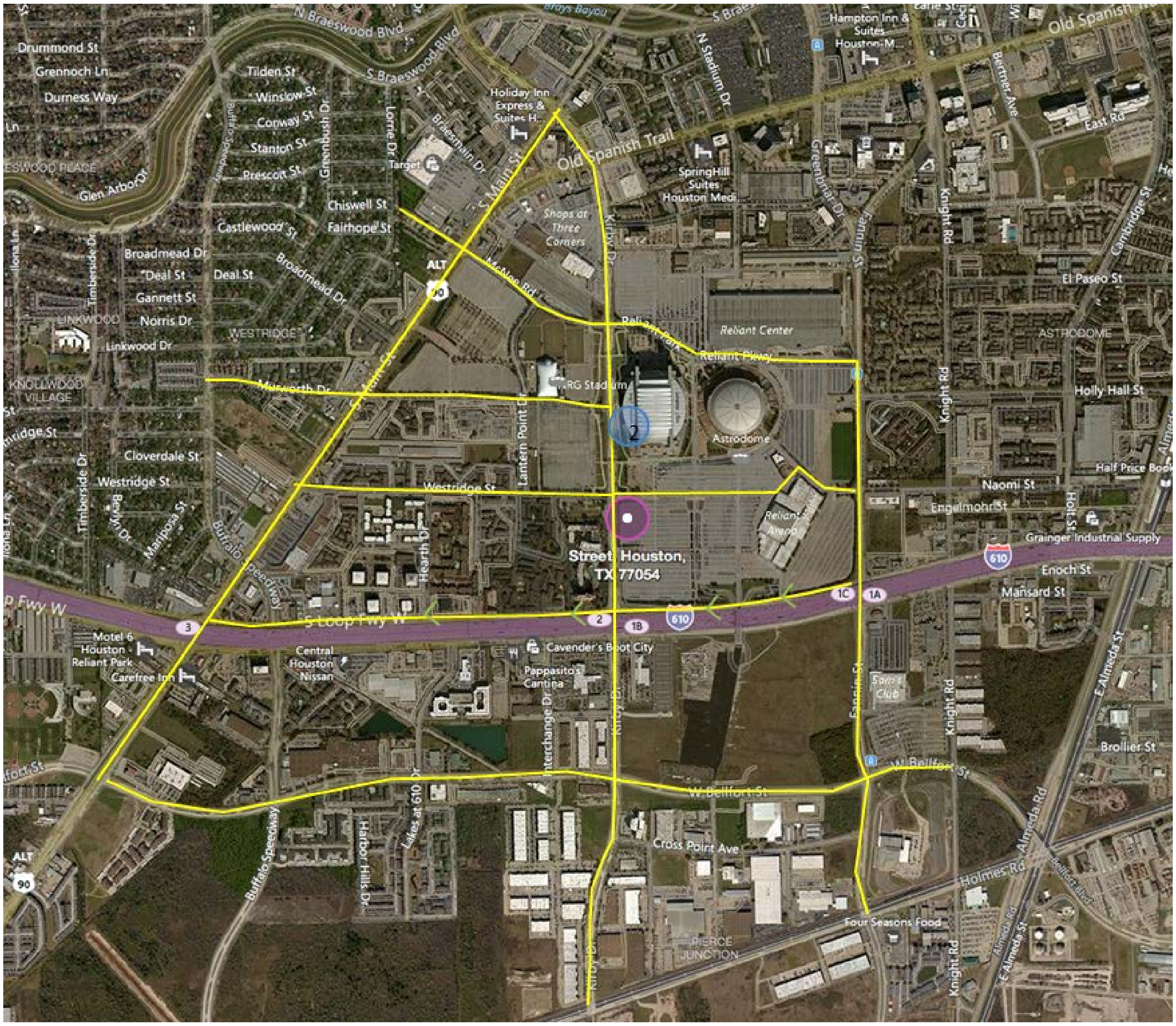


Figure 8: Pre-defined Drive Route

In summary, the PWPW LTE network configured for the higher elevation antenna consisted of the following components:

- PWPW CWS and an embedded server;
- High-gain directional LTE antennas (manufactured by Laird Technologies) mounted on a tripod at 85 ft.;
- GPS antenna;
- 12-VDC-to-120-VAC 300-W pure sine wave power inverter;

- Ruggedized Sonim XP7 Android smartphone;
- Laptop to access and communicate with the VMs in the PWPW system; and
- Miscellaneous hardware and cables.

The DHS test team successfully demonstrated the ability to configure and perform baseline testing. More specifically, the following were demonstrated:

1) The team demonstrated the ability to use the PW deployable LTE system.
2) The team verified the LTE system provided localized Band 14 LTE coverage.
3) The team tested two different LTE antennas.
4) The team set up the eNodeB at two locations with different elevations above ground.
5) The team collected data to characterize the LTE footprint of two different LTE antennas and their configurations.

The results of this coverage characterization can be found in Section 4.1.2.2.

3.1.3 Datacasting Enclave Tests

Datacasting enclave testing was performed on February 9, 2016 at the Houston City Hall Annex at 900 Bagby Street, and also outside the HPD Station at 33 Artesian Place. Figure 9 identifies these test locations in downtown Houston. Representatives of the City of Houston, JHU/APL and SpectraRep executed the test. The Harris County Sheriff's Office provided remote support for the additional ad hoc tests to be described.

Figure 9: Datacasting Enclave Test Locations

The primary objective of the datacasting enclave tests on February 9 was to verify the ability to initiate incident alerts and messages, and transmit data (especially real-time video streams) from a second site in Houston. In July 2015, a datacasting enclave was set up at the television broadcasting offices of KUHT, from which the capability to initiate messages, transmit data files and stream videos was previously demonstrated. In order to support this 2016 test, a representative of SpectraRep configured the system as shown in Figure 10.

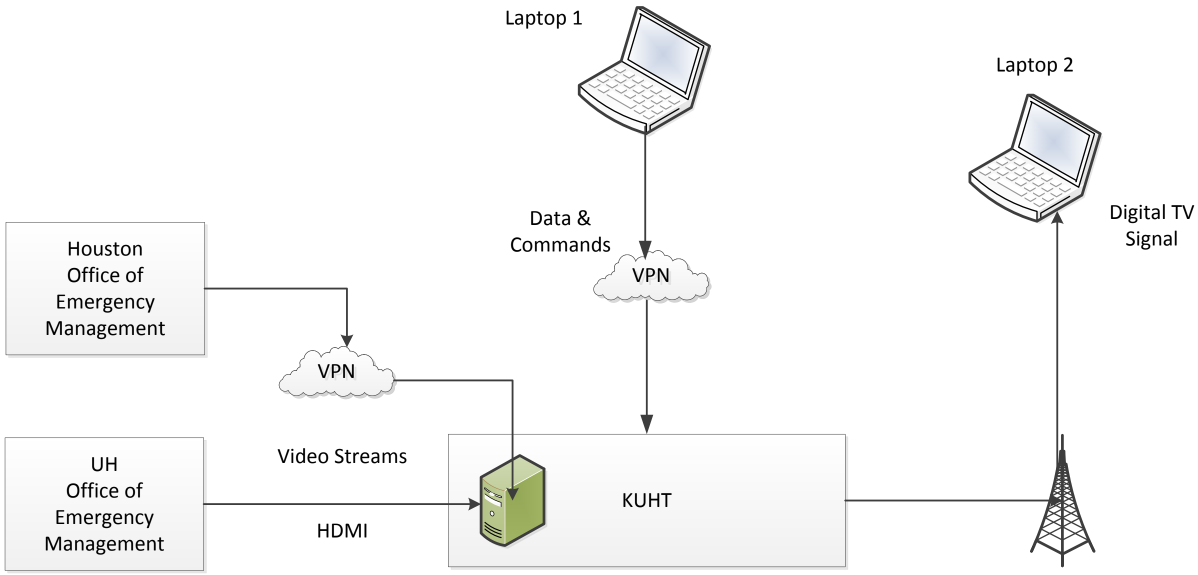


Figure 10: Datacasting Test Configuration 1

As a result of the 2015 tests, the datacasting system at KUHT was already configured to receive data via an HDMI interface from the UH OEM Video Management System directly to the datacasting server at KUHT. The datacasting system could then transmit these data via the KUHT digital television signal to registered laptops configured with the SpectraRep IncidentOne software. This software also had the capability to monitor and control the transmission of video streams input to the datacasting system and to transmit alerts and data files via datacasting from a remote laptop. This capability was expanded to enable data from the Houston EOC to be input, via a Virtual Private Network (VPN) connection, to the datacasting system.

The team conducted tests of the configuration represented in Figure 10 from both the City Hall Annex and from the parking lot outside the HPD station. Specifically, the test team demonstrated the following:

1) The ability to monitor the video streams being input to the datacasting server using a laptop configured to do so (identified as Laptop 1 in Figure 10). Observers monitored real-time video streams transmitted from KUHT to the configured laptop via a VPN connection.

2) The ability to initiate messages and file transfers from Laptop 1. This included transmission of data files loaded onto Laptop 1, but not the datacasting server.

3) The ability to initiate the transmission of video streams from Laptop 1. Real-time video from the UH OEM and Houston EOC were both transmitted via datacasting.

4) The ability to receive target messages and video streams on a second laptop configured with IncidentOne software and hardware to receive datacasting information encoded in the KUHT digital television signal.

Because the planned test was executed so efficiently, the test team had time to execute three additional sets of ad hoc tests. In the first set of tests, users on local cellular LTE networks (one using a local commercial carrier and the other one using the Harris County Band 14 Public Safety network) streamed real-time video to the datacasting system. Figure 11 is a representation of the test configuration used to execute this ad hoc test. In addition, the web camera in Laptop 1 (indicated in Figure 11) was used to input real-time video to the datacasting server via the VPN connection used to transmit data and commands.

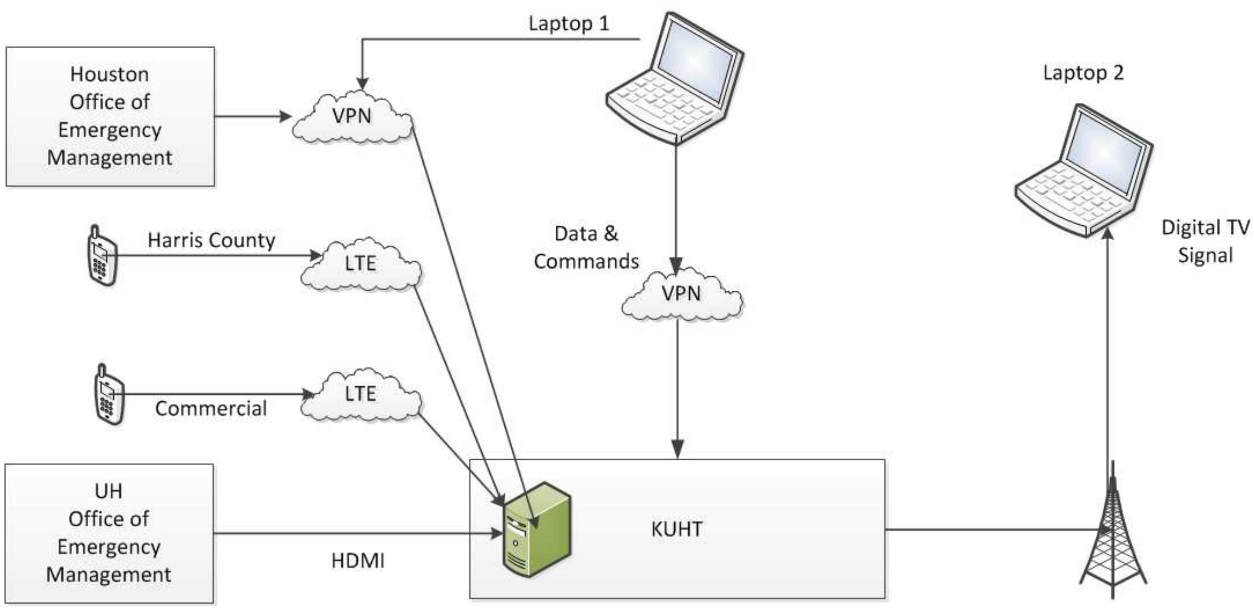


Figure 11: Testing of ad hoc LTE to Datacasting Architecture

Video streams were transmitted to the server at KUHT using both cellular and Wi-Fi as backhaul. Those video streams were then re-transmitted using datacasting to the two laptops configured with IncidentOne software. Both laptops and the cell phone operating on a commercial network were located in a vehicle parked outside the HPD station at Artesian Place. For the test using the Harris County Band 14 Public Safety Network, an officer with the Harris County Sheriff's Office streamed data from a location near the David Wayne Hooks Memorial Airport, which is located approximately 20 miles north of downtown Houston (see Figure 12).

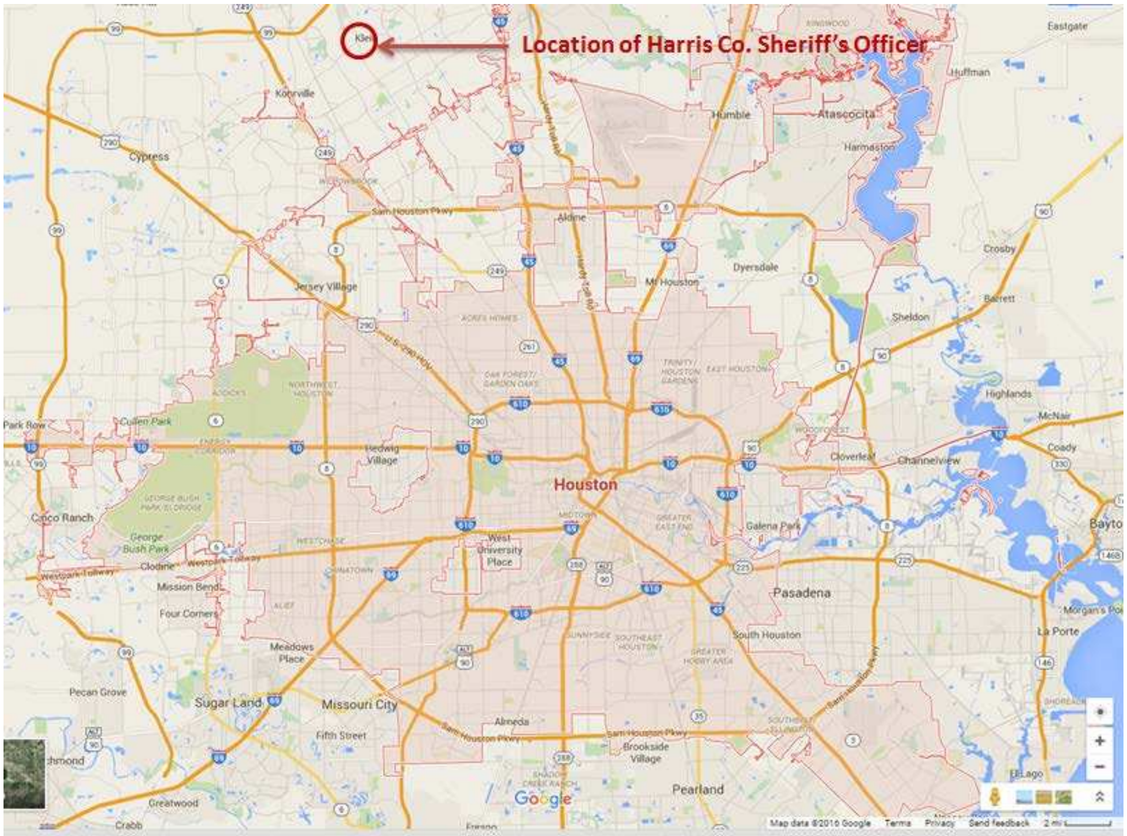


Figure 12: Location of Harris County Sheriff's Officer Supporting the Test

The second set of ad hoc tests involved driving around downtown Houston and observing the reception quality at various locations. Figure 13 contains a map outlining the approximate route of the vehicle that the test team drove around downtown Houston. For most of this test, the test team was limited to observing the reception of video from the City of Houston EOC and the UH OEM (i.e., test configuration represented in Figure 10), although there were also periods during which the Harris County Sheriff's Office was transmitting video using the Band 14 system (Figure 11).

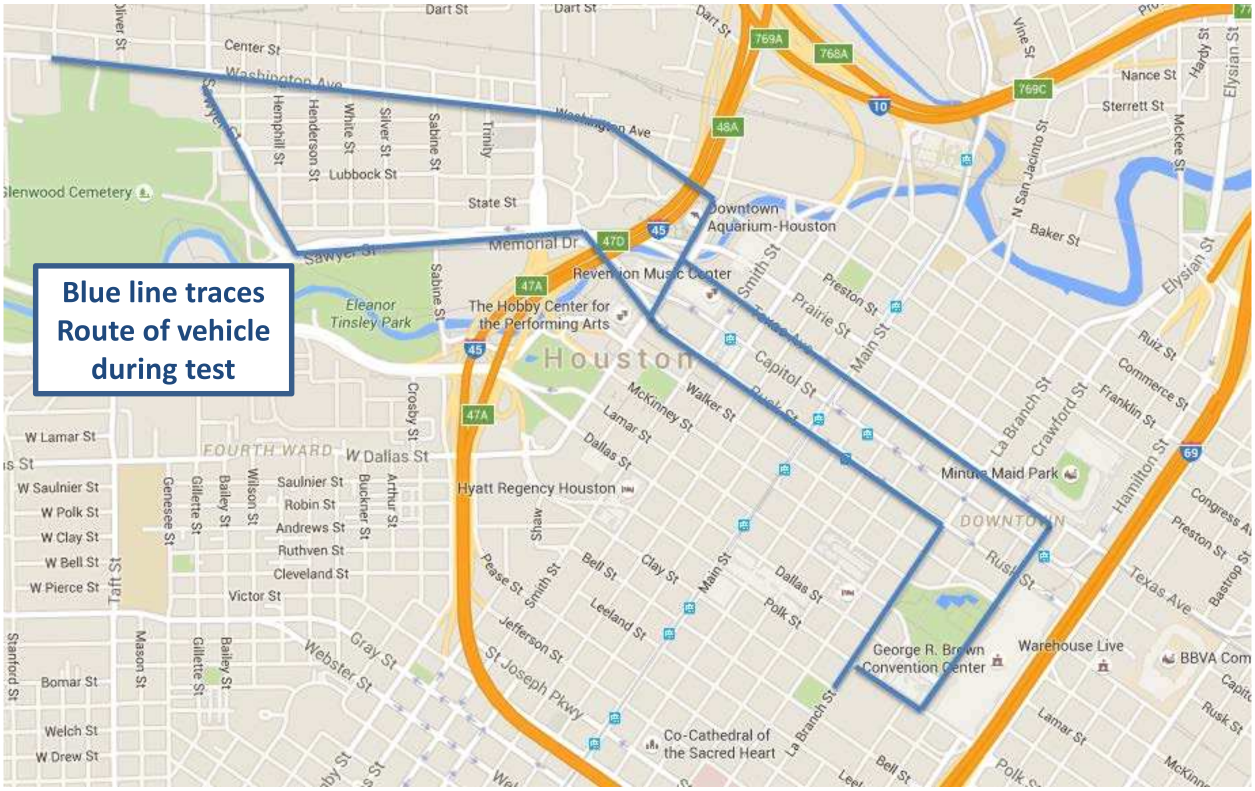


Figure 13: Approximate Vehicle Route for the Datacasting Tests

During the third and final ad hoc test, the receiving antenna was removed from the laptops and affixed to a Linux-based datacast receiver appliance. This appliance was configured to generate an 802.11N Wi-Fi signal to test delivery of content that originated as a datacast and was ultimately viewed by end users on devices only connected over Wi-Fi. The objective was to determine suitability for untethered reception, while in range of the Wi-Fi rebroadcast. Wi-Fi is unlicensed and often becomes congested. The downtown test location, near office buildings and hotels, proved to be extremely congested. At this point, the test team was augmented by a second representative of the City of Houston who brought another laptop. The test team attempted to connect all three laptops to the Wi-Fi router. While reception directly from the KUHT datacast was successful at this location, reception from a Wi-Fi rebroadcast was less reliable. This was exacerbated incrementally as each of the three targeted recipients became attached to the Wi-Fi signal. This is because Wi-Fi requires a separate dedicated connection for each user (like most other existing wireless paths) even if the users are receiving the same content. When this test was repeated using two of the laptops connected to the router via Ethernet, the results were much better, thereby validating that the issue was the unlicensed Wi-Fi instead of the direct datacast reception over the KUHT licensed spectrum.

The results of this coverage characterization can be found in Section 4.1.3.

3.2 Interconnected Enclave Testing

Interconnected enclave testing consisted of the following tests:

1. LTE Enclave Mesh Network Tests
    a. Meshing distance determination with ground level antenna
    b. Meshing distance determination with elevated high-gain antenna
    c. Basic verification of a disconnected LTE network created by a mesh network
        i. Reselection validation in a disconnected network
        ii. Application functionality testing in a disconnected network
2. Datacasting Load Tests

These tests are described in the following subsections.

3.2.1 LTE Enclave Mesh Network Tests

The LTE mesh network testing began on February 9, 2016 and continued through February 10, 2016 at the NRG Park location. There were two goals in this phase of the testing: 1) to determine the meshing distance between two CWS nodes; and 2) to verify the basic functionality of the expanded LTE network created by meshing together two separate CWS nodes. For simplicity, two CWS nodes were used to measure the meshing distance and validate the functionality of the expanded access network.

The CWS nodes provided by PW were pre-configured to automatically recognize each other's CWS, thereby allowing the automatic establishment of a mesh network. When one of these CWS nodes comes within the meshing range of the other, a secure link is created through a Wi-Fi backhaul connecting the two nodes. The LTE network can then be automatically expanded between two spatially separated, but connected CWS nodes, and orchestrated by the HNG. As a result, a scalable localized LTE network can be created by the meshing ability of the PW CWS nodes. As more CWS nodes converge into an area with an established mesh network, these additional CWS nodes can link to other CWS nodes to expand the operational LTE footprint. Two 5-GHz Wi-Fi radios are built into the CWS node and were used for the mesh network backhaul.

Figure 14 shows the test configuration used in this test, which illustrates the expanded LTE network created by meshing together two geographically separate CWS nodes.

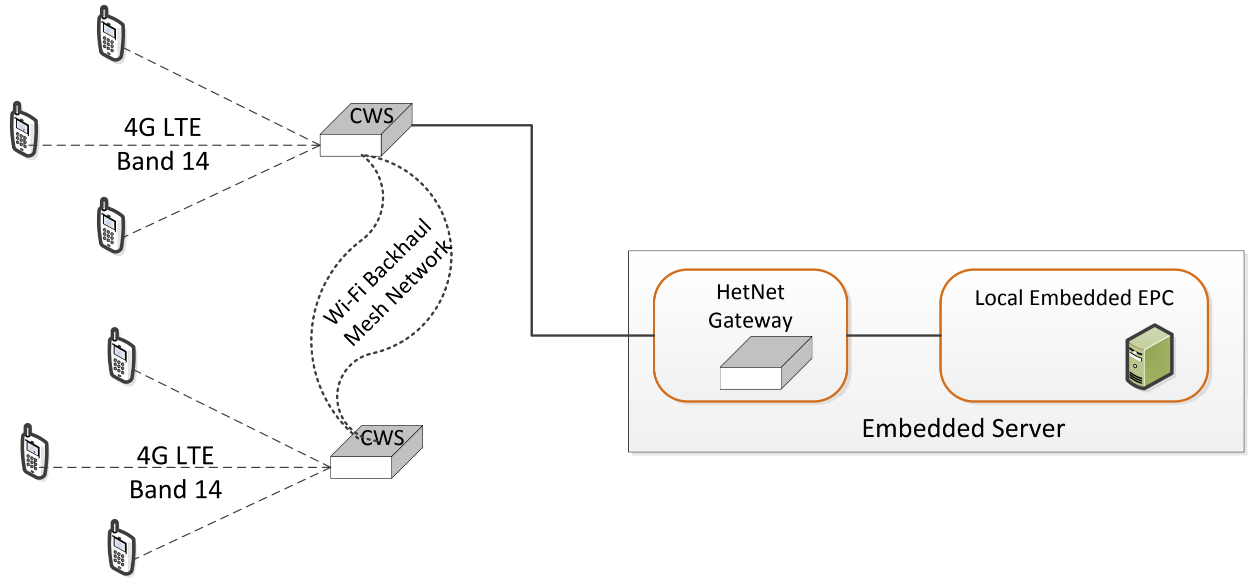


Figure 14: Mesh Network Configuration

3.2.1.1 Meshing Distance Determination with Ground Level Antenna

On February 9, 2016, Location 1 was used to stage the meshing distance test. The goal of this test was to determine the maximum mesh establishment distance between two CWS nodes at ground level.

To carry out this task, the NGA CWS was connected to the embedded server and set as the "host" CWS. The embedded server (containing the HNG and EPC) and the CWS were installed in the back compartment of a Chrysler minivan vehicle. The DHS CWS node was set up as the "remote" CWS by physically disconnecting it from its embedded server. This remote node was mounted in the back compartment of a Toyota.

Both CWS units came with generic "rubber ducky" Wi-Fi antennas with no means to extend the antennas to the exterior of the vehicle. This setup would have negatively affected the Wi-Fi meshing distance test. Fortunately, PW had also brought a set of Wi-Fi antennas that could be mounted to the roof of the minivan (shown mounted in Figure 15).

Figure 15: External Wi-Fi Meshing Antenna

The details of the exterior Wi-Fi antennas are listed in Table 3.

Table 3: Details of Host and Remote Wi-Fi Antennas Used in Meshing Test

Host WiFI-Antenna				Remote Wi-Fi Antenna			
Manufacturer	Model	Gain	RC	Manufacturer	Model	Gain	RC
Panorama	LGMM-7-27-24-58	2 dBi	6 ft.	Panorama	LGMM-7-27-24-58	2	6 ft.

Power to both systems was supplied by 12-VDC-to-120-VAC inverters. A laptop was used to connect to the embedded server to control the VMs running the HNG, EPC and other virtualized nodes required to operate and monitor the meshing functionality.

In summary, testing to determine the range of the mesh network at ground level consisted of the following components:

- One PW CWS node configured to establish a mesh network with another CWS and anchored to an embedded core with a HNG;
- One PWPW CWS node configured to establish a mesh network with another CWS;
- One Panorama Wi-Fi antenna mounted on the roof of each vehicle;

- GPS antenna for each vehicle;
- One 12-VDC-to-120-VAC power Inverter for each vehicle;
- Laptop to access and communicate with the components and VMs in the PW network; and
- Miscellaneous hardware and cables.

As mentioned above, the CWS came pre-configured from PW to mutually recognize other CWS and establish a mesh network when the CWS nodes come within range of each other. The NGA CWS was anchored to an embedded server (host), while the DHS CWS was disconnected from the embedded server (remote).

In order to start the meshing distance verification, all components in the PW system were powered on. Once all components on the host CWS were active, the DHS CWS established a localized mesh network. A solid blue status light on the front panel of the remote CWS served as an indicator of mesh establishment.

Upon confirming the establishment of a mesh network, the vehicle designated as the remote CWS drove away from the host CWS to disconnect at some distance from the mesh network. As the remote CWS node was moved away from the range of the host CWS, the mesh link was eventually disconnected. The location where the mesh network disconnected was noted and recorded as the mesh range. Figure 16 further illustrates this concept. This process was also used at Location 2 for meshing distance determination, to be described next.

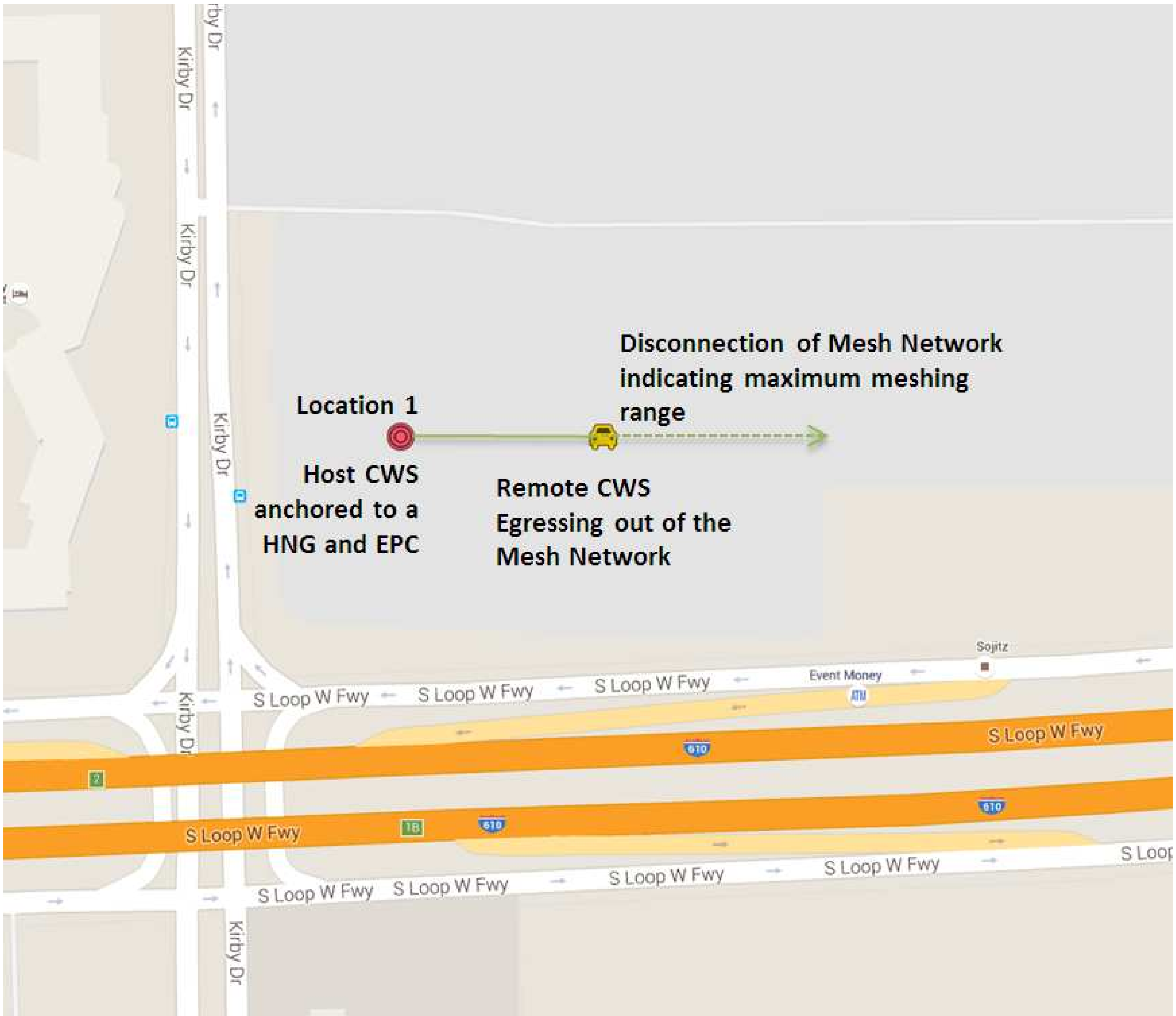


Figure 16: Meshing Distance

The results of this mesh distance determination can be found in Section 4.2.1.1.

3.2.1.2 Meshing Distance Determination with Elevated High-Gain Antenna

On February 10, 2016, the staging area for mesh distance testing was moved to Location 2. The purpose of choosing this location was similar to the reason for choosing it for the LTE coverage characterization. Location 2 allowed the antennas' installation at a higher elevation above ground. The results of this test would allow the maximum meshing distance to be compared at different elevations. Like the LTE high-gain antenna configuration, testing with a high-gain directional Wi-Fi antenna was not in the original scope of the test. However, because testing the antenna at a higher elevation would produce meaningful data, it was added to the test.

The high-gain directional Wi-Fi meshing antenna was mounted on a tripod next to the LTE antenna on the fifth level of the stadium ramp, elevating the antenna to 85 ft above ground level, as shown in Figure 17.

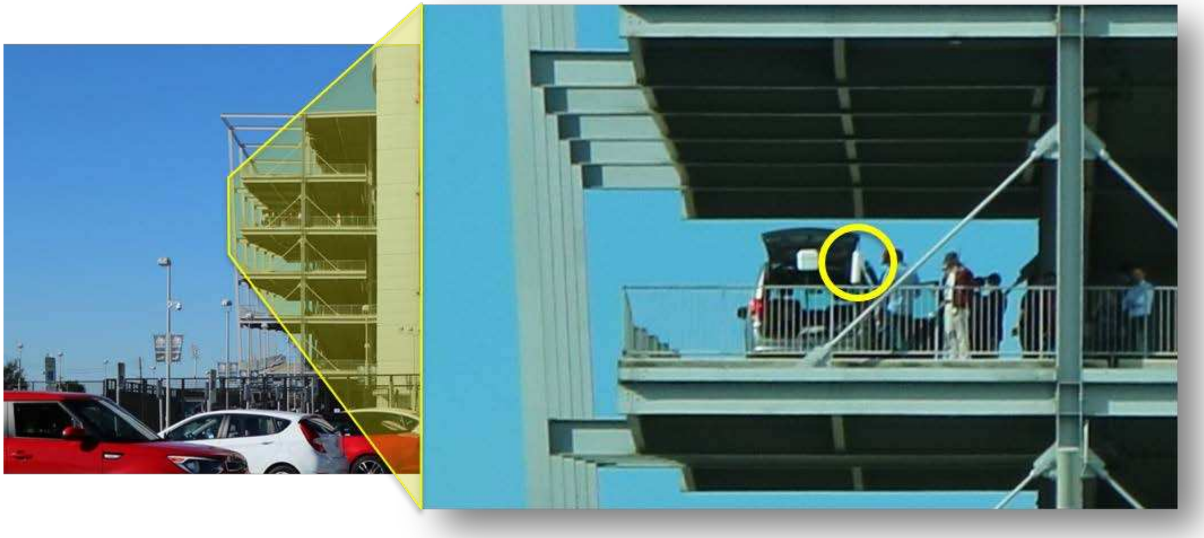


Figure 17: eNodeB and High-gain Wi-Fi Antenna Location 2

The high-gain directional Wi-Fi meshing antenna was pointed due south to point parallel to Kirby Road to provide the best line of sight toward the target area for measuring the meshing distance, as shown in Figure 18.

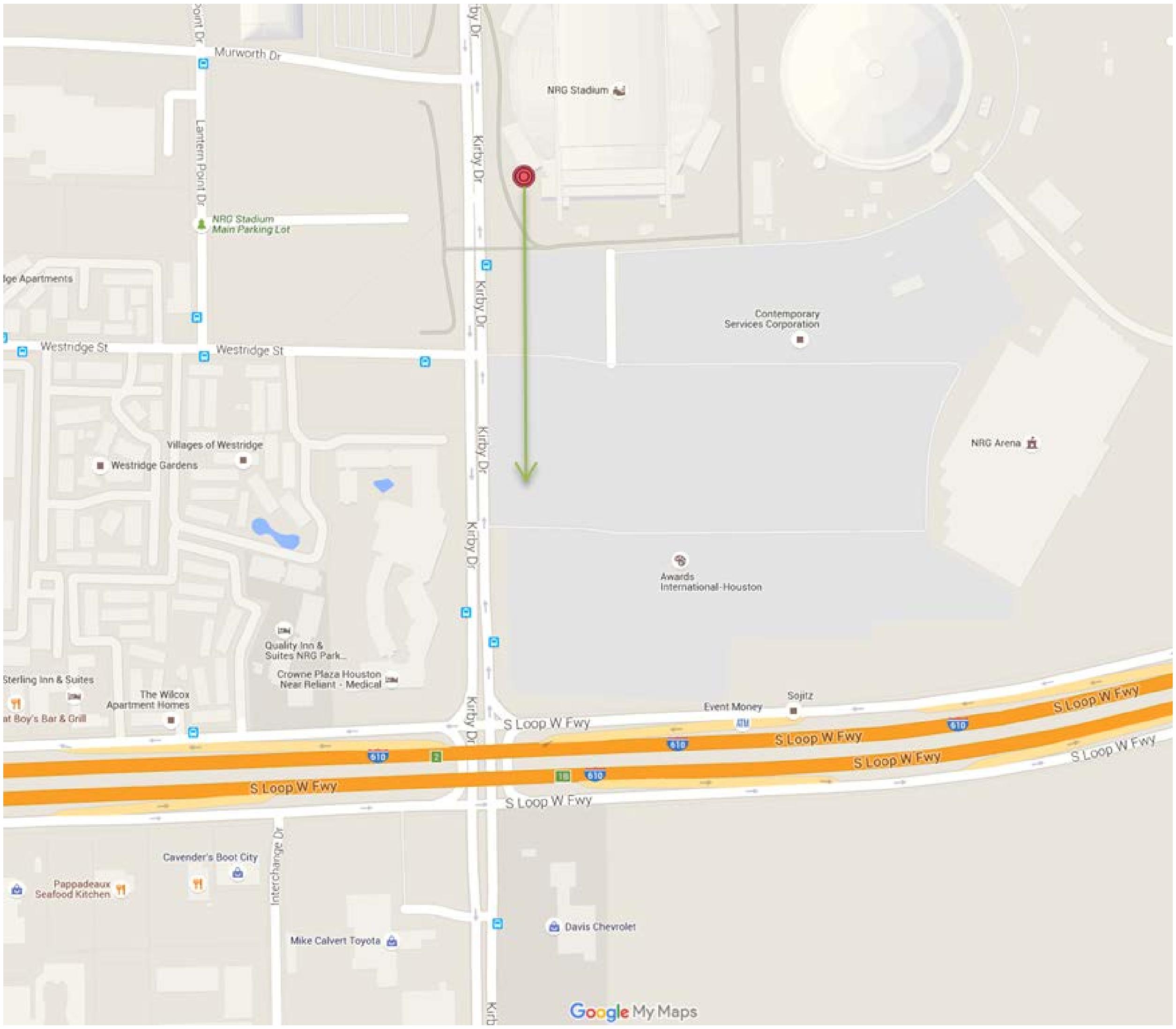


Figure 18: High-gain Wi-Fi Antenna Orientation at Location 2

Descriptions of the high-gain directional Wi-Fi antenna for the host CWS and the exterior Wi-Fi antennas for the remote CWS are listed in Table 4.

Table 4: Details of Host and Remote Wi-Fi Antennas Used in Meshing

Host WiFI-Antenna				Remote Wi-Fi Antenna			
Manufacturer	Model	Gain	RC	Manufacturer	Model	Gain	RC
L-COM	HG4958-17DP-090	17 dBi	85 ft.	Panorama	LGMM-7-27-24-58	2	6 ft.

The process to activate the PW mesh network remained the same as in the previous test. The host CWS and remote CWS assignments also remained the same. The only notable differences between the two tests were: 1) a high-gain directional Wi-Fi antenna was used; and 2) the radiation center of the antenna was higher.

The process to determine the meshing distance also remained the same. The remote CWS was located near the base of the stadium to establish a mesh network with the host CWS. Once the mesh network establishment was confirmed, the vehicle containing the remote CWS was driven around the NRG Park parking lot and outside on Kirby Road. Interstate 610 blocks the southern end of the parking lot, so the remote CWS could not be driven any further south within the parking lot.

In summary, the test to determine the range of the mesh network with the antenna at a higher elevation consisted of the following components:

- One PWPW CWS node configured to establish a mesh network with another CWS and anchored to an embedded core with an HNG;
- One PWPW CWS node configured to establish a mesh network with another CWS;
- One L-COM High-Gain Directional Wi-Fi Meshing Antenna mounted on a tripod at Location 2;
- GPS antenna at Location 2;
- One Panorama external Wi-Fi antenna mounted on the roof of the remote CWS vehicle;
- GPS antenna for the remote CWS vehicle;
- 12-VDC-to-120-VAC power inverter for each vehicle;
- Laptop to access and communicate with the components and VMs in the PW network; and
- Miscellaneous hardware and cables.

The results of this mesh distance determination can be found in Section 4.2.1.2.

3.2.1.3 Basic Verification of a Disconnected LTE Network Created by a Mesh Network

The PW system can be used to support voice, video streaming or other applications within the disconnected network by using localized application servers or by accessing remote application servers when it is connected to an external IP network

The second objective of the test was to verify basic functionality of the disconnected LTE network supported by the mesh network. During the morning of February 10, 2016, two tests were performed at Location 1. One test involved reselection testing, and the other involved application functionality testing.

The NGA CWS served as the host CWS and was assigned Location 1. The DHS CWS was set up as the remote CWS in a vehicle parked within the meshing range of the host CWS. These locations are shown in Figure 19. Once the mesh network was established, these locations were used for the duration of the functional verification.

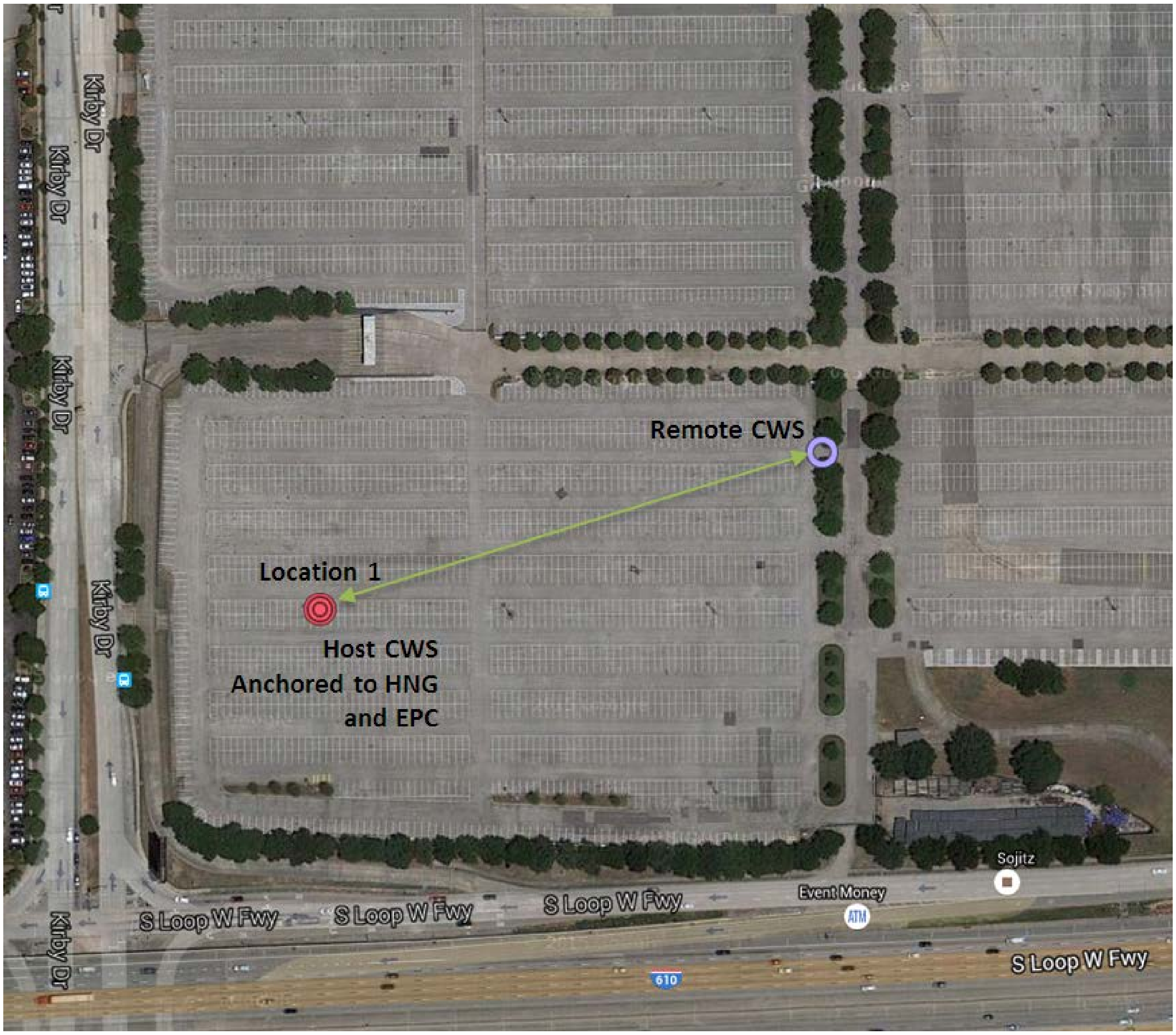


Figure 19: CWS Locations for Functional Verification of the LTE Mesh Network

Figure 20: High-gain Directional Wi-Fi Antenna mounted on a Tripod

For these tests, the host CWS was attached to a high-gain directional Wi-Fi antenna mounted on a tripod, shown in Figure 20. This antenna was pointed toward the remote CWS. The remote CWS was set up with the generic Wi-Fi antenna supplied with the packaged PW configuration. In order to make certain that the secure link between the two CWS nodes stayed connected, the rear of the vehicle carrying the remote CWS was pointed towards the host CWS with the rear hatch left open. All PWPW LTE systems were installed in the rear of each vehicle. The details of the antennas used are shown in Table 5.

Table 5: Details of the Anchored and Remote CWS Wi-Fi Antennas Used in Meshing

Anchored CWS WiFI-Antenna				Remote CWS Wi-Fi Antenna			
Manufacturer	Model	Gain	RC	Manufacturer	Model	Gain	RC
L-COM	HG4958-17DP-090	17 dBi	4 ft.	Generic	Rubber Ducky	n/a	3 ft.

This test was designed to test basic functionality, but unlike the previous two tests, it did not include determining the maximum meshing range. As long as the mesh network could be established and the resulting LTE network maintained, the selection of Wi-Fi antenna type was not critical.

An inverter supplied power to the LTE network. A laptop was used to connect with the embedded server to control the VMs running the HNG, EPC and other virtualized nodes.

To begin the mesh network functionality test, all components of the PW system were powered on to begin the process of bringing up the LTE network. Once all components on the anchored LTE system were running, the remote CWS was activated to set up a mesh network between the two CWS nodes. A solid blue status light on the front panel of the mobile CWS served as an indicator for mesh network establishment

In summary, testing to validate the basic functionality between the two CWS nodes in an established mesh network consisted of the following components:

- One PW CWS node configured to establish a mesh network with another CWS and anchored to an embedded core with an HNG;
- One PWPW CWS node configured to establish a mesh network with another CWS;
- One L-COM high-gain directional Wi-Fi meshing antenna mounted on a tripod in Location 1;
- GPS antenna for Location 1;
- Generic Wi-Fi meshing antennas mounted on each remote CWS;
- GPS antenna for the remote CWS;
- 12-VDC-to-120-VAC power inverter for each vehicle;
- Laptop to access and communicate with the components and VMs in the PWPW network; and
- Miscellaneous hardware and cables.

The basic verification is broken into two separate tests using the same configuration. The specific steps used to perform each test are further explained in the following subsections.

3.2.1.3.1 Reselection Validation in a Disconnected Network

This test involved validating that reselection occurred successfully between the two LTE enclaves serving areas created by meshing together two CWS nodes. Reselection is the LTE process for selecting sites when the serving cell signal strength is poor and a suitable neighbor cell with high signal strength is available. This test scenario involved walking in a straight line between the two CWS nodes to confirm that reselection occurred as expected. A UE was used to monitor and validate the reselection process. Results were logged and recorded.

The steps to validate the reselection process are as follows:

- A UE was activated and allowed to camp on the host CWS.
- Once the LTE RAT appeared on the UE display, the Cell ID and RSRP were noted.

- The UE was then carried from host CWS coverage area to the remote CWS coverage area, while being monitored for reselection events.
- Once the UE was in close proximity to the remote CWS, the Cell ID and RSRP were noted.
- This was followed by repeating the same steps in the opposite direction.

The results of this reselection validation can be found Section 4.2.1.3.1.

3.2.1.3.2 Application Functionality Testing in a Disconnected Network

This test involved validating services such as texting and file sharing within the disconnected LTE network created by the two CWS nodes in an established mesh network. The PW system alone does not provide communication services between the end users. Currently, it only serves to create a data pipe using LTE technology to facilitate services through applications and servers.

To test services in the disconnected LTE network, NGA brought their MAGE application and a local server application. The server application was installed on their embedded server to enable localized communication. MAGE is available as an Android application from an app store. MAGE is designed to provide relevant geospatial information, whether connected or disconnected from an external IP network.

During initial testing, the Android version of MAGE was found not to work with the localized application server. However, the PC version of MAGE did work. In order to test the mesh network as originally intended, NGA developed a work-around in the field. The work-around used a Sonim XP7 smartphone with an enabled hotspot and connected to the Band 14 network. The laptop was then tethered to the XP7 through Wi-Fi. This enabled the laptops to connect to the PW LTE network to share MAGE data. Any MAGE data originating from the laptop or received by the laptop could now transit the LTE network created by the meshed CWS nodes, thereby replicating the original testing scenario.

The steps to validate the application functionality in a disconnected network are as follows:

- Two UEs were actuated with the hotspot enabled and allowed to camp on the host CWS.
- Once the LTE RAT appeared on each display, both laptops were tethered to their respective UEs.
- The MAGE application on the laptop was launched. A text message and a file were sent from one laptop to the other laptop in the same coverage area.
- The receiving laptop was monitored to verify that the text message and file were received.
- Upon completion this test, one of the laptops (with a UE tethered to it) was moved to the location of the remote CWS.

- Once both UEs were attached to their respective serving cells (i.e., the cell site serving the UE), a text message and a file were sent from one laptop to the other laptop, across the mesh network and between two CWS nodes.
- The receiving laptop in the coverage area of the host CWS was monitored to verify that the text message and file were received from the laptop in the coverage area of the remote CWS.

The results of the Application Functionality Validation can be found Section 4.2.1.3.2.

In summary, the DHS test team configured and tested the meshed LTE network for validation of basic functionality, including determining the meshing range between two CWS nodes. Specifically, the test team performed the following tests:

1) Demonstrated the ability to use the PWPW system as a deployable LTE network.
2) Tested various Wi-Fi meshing antenna configurations at different elevations.
3) Collected data to help assess the meshing range between the two CWS nodes.
4) Demonstrated the ability to use the PWPW system to automatically set up a mesh network, and thereby extend the LTE coverage.
5) Verified basic functionality of the LTE system created by the mesh network:
    a) Validated serving cell reselection across the two nodes; and
    b) Validated text and file sharing between two UE within the LTE network established by the mesh network.

3.2.2 Datacasting Load Tests

On February 10, 2016, the test team executed a battery of tests designed to assess how the datacasting system would respond to higher loading levels. Three sets of tests were executed:

1) Tests to identify how the system would respond to commands to transmit large files (i.e., files with sizes many times the allocated capacity of the datacasting transmission, so that it would require minutes to complete a transmission).
2) Tests to evaluate how the system would respond to concurrent commands from multiple sites.
3) Tests to evaluate how the system would respond to commands to transmit multiple concurrent video streams.

The original test plan called for the tests to be executed at two sites: the City Hall Annex and the UH OEM (located in the offices of KUHT). However, during testing, it was decided to move the test to a single site. Although the original decision to execute the test in separate locations was to provide a more realistic appearance, this was deemed

unnecessary in the absence of local stakeholders to observe the test. Furthermore, collocation of the tests facilitated delivery time measurement and assessment of video quality without compromising test objectives. Therefore, all three of the above tests were performed at the offices of KUHT. Although the two laptops used to control the datacasting system were located within a few feet of each other, they operated as completely independent entities. The results would have been the same if they had been in separate locations, but data collection would have been significantly more difficult. In practice, the receiving laptop could have been located anywhere within the KUHT coverage area, while the laptop used only to transmit data and issue commands could conceivably have been anywhere with secure Internet access.

Two laptops, each configured with the IncidentOne software, were placed side by side in the conference room at KUHT. Both laptops were configured to initiate transmissions using the datacasting system, but only one of the two laptops was configured to receive transmissions. Although the laptops were co-located, each had a separate and independent wireless VPN connection to the datacasting equipment at KUHT. Figure 21 represents the test configuration. Figure 22 is a photograph showing the two laptops during the test. In this particular test, all data and commands were transmitted from a single laptop (designated as Laptop 1) located in a conference room at KUHT to the datacasting server. Datacast information embedded in the KUHT digital television signal was received at the other laptop (designated Laptop 2), also located in the KUHT conference room.

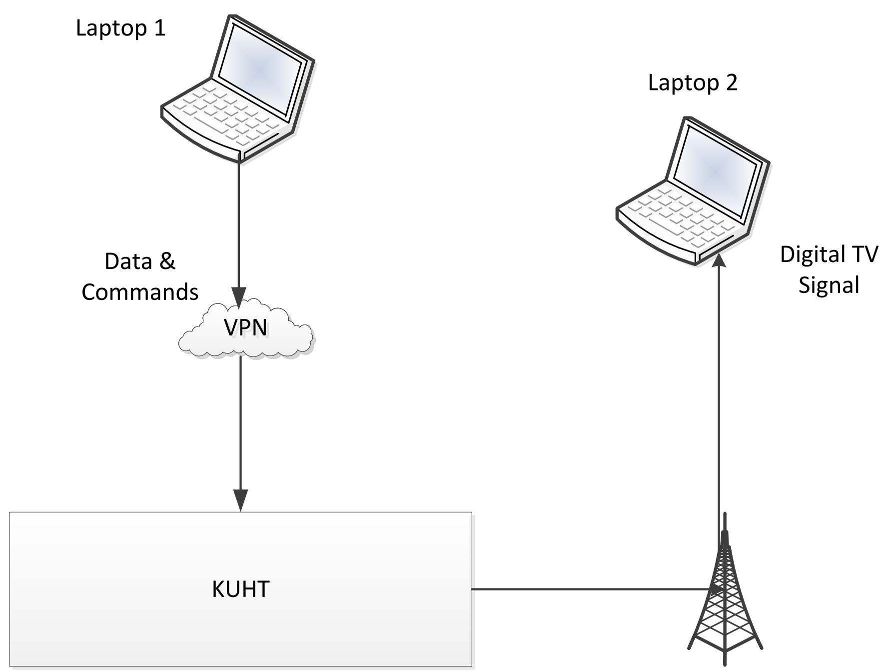


Figure 21: Test Configuration for the First Set of Load Tests

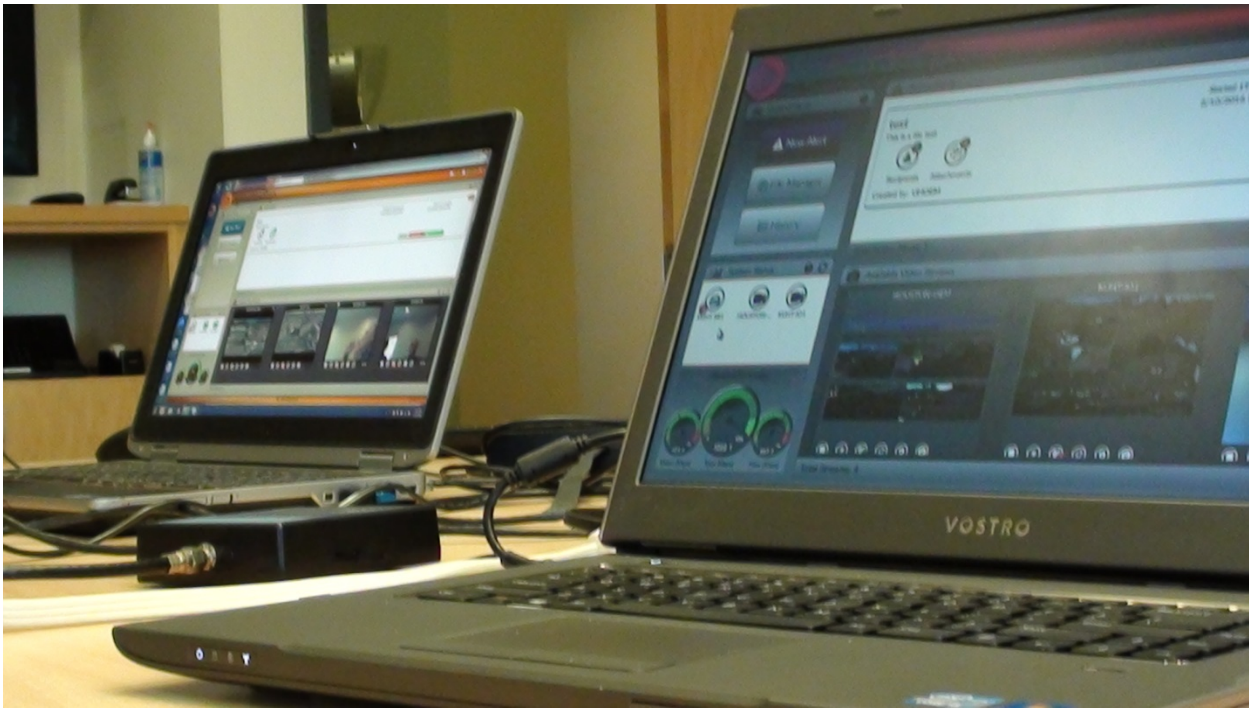


Figure 22: Laptops Used in the Load Tests

In preparation for the test, the test team created a number of files ranging in size from 0.5 MB to 25 MB. (Note: by convention, file size is expressed in terms of bytes or B; system throughput is measured in terms of bits per second or bps.) For this test, the test team had a continuous 1.2-Mbps throughput. Although it would have been possible, there was no attempt to modify the technical agreement with the television station to increase this throughput. Thus, a maximum file size of 25 MB, approximately 166 times the size of the available throughput per second, was selected. For each test performed, two delivery time measurements were captured. The first delivery time was measured from physical initiation of the transmit process on one laptop until the alerting message crawl appeared on the second laptop. The second delivery time was measured from physical initiation of the transmit process until all attached files were received by the second laptop. Figure 23 is a photograph of the delivery time measurement in progress. In this photograph, the laptop is being used to transmit a file, and the cell phone is being used as a stopwatch to measure the delivery time of the transmission. Results of the tests are documented in Section 4.2.2.

File size is important not only because of the additional time it takes to receive, but also because every bit must be received to validate the file. Larger files contain more bits and therefore test the ability of the transmission system to use effective forward error correction (FEC) to deliver all of the bits and for the receiver to reassemble the increasingly large files from the received bitstream.

Datacasting transmits User Datagram Protocol/Internet Protocol (UDP/IP) packets that, unlike Transition Control Protocol/Internet Protocol (TCP/IP), do not require Acknowledged/Not Acknowledged (ACK/NAK) handshaking between the send and receive devices. FEC compensates for this missing feedback loop. FEC was left at the default

setting of 10%, which means that 10% additional information was transmitted for each file so that any bits lost in transmission could be re-created.

The datacasting system in place at KUHT also uses file carouselling; that is, repeating each file multiple times. As defined by ATSC (www.ATSC.org), a carousel is a group of objects transmitted repeatedly from a particular service provider for a specific purpose or service. Carouselling allows the receiver to pick up missed bits on a subsequent retransmission if they are not received on the first pass and if the missing data exceed the ability of FEC to correct. The SpectraRep datacasting default carouselling interval is three times, meaning each file is transmitted three times to ensure reliable delivery. The combination of FEC and carouselling ensures reliable file delivery, even when reception conditions are not ideal. However, this improved reliability comes at the expense of additional bandwidth consumption while files are being transmitted. Testing did not address whether the current tradeoff between bandwidth consumption and reliability was in fact optimal. Thus, additional future tests may be desired.

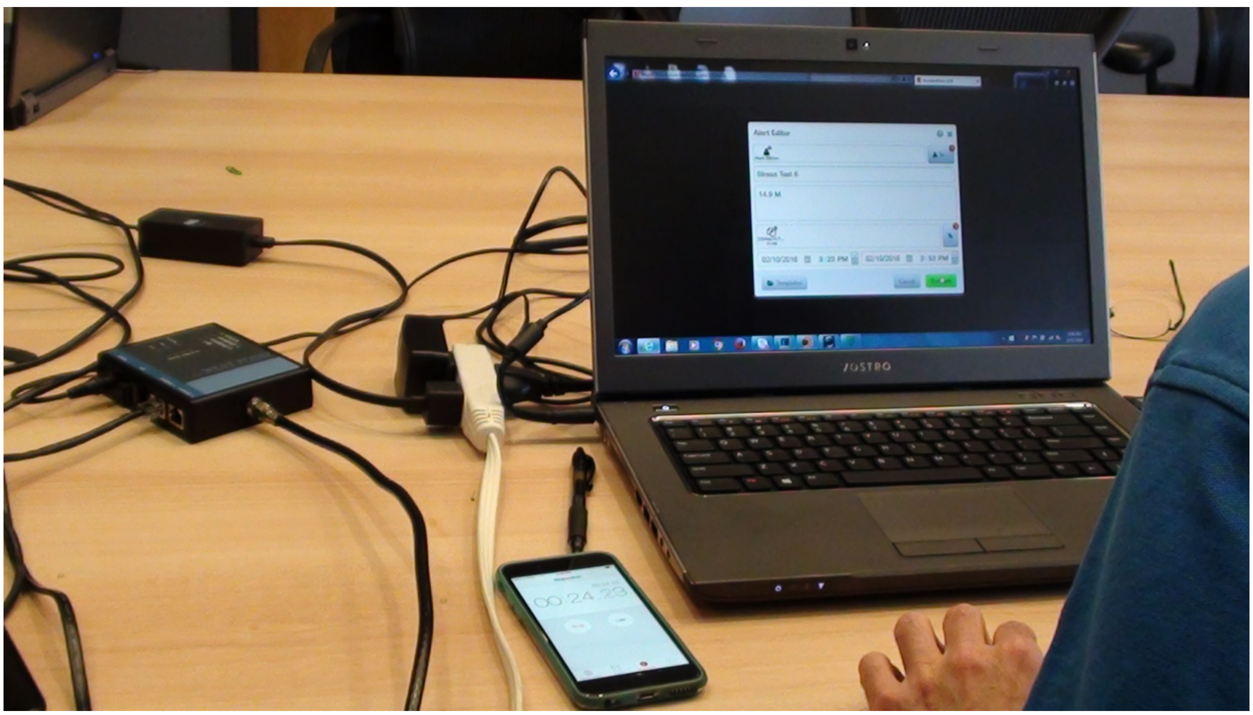


Figure 23: Measuring Datacasting Delivery Time

A second set of load tests was executed using both laptops to initiate and transmit data as configured in Figure 24. Messages were received on one of the two laptops. Four separate tests were executed. In three of the tests, transmissions were timed to begin at the same time. On the fourth test, the second transmission was initiated one minute after the first. In each test, relatively large files were appended to the messages transmitted. The size of the attached files was incrementally increased from a combined 4.0 MB to a combined 25 MB. As with the first set of load tests, 25 MB was considered a reasonable maximum file size. Results of the tests are documented in Section 4.2.2.

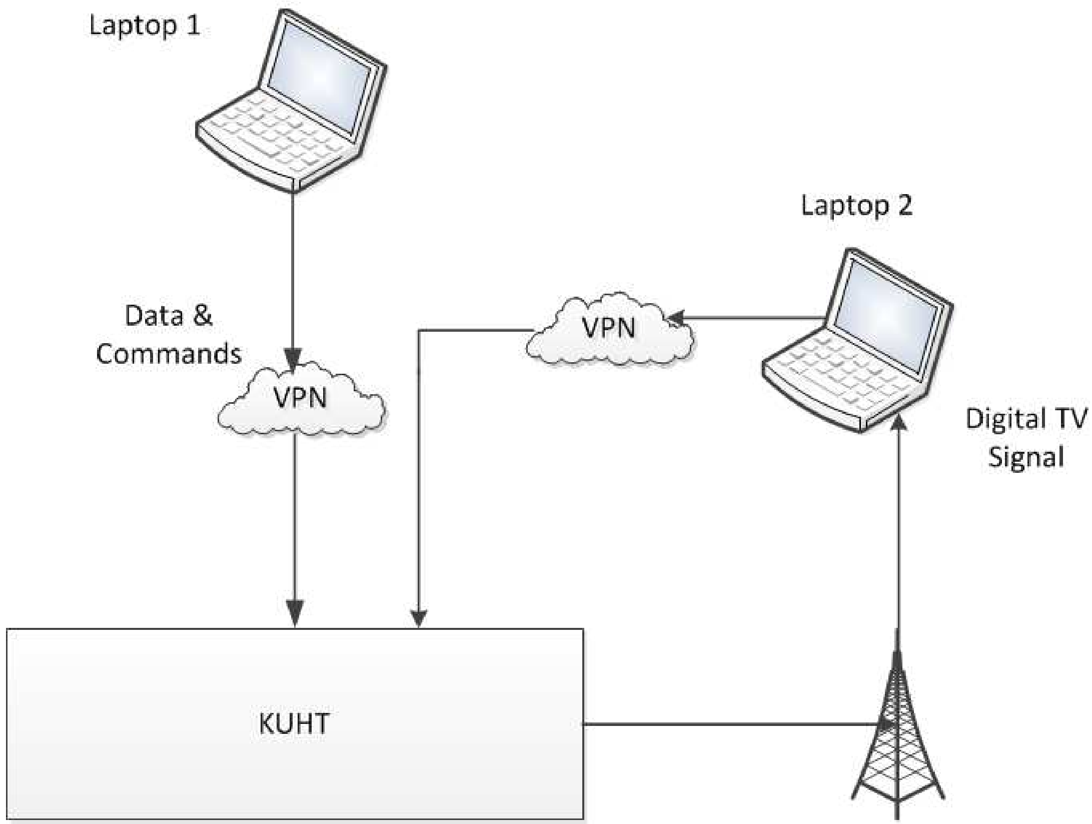


Figure 24: Test Configuration for the Second Set of Load Tests

The final set of load tests involved streaming of multiple video streams. Four input streams were established for use in these tests:

1) HPD surveillance video streamed via a VPN connection from the Houston EOC to the datacasting server at KUHT.

2) UH surveillance video streamed via an HDMI connection from the UH OEM to the datacasting server.

3) Video from Laptop 1's webcam streamed via a VPN connection over Wi-Fi to the datacasting server. This was the same VPN connection used to transmit commands and data to the datacasting system in load tests 1 and 2, and to receive video streams used to monitor the video input to the datacasting system.

4) Video from Laptop 2's webcam streamed via a VPN connection over Wi-Fi to the datacasting server. This was the same VPN connection used to transmit commands and data to the datacasting system in load test 2, and to receive video streams used to monitor the video input to the datacasting system.

Figure 25 identifies the "pathways" described in the previous paragraph. Results of this test are contained in Section 4.2.2.

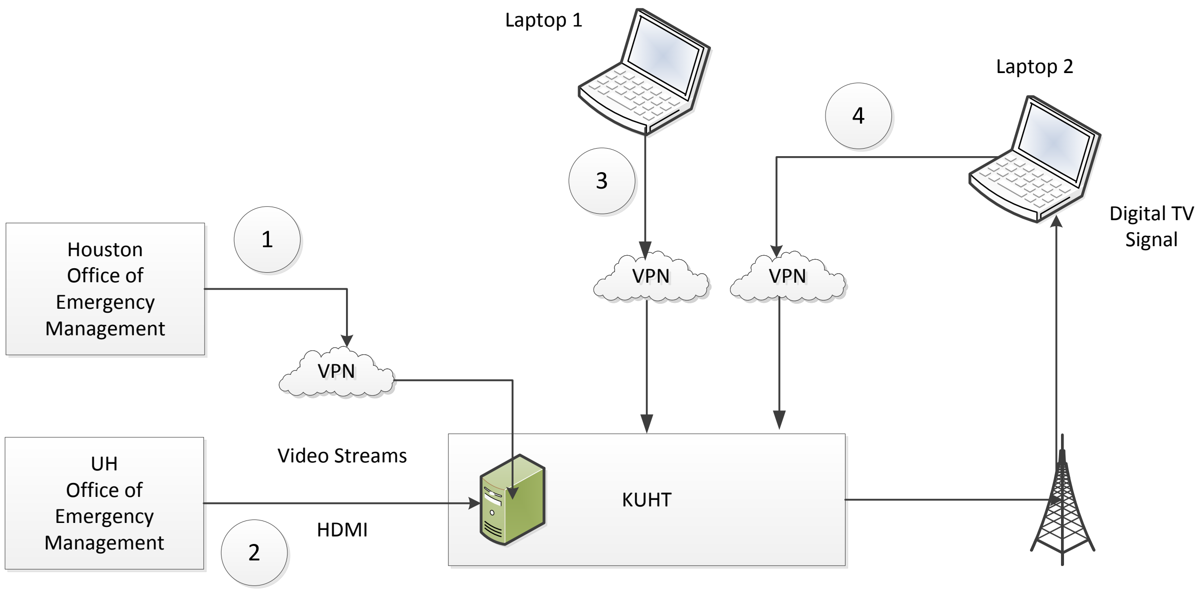


Figure 25: Test Configuration for the Video Load Test

3.3 Connectivity of Enclaves to External Networks Testing

On February 11, 2016, the test team assembled at Location 1 to integrate the PW LTE network to an external IP network. This was in preparation for later end-to-end testing of various architectures of the LTE network interoperating with the datacasting network. Testing consisted of the following connectivity tests, described in the following subsections:

1. PW LTE Node Connectivity to an External Network via Remote HNG; and

2. PW LTE Node Connectivity to an External Network via Commercial Wireless.

3.3.1 PW LTE Node Connectivity to an External Network via Remote HNG

PW personnel configured a CWS node to connect to a remote HNG and the Harris County Public Safety Broadband Network core. An LTE modem built into the CWS node served as the backhaul to connect the CWS node to the remote HNG. The LTE modem operated through a commercial carrier network. This topology is illustrated in Figure 26.

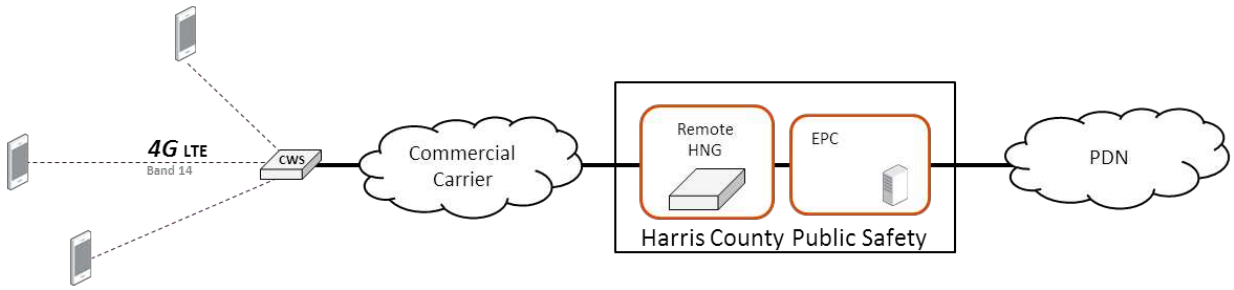


Figure 26: PW Node with External Network Connectivity via the HNG

This architecture in effect extended the operational coverage of the Harris County Public Safety Broadband Network. As a result, a device with a SIM provisioned to work on the Harris County Public Safety Broadband Network had to be utilized to obtain service through the Band 14 coverage provided by the CWS node. A device with the Subscriber Identity Module (SIM) provisioned for the DHS or NGA deployable network would not have worked.

A streaming application required to support live video from the field was downloaded from the Google Play Store. The test team could then verify that an external network was successfully integrated through the Harris County LTE core by attaching the UE to the extended Harris County Public Safety Broadband Network, and then accessing this streaming video app.

Verification of this architecture was a desired (as opposed to required) test objective. However, the PW team was able to make the connections so that the architecture was successfully demonstrated. The results of this testing can be found in Section 4.3.1.

3.3.2 PW LTE Node Connectivity to an External Network via Commercial Wireless

A second PW deployable network was configured to connect to an external PDN from the embedded server. This network architecture is shown in Figure 27. A commercial carrier's wireless LTE network provided the backhaul to an external IP data network.

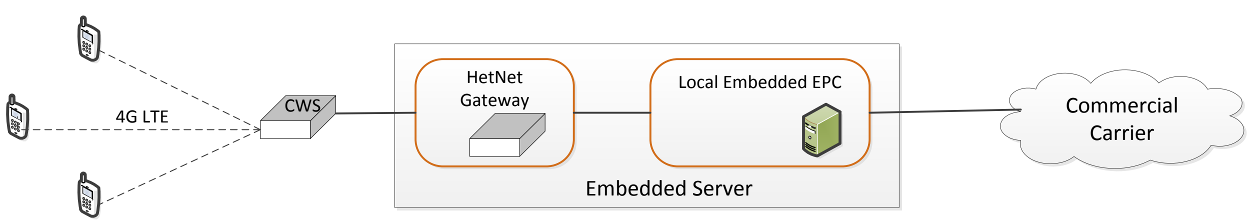


Figure 27: PW Solution with External Network Connectivity via Commercial Carrier

The embedded server and the CWS were installed in the rear compartment of the Toyota Sienna vehicle. The packaged LTE antennas were mounted on the roof of the vehicle. Power

to the system was supplied by an inverter capable of producing up to 300 W of power. A Dell laptop was used to connect to and operate the PW LTE network.

All of the components in the PW network were powered on to activate the LTE network. Once all of the VMs were ready, the *admin-state* was enabled to activate the eNodeB. The UE devices were then able to connect to the LTE network and to the external PDN.

Several tests were performed to confirm connectivity to an external network:

- Download/upload speeds were measured at several points to determine the available bandwidth baseline in preparation for video streaming.
- A streaming video application compatible with the datacasting network was downloaded from the Google Play store. It was installed and configured on the UE.
- A Push-To-Talk (PTT) application was downloaded from the Google Play Store. It was installed and configured to test basic application functionality in a connected network.

The results of testing connectivity to an external network using this architecture can be found in Section 4.3.2.

3.4 End-to-End Test

On February 11, a series of end-to-end tests were executed to demonstrate the ability of the other wireless systems to provide backhaul to augment the datacasting system. Exercises were controlled and monitored by the test team. The primary origin of the data used for backhaul was from NRG Park at a location outside NRG stadium. Additional wireless backhaul testing was provided from a remote location in Harris County. Datacasting transmission capability was located at KUHT.

The first end-to-end test used video input from a member of the test team's personal cell phone. Video was streamed from the phone to the datacasting server at KUHT via the local commercial wireless service (LTE/Internet). The video was multiplexed into the KUHT digital television signal. Figure 28 contains a representation of the test configuration.

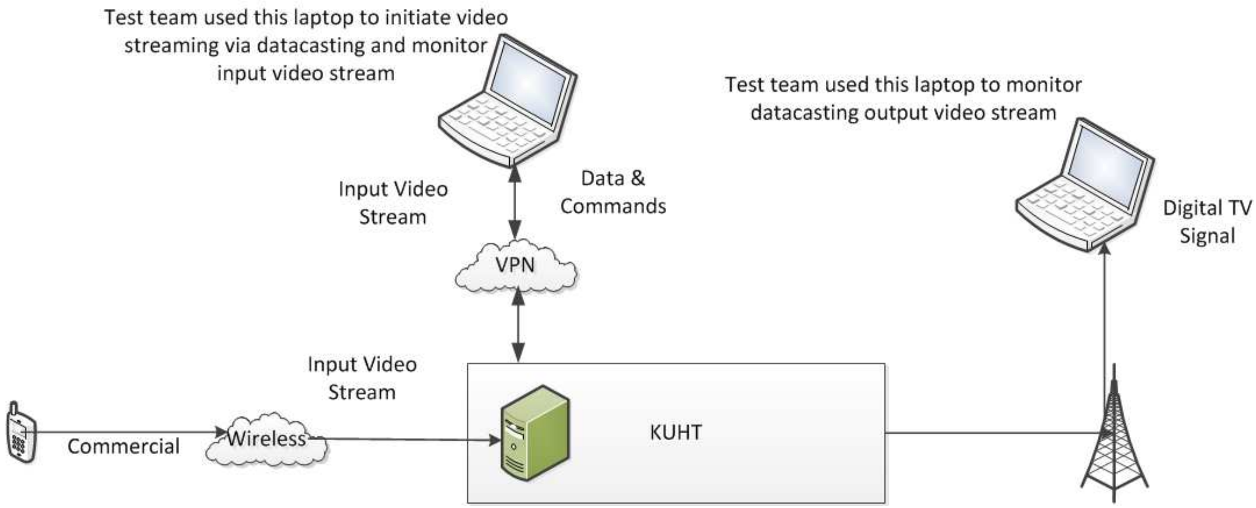


Figure 28: End-to-End Test Configuration via Commercial Wireless

The second test involved integration of the datacasting system with the Harris County LTE Band 14 Public Safety Network. An officer with the Harris County Sheriff's Office was located near the David Wayne Hooks Airport (see Figure 12), and streamed video using a commercial smartphone to the datacasting server at KUHT. From KUHT, the video stream was transmitted to a laptop at NRG Park and observed by the test team. Concurrently, members of the test team communicated and coordinated with the Sheriff's County officer. In response to a request by the test team, the officer made a series of motions into the camera so that the test team was able to perform rough estimates of the delivery time. Using a second laptop with IncidentOne software, the test team was able to compare the video quality of the received video data stream with the input stream. Figure 29 contains a representation of the end-to-end test configuration.

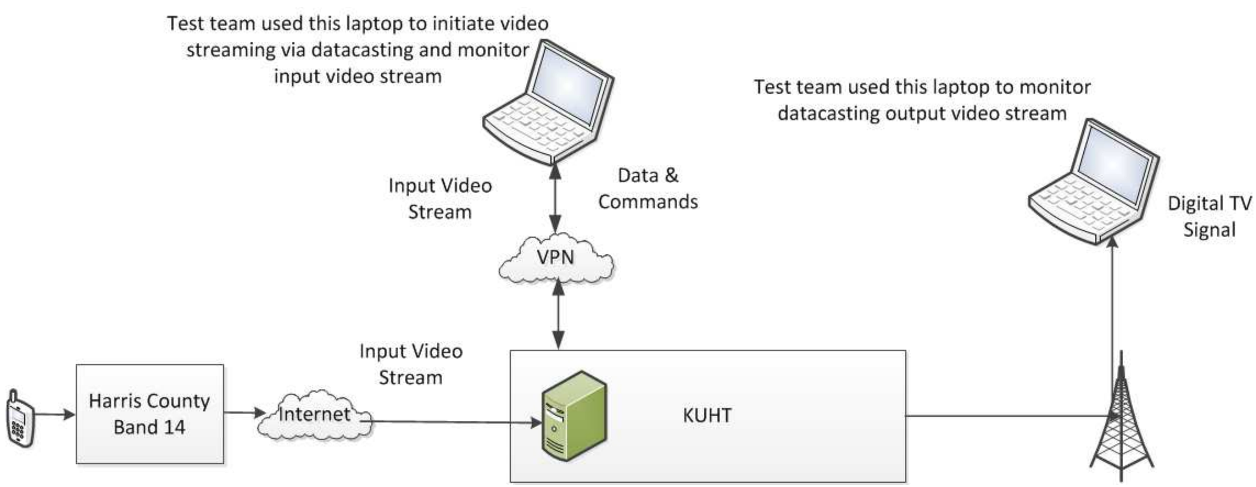


Figure 29: End-to-End Test Configuration via Harris County LTE Band 14 Network

The third test involved integration of the datacasting system with the PW deployable LTE System. Figure 30 represents the end-to-end test configuration.

Real-time video data was streamed from a Public Safety Band 14 UE to the datacasting server at KUHT via a PW deployable LTE enclave with a wireless connection to a local network. From KUHT, the video stream was transmitted to a laptop at NRG Park and observed by the test team. In order to measure the delivery time, the Band 14 UE was pointed at a digital clock (Figure 31). Observers could measure the delivery time in the transmission by comparing the clock time with the time observed in the video. Using a second laptop with IncidentOne software, the test team was able to compare the video quality of the received video data stream with the input stream.

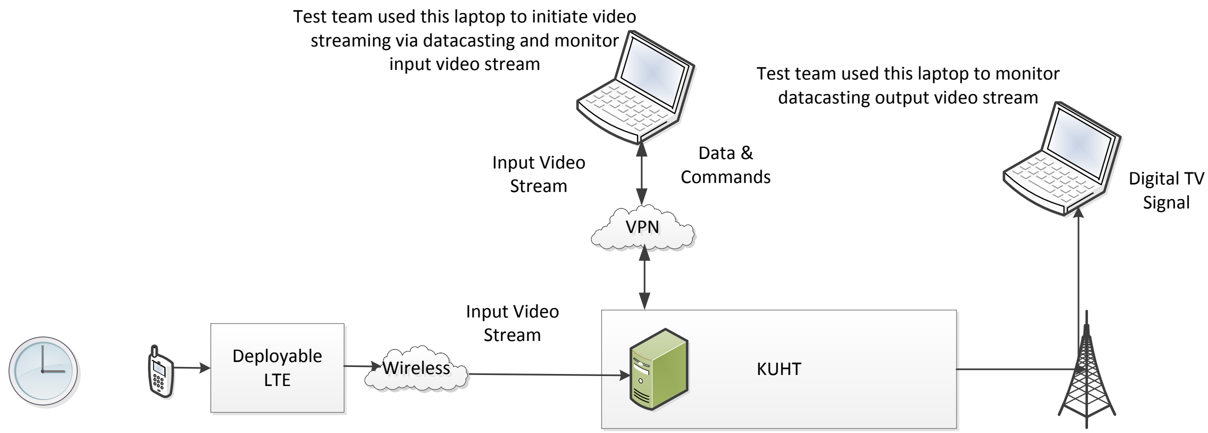


Figure 30: End-to-End Test Configuration Using PW Deployable LTE and Local Wireless

Figure 31: Video Streaming of a Digital Clock from a Cell Phone in Stopwatch Mode

The fourth test involved routing the video from the PW deployable LTE system through the Harris County LTE Band 14 Public Safety Network to KUHT as shown in Figure 32. As in the previous test, delivery time was measured by recording video of a digital clock.

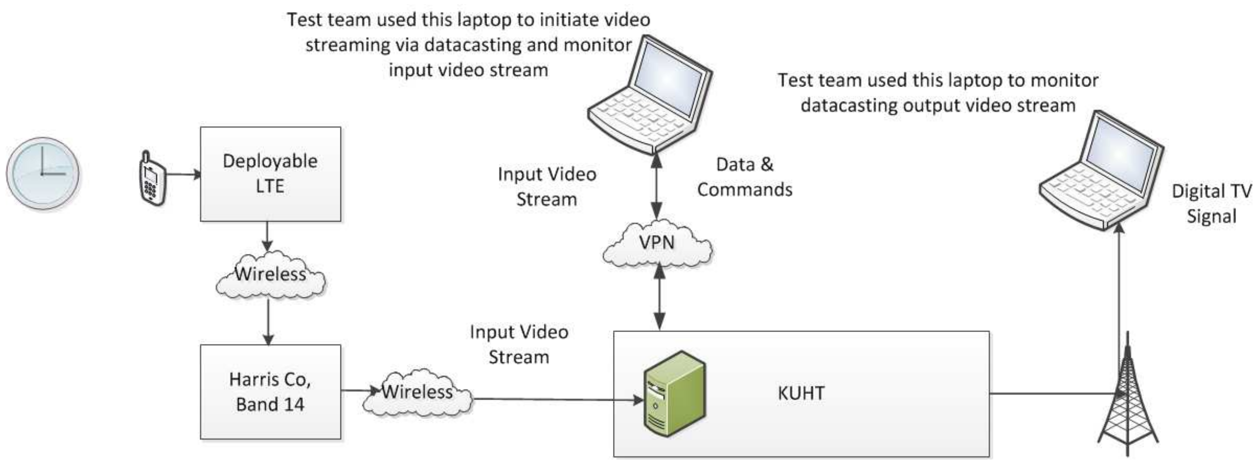


Figure 32: End-to-End Test Configuration Using PW Deployable LTE and Harris County Public Safety Band 14 Connectivity

Results of this end-to-end testing are documented in Section 4.4.

4 Houston Datacasting Pilot Demonstration with LTE: Results

4.1 Independent Enclave Testing Results

4.1.1 NGA PW LTE Enclave Testing Results

NGA testing confirmed the capability of a deployable, mobile LTE system to provide LTE service in an area without coverage, including the ability to integrate with partner and commercial systems. Datacasting was determined to be a viable means of one-way communication during a disaster or other emergency event. LTE could be used as a means of providing content from remote locations for subsequent transmission by datacasting. In addition, NGA identified several lessons learned and issues to be resolved for future operational integration of LTE backhaul with datacasting. For example, further investigation is needed to determine the sources of some of the problems encountered using the apps. For further information, the reader is referred to the NGA test conductor, Chris Allen.

4.1.2 DHS PW LTE Enclave Testing Results

As mentioned earlier, the purpose of the DHS LTE enclave testing was to determine the coverage characteristics of the PW deployable LTE network. The PW LTE system consists of a prototype CWS-200 eNodeB designed for in-vehicle applications. It operates on the

700-MHz public safety spectrum with a transmitter output of 1 W. The system delivered by PW included a server with embedded HNG and EPC (i.e., the embedded server described previously), and the following antennas (note: antennas were selected to support a proof-of-concept test and were not optimized based upon performance):

- Two (2) Omnidirectional LTE Antennas – Laird: TRA6927M3NB-TS1;
- One (1) GPS Antenna; and
- Four (4) Generic Wi-Fi Meshing Antennas.

Two types of antennas were tested at two locations. Section 4.1.2.1 describes the results of the coverage characterization using the packaged antenna at Location 1. Section 4.1.2.2 describes the results of the coverage characterization using the high-gain directional antenna at Location 2. For consistency, the *lte-reference-signal-power* (the power setting for the Reference Signal) was set at 2 dB below the 0-dBm reference level for both tests.

After the PW network was activated and the eNodeB began transmitting the reference signal, a Sonim XP7 device was used to measure and log the Reference Signal Receive Power (RSRP). Recall that the RSRP is an indicator of received signal strength used to measure the downlink coverage of an LTE cell. A pre-defined vehicle drive route was followed and adjusted as the RSRP level degraded. The data collected were then post-processed for coverage characterization, targeting an RSRP value of -110 dBm as the threshold of cell coverage [12].

4.1.2.1 Coverage Characterization with Packaged Antenna Results

The logs from the data collection were post-processed and entered into Google Maps to graphically represent the extent of the LTE coverage created by the PW deployable LTE network. The measured RSRP values were thematically mapped using five ranges (from better than -80 dBm to worse than -110 dBm) in increments of 10 dB. The location of the antenna was also entered into Google Maps and marked with a red circle. The distance between the antenna and the area where the RSRP degrades to less than -110 dBm was measured and noted as the coverage range. This is shown in Figure 33. This RSRP plot was based on measured values from two different days. There were day-to-day variations in the measured data, so the range was obtained by using the furthest location where the RSRP value crossed the -110 dBm threshold.

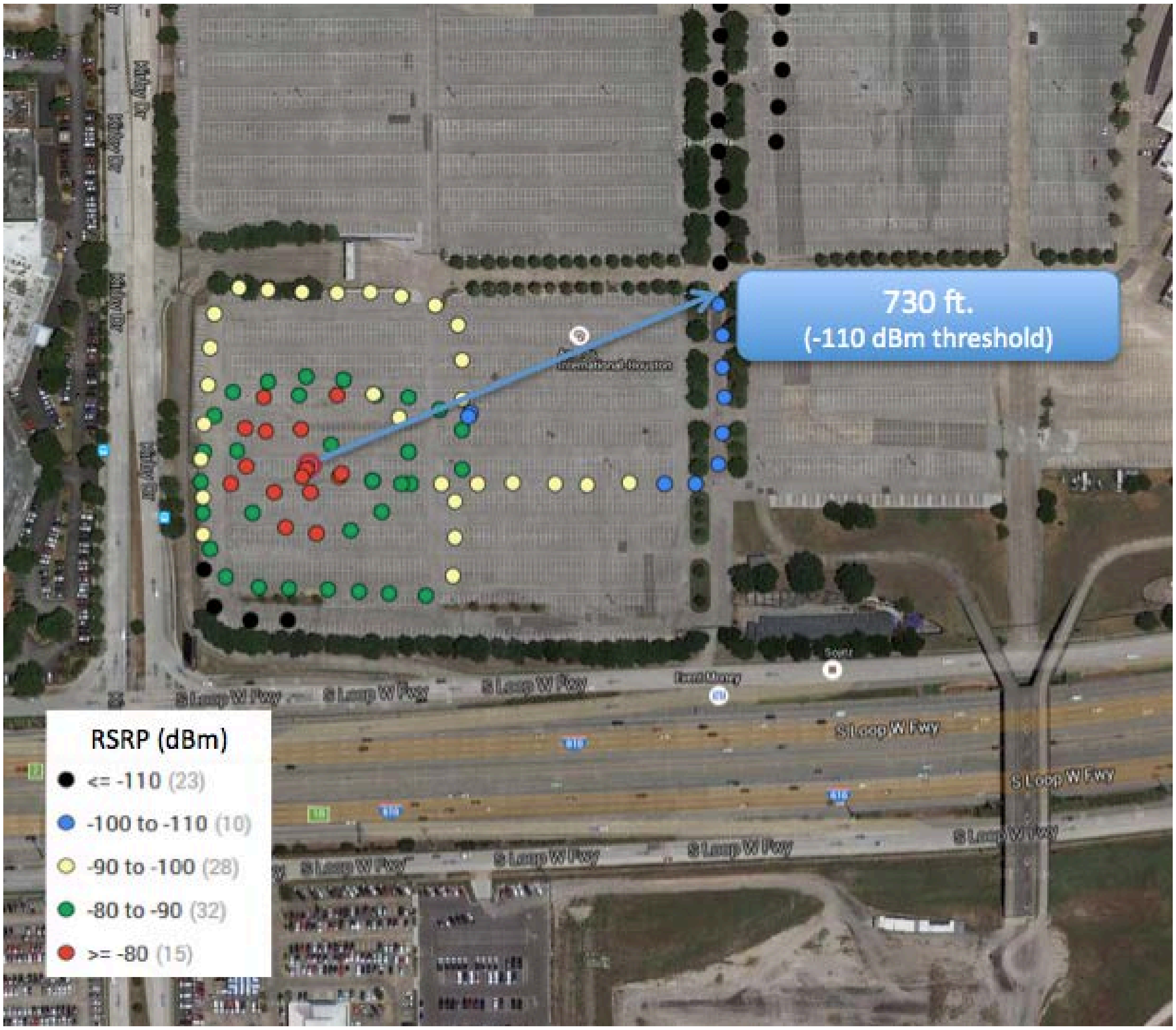


Figure 33: Measured RSRP with the Antenna RC at 6 ft, Overlaid on a Google Maps Image of the Parking Lot at NRG Park

<u>The results of the coverage characterization using the packaged antenna:</u>

- The signal level fades to less than -110 dBm at approximately 730 ft.
- The signal level fades to worse than -90 dBm at approximately 275 ft.
- The range of the deployable system using the packaged configuration did not extend beyond the parking lot.

4.1.2.2 Coverage Characterization with High-Gain Antenna Results

The logs from the data collected with the high-gain antenna were post-processed and reviewed in the same fashion as in the previous analysis. The range of RSRP values and the colors representing those values have been duplicated for consistency. As before, the location of the antenna was entered into Google Maps. Using this location, the distance to

the area where the RSRP degraded to less than -110 dBm was measured, and this value was noted as the coverage range. The results of the post-processed data analysis are shown in Figure 34.

This plot is overlaid on Google Maps of the parking lot at NRG Park.

Figure 34: Measured RSRP using the High-gain Directional Antenna with its RC at 85 ft.

<u>The results of the coverage characterization using the high-gain directional antenna:</u>

- The coverage range from the transmitting antenna is estimated to be 2,000 ft.
- The signal level fades to worse than -90 dBm at approximately 1,400 ft.

- As expected, the deployable system using a high-gain antenna with a higher elevation radiation center (RC) had a larger coverage radius compared to the packaged antenna at ground level.

- As expected for a directional antenna, the coverage to the back and sides of the antenna are significantly degraded, while the overall range increased.

- NRG Stadium is approximately 1,000 ft end-to-end. Therefore, this deployable LTE network using the high-gain, elevated configuration could cover the open areas of the stadium sufficiently.

Table 6 summarizes the coverage range of each of the above configurations. The *Range from Antenna* is the distance from the antenna to the location where the RSRP starts to degrade below -110 dBm.

Table 6: LTE Coverage Range for the Evaluated Configurations

LTE Transmitter Antenna					Coverage Characterization
Manufacturer	**Model**	**Gain (dBi)**	**Radiation Center (ft.)**	**Type**	**Range From Antenna (ft.)**
LAIRD	TRA6927M3NB-TS1	3.5	6	Omnidirectional	730
LAIRD	PAS69278P-FNF	9.1	85	Directional Panel	2000

<u>Key Observations from the Coverage Characterization Exercise:</u>

1) It is important to develop the appropriate power requirement to meet the coverage needs. PW systems are available with various configurations ranging from 1 W to 40 W. The PW system provided for this test had a maximum power of 1 W. Having more available power offers the flexibility to provide more expansive coverage (limited by the link budget). The power can always be scaled down to reduce downlink coverage, but cannot be increased beyond its designed output without external amplifiers.

2) It is important to select the appropriate antenna for the application. When used with the omnidirectional Laird antenna, coverage from the CWS-200 was found to be limited. The coverage range increased by almost three times (from 730 ft to 2,000 ft) when using the directional antenna elevated to 85 ft. The increase in coverage is due to both the antenna type (directional) and the increased height. A directional antenna may offer better performance over an omnidirectional antenna (and vice versa) depending on the use case.

3) The CWS-200 nodes received from PW were prototype units. As a result, these units may not provide consistent performance.

a) On some occasions, it took 45 minutes or more to activate the LTE network completely.

b) Coverage created by the PW deployable LTE network appeared to be inconsistent from day to day.

c) The PW equipment, as received by DHS, had other issues as a result of this equipment being a prototype and not an operational configuration.

4) An easier user interface is definitely needed. For this test, a Command Line Interface (CLI) was used for most of the commands to operate and configure the deployable PW LTE network. Thus, the current user interface requires knowledge that the First Responder Community may not have sufficient resources to dedicate when responding to a large-scale incident. In emergencies involving multiple jurisdictions and agencies, the current PW user interface would likely become a key issue.

4.1.3 Datacasting Enclave Testing Results

The test team was able to meet all of its objectives during the February 9, 2016 datacasting enclave test. Critical results and observations include the following:

1) The test team verified the ability to monitor the video streams input into the datacasting system using a remote laptop configured with the IncidentOne software. Although this capability is independent of datacasting itself (the required connection was achieved via VPN over Wi-Fi) and was largely implemented to facilitate testing, representatives of the City of Houston identified this as a separate use case for this capability. Consequently, SpectraRep implemented this capability for the City of Houston to enhance video sharing between multiple agencies during the February 25, 2016 Republican Presidential Primary Candidates' Debate (see Appendix D for details) and the National Collegiate Athletics Association Men's Basketball Championships on April 2-4, 2016.

2) The test team verified the ability to command transmission of datacasting messages and video streams from a remote laptop configured with IncidentOne software, and the ability to receive transmitted messages and video streams on a second collocated laptop also configured with IncidentOne software. Collocation of the two laptops was not relevant to the test results, but it facilitated analysis of system performance. Specifically, members of the test team could readily compare the quality of the input and output video streams.

3) The test team was able to assess the quality of video streams transmitted using datacasting vis-à-vis the quality of the input video streams. For the duration of the planned tests at the HPD station, the video quality remained consistently equivalent with no readily discernible differences between the input and output video streams.

4) The test team verified the ability to use Wi-Fi, a commercial cellular provider and the Harris County Band 14 LTE Public Safety Network as a backhaul to the datacasting system. All three hybrid architectures were used to stream data from handheld devices and laptops through the datacasting system back to the laptop located in a vehicle

moving through Houston. Each of these three paths could be used for the duration of the testing on February 9.

5) Using the test configuration indicated in Figure 11, the test team was able to make imprecise, but useful measures of the delivery time. Using a cell phone camera or the laptop webcam, the test team could measure the delivery time from when an event occurred in the vehicle until it was observed in the input video stream, and then again in the digital television signal. On average, delivery times of between 10 and 15 seconds were observed between the event and the actual observation of the event by the test team monitoring the laptop receiving datacasting transmissions. A more precise delivery time measurement was performed during subsequent end-to-end testing, and results of the two tests were consistent. In addition, the test team observed a consistent 1- to 2- second time difference between receipt of the datacasting input stream and the datacasting output stream. As both video streams were beginning at KUHT and being transmitted via different media (the input stream was being transmitted via VPN over Wi-Fi, the output stream in the digital television signal), it could be concluded that the delivery time via Wi-Fi was slightly less than that via datacasting in this scenario.

6) Datacasting reception was poor to nonexistent while the vehicle was in motion. The current standards do not support receipt of datacasting data in a moving vehicle, and it is not a requirement within the current system. However, in previous tests executed in Houston (July 2015) and Chicago (August 2015), the test team observed surprisingly good reception at speeds of up to 35 mph or more. That was not observed during this enclave testing. Mobile datacast reception is a core capability of the new broadcast standard expected to be finalized by the Advanced Television Systems Committee (ATSC) later this year and broadly deployed in 2–3 years.

7) The majority of the time, video quality at the receiving laptop was consistent with the quality of the data at the laptop monitoring the input to the datacasting system. This was not, however, achieved in all cases. Although received video quality closely tracked transmitted video quality, there were significant periods in which the received video “froze” (i.e., reception was lost and the last image received continued to be displayed). Conspicuously, there appeared to be times in which video from only one source froze, suggesting that this was more than just a case of lost reception. Because this was an unplanned test event, the test team was not equipped to evaluate in real time whether the loss of video was a result of poor reception (which would not be unexpected, because much of the test was being executed in an “urban canyon” environment amidst numerous tall buildings). In the weeks prior to the test, SpectraRep implemented additional software to enable the system to enforce priority transmission in cases where data demands begin to significantly exceed the capacity, and there were indications that the loss of signal might be a product of this new software. This issue will require additional investigation and testing.

8) The third ad hoc test (where three laptops were connected to datacasting via a wireless router) failed. Although it was possible to connect two separate laptops to a wireless network centered in the vehicle, the bit rate was not sufficiently high to support video transmission. Because the datacast information is extracted within the receiving laptop, the wireless router was required to transmit the entire digital television signal (19.3 Mbps) to each receiving laptop. The router used in the Houston tests was not able

to provide sufficient bandwidth to support multiple channels of that size in an urban area. Because of the presence of other Wi-Fi signals, finding available channels of sufficient size (i.e., finding multiple bands of sufficient contiguous unused bandwidth) to support a data transfer of that size would likely require a large amount of bandwidth. We believe a significant contributor to the failure of this test was inadequate Wi-Fi signal strength and bandwidth generated by the USB dongle Wi-Fi adapter that was used. It is recommended that this test be repeated with an external router in a controlled laboratory environment and in a remote or rural environment, where less bandwidth would likely be required to support multiple Wi-Fi channels.

a) The test was repeated with two laptops connected to the router via Ethernet with much better results validating that the issue was the unlicensed Wi-Fi and not the direct datacast reception over the KUHT licensed spectrum. The new ATSC 3.0 broadcast standard, expected in 2-3 years, will address this issue with support for targeted reception on smartphones and tablets directly from the television broadcast. Until that standard is implemented, the ability to reach untethered devices today remains a goal.

4.2 Interconnected LTE Enclave Testing Results

4.2.1 LTE Enclave Mesh Network Testing Results

The goals of the mesh network tests were to determine the meshing distance and validate basic functionality in the LTE coverage area created by two meshed CWS nodes.

The packaged CWS-200 (as received from PW) was a prototype unit that came pre-configured to establish a mesh network when one of the nodes came within the meshing range of the other. During the entire test, the NGA CWS was connected to the embedded server and acted as the host CWS. The DHS CWS was not connected to an embedded server and acted as the remote CWS.

4.2.1.1 Meshing Distance Results with Ground Level Antennas

A solid blue status light indicates when a remote CWS is successfully connected by a mesh network to the HNG/EPC via the host CWS. A blinking blue status light indicates that the remote CWS is not connected to a mesh network, and thus not connected to the HNG/EPC via the host CWS. Therefore, the status light can be used as an indicator for successful mesh network establishment.

The first step in determining the meshing distance between the two CWS nodes was to allow the mesh network to be established. Once this was established, the vehicle with the remote CWS was slowly driven away from the host CWS to force the mesh network to disconnect. The spot where the mesh network disconnected was noted as the meshing distance.

Using this information, Google Maps was used to mark the location of the spot where the remote CWS lost mesh connectivity. The location of the host CWS was also entered into Google Maps. Figure 35 shows the location of the host CWS with a *red circle* and the mesh disconnection spot with a *green/yellow car*. The distance between the two locations was

measured and depicted on the map. The view from the remote CWS (black minivan) to the host CWS (silver minivan) is also embedded on the map to assist in visualizing the distance between the two CWS nodes.

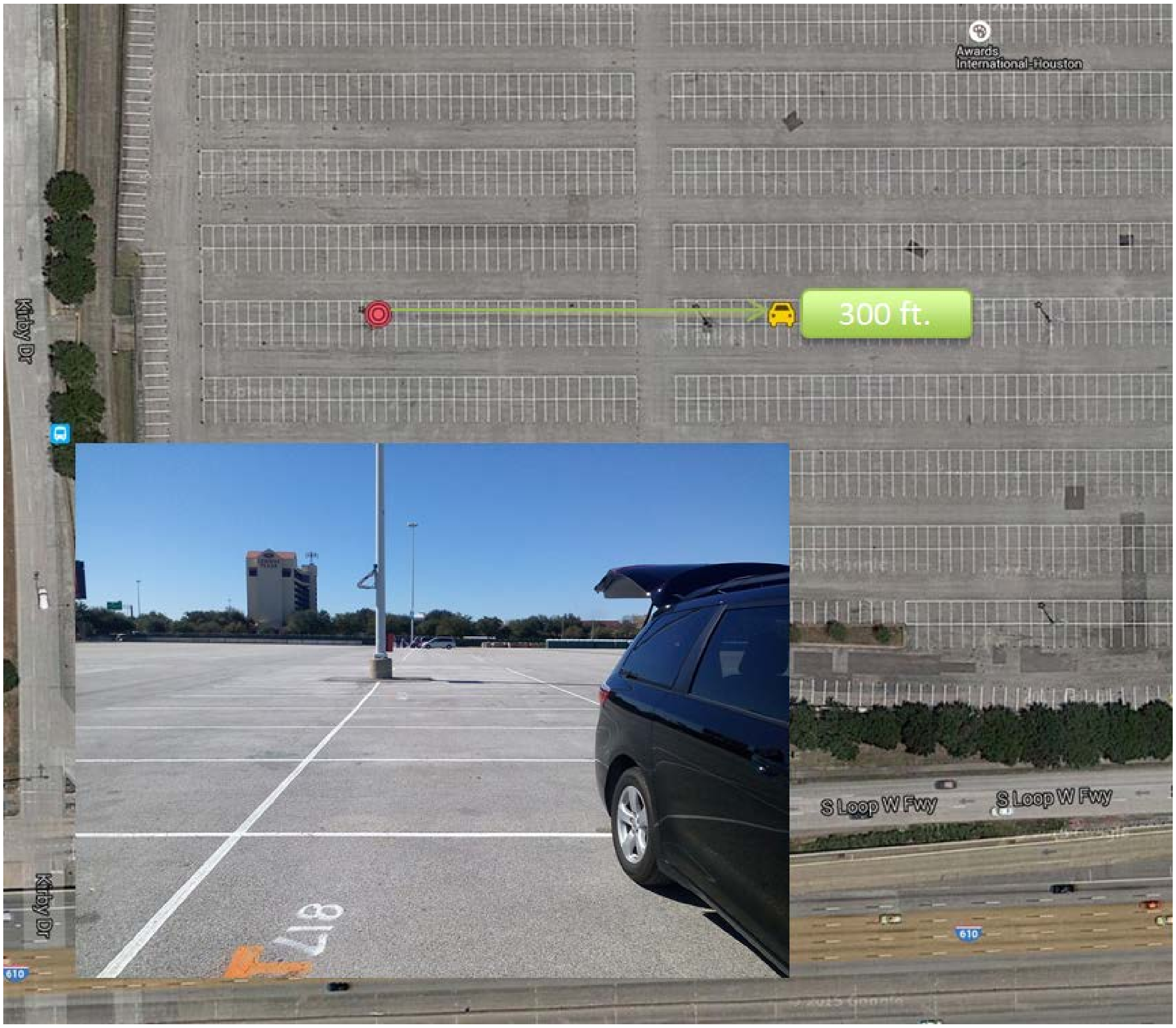


Figure 35: Meshing Distance Measured Using the Wi-Fi Antennas Mounted to the Vehicle Rooftop

The results of the mesh distance using roof top Wi-Fi antennas:

- The meshing distance was estimated to be 300 ft.
- The mesh range appeared to be shorter than expected.

At the end of the day, a connector on Mesh Backhaul Radio P0 located on the remote CWS was found to be loose, so it was then tightened. However, on the following day, the same connector became extremely loose while a jumper was being attached. In an attempt to repair the loose connector, the CWS box was opened. Upon opening the cover panel, the inside jumper with the loose SMA connector was found to be detached from one of the branches of the mesh radio. This could have had an impact on the meshing distance measured on the day before. Unfortunately, due to time and scheduling constraints, the previous test could not be repeated to determine if the meshing distance measurement was negatively impacted. Because of this loose/detached connector, the meshing distance measurement of 300 ft should be considered with caution.

4.2.1.2 Meshing Distance Results with Elevated High-Gain Antenna

This test involved relocating the host CWS to Location 2 and using a high-gain directional Wi-Fi antenna. The process for establishing the mesh network and detecting a disconnected mesh network remained the same as the previous test.

As in the previous test, once the remote CWS established a mesh network with the host CWS, the vehicle with the remote CWS was driven around the parking area in an attempt to force the mesh network to disconnect. The parking area was driven extensively, but even at the far end of the parking area (2350 ft away from the antenna), the mesh network remained connected (see Figure 36).

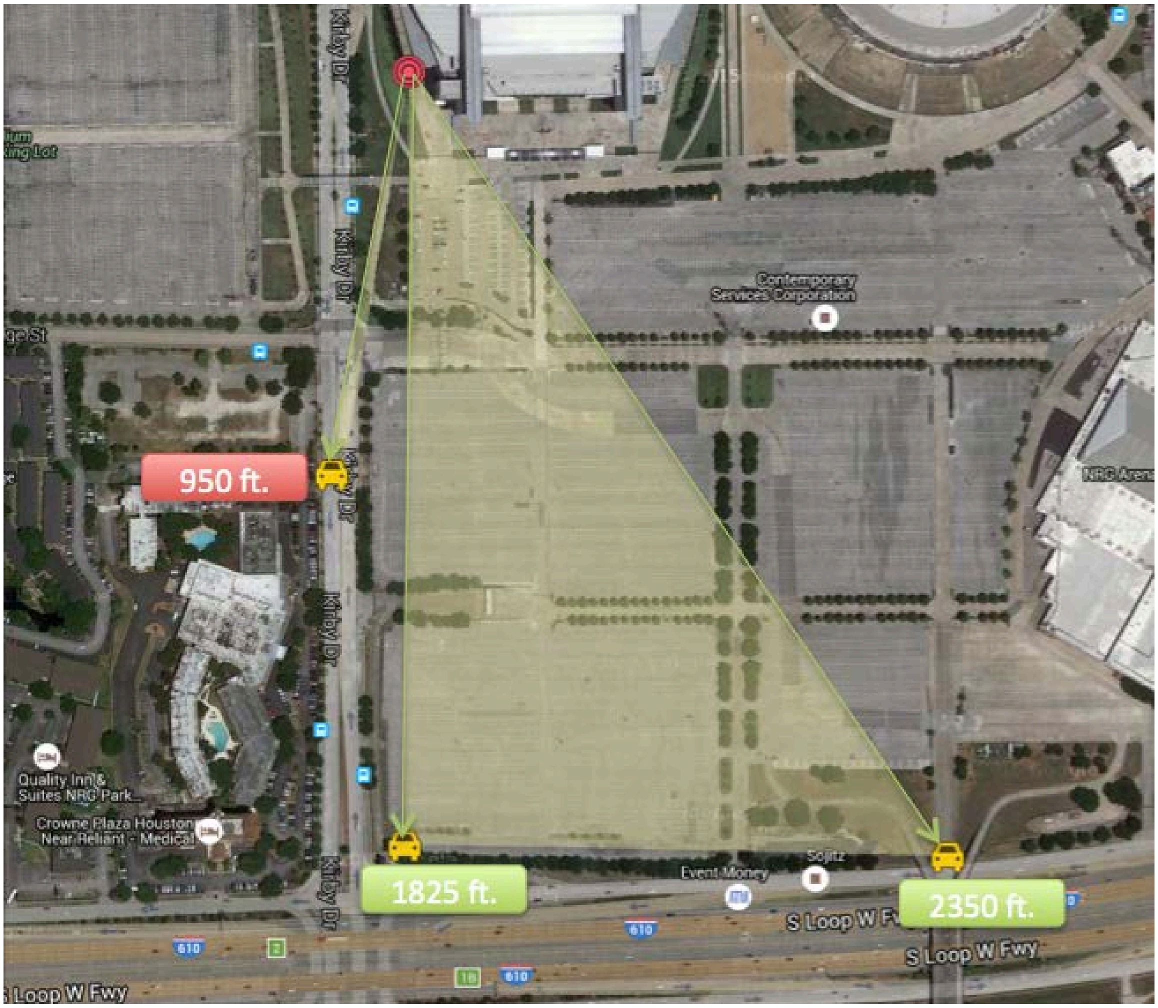


Figure 36: Meshing Distance Measurement using the High-gain Directional Antenna at Location 2

Because the parking area is bounded by Interstate 610 to the south, a longer straight-line distance determination could not be measured from the parking lot. When the vehicle with the remote CWS was driven further east of the highlighted area, the mesh network started to degrade due to the shadowing effect from the NRG Stadium. Such shadowing effects are fluctuations in received signal power due to obstructions in the propagation path. Therefore, going in this direction would not yield a longer meshing distance.

The vehicle with the remote CWS was then driven out of the parking lot and onto Kirby Road to determine the maximum meshing distance using another route. As the vehicle left the parking lot heading south, the mesh network connection was lost relatively quickly. This location was noted and then plotted on Google Maps to determine the distance. The results are shown in Figure 36 above by a *red rectangle* with 950 ft marked as the disconnection distance.

The results of the mesh distance using high-gain Wi-Fi antenna at 85 ft elevation:

- The far corner of the parking area was the longest distance measured, but the connection could not be disconnected. Therefore, the measurement of 2,350 ft should not be considered the *maximum* meshing distance.

Table 7 summarizes the meshing distance measurements with the two types of Wi-Fi antenna configurations. The ground level result of 300 ft shown in Table 7 should be considered with caution due to the possibility of a detached inside jumper cable during measurement, as mentioned earlier. Additionally, the meshing distance of 2,350 ft measured from the 85 ft antenna elevation was constrained by the area of the test range. The actual range is expected to be greater.

Table 7: Meshing Distance Measurements Using Different Antenna Configurations

Wi-Fi Transmit Antenna				Wi-Fi Receive Antenna				Minimum Mesh Distance (ft.)
Manufacturer	Model	Gain (dBi)	Radiation Center (ft.)	Manufacturer	Model	Gain (dBi)	Radiation Center (ft.)	
Panorama	LGMM-7-27-24-58	2	6	Panorama	LGMM-7-27-24-58	2	6	300
L-COM	HG4958-17DP-090	17	85	Panorama	LGMM-7-27-24-58	2	6	2350

4.2.1.3 Basic Verification of Disconnected LTE Network Created by a Mesh Network

The PW system can be used to support voice, video streaming or other applications within the disconnected network by using localized application servers or by accessing remote application servers when it is connected to an external Internet Protocol (IP) network.

4.2.1.3.1 Reselection Validation in a Disconnected Network Results

The host and remote CWS were located in an area where a mesh network could be maintained. Figure 37 shows the location of the host CWS (marked in red) and remote CWS (marked in blue). Figure 37 also shows the results of the reselection test and illustrates the reselection (transition) area between the two serving cells: host CWS and remote CWS.

The circle and diamond shapes represent the serving cell logged on the UE while walking between the two CWS nodes. As can be seen in the legend, the grey color indicates the serving area of the host CWS. The black color indicates the serving area of the remote CWS. The circle represents the direction of travel from the host CWS to the remote CWS, and the diamond shape represents the reverse direction.

Figure 37: CWS Locations and Mesh Connectivity Reselection Results

The reselection area shown in Figure 37 represents the transition between the coverage areas of host CWS and remote CWS. This is the area where reselection or hand-off can occur.

The expected results for this test are that the UE initially camps on the coverage area of the host CWS and then transitions to the coverage area of the remote CWS as the UE leaves the reselection area. This should be true for the reverse direction. The reselection areas should also be in an area between the two CWS nodes. Figure 37 shows that all three scenarios occurred successfully.

The RSRP and the Cell ID were also logged in close proximity to the serving cell while walking between the coverage areas of each CWS. The expected result should be that the UE camps on the correct serving cell and measures a strong RSRP reading. Table 8 shows the results of this test and demonstrates that the expected outcomes are validated.

Table 8: Mesh Re-selection Validation Results

Reselection Test	Starting Cell		Ending Cell		Successfully Reselected?	Status
	Cell ID	RSRP	Cell ID	RSRP		
Proceed from host CWS to remote CWS	0	-65	1	-65	Yes	Pass
Proceed from host CWS to remote CWS	1	-69	0	-59	Yes	Pass

The results of the reselection testing:

- As expected, the transition area is approximately at a midpoint between the two serving cells.
- As expected, the point at which the UE changes serving cell is extended closer into the coverage area of the neighboring cell (in both directions).
- The results of the Cell ID and RSRP measurement confirm that the UE reselected to the appropriate serving cell.
- The Cell ID was automatically provisioned to 0 for the host CWS and 1 for the remote CWS, thus demonstrating Self-Configuration.

4.2.1.3.2 Application Functionality Validation in a Disconnected Network Results

The original intent was to use the MAGE on the Sonim XP7, but as mentioned earlier, the Android app did not work. However, the local application server for MAGE leveraged by the PC client was used to demonstrate application functionality within and across the LTE network created by the mesh network.

The expected outcome would demonstrate that data could be shared between the application server and LTE endpoints, as well as across the mesh network. Table 9 shows the results of the application functionality testing using the PC version of MAGE. All scenarios passed.

Table 9: Application Functionality Validation Results

Basic Functional Test	Successfully Sent Text Message and File?	Successfully Received Text Message and File?	Status
Both devices in the host CWS coverage area	Yes	Yes	Pass
One device in the host CWS coverage area, the other device in the remote CWS coverage area	Yes	Yes	Pass

The results of the application functionality testing:

- The deployable LTE network with a hosted application can serve to create localized communication in a disconnected network.
- PW CWS can automatically establish a mesh network and enable data to be shared between different CWS nodes using Wi-Fi as the backhaul.

Key Observations from the Mesh Network Exercise:

1) Just like the LTE antenna, it is important to select the appropriate antenna for the application. As shown by this exercise, antennas designed for a specific use will have different performance characteristics.

2) The mesh network was consistently established when the remote CWS was activated in close proximity to the host CWS. The capability to automatically establish a mesh network between two (or more) CWS nodes to expand the access network is one of the main features of the PW deployable system. The testing demonstrated that this functionality works as expected.

3) The time to establish a mesh network between two CWS nodes was not instantaneous. Instead, it took up to 2 or more minutes. This may be due to the time it takes to set up a secure tunnel between the two CWS nodes. This is an adjustable parameter, but it was not optimized during this exercise.

4) The two meshed CWS nodes provided separate serving areas as expected. The physical cell identification (PCI) of the UE was automatically provisioned demonstrating basic self-configuration.

5) It would be preferable to have an option for an in-band mesh solution. The backhaul for the mesh network operates at 5 GHz, while the access network operates at 700 MHz. These two frequencies have different transmission capabilities and propagation characteristics. As a result, the difference in range can be significant. While using an in-band backhaul solution may help to equalize the propagation characteristics between the access and backhaul networks, there may be a tradeoff by leaving less spectral resources for user communications.

6) For a mobile solution, the radio frequency connections need to be more robust. SMA jumpers on the prototype broke and disconnected on several occasions causing delays and inconclusive results. The commercial version is expected to have ruggedized SMA connections for in-vehicle applications.

7) The ability to provide localized communication to multiple end users in a disconnected network was successfully demonstrated. The MAGE application, which was hosted locally, sent and received data successfully through the LTE access network created by two meshed CWS nodes.

4.2.2 Datacasting Load Testing Results

4.2.2.1 Results of Load Test 1

Results of the first set of load tests are contained in Table 10. Those same results are presented in graphical form in Figure 38.

Table 10: Results of Load Test 1: One Transmitting Site, One Receiving Site

File Size	Delivery Time (Crawl)	Delivery Time (Files)	Receipt Confirmed	Comments
0.5 M	15 s	16 s	Y	
2.5 M	14 s	27 s	Y	
4.5 M	16 s	68 s		
7.8 M	14 s	95 s	Y	
8.8 M	18 s	111 s	Y	Test consisted of sending three files of 2MB, 3.1 MB and 3.7 MB.
12.3 M	15 s	152 s	Y	
14.9 M	19 s	187 s	Y	
20 M	25 s	233 s	Y	
25 M	22 s	337 s	Y	Test consisted of sending two files of 12.3MB and 13.0 MB

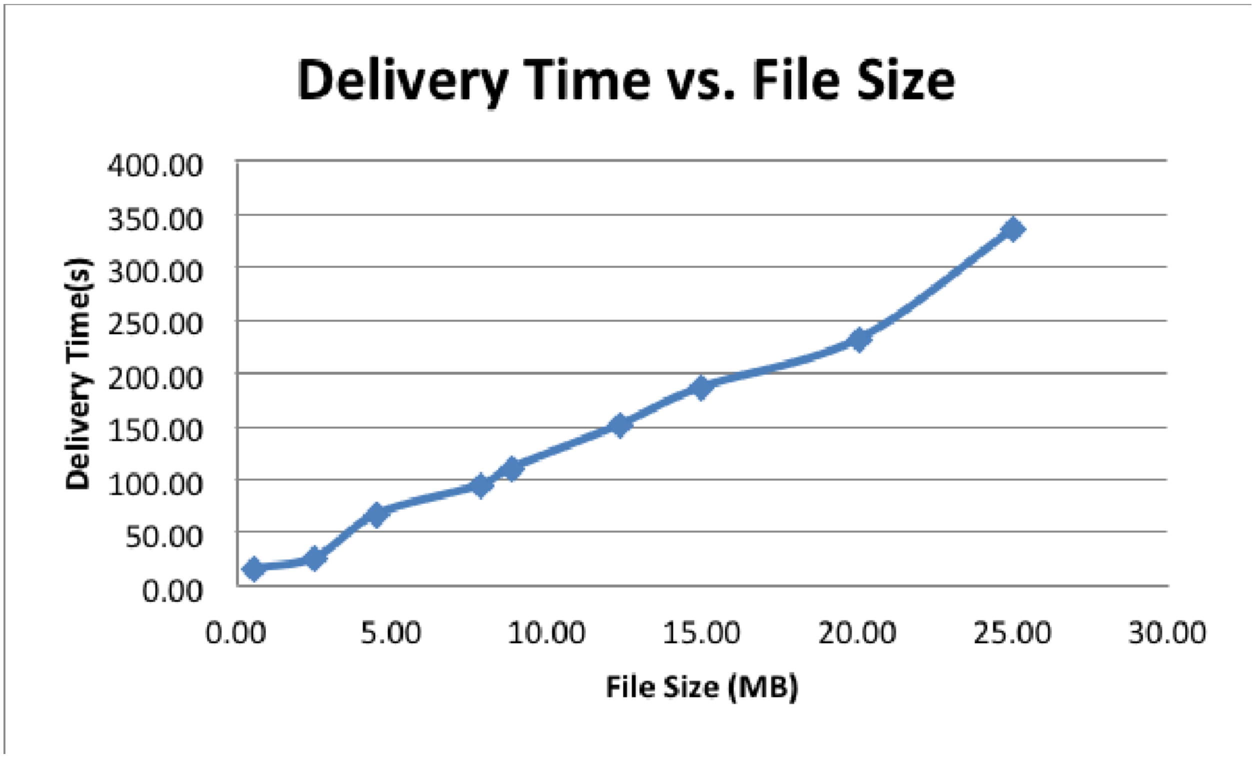


Figure 38: Observed File Delivery Time vs Size

Key observations from the first set of load tests included the following:

1) All content transmitted was successfully received, opened and read at the receiving computer.

2) Crawl messages were displayed at the receiving laptop within 14 to 25 seconds after transmission initiation. As expected, the delivery time increased as the size of the attachment increased. The datacasting processor is multi-tasking between processing required to transmit the crawl message and pre-processing (compression, application of error correction) of the attachment file.

3) Transmission delivery times increased relatively linearly as a function of content size. This suggests that the datacasting system has the ability to continue to operate reliably even when used to transmit files many times its capacity. Data delivery times would be expected to decrease if capacity allocated to datacasting were to be increased (or to increase if the committed throughput were to be decreased).

4) In those cases in which multiple files were transmitted simultaneously, file delivery occurred concurrently (as opposed to serially). Test team members could observe both files being received in parallel.

5) Transmission of a 25 MB file required approximately 5 ½ minutes using datacasting (with an allocated throughput of 1.2 Mbps). As this seemed a reasonable maximum wait time for information for an Emergency Management System, there was no attempt to evaluate the delivery time using larger files.

4.2.2.2 Results of Load Test 2

Results of the first set of load tests are contained in Table 11.

Table 11: Results from Load Test 2

File 1 Size	File 2 Size	Delivery Time (Crawl)	Delivery Time (File 1)	Delivery Time (File 2)	Comments
2.0 MB	2.0 MB	16 s	53 s	53 s	File 2 crawl received ahead of File 1
5.0 MB	5.0 MB	17 s	112 s	100 s	File 2 crawl received ahead of File 1
10.0 MB	10.0 MB	22 s	206 s	120 s	File 2 crawl received ahead of File 1
14.2 MB	10.0 MB	20 s 140 s	235 s	194 s	Second message sent one second after the first

<u>Key observations from the second set of load tests include the following:</u>

1) All content transmitted was successfully received, opened and read.

2) When both transmissions were initiated simultaneously, only the first crawl to arrive would be displayed, but the second crawl message was lost. This is a relatively minor implementation issue and does not reflect the inherent utility of datacasting.

3) The test team could observe files transmitted from both laptops loading concurrently. In all cases, the smaller file would finish loading first.

4) The 10 MB files transmitted from Laptop 2 were PDF files that, when compressed, had an approximate size of 6 MB. All the files transmitted from Laptop 1 were PowerPoint files containing JPEG images. Because JPEG images were already compressed, the compression applied by the datacasting system resulted in smaller changes in the file size. This explains some of the differences in delivery time in tests 3 and 4.

5) When the transmission times were staggered, both crawl lines appeared.

6) In the last test, the smaller file from Laptop 2 completed loading prior to the larger file from Laptop 1, despite transmission beginning almost a minute earlier. This case further illustrates how data transmissions are interleaved (rather than queued) during transmission.

4.2.2.3 Results of Load Test 3

Observations for the video load test included the following:

1) The test team was able to transmit four separate video streams from the transmitting laptop to the receiving laptop via the datacasting system. For an allocated bandwidth of 1.2 Mbps, four is deemed a reasonable maximum number of video streams for the system. Test team members verified that the system was consistently allocating approximately 300 kbps to each video stream. Note: the datacasting software samples the throughput allocated to each stream periodically, but it does not compute continuous averages. By monitoring the sampled throughput, test team members could characterize how well the system was allocating throughput.

2) Video observed with four concurrent video streams appeared in bursts (i.e., receipt of data was not consistent as evidenced by frames appearing to freeze from time to time). This is to be expected with only 300-kbps throughput per stream. For purposes of this test, 300 kbps was chosen as a reasonable minimum data rate. The test team did not feel comfortable making assessments regarding the usefulness of data with a lower throughput, although actual end users might do so.

3) The test team also initiated transmission of a 2 MB file concurrent with transmission of four video streams. In this particular test, the datacasting system allocated 500 kbps for file transfers and 700 kbps for video streaming. The crawl message was received within 21 s and the file transfer required 60 s. The test team did not assess the video quality in this test. There was no expectation that four video streams could be adequately supported with 700 Mbps.

4) Finally, the test team verified that allocation of throughput to video streams was based upon the priority assigned to each video stream. It was verified that priority was strictly a relative assignment (stream A was either of lower, equal or greater priority). There was no attempt to quantify the priority relationships (i.e., there was no attempt to determine whether video A had two or three times the priority of video B).

4.2.2.4 General Results of Load Testing

Based upon the trials executed, the test team concluded that the SpectraRep system design is very robust. Specifically:

1) The SpectraRep software is capable of automatically re-allocating bandwidth between video streaming and file sharing without performance degradation. If a file transfer were to be initiated while four equal-priority videos were being streamed, there would be degradation of all four video streams. Without having end-user specified requirements, this is considered an acceptable result.

2) The SpectraRep software is capable of automatically re-allocating capacity between video streams of equal or differing priority. It also provides a comprehensive and user-friendly set of tools to enable users to monitor throughput allocation and modify the priority of individual video streams. Figure 39 contains a snapshot of the allocation monitoring tools displayed on a laptop. The three dials in the lower left

display the total capacity (1128 kbps) and how that capacity is allocated between video (1077.2 kbps) and files (50.9 kbps). In this particular instance, the entire bandwidth has been allocated for video streaming, except for a small amount reserved for system housekeeping files. The two dials in the center screen display the throughput and frame rate for a selected individual video. In this photograph, approximately half the selected video stream is being allocated to the selected track. In this particular case, there are actually video streams being broadcast. However, the priority of the other videos was reduced, with the result that this video had the highest priority and received the highest allocation of bandwidth. Additional ad hoc tests were executed during the testing with similar results.

Figure 39: Datacasting Throughput Allocation Monitoring

3) There are limits to what can be achieved with 1 to 2 Mbps of bandwidth. If the system begins to enjoy wider use, saturation of the system will eventually become an issue. The test team established that the system would continue to operate even when presented with loads many times the system capacity; however, it may be advisable to apply limits on the size of files to be transmitted.

During load tests, there was no attempt to assess whether the responses of the SpectraRep datacasting system were "optimal." The objective of these tests was to evaluate the potential of datacasting technology in support of public safety, not to evaluate the SpectraRep implementation of that technology. SpectraRep was able to develop a datacasting system capable of transmitting content equivalent to over 200 s of its capacity without performance degradation. This was considered a sufficient quantity of data to test at this time. The SpectraRep system is not an "off-the-shelf" system. Public safety

customers hoping to make use of a datacasting system will need to integrate the system with their existing public safety communications infrastructure. Specifically, they will need to make integration decisions regarding the amount of capacity allocated to public safety, how many users will be provided access and how the system should respond to multiple demands for access. The test team obviously cannot anticipate how future users will want to use the system, or how much they are willing to commit to achieve desired levels of capacity, and limits will likely need to be enforced. However, this test provides evidence that a useful capability is achievable.

4.3 Results of Testing Integration to External Networks

4.3.1 PW LTE Node Connectivity to External Network via Remote HNG

As mentioned earlier, PW personnel configured a CWS node to connect to a remote HNG and the Harris County Public Safety Broadband Network core (see Figure 26). An LTE modem built into the CWS node served as the backhaul to connect the CWS node to the remote HNG, thereby extending the operational coverage of the Harris County Public Safety Broadband Network.

By attaching the UE to the extended Harris County Public Safety Broadband Network and then accessing the streaming video app (described in Section 3.3.1), the test team verified that an external network was successfully connected through the Harris County LTE core. There was no observable degradation, so more detailed measurements were deemed to be unnecessary for this configuration.

4.3.2 PW LTE Node Connectivity to External Network via Commercial Wireless

A connection to an external PDN is needed to stream video from the deployable LTE network to the datacasting network. The goal of this test is to integrate the deployable LTE network with an external IP data network and then validate that the connection would be suitable for live streaming video.

The PDN Gateway (P-GW) on the embedded server requires a physical Ethernet connection. There were several options available, but the most convenient option during the exercise was to use a commercial LTE hotspot with a wireless bridge to provide the connection needed to tie the LTE network to an external IP data network. Figure 40 shows the details of this architecture.

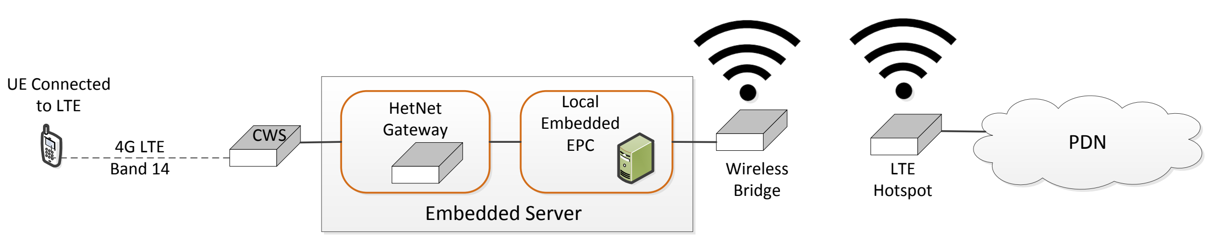


Figure 40: External Connection Detail

An AirCard 754S Elevate Hotspot was used as the wireless access point to provide an external data network connection in this architecture. This device is 4G LTE compatible and supports Wi-Fi 802.11 b/g/n (which can handle bandwidths up to 11 Mbps/54 Mbps/300 Mbps, respectively). A Netgear Trek N300 Wi-Fi extender served as the wireless bridge between the access point and the embedded server. The extender provides two 10/100 Mbps Ethernet ports with auto-sensing technology, and also supports Wi-Fi 802.11 b/g/n.

Integrating the deployable LTE network to an external network to stream video from the field was the goal of this phase of the exercise. Any lack of available uplink bandwidth would likely impact video quality ingested by the datacasting network. In order to support live video streaming and rule out lack of bandwidth as a potential cause of video quality degradation, the data speed and delivery time were measured at several interfaces as shown in Figure 41.

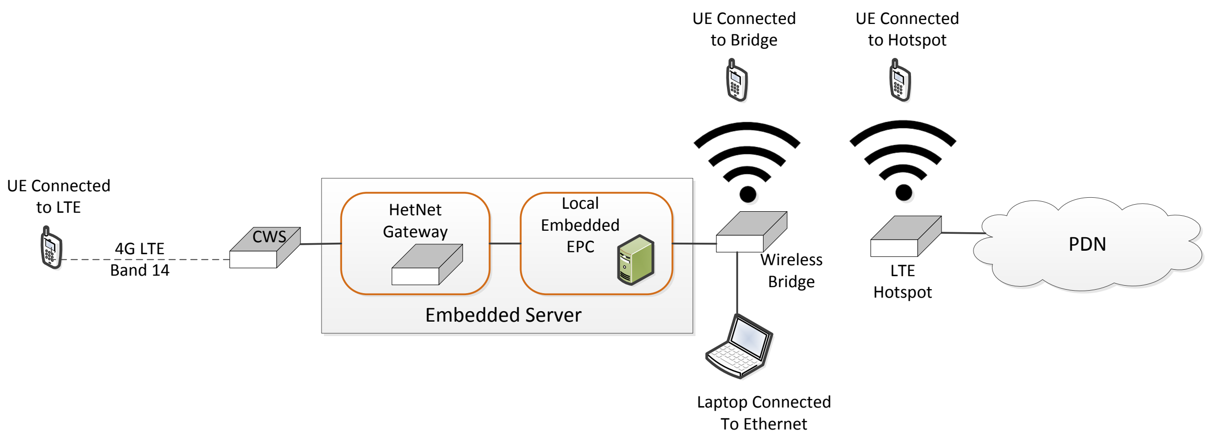
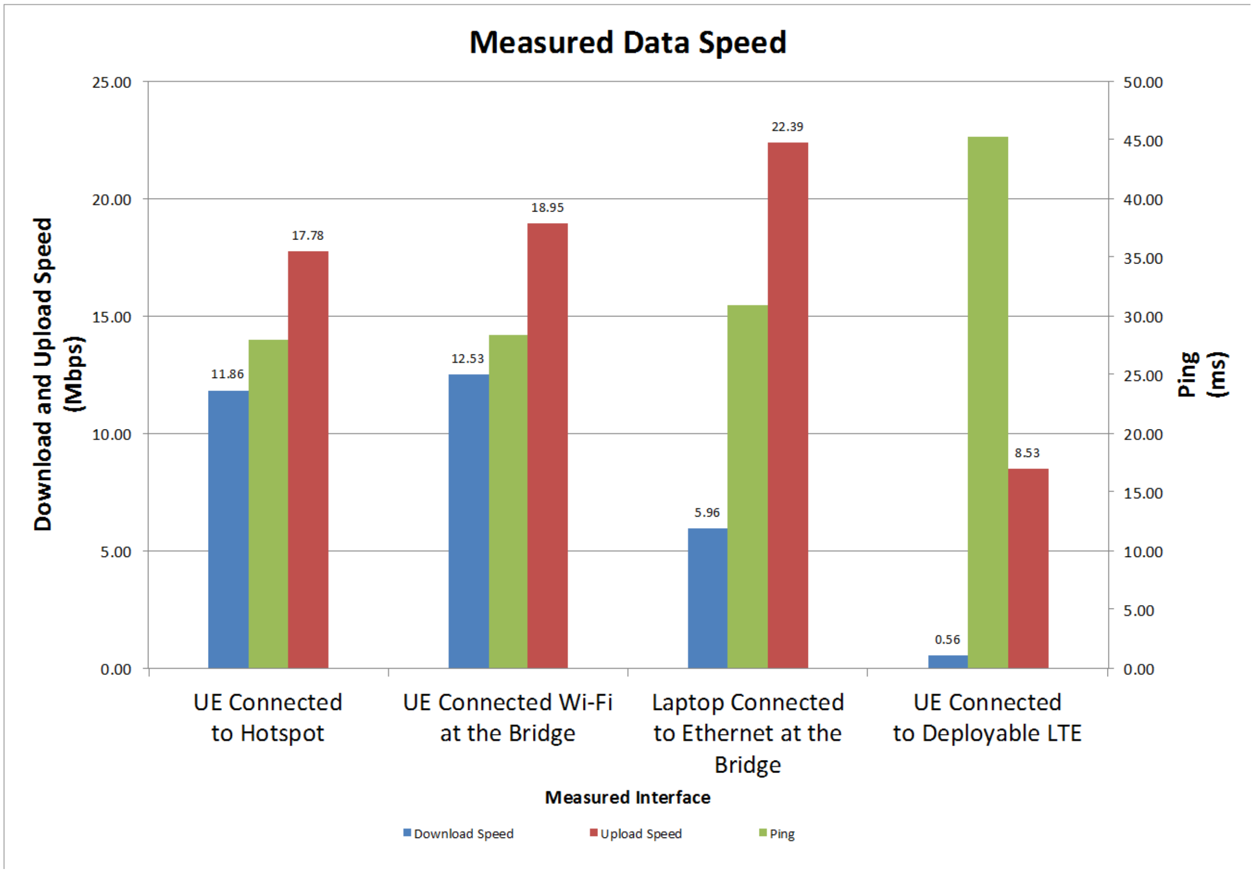


Figure 41: Bandwidth Measurement Points

Data transfer rate may not be the only factor impacting delivered video quality, but it is a good starting point to determine potential video quality impacts due to limited bandwidth. Additionally, the ability to measure the available bandwidth with an Android application would validate that the integration to an external packet data network had been successfully completed.

In order to obtain the data transfer rate and ping duration to verify connectivity, the SpeedTest.net application was downloaded from the Google Play store and installed on a Sonim XP7 provisioned to work on the deployable LTE network. The SpeedTest.net web site was used to obtain the results from the laptop attached to the Ethernet port on the wireless bridge. SpeedTest is only used for basic relative comparison between measurement points. Figure 42 shows the results of the speed and ping time measured at the different interfaces shown above: at the hotspot, at the bridge on Wi-Fi and Ethernet, and at the end user equipment (UE).



The SpeedTest server for the laptop was located in San Antonio, Texas. All other servers were located in Houston.

Figure 42: Measured Bandwidths at Different Interfaces

The results of the data speed test showed that the PW network could provide sufficient bandwidth to stream live video from the LTE UE to the datacasting network. The Android application supporting the datacasting server would be configured to stream video at a bit rate of 700 kbps (using 640 x 480 resolution, at 30 frames per second). Because the video would be streamed from a mobile device and then ingested by the datacasting network, an upload speed exceeding the minimum bit rate is needed to support live streaming with original quality.

The available bandwidth at the UE was measured as 8.53 Mbps. The bit rate for the live video-streaming app being used was configured to be 700 kbps. Because live video streaming requires 700 kbps, having 8.85 Mbps of available bandwidth would support it. However, the ping time of 45 ms may or may not have an impact.

The SpeedTest server was located in Houston for the UEs. The server for the laptop was located in San Antonio. As a result, the transfer speed for the laptop may be impacted differently. Additionally, while the speed test was performed sequentially, these results may be dependent on variables that may or may not be consistent across all the interfaces measured at the time of testing.

The results of the connectivity test also produced an unexpected outcome. The UE connected to the deployable LTE network had disproportionally slower transfer speeds and longer ping time when compared to other connections. This was especially noticeable from the download speed perspective. This could be due to the prototype nature of EPC software used during this trial or the wireless bridge itself. Additional investigation is needed to determine whether and how the wireless bridge may be degrading the performance. It should also be noted that PW had hoped to use a higher performance version of the EPC code, but was unable to do so due to time constraints.

This test was designed to test the connectivity to an external PDN, and to verify that sufficient uplink bandwidth is available to meet the minimum bitrate requirements of the live streaming application. With respect to that goal, the deployable LTE network has shown that ample bandwidth can be provided.

At this stage, the PW LTE network has been successfully connected to an external network and verified to work. As a result, a PTT application was also downloaded from the Google Play Store and installed to test application functionality in a connected network. The app was installed on three DHS Sonim XP7 devices and configured to use for the test. The devices were distributed to individual testers who were spread out across the coverage area of the DHS eNodeB.

Once in position, basic application functionality was tested and validated by the group. These results are shown in Table 12.

Table 12: Remote Application Server Functional Verification Results

Basic Functional Test	Successfully Sent?	Successfully Received?	Status
Group Talk	Yes	Yes	Pass
Text Message	Yes	Yes	Pass

By using an app that relies on a remote server to function, the capability of the PW deployable CWS to create an LTE-based data pipe has been successfully demonstrated. In addition, its capability to connect to an external network in order to access servers and services has been successfully demonstrated.

<u>The results of these tests demonstrate:</u>

- The PW LTE Network can connect to an external network using flexible backhaul.
- The capability of the PW solution to create a LTE based data pipe has been demonstrated.
- UEs connected to the deployable network can obtain services through appropriate applications by accessing remote services once an external connection has been established.

Key Observations from the Commercial Wireless Integration Exercise:

1) The PW LTE Network can be connected to an external network with flexible backhaul options.

2) The deployable LTE network can be set up to communicate with outside networks using Commercial Off-the-Shelf (COTS) or Government Off-the-Shelf (GOTS) wireless solutions.

4.4 End-to-End Test Results

The test team was able to successfully execute all four of the end-to-end pathways attempted. Table 13 summarizes the results of end-to-end testing via four separate paths.

Table 13: Results of End-to-end Testing

Test	Video Transmitted	Video Received	Delivery Time (s)	Quality 0-3
Commercial Wireless to Datacasting	Yes	Yes	10–12	3
Harris County Band 14 to Datacasting	Yes	Yes	5–7	3
Deployable LTE to Datacasting via Internet	Yes	Yes	10–12	2–3
Deployable LTE to Datacasting via Harris County Band 14	Yes	Yes	10–12	2–3

Video Transmitted (Yes/No) is an indication that the video was (a) received at KUHT, (b) transmitted via datacasting, and (c) the test team was able to view the input stream at the test site.

Video Received (Yes/No) is an indication that the video was successfully transmitted from KUHT and received at the second laptop configured to receive datacasting messages.

Delivery Time represents the time from initial video transmission using the Band 14 UE until receipt and display on the datacasting laptop. Delivery Time was readily measurable by comparing the current time (on the digital stopwatch) to the time in the video.

Quality represents a qualitative assessment of the quality of the datacasting video. Although the goal was to assess the relative quality of the input and output data, the actual differences were too small for observers to effectively characterize:

0 = Video not received or not useable.

1 = Video received, but of poor quality (bursty or blurred). Deficiencies in quality of sufficient severity to reduce the usefulness of the video.

2 = Video received and of mostly good quality. However, there is sufficient degradation to reduce the usefulness or make it difficult to use.

3 = High quality video. Quality is sufficient to make the video useful.

The commercial wireless to datacasting test was performed on February 9 outside the Police Station at 33 Artesian Place in Houston.

In addition, the test team made the following observations during end-to-end testing:

1) Delivery time estimates from the two end-to-end tests (both involving deployable LTE) using the digital clock were deemed more accurate than those using other methods. This technique could not be employed in all cases, however. In particular, it could only be used in those cases in which the person capturing the video was collocated with the test team.

2) There was a fairly consistent 10- to 12-second delivery time between recording of a video stream on a handheld and observation of the same events in the datacast video stream received at the laptop. The one exception was the end-to-end test in which an officer from the Harris County Sheriff's Office transmitted video from a remote location using the Harris County LTE Band 14 Public Safety Network. However, because the officer and the test team were not collocated, the delivery time measurements in this particular test were inherently less accurate than for the other tests.

Upon analysis, it was determined that the 10 to 12 seconds is a product of the time required to initiate datacasting video transmissions. Video input to the datacasting system is buffered until it can be transmitted to ensure that there is no loss of content. As a result, there were 10 to 12 seconds of video data in the buffer when transmission began. Since video is streamed in real-time, the buffer is filled at exactly the same rate at which it is emptied. The critical result in these tests is that once video streaming via datacasting begins, the delivery time remains constant. Delivery times could be reduced by reducing the size of the buffer, although this would result in some loss of content. Delivery time may also be less in a more permanent configuration.

3) There was a fairly consistent 5- to 6-second delivery time observed between the video stream input to datacasting and transmitted to the test team at NRG Park by a VPN over wireless and the video in the datacasting stream. This was true during all four end-to-end tests. Because both sets of videos were routed through KUHT prior to transmission, the 5- to 6-second delivery time is the difference between the time of transmission from the television station to the test team via VPN and the time required via datacasting.

4) Video transmitted via datacasting was consistently of useable quality; video observed at receiving terminals was consistently of quality equal to that of the video being input to the datacasting system. There was significant "burstiness" in both sets of video transmitted via the deployed LTE system. However, based upon subjective visual comparisons of the input and output streams, the test team felt the two streams were of similar quality. Because there was approximately 6 seconds (due to delivery time) between where the two streams were identical at any point, it was slightly difficult to compare the two streams.

Quality assessments performed as part of the end-to-end tests were subjective. Although the datacasting system provides measures of frame and bit rate for received videos, it does not provide a measurement of the frame and bit rates of the input video stream. Since the objective in these tests was to assess the contribution of datacasting to video dissemination and there was no way to quantitatively assess the state of the video stream when it reached the datacasting system, the test team opted to limit evaluation to subjective assessment.

5 Summary and Conclusions

Under the direction of the DHS Science and Technology Directorate's (S&T) First Responders Group (FRG) Office of Interoperability and Compatibility (OIC), JHU/APL executed a demonstration and evaluation of a prototype datacasting system installed at the offices of Houston Public Media (Public TV Broadcasting Station KUHT) and operated by the University of Houston OEM in Houston, Texas. On February 9-11, 2016, a team sponsored by DHS S&T and led by JHU/APL, successfully conducted a first-of-its-kind test of ad hoc hybrid architectures to provide backhaul for datacasting. A PW deployable LTE system and a datacasting system (installed at KUHT in July 2015 and expanded for the February 2016 tests) were tested separately. These systems were configured to operate over a number of local wireless networks, including commercial networks and the Harris County LTE Band 14 Public Safety Network, in order to create an end-to-end capability to collect data and real-time video in the field, and subsequently datacast it to first responders.

At first, the February tests were designed as a proof of concept for a notional public safety communications architecture in which data could be collected in the field, transmitted to a command center using an available wireless network and then disseminated using datacasting. Original plans included integration with either the Harris County LTE Band 14 Public Safety Network (preferred) or a local commercial network. Eventually, the scope of this test was modified to include integration with the PW deployable LTE network. By incorporating the deployable LTE capability, the test objectives were expanded to include demonstration of the feasibility of extending communications coverage into areas in which there is no telecommunications infrastructure or that infrastructure has been rendered inoperable. Deployable networks can be used to create small autonomous coverage

enclaves, or to extend the coverage area of an existing network by "daisy-chaining" connected deployable enclaves. As a result, the test team was able to simultaneously achieve a proof of concept of both the hybrid datacasting architecture and an ad hoc architecture using deployable networks to extend coverage.

During the course of the tests, the following were achieved:

1) The test team demonstrated the ability of the PW deployable system to operate autonomously and create a coverage enclave for authorized end users.

2) The test team demonstrated the ability of multiple PW deployable systems to be operated as a mesh network, thereby creating an extended LTE access network.

3) The test team demonstrated the ability to connect the PW deployable system to local commercial carriers.

4) The test team demonstrated the ability to connect the PW deployable system to Harris County Band 14 LTE Public Safety Network.

5) The test team demonstrated the ability of the PW deployable system to support Android-based applications.

6) The test team demonstrated the ability to simultaneously control the datacasting system from two different sites without performance degradation.

7) The test team demonstrated the ability of the datacasting system to dynamically reallocate capacity and deliver content without degradation when loads (e.g., large files and video streams) significantly exceeded the capacity allocated by the television station. The test team also demonstrated the ability of the system to allocate bandwidth based upon operator-selected priorities.

8) The test team verified the ability to disseminate content and real-time video using datacasting in a number of ad hoc architectures with various wireless networks and technologies:

    a) Verified the ability to stream real-time video to the datacasting server using the Harris County LTE Band 14 Public Safety Network and to then stream the video using the datacasting system.

    b) Verified the ability to stream real-time video to the datacasting server via a commercial wireless network and to then stream the video using the datacasting system.

    c) Verified the ability to stream real-time video to the datacasting server via a deployable LTE network connected to a commercial wireless network and to then stream the video using the datacasting system.

    d) Verified the ability to stream real-time video to the datacasting server via a deployable LTE network connected to the Harris County LTE Band 14 Public Safety Network and to then stream the video using the datacasting system.

Throughout testing, the datacasting system was able to deliver content and useable video. In general, datacast video quality was deemed equal to that of the video streams input to the server. However, this was a subjective assessment based upon side-by-side comparison of the two data streams. One limitation inherent in the testing was that, although the test team could measure and monitor bit rates and frame rates of the video transmitted via datacasting, there was no capability in place to measure the frame rate and bit rate of the input streams. Because the tests were conducted with low-cost integration solutions, there was some degradation in the input streams that would not have been present had the test team had the time and resources to implement a more robust, permanent architecture for delivering data and video to the datacasting system. Based upon visual comparison of the two video streams, there was no evidence that the video transmitted by the datacasting system was degraded or of lower quality than the original input video.

Reception using the datacasting was for the most part good. There were losses and degradation in reception while in moving vehicles and occasionally in areas of downtown Houston where there were a significant number of large buildings (i.e., urban canyons). There were occasions when video images would have significant numbers of missing pixels or the image would temporarily freeze.

In addition, delivery times of between 10 to 12 seconds were observed in datacasting video streams. Upon investigation, the test team concluded that this resulted from buffering data while the datacasting system performed data processing to initiate transmission. If these delivery times are deemed too long, they can be decreased by reducing the size of the buffer used.

The tests conducted in Houston during the first week in February provide additional verification of the feasibility of using datacasting technology to augment public safety communications. Working with representatives of the Houston and Harris County public safety community, the test team was able to achieve the first ever demonstration of datacasting and LTE within a single public safety communications architecture. Using this capability, the test team was able to deliver useable video data within a useful timeframe. This was achieved despite ad hoc integration efforts and a relatively small bandwidth allocation. If a more permanent capability were to be developed, improved methods for delivery of data and video to the television station could be implemented, the allocation of capacity could be increased, and other aspects, including prioritization, redundancy and buffering of data, could be optimized.

In addition, the tests and subsequent operational use of the system to support critical public safety events provide validation of the potential utility of the system. Public safety representatives in Houston and Harris County were not only enthusiastic about the capability, they have been actively using the system during times of higher stress on their communications systems. Based upon this test and the previous tests performed in Houston and Chicago, there is a strong case to be made that datacasting is a valuable component of a public safety communications architecture, at least during times of higher demand and stress. JHU/APL and DHS will continue to work to quantify the benefits of this capability in daily operations.

6 References

1. U.S. Department of Commerce – Boulder Laboratories, Public Safety Communications Research, “Video Quality in Public Safety (VQiPS) Guide to Defining Video Quality Requirements,” available at: http://www.pscr.gov/outreach/video/vqips/vqips_guide/ (accessed 1 March 2016).

2. U.S. Department of Commerce – Boulder Laboratories, Public Safety Communications Research, “Digital Video Quality Handbook,“ U.S. Department of Homeland Security Office of Interoperability and Compatibility. Available at: http://www.pscr.gov/outreach/video/vqips/vqips_guide/downloads/Digital_Video_Quality_Handbook-DHS-OIC_06132013.pdf (accessed 1 March 2016).

3. JHU/APL, “Video Datacasting: Houston Pilot After Action Report,” U.S. Department of Homeland Security Document HSHQPM-15-X-00122, October 2015. Prepared by JHU/APL for the Science and Technology Directorate First Responders Group Office for Interoperability and Compatibility. Available at: https://www.dhs.gov/publication/video-datacasting-houston-pilot-aar (accessed 29 February 2016).

4. JHU/APL, “Video Datacasting: Chicago Pilot After Action Report,” U.S. Department of Homeland Security Document HSHQPM-15-X-00122, October 2015. Prepared by JHU/APL for the Science and Technology Directorate First Responders Group Office for Interoperability and Compatibility. Available at: https://www.dhs.gov/publication/video-datacasting-chicago-pilot-aar (accessed 29 February 2016).

5. Chernock, R, “ATSC 3.0: Where We Stand,” reprinted from Broadcast Engineering and available at http://atsc.org/newsletter/atsc-3-0-where-we-stand/ (accessed 29 February 2016).

6. U.S. Department of Homeland Security Office of Emergency Communications, “Emergency Communications Case Study: Emergency Communications During the Response to the Boston Marathon Bombing,” August 2013. Available online at: http://www.dhs.gov/sites/default/files/publications/oec-case%20study-support%20for%20response%20to%20boston%20marathon%20bombing-2013_0.pdf (Accessed 3 March 2016).

7. DeMorat, D., “Federal Actions in Response to the August 23, 2011, Virginia Earthquake Report,” Federal Emergency Management Agency, 5 December 2013. Available online at: https://www.hsdl.org/?view&did=747579 (accessed 3 March 2016).

8. Miller, R., “Hurricane Katrina: Communications and Infrastructure Impacts,” Chap. 5, in *Threats at Our Threshold: Homeland Defense and Homeland Security in the New Century*, B. B. Tussing (ed.), U.S. Army War College, undated. Available online at: http://csis.org/images/stories/HomelandSecurity/071022_ThreatsAtOurThreshold.pdf (accessed 3 March 2016).

9. Kwasinski, Alexis, "Lessons from field damage assessments about communication networks power supply and infrastructure performance during natural disasters with a focus on Hurricane Sandy." *FCC Workshop on Network Resiliency 2013*. 2013. Available online at: http://users.ece.utexas.edu/~kwasinski/1569715143%20Kwasinski%20paper%20FCC-NR2013%20submitted.pdf (Accessed 3 March 2016).

10. Jackson, Donny, "Harris County to Expand Public-Safety LTE Network, Other Early Builders Prepare To Complete Projects." *IWCE Urgent Communications*, 19 August 2015. Available online at: http://urgentcomm.com/public-safety-broadbandfirstnet/harris-county-expand-public-safety-lte-network-other-early-builders- (accessed 3 March 2016).

11. U.S. Department of Homeland Security Science and Technology Directorate, “Datacasting: Public Safety Communication over Broadcast Television.” Available online at: http://www.firstresponder.gov/Pages/Datacasting-Public-Safety-Communication-Over-Broadcast-Television.aspx (accessed 2 March 2016).

12. Redding, Christopher, and Gentile, Camillo, “Extended Range Cell Testing,” Public Safety Communications Research (PSCR) Broadband Stakeholder’s Meeting, Westminster, CO, June 4, 2014.

APPENDIX A: Technical Details of Datacasting

Television stations transmit aggregate broadcast streams at a constant 19.39 Mbps data rate. Various programs are multiplexed into the aggregate stream. Often television content will not consume the full data rate, or content can be set to use less than the full data rate. When this is the case, null packets are used to fill the unused data rate (see Figure A1). In datacasting, the null packets are replaced with datacasting information that can be received and interpreted by registered recipients with the required equipment.

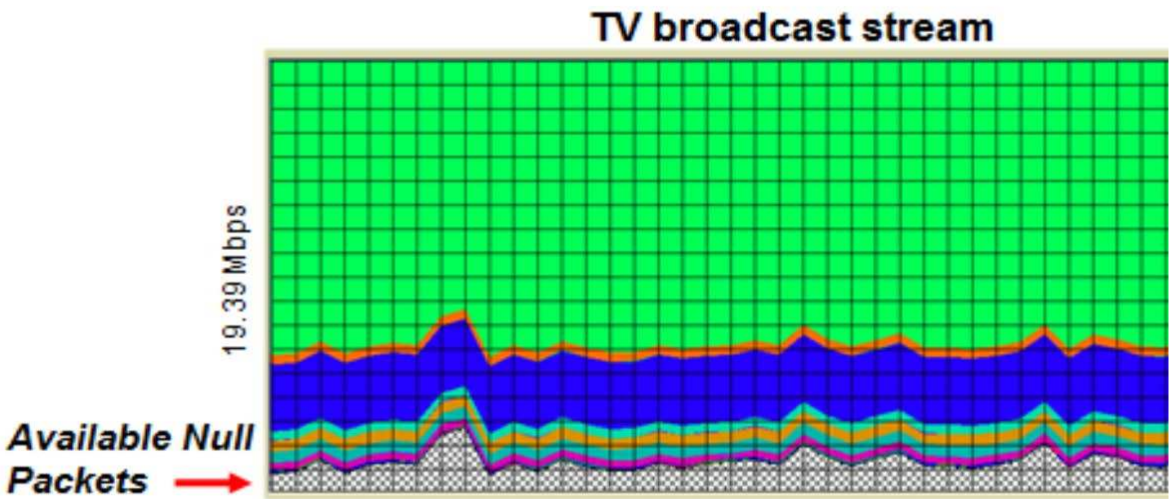


Figure A1. Digital TV Broadcast

There are three distinct aspects to the datacasting system: (1) information collection and processing, (2) transmission processing, and (3) reception processing (see Figure A2). Optionally, datacasting can be integrated into other systems to create a return path for two-way communication and services. In the prototype system implemented in Houston, information collection and processing, including decisions as to what information to send and to whom, were performed at the University of Houston Office of Emergency Management (OEM Emergency Operations Center (OEC). Transmission was performed at Houston Public Media, Public Broadcast System (PBS) station KUHT. Reception equipment was implemented in laptops belonging to the various public safety agencies participating in the demonstration.

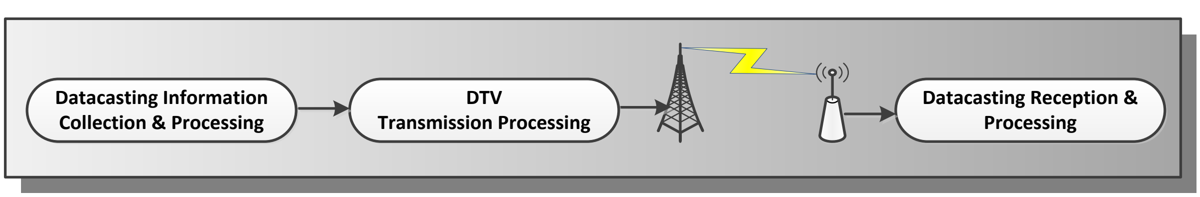


Figure A2. Components of a Datacasting System

Similar to satellite television providers (such as DirecTV), more than one TV program may be included (i.e., “multiplexed”) into one digital television transport stream. Datacasting is an additional program stream in that broadcast channel, but it is not referenced in the Program and System Information Protocol (PSIP), so it does not appear as a “channel” to television sets.

Transport streams are based upon Moving Pictures Experts Group (MPEG)-2 standards. Datacasting information could be embedded within the DTV signal, as represented in Figure A3. In the figure, each packet of the broadcast stream including the datacasting packet consists of a 4-byte header and 184 bytes of information.

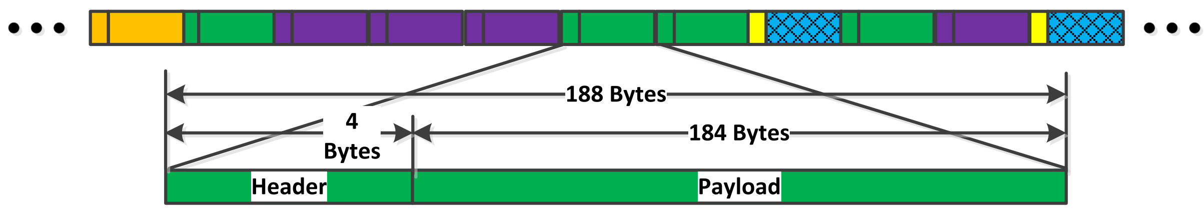


Figure A3. Datacasting within a DTV Stream

The header consists of 32 bits, including a 13-bit Packet Identifier (PID) as shown in Figure A4.

Sync	Error Indicator	Payload Unit Start Indicator	Transport Priority	PID	Transport Scrambling Control	Adaptation Field Control	Continuity Counter
8 Bits	1 Bit	1 Bit	1 Bit	13 Bits	2 Bits	2 Bits	4 Bits

Figure A4. DTV Broadcast Stream Header Format

Figure A5 illustrates the DTV transport components. The transport consists of services (i.e., television channels), which are made up of events (i.e., television programs) that each have their own elementary service streams (i.e., packetized MPEG 2 streams consisting of video, audio, metadata and service information as examples).

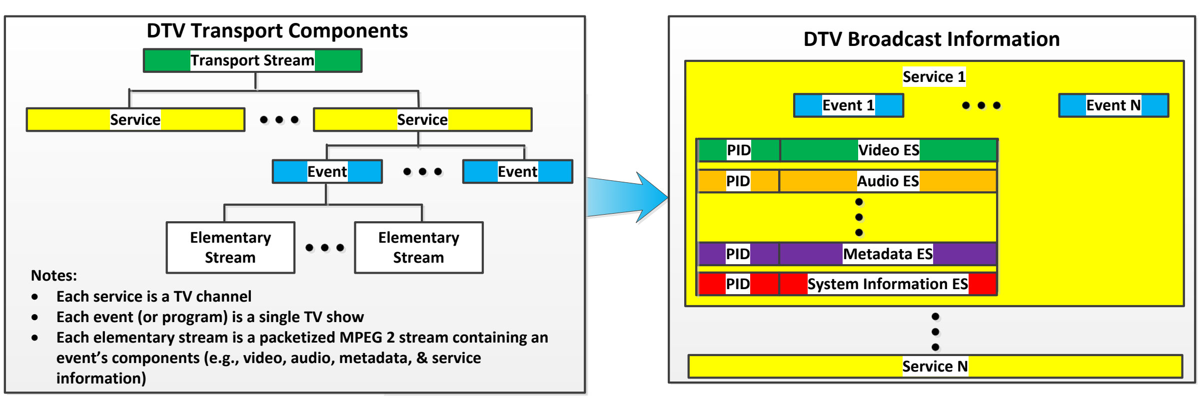


Figure A5. DTV Transport Components

The elementary service System Information contains various tables, including:

- Program association;
- Program map;
- Network information;
- Service description;
- Event information;
- Conditional access;
- Bouquet association;
- Time and date; and
- Time offset.

System Information tables include PID assignments to elementary streams, events and services. System Information packets are assigned pre-determined Packet Identifiers (PIDs).

Figure A6 contains a representation of the Datacasting Transport information, which is different than that of the regular television transport. Datacasting does not use the System Information tables and PIDs are pre-assigned to datacasting. PIDs are not included in the System Information tables to prevent DTV receivers from searching for a "ghost" service, event or elementary stream. Datacasting uses "Access Control" to identify PID Assignments, Receiver Assignments, Receiver Group Assignments, Protocol Assignments (e.g., video, file and messaging assigned to individual and/or group receivers) and key list assignments (for encryption/decryption). Access Control is transmitted on a regular periodic interval.

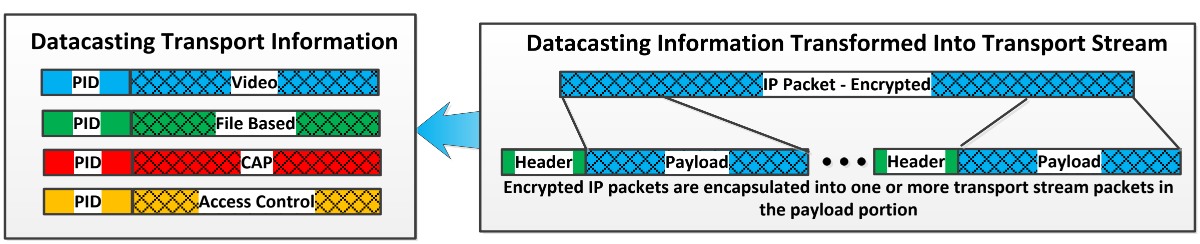


Figure A6. Datacasting Transport Stream

Datacasting Information Collection and Processing

In general, the datacasting system is configured to incorporate four types of data into the datacasting transport stream as shown in Figure A7:

Real-Time Streamed Data (blue in Figures A6 & A7): Typically the streamed data may consist of video information, such as from a Closed-Circuit Television (CCTV) system. Other streamed data such as audio, weather information and news broadcasts can also be incorporated.

File-Based Information (green in Figures A6 & A7): This information includes documents, images, and audio and video clips. It can include other types of digital information including software. Forward error correction (FEC) and carouselling are used to assure all packets are received, even in degraded reception environments.

Message Based Information (red in Figures A6 & A7): Generally, the messages are Common Alerting Protocol (CAP) compliant messaging, allowing messages and notifications to be processed by any CAP compliant alerting platform.

Access Control Information (yellow in Figures A6 & A7): File-based data is used to control registration and access. This information includes receiver registration, receiver group assignments, protocol assignments, key list assignments and PID assignments.

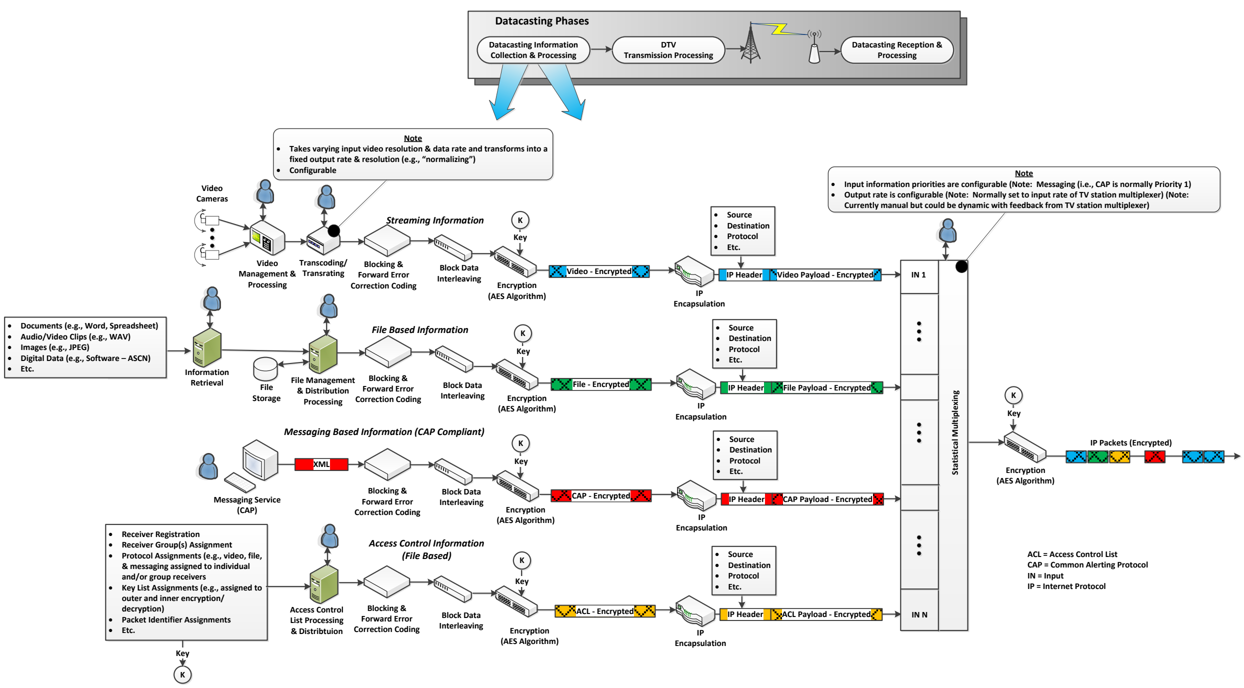


Figure A7. Datacasting Information Collection and Processing

Some portions of the data preparation process are common for all information types. Data are blocked and forward-error correction[2] is applied. The block data are interleaved and encrypted. Encrypted data are encapsulated using IP encapsulation into the MPEG transport packets. Source, destination and protocol data are packaged into the header. The datacasting packets are multiplexed to form a stream that is further encrypted using AES-256.

Transmission Processing

Transmission processing (see Figure A8) consists of merging (multiplexing) the datacasting data stream with the television programming stream(s) as depicted in Figure A9. Prior to the merging, the datacasting stream is processed into DTV transport packets and each transport packet is assigned a PID.

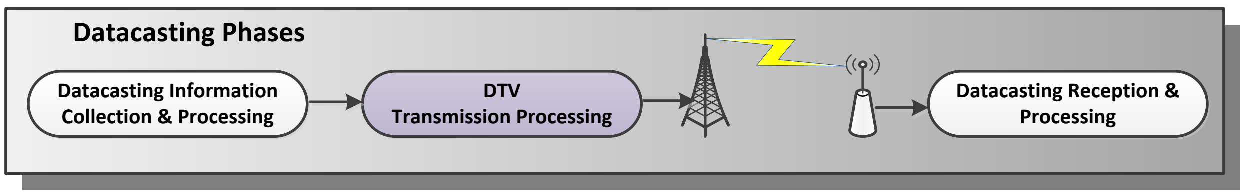


Figure A8. Transmission Processing

[2] Forward Error Correction is an encoding technique that protects the transmission and reception integrity of the data. It is used to detect and correct "bit-errors," technical problems that cause an occasional bit in a data stream to be misinterpreted. Provided the rate of errors in a data stream remains below a threshold, the Forward Error Correction Code can correct errors in the data stream. Forward Error Correction is a ubiquitous technique; it has no encryption value.

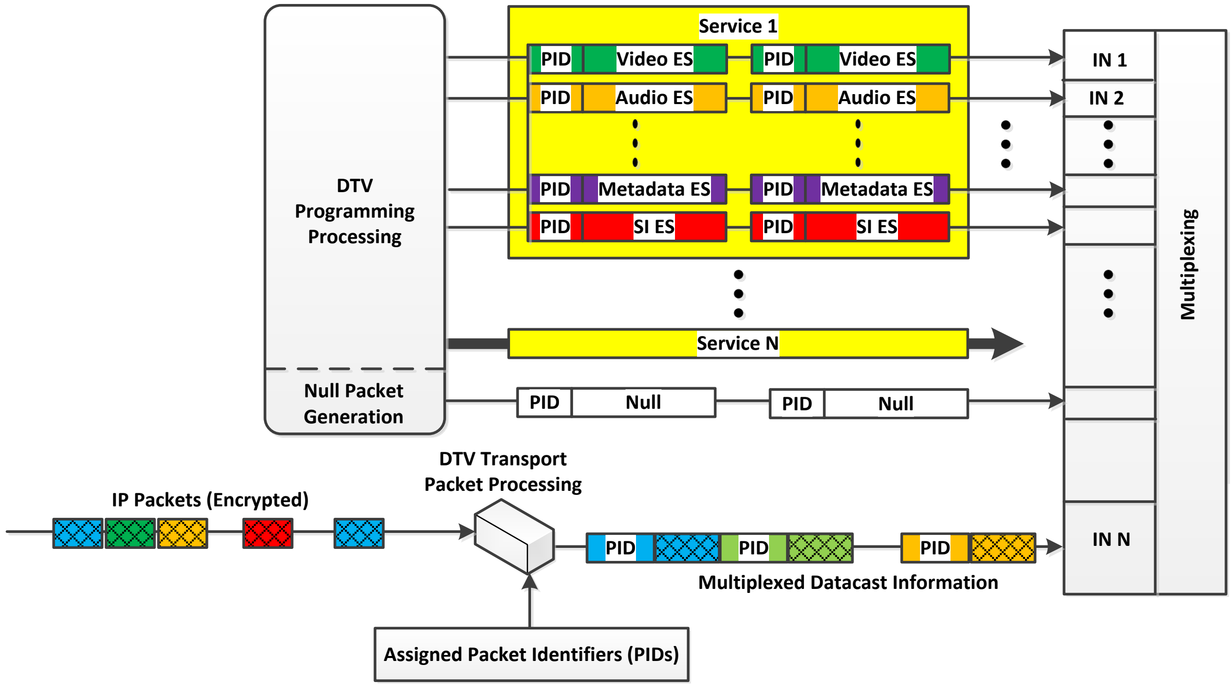


Figure A9. Multiplexing Datacasting and Television Streams

The overall output rate of the resulting merged stream (including datacasting and programming information) is 19.39 Mbps. Bit rate allocations are configurable. However, under normal conditions, there will be approximately 1-2 Mbps available for datacasting. This bit rate can be increased should conditions warrant it. Maximum bit rate is currently set manually. In the future, it may be possible to enter the information electronically into the information collection statistical multiplexor, which would enable the system to dynamically re-allocate the bit rate.

Null packets are required to maintain a constant 19.39 Mbps bit rate.

Figure A10 depicts the functions performed on the multiplexed signal through transmission. The signal is modulated using 8 level vestigial sideband modulation (8-VSB) and transmitted.

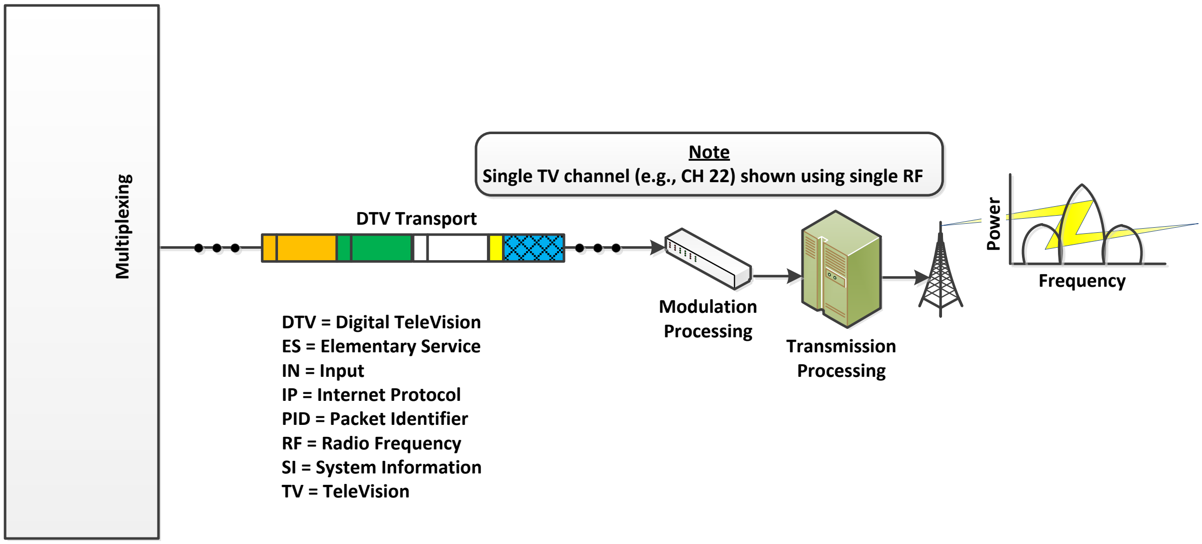


Figure A10. Transmission of Multiplexed Data

Datacasting Reception and Processing

Datacasting reception (see Figure A11) begins with reception of the signal by a receiver connected to a computing device, not a television set. The receiver can be a USB "dongle," or Linux based appliance. Any UHF or VHF antenna will capture the signal. However, only devices with the required software, decryption and registration will actually be able to convert the signal into useful information. Upon receipt of a signal, the datacasting system demodulates the signal and identifies the packets directed to the device according to the assigned PIDs. A device can be designated as the unique registered recipient or as part of a group registration.

When a device is authorized to receive data, the encrypted IP packets are decrypted for processing by the appropriate application software in the device. Figure A12 depicts the process.

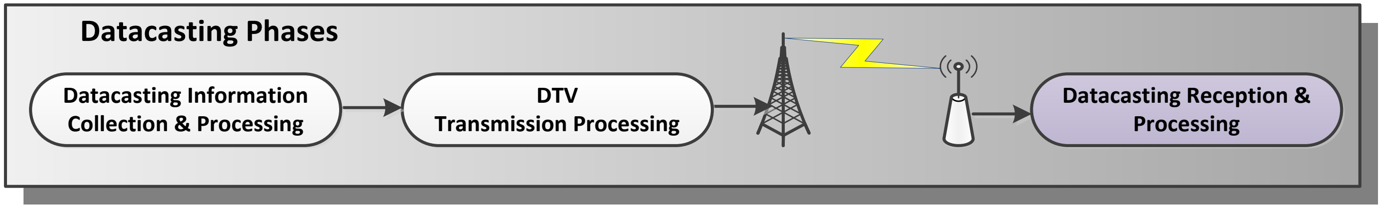


Figure A11. Datacasting Reception and Processing

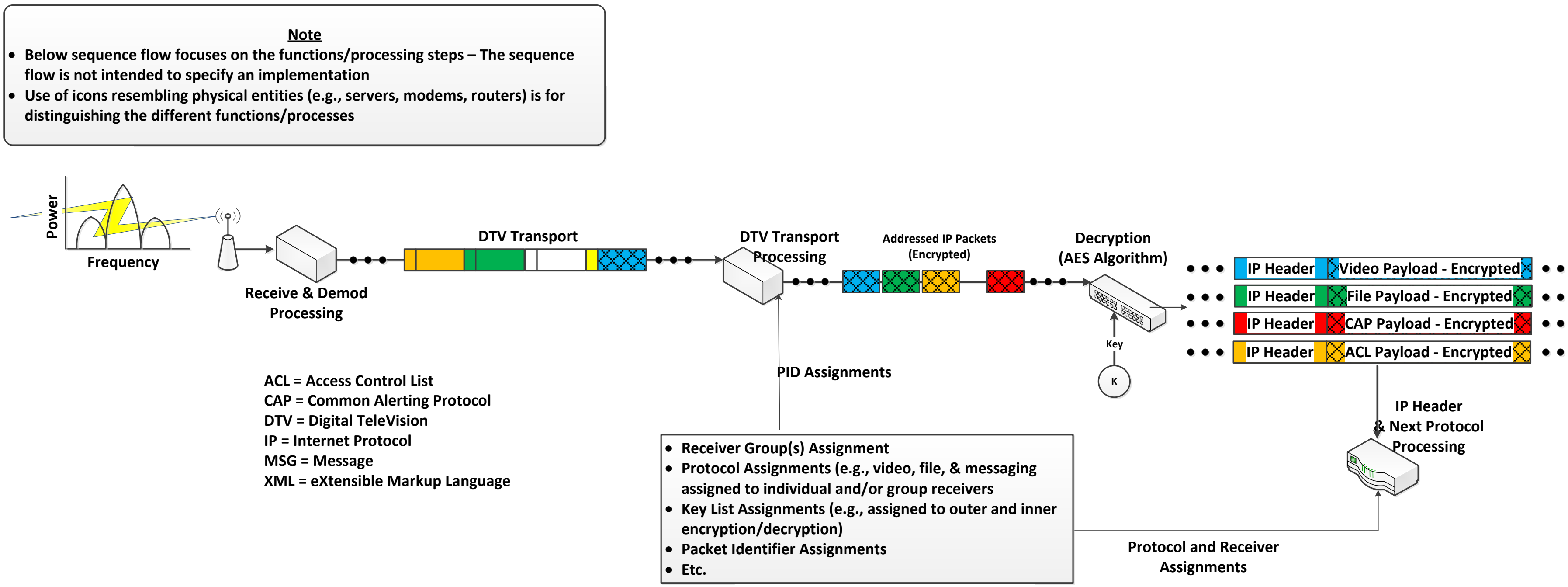


Figure A12. Datacasting Receipt

Finally, IP packets are processed according to type (streamed data, files, messages and access control) as shown in Figure A13. The further processing of data type is contingent on the access control list that identifies the encryption keys and receiver assignments to be used for each data type processed by this receiver.

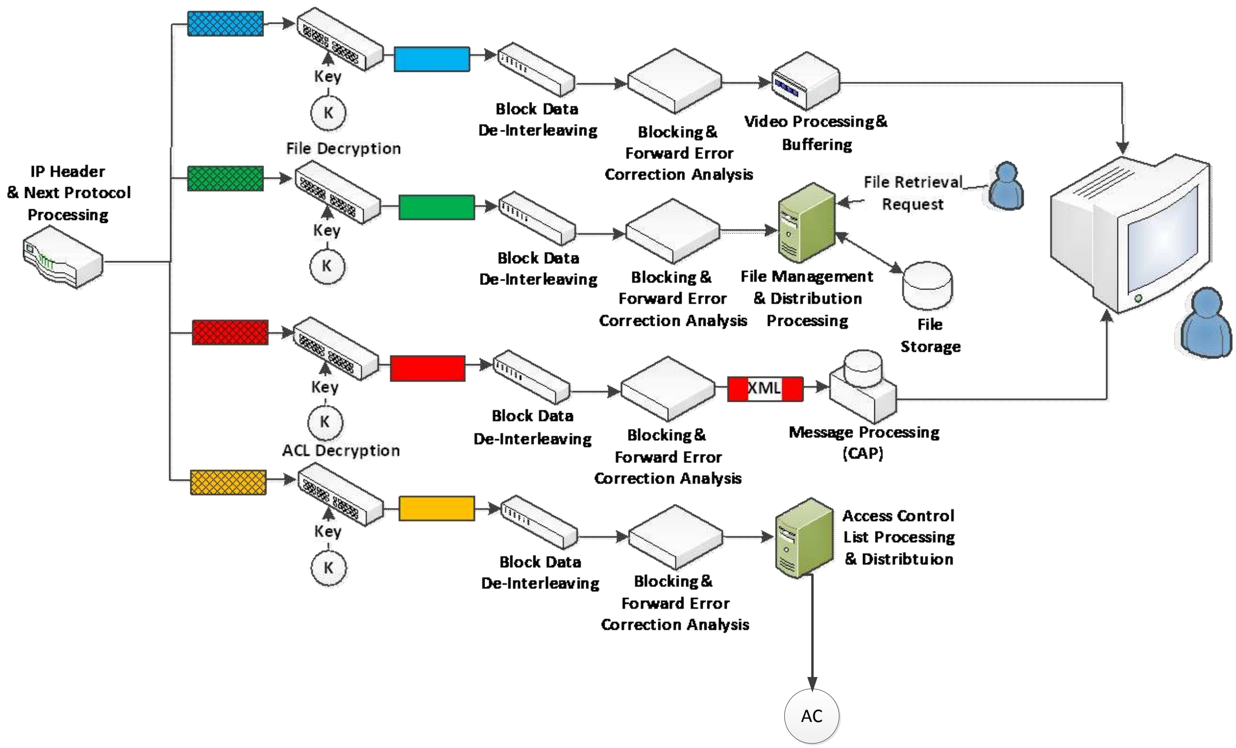


Figure A13. Processing Received Datacasting Information

APPENDIX B: Technical Description of Deployable LTE Networks

During the Houston exercise, a PW deployable LTE Band 14 system was tested. Deployable PW LTE systems, with three SONIM handheld UEs configured to work on these PW systems, were deployed and tested at NRG Park on February 9-11. One of the systems was brought to the exercise by DHS S&T and operated by JHU/APL personnel. The other two systems were brought to the exercise by NGA and operated by NGA personnel and their contractors.

LTE System

LTE is a high-speed wireless mobility standard based upon Global System for Mobile Communications (GSM)/Enhanced Data Rates for GSM Evolution (EDGE)[3] and Universal Mobile Telecommunications System (UMTS)/High-Speed Packet Access (HSPA) technologies. The standard is maintained by the Third-Generation Partnership Project (3GPP). In the technological evolution of Time Division Multiple Access (TDMA)-based mobile broadband standards, GSM is known as second-generation (2G) and UMTS as third-generation (3G). Because LTE is built upon UMTS [otherwise known as Wideband Code Division Multiple Access (WCDMA) standards) and their respective broadband speed improvements, it is known as fourth-generation (4G). Code Division Multiple Access (CDMA) and CDMA2000/EV-DO are competing wireless standards supported by the Third-Generation Partnership Project 2 (3GPP2). The Worldwide Interoperability for Microwave Access (WiMAX) is another wireless broadband standard maintained by the Institute of Electrical and Electronics Engineers (IEEE) and deployed by commercial wireless carriers. These and other technologies are operational today, but large domestic wireless carriers have shifted away from these competing technologies and instead have selected LTE as their path to 4G mobile broadband.

The goal of the 4G LTE standard is to leverage relatively recent digital signal processing and modulation advances to increase the capacity and speed of wireless mobile networks to enable them to respond to the increase in data usage. In addition, the standard will unify voice and data communications services into a simpler IP-based architecture that will reduce transfer latency. LTE standards are backward compatible to support interoperability with 2G and 3G networks. All major domestic carriers have implemented LTE capability.

Within an LTE network, the primary hardware element connecting User Equipment (UE) to the evolved packet core (EPC) is referred to as an Evolved Node B (eNodeB). Unlike UMTS NodeBs, the control function of the Radio Network Controller (RNC) is moved to the eNodeB to allow faster response times and simpler architecture. The EPC was introduced in 3GPP Release 8 and designed to minimize network nodes, while providing greater scalability compared to previous mobility standards. The EPC connects the UE to external

[3] Networks evolved from Time Division Multiple Access (TDMA) are the most widely used cell phone technology worldwide; AT&T and T-Mobile use GSM, UMTS and LTE in their networks. Verizon and Sprint networks operate on Code Division Multiple Access (CDMA) technology. Major carriers using CDMA have also migrated to LTE.

networks over the Evolved Universal Terrestrial Radio Access Network (E-UTRAN). Figure B1 represents a basic cellular network architecture.

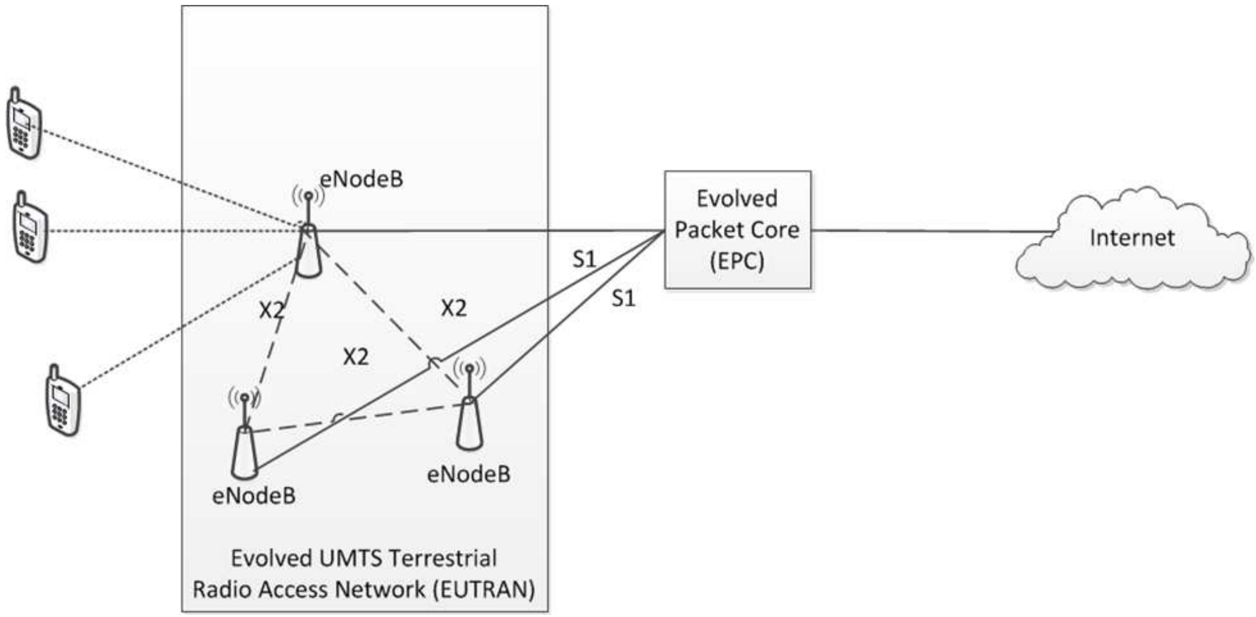
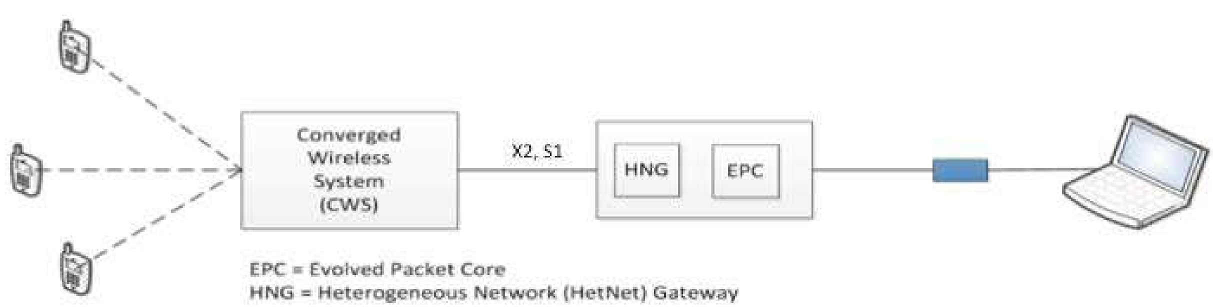


Figure B1: Nominal Cellular Network Architecture

There are various configurations available from PW. Figure B2 represents the components in the PW Deployable System as delivered to DHS. (Note: the laptop is not part of the system and is required only for start-up and configuration.) The deployable LTE network in a stand-alone configuration means that there are no connections to external networks (i.e., disconnected mode), but it functions as a LTE access network. The system can also be set up in a connected mode that allows connection with external networks.



The laptop depicted in the figure is not part of the PW deployable LTE system. Users will need to use a personal laptop to configure the system.

Figure B2: Deployable Wireless in Stand-alone Configuration

The components of the deployable PW system used by DHS (Figure B2) correspond to those in Figure B1:

1) Converged Wireless System (CWS) is a high-capacity 3GPP-compliant, multi-radio access device capable of interacting with handheld devices using LTE Band 14 (788- to 798-MHz uplink and 756- to 766-MHz downlink). Each CWS comes with two attachable LTE antennas for the access network and Global Positioning System (GPS) antenna. There are also two sets of Wi-Fi antennas to support wireless backhaul mesh connections with other CWSs. The CWS 200 used in the Houston tests had a power output of 1 W.

2) Heterogeneous Network (HetNet) Gateway (HNG) is the central hub supporting connectivity between the CWS and the EPC. Self-Organizing Network (SON) functionality—including features that support self-optimization and self-healing—are hosted in the HNG.

3) The EPC in the PW system performs many of the same tasks as the EPC in a cellular network, including:

    a) User authentication;

    b) Packet routing within the network;

    c) Routing of Packets to external networks; and

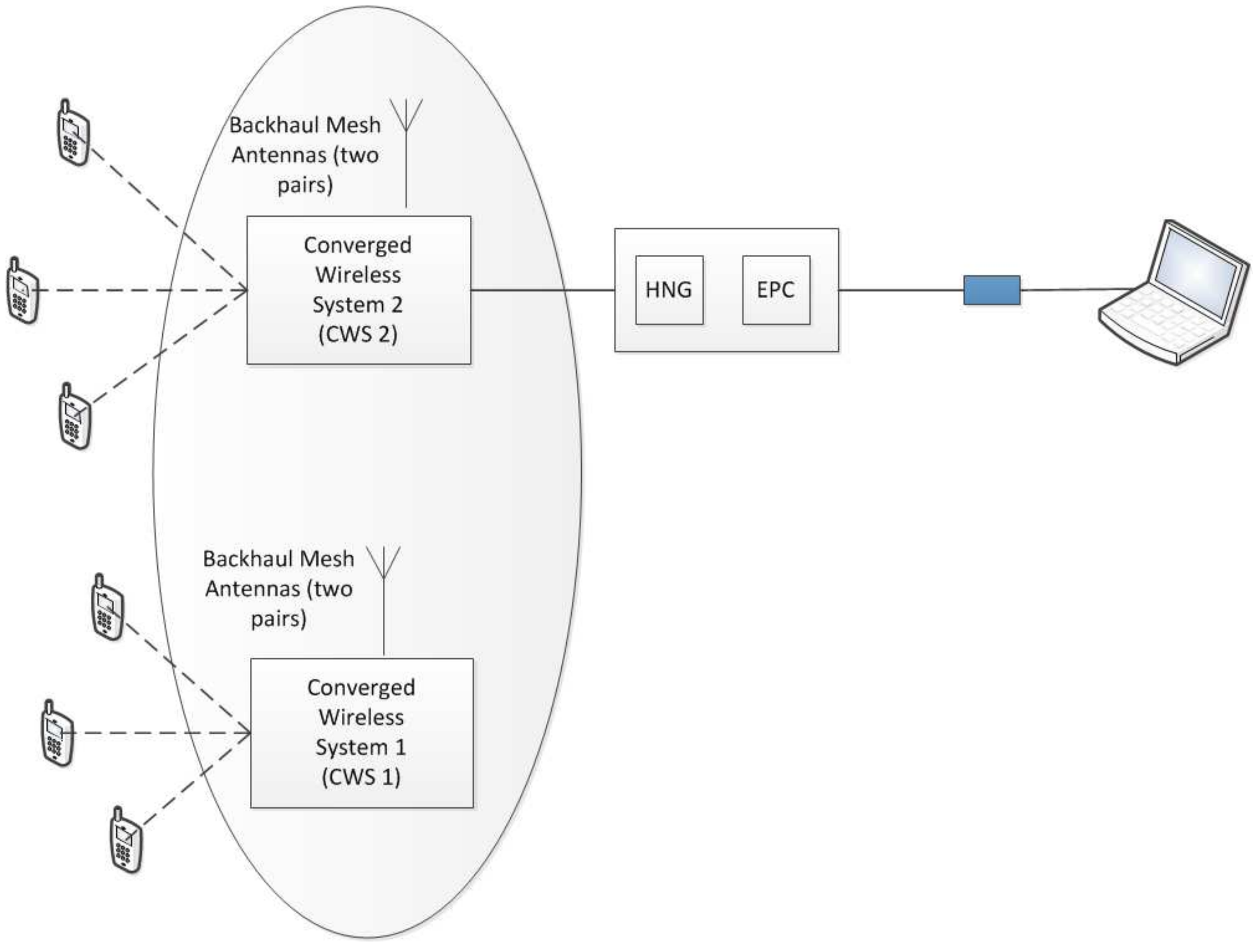
    d) Application servers required to support the use of apps not connected to external packet data networks would also be hosted in the EPC.

4) SONIM XP-7 UEs used during the tests are ruggedized Android smartphones.

The PW deployable system differs from a more common cellular LTE architecture in three ways. First, as a deployable LTE solution, it contains its own local embedded EPC, which enables it to operate when not connected to an external network. Second, the control functionality that would be in an eNodeB and the SON functionality are controlled by the HNG. Third, the CWS is able to connect with other CWS using flexible backhaul to expand the access network. Otherwise, the LTE access network created by the PW solution operates liked a regular LTE network from an end user perspective.

Multiple Mesh Networks

Each CWS is equipped with two 5-GHz Wi-Fi radios to support connections with other CWS in a mesh network. Mesh networking is a network topology in which nodes in a network manage connections with other nodes in close proximity and relay data targeted at users on other nodes (i.e., it is essentially a wireless peer-to-peer network). Each node in the mesh manages its connections with other nodes. Note that, in the PW system, this functionality needs to be pre-configured. Whenever one CWS is brought within the mesh range of another CWS, a secure link is created using the system’s backhaul Wi-Fi to create an expanded LTE access network that is managed by the HNG. Two CWS configured in a mesh network are depicted in Figure B3. Note, however, that additional CWS nodes can be connected via the Wi-Fi backhaul to create an extended coverage area.



As in Figure B2, the laptop is not part of the system; it is required for initial start-up and configuration.

Figure B3: Two Deployable LTE Systems Configured in a Mesh Network

Connecting to Local Service Providers

The PW deployable LTE solution offers various methods to connect to other networks. The deployable LTE can be connected directly to a packet data network (PDN) using various backhaul options. Alternatively, a CWS node can be connected to a remote HNG and EPC to access a PDN using flexible connections, including Local Area Network (LAN), commercial Wireless or any other connection capable of providing a routable IP address. By connecting the CWS to a remote HNG/EPC, the operational area of a carrier's network may also be extended.

During the course of testing in Houston, the test team made special effort to connect the deployable network to the Harris County LTE Band 14 Public Safety Network. Band 14 consists of 20 MHz (10 MHz uplink and 10 MHz downlink) in the 700-MHz range allocated to public safety for use in developing the Nationwide Public Safety Broadband Network (NSPBN), which is being implemented as part of the Middle Class Tax Relief and Job Creation Act of 2012. This Act also created the First Responder Network Authority (aka FirstNet) as an independent authority within the National Telecommunications and

Information Administration (NTIA) to manage the development, operation and maintenance of the NPSBN. Harris County, Texas, is the first jurisdiction in the nation to implement an operational Band 14 public safety broadband network [10]. As of August 2015, this network had 14 sites, with plans to expand to additional sites. The network operates under a three-year spectrum manager lease agreement (SMLA) with FirstNet.

Connectivity with Harris County Band 14 LTE was achieved by leveraging a commercial carrier. A connection between the CWS and a remote HNG within the Harris County Public Safety Network was achieved using the LTE modem inside the CWS to connect to the commercial carrier, which then connected to the HNG.

Implications

PW envisions its system as the primary component in a "Bring your own coverage (BYOC)" deployable LTE solution that would enable first responders and emergency management personnel to establish Radio Access Networks (RANs) in areas where telecommunications infrastructure was lacking or damaged. The system could be deployed to create ad hoc stand-alone communications networks for a specific response team or it could be used to provide and extend access to the Internet or another network. Figure B4 conveys the basic architecture.

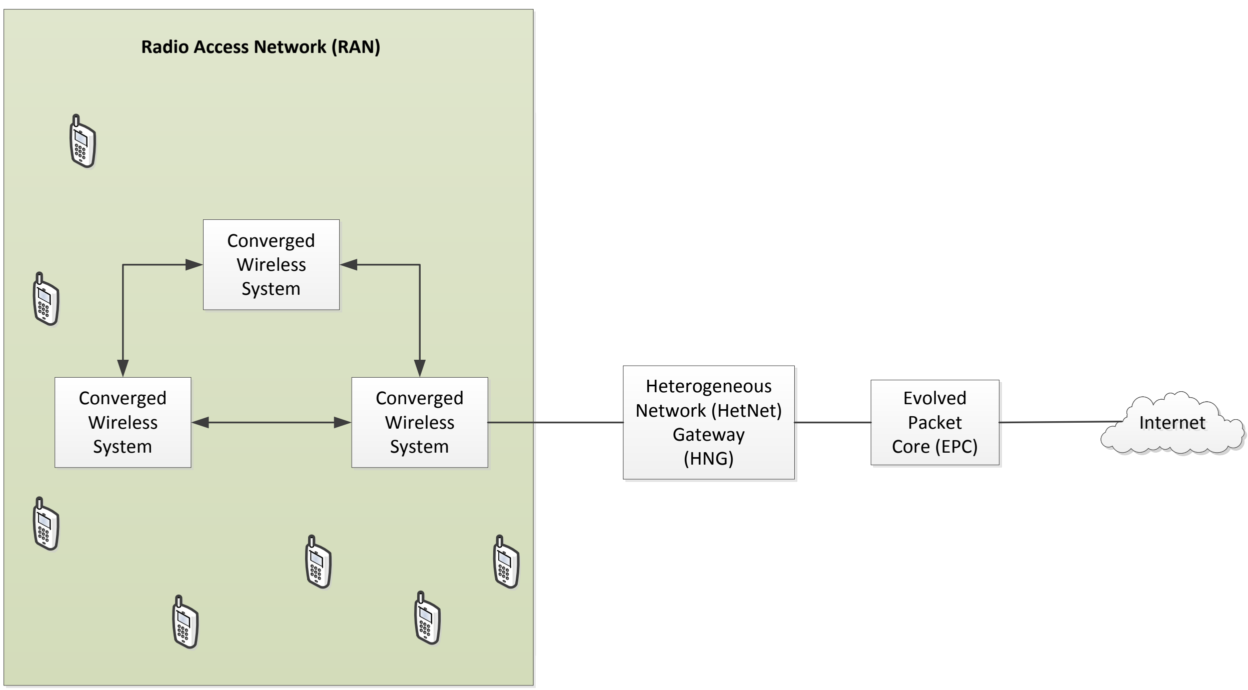


Figure B4: Notional Land Mobile LTE Architecture (https://trademarks.justia.com/860/08/lmlte-86008880.html)

Deployable wireless systems are used by the military to establish stand-alone RANs to support communications when there is no ready secure infrastructure in place. There are public safety scenarios in which this concept can also be applied. First responders at times have to respond to incidents (e.g., forest fires) in remote areas that are wholly lacking in wireless or other telecommunications infrastructure. RANs can be used to support

communications between members of the response team. Also, during certain kinds of extreme conditions (e.g., hurricanes), infrastructure can be rendered inoperable for significant periods of time due to damage, prolonged power outage or the loss of backhaul. Coverage could conceivably be restored by connecting a series of converged wireless systems to an operable local network (i.e., "daisy-chain") to restore wireless capability into the affected area.

APPENDIX C: Test Plan for February 2016 Houston Datacasting with LTE

The following test plan was distributed to the participants prior to the exercise.

Test Objectives

The test has the following objectives:

1) Demonstrate the technical capabilities of datacasting.

    a. Demonstrate the ability of the datacasting system previously configured in Houston (at Houston Public Media) to support multiple participants using the system concurrently.

    b. Demonstrate the system's ability to function under medium loading conditions.

    c. Demonstrate the system's ability to degrade gracefully when demand exceeds system capabilities.

2) Demonstrate the capability to configure a deployable Long-Term Evolution (LTE) telecommunications enclave.

    a. Demonstrate the ability to rapidly deploy an LTE telecommunications enclave using technology developed by PW.

    b. Demonstrate interoperability between multiple (two or more) enclaves using common deployable LTE technology.

    c. Demonstrate interoperability between the deployable LTE enclave and a local telecommunications network.

    d. Demonstrate the value of applications supporting first responders provisioned on LTE enclaves that do not have Internet connectivity.

3) Demonstrate the capabilities of integrated public safety telecommunications consisting of LTE and datacasting components.

    a. Demonstrate a concept in which the Public Safety Band 14 LTE network provides backhaul in support of efficient and wide dissemination of information via datacasting

    b. Demonstrate a concept in which a deployable LTE network provides backhaul in support of efficient and wide dissemination of information via datacasting.

Test Summary

The objectives of this test are to demonstrate the technical aspects of a proposed public safety architecture to provide efficient dissemination of information in response to a wide range of incidents. Consistent with that goal, a specific operational scenario has not been generated. Instead a more generic scenario is envisioned. Specifically, the test has been designed to simulate a public safety officer arriving at an incident scene and transmitting data to a larger response team (both on site at the incident and in remote locations). In this test scenario, a deployable LTE telecommunications capability acts as a backhaul carrier for text, images, video and application data, and the data are broadcast to targeted response team members using the datacasting capability at KUHT. These deployable LTE communications capabilities are those that might be used post disaster when commercial and other LTE communications infrastructure may be overwhelmed or destroyed.

There are four test stages:

(1) The Department of Homeland Security (DHS) and the National Geospatial-Intelligence Agency (NGA) will establish and test LTE enclaves using the PW deployable system. Testing within each enclave will consist of the following:

a. Text.

b. Voice.

c. Collaboration – Mobile Analytic GEOINT Environment (MAGE) is a Geographic Information System (GIS) application developed by NGA to support geographically distributed data collection and collaboration operations. MAGE testing may be limited to the NGA enclave. More information on MAGE can be found in this test plan's attachments.

d. Video – via file (non-real-time) and streaming (real-time). GLIMPSE is an NGA developed application supporting the collection and dissemination of video (including real-time) from smartphones. GLIMPSE testing may be limited to the NGA enclave.

e. Network Coverage Mapping – NGA is developing an application to support network coverage planning and awareness. Testing of this application may be limited to the NGA enclave.

The datacasting enclave established at the University of Houston (UH) Office of Emergency Management (OEM) and at Houston Public Media (KUHT) will be expanded to provide connectivity to a second location from which test members will be able to initiate incidents and data transmission (simulating integration with a second EOC). The City of Houston has provided a conference room in the City Hall Annex (900 Bagby Street, Houston, TX 77002). Testing of the expanded datacasting enclave will include the following:

a. Text.

b. Files (including images).

c. Video (including real-time streaming).

(2) The DHS and NGA enclaves will establish connectivity with each other and interoperability between the two enclaves will be verified. Concurrently, a load test will be performed using the expanded datacasting enclave.

(3) The DHS and NGA enclaves will establish connectivity with a local carrier network – either via a commercial carrier or via a local public safety network.

(4) An end-to-end test using a deployed enclave, a local network and the datacasting system will be executed.

Test Location

Two separate test locations are required.

Testing of the PW deployable LTE system will require sufficient space to enable users to be located as much as 1 km apart. To avoid interference, the tests must be conducted in an area outside the coverage of the Harris County Band 14 Public Safety Network. Ideally, the test site would provide access to an elevated space, such as a rooftop, to maximize coverage.

NRG Park has been selected as a test site. The 350-acre complex includes wide areas of open space (parking lots) and NRG stadium. If access can be obtained to this stadium, it would provide an elevated structure. NRG Park is currently outside of the coverage area of the Harris County Band 14 Public Safety Network.

During a datacasting test executed in July 2015, a datacasting transmission capability was configured in the University of Houston Office of Emergency Management (EOM) Emergency Operations Center (EOC). From this site, the datacasting system could be readily connected to the University of Houston's surveillance cameras. For the February 2016 test, a second site for initiating datacasting transmissions (with access via a video management server to HPD surveillance cameras) will be configured in the City Hall Annex at 900 Bagby Street (Houston, Texas) in Conference Room 243. Additional equipment will be installed at the Houston EOC at 5320 N. Shepherd Drive (Houston, Texas) to support transmission of surveillance video across the datacasting system.

Datacast transmissions will be broadcast from Houston Public Media television station (KUHT). The test team will require periodic access to the equipment at KUHT. In addition, the test team will work with UH OEM to support a proposed datacasting load test as part of Stage Two testing (to be described later).

Participants/Responsibilities

The following organizations will participate in the demonstration and will have the following responsibilities:

1. DHS S&T: DHS S&T is the authority for this demonstration. They will also act as observers for the test. In addition, DHS S&T will provide regulatory authority to operate the deployable LTE systems in the designated geographical locations.

2. City of Houston Government/Houston Police Department (HPD): City of Houston and HPD are critical stakeholders for this test. They will provide input regarding test planning and execution, provide access and facilities, observe test execution, and record observations. Specific responsibilities include the following:

    a. City of Houston and HPD will identify critical test objectives. They have identified NRG Park as an acceptable location for conduct of the test. City of Houston and HPD will obtain required approvals for using NRG Park.

    b. City of Houston and/or HPD will provide access to a conference room in the City Hall Annex from which datacasting messages can be formed and transmitted.

    c. City of Houston will provide access to the Houston EOC to enable installation of equipment to support transmission of surveillance video using the datacasting system.

    d. City of Houston and/or HPD will provide access to real-time video from surveillance cameras under their control.

    e. A representative of the City of Houston or HPD will transmit data to the City Hall Annex for injection into the datacasting system. Data should include at least one video. It is preferred that the video be streamed in real-time, but transmission of a recorded video clip will be sufficient to achieve test objectives.

    f. Representatives of the City of Houston and/or the HPD will receive data using a datacasting receiver and provide observations. At their discretion, the City of Houston may identify other datacasting recipients, such as the Houston Fire Department and Harris County Sheriff's Office.

3. NRG Park: NRG Park will host a portion of the test and may provide data and video in support of the demonstration.

    a. NRG Park will make its spaces available for this test.

4. National Geospatial-Intelligence Agency (NGA): NGA will set up their deployable mesh wireless network from PW, including application services for the enclave. If possible, they will also establish an interface with the Harris County Public Safety LTE network.

    a. Planning: NGA will participate in planning to identify scenarios and procedures that will enable testing of their equipment.

    b. Resource Provisioning: NGA will provide the required equipment and applications required by the identified scenarios and procedures for the portion of the test NGA is supporting.

    c. Execution: NGA will set up, operate, and test the equipment and applications in the identified scenarios and procedures.

d. Review: NGA will participate in capturing lessons learned and next steps from the exercise.

5. University of Houston: UH will host technical equipment in support of the demonstration and provide the following support:

    a. Broadcast infrastructure (KUHT): KUHT will provide access to selected portions of its broadcast signal for the purpose of transmitting encoded datacast data in support of the demonstration and prior to the demonstration to enable testing of the pilot architecture. It will also provide physical access of its equipment to SpectraRep for the purpose of installing equipment necessary to integrate KUHT broadcast equipment with the University of Houston EOC. Representatives of KUHT will work with SpectraRep to define the integration requirements for the demonstration.

6. Johns Hopkins University Applied Physics Laboratory (JHU/APL): JHU/APL is DHS S&T's technical authority for this test. JHU/APL responsibilities include:

    a. Test Design: JHU/APL will coordinate stakeholders in designing a test that meets the objectives of the stakeholders. JHU/APL will develop required test plans and procedures.

    b. Test Preparation: JHU/APL has sub-contracted SpectraRep to provide and install required datacasting test equipment. JHU/APL has responsibility for overseeing SpectraRep during this process.

    c. Test Execution: JHU/APL is responsible for ensuring that participants understand their roles during the exercise and can perform them.

    d. Test Analysis: JHU/APL is responsible for test analysis.

7. PW: Support includes:

    a. Planning – PW will support planning of the event in Houston to ensure the technical requirements for provisioning LTE Band 14 service from CWS200 devices and extending Harris County LTE services are known.

    b. Test Support: PW will provide engineering support during testing for configuration and troubleshooting of any PW equipment provided through the In-Q-Tel work program.

8. SpectraRep: Support includes:

    a. Planning – SpectraRep will support planning of the event in Houston. This includes working with all the participants to develop integration requirements for the test.

    b. Provision of equipment – SpectraRep will provide the necessary equipment to enable datacast information to be transmitted from KUHT and to be received by test participants.

c. Installation – SpectraRep will install and integrate the equipment in Houston.

d. Maintenance – SpectraRep will be responsible for maintenance to ensure that the datacasting system equipment is functional throughout the demonstration.

Test Preparation

Preparation for this test consists of the following steps:

4) Test Planning: An integration working group will be established to define integration issues related to provision of desired data from NRG Park and from HPD to KUHT. In addition, the working group will identify and resolve any integration requirements associated with installation of datacasting receiver equipment.

5) Test Procedures: Agreement on test procedures will occur no later than two weeks prior to the test. Modifications will be allowed up until test execution to accommodate availability of public safety assets.

6) Test Equipment: Any test equipment in addition to what was required for the July test will be shipped, installed and tested no later than February 8.

7) Equipment Checkout: Representatives of SpectraRep will arrive in Houston on February 5 to begin datacasting equipment installation, configuration and testing. Members of the test team from JHU/APL will arrive in Houston on February 8 and meet with SpectraRep representatives to perform final tests on the equipment to be used during the test.

Stage One Testing: Independent Enclave Testing (February 9, 2016)

Three separate enclaves will be configured for this test. Two of those enclaves will use a deployable LTE mesh network (CWS) developed by PW. The third enclave will be an expanded datacasting enclave (i.e., the configuration implemented for a July 2015 test will be expanded to provide continuous access to the HPD). Of the two PW enclaves, one will be operated by NGA and one by DHS (and/or their designated contractors).

PW LTE enclave Testing (February 9, 2016)

The objective of Stage 1 Testing is to establish and verify the communications enclaves that will be used in subsequent stages. Stage 1 will include testing of two deployable LTE enclaves using technology developed by PW without connectivity to any other network provider. NGA and its contractors will establish and operate the first enclave. JHU/APL will establish and operate the second enclave to establish a baseline footprint of the CWS eNodeB.

Figure C1 contains a representation of a PW enclave and represents the configuration that will be operated by JHU/APL as part of the test. The enclave will need to be located outside the range of Harris County's existing Band 14 LTE public safety communications network. NRG Park has been identified as the test location because it meets this requirement. The enclave represented in Figure C1 is completely stand-alone; no connectivity to the Internet is envisioned in support of Stage 1 testing of the LTE Enclave.

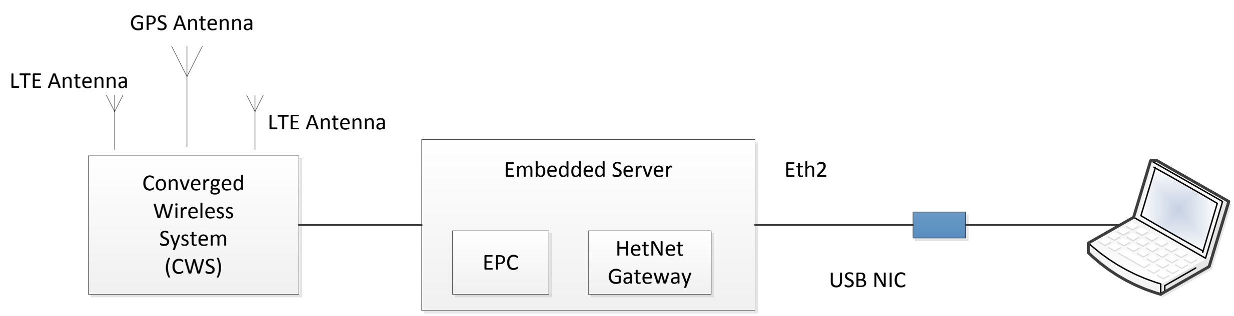


Figure C1: A Single Deployable LTE Enclave (from PW "Current Product Quick Start Guide," TCHPB-REL3.0.2-0020, July 2015)

- The CWS is configured as follows:

1. Two LTE antennas are connected to ports L0.0 and L0.1 on the CWS chassis.
2. A GPS antenna is connected to the GPS Port on the CWS chassis.
3. Ports P1.0, P1.1, P3.0 and P3.1 will be capped to prevent a mesh network from being established so that the CWS may operate as individual enclaves.
4. Connect the CWS to AC power using the power cable and adapter provided.

- The embedded server (containing an Evolved Packet Core and a HetNet Gateway) is configured as follows:

1. Connect the embedded server to an AC power source via the AC Port on the box.
2. Connect the embedded server to a laptop (going from a USB port on the laptop to Ethernet connection on the laptop).
3. Connect the embedded server port Eth1 to the CWS port GE1.

- Once the CWS and embedded server are connected, the following procedures are executed to initiate the first enclave:

1. The laptop is configured with the following IP parameters: 10.60.0.1/255.255.0.0.
2. The embedded server is powered up. It should take between two and five minutes to complete. The embedded server is a XEN server running four virtual machines. Once the XEN server has finished booting, it will activate the other four virtual machines.
3. Using the laptop, connect using PuTTY to each of the four virtual machines using the following credentials:
    a. Root/password.
    b. 10.60.253.249 – XEN Server.
    c. 10.60.254.241 – Content Server.
    d. 10.60.254.231 – Evolved Packet Core.
    e. 10.60.254.228 – LTE/Het-Net Access Controller.
    f. 10.60.253.228 – Element Management System for the HNG.
4. Once the Evolved Packet Core starts (10.60.254.231 – Evolved Packet Core), run the following commands:
    a. Service epc stop
    b. Service epc start
5. Prior to powering up the CWS, perform the following steps:
    a. Plug in the LTE antennae.
    b. Plug in GPS antenna.
    c. Place Terminators on unused antenna terminals.
6. Power on the CWS. When the blue light stops blinking and remains in a constantly illuminated state, the connection between the CWS and HNG has been established.
7. Check the status of the LTE Cell as follows:

a. In the PuTTY session opened in step 5, enter the PW command line of the HNG by typing "cli" upon receiving a prompt from the Linux shell.

b. Enter the following command: "show access nodes cws oper-data"

c. Four CWS units should be displayed; only one should be in a "*connected*" state.

d. Enter the following command: "show access nodes cws lte cell oper-data"

e. Four CWS units should be displayed; only one should be in an "*InService*" state.

8. Power on the Sonim handsets.

- Once the LTE cell enclave has been established, the test team will document the LTE coverage to establish the footprint of the CWS eNodeB. The test team (JHU/APL) will load an application obtained from the Android Playstore and use it to measure the Reference Signal Received Power (RSRP) on at least one Sonim handset. The CWS will be placed at location outside the NRG Stadium (see Figure C2) and at a suitable location within NRG Park (see Figure C3). In addition, JHU/APL test team will move to different positions within NRG Park to record the signal strength as a function of distance from the CWS and the height of the CWS placement.

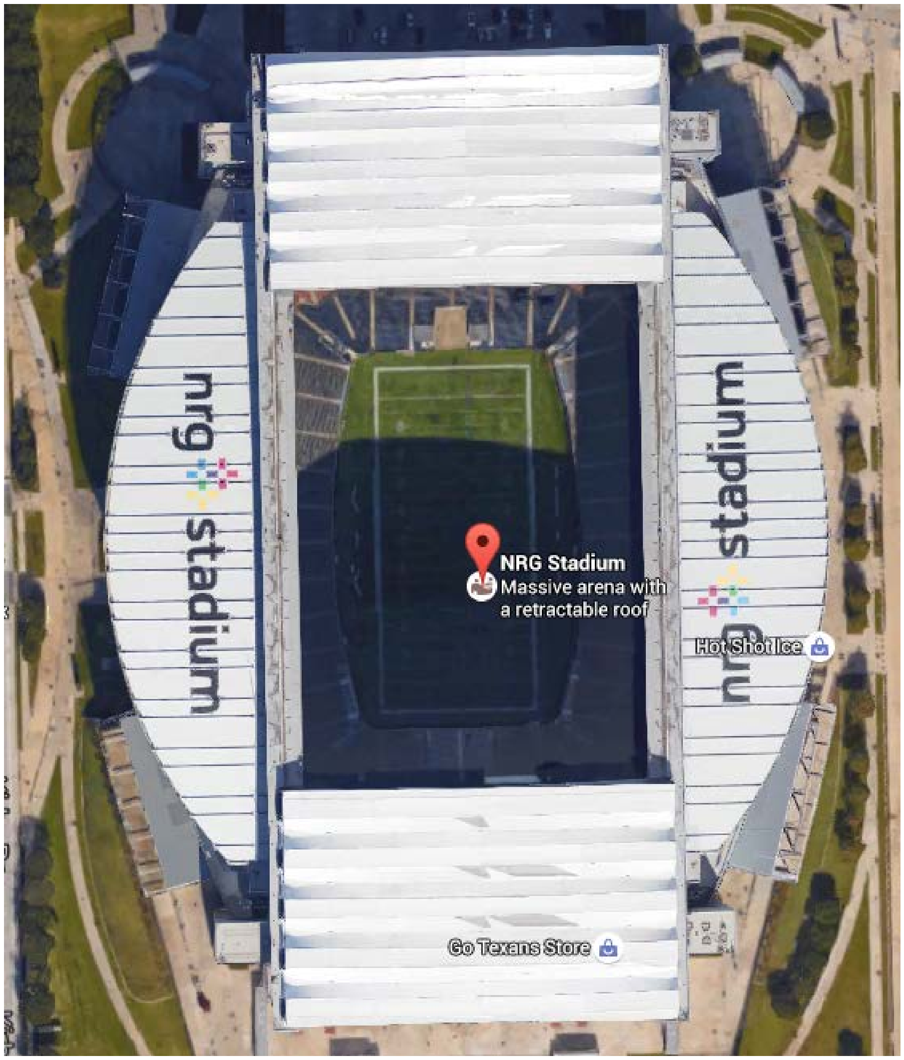


Figure C2: NRG Stadium (Located Within NRG Park)

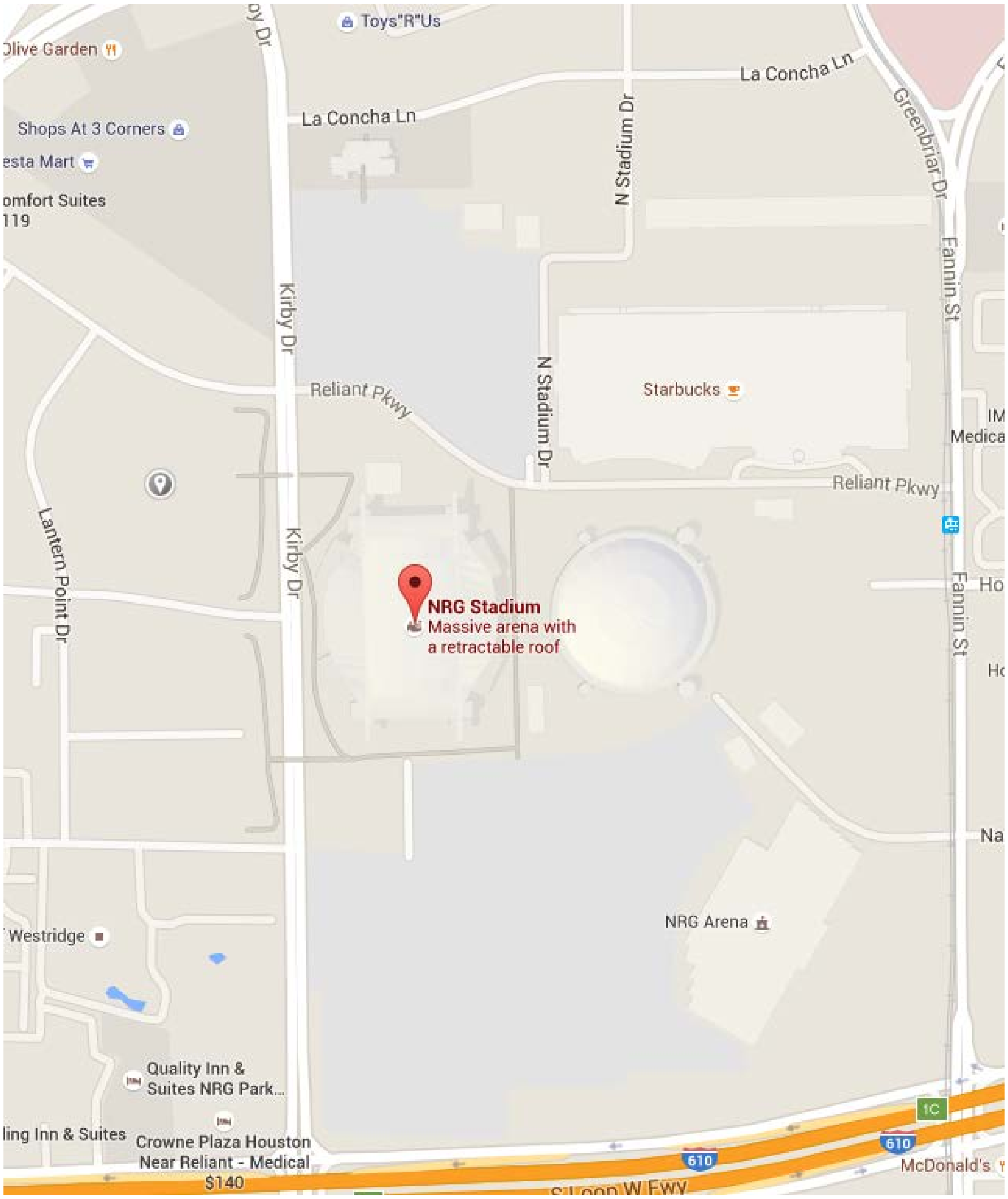


Figure C3: Map Showing Location of NRG Park (Includes NRG Stadium)

- Upon completion of the LTE enclave coverage verification, NGA will verify the following enclave capabilities. In each case, NGA will load applications from the application server (provided by NGA) and execute test procedures to verify each capability:

1) Using an application of their choosing (Asterix), NGA shall verify the ability to exchange voice messages within the enclave using the Sonim phones.

2) Using an application of their choosing (MAGE), NGA shall verify the ability to exchange Geographical Information System (GIS) data within the enclave using the Sonim phones.

3) Using an application of their choosing (GLIMPSE), NGA shall verify the ability to transmit real-time video streams within the enclave using the Sonim phones.

4) Using an application of their choosing, NGA shall verify the ability to sense and visualize the LTE Band 14 network coverage.

- NGA will provide test procedures and identify data captured for each of the four application tests identified above and for any additional tests executed at their request.

Overall Schedule for Stage One

9:00 Arrive at NRG Park.

9:00– 10:00 Coordination meeting for independent testing of DHS and NGA scenarios. Determine suitable locations for testing, and identify and coordinate testing needs in support of the planned exercise.

10:00 - 11:00 Stage and setup testing configuration, and validate the configuration will meet testing requirements.

11:00 – 16:00 Conduct Planned Testing.

16:00 – 17:00 Post Test debriefing to share lessons learned.

High-level JHU/APL Test Plan

- Objective: To determine the baseline coverage footprint provided by the PW eNodeB.

1) Verify if there is existing Harris County LTE coverage at the testing location by using the DHS Sonim XP7 and a commercially available application from the Android Playstore with a Harris County LTE SIM inserted into the testing device.

2) Determine baseline coverage of PW eNode by inserting the test SIM provisioned to work on the PW LTE network in the Sonim device that contains the measuring app obtained from the Android Playstore.

3) Find a suitable location that offers a range of heights for the transmitter, as far away as possible from a structure, in order to document the footprint of the CWS eNodeB.

4) Ensure that the lte-ref-signal-power is fixed to the maximum recommended value of -3 on the DHS PW enclave.

5) Ensure that the Physical Cell ID (PCI) is unique to the DHS and NGA eNodeB to distinguish the two different eNodeBs.

6) Measure and collect sufficient RSCP samples to characterize the coverage footprint of the PW eNodeB, including at different radiation centers if available.

7) The collection points should be up to the edge of LTE coverage.

High-level NGA Test Plan

- NGA will verify the following enclave capabilities. In each case, NGA will load applications from the application server (provided by NGA) and execute test procedures to verify each capability:

1) Using an application of their choosing, NGA shall verify the ability to exchange text messages within the enclave using the Sonim phones.

2) Using an application of their choosing, NGA shall verify the ability to exchange voice messages within the enclave using the Sonim phones.

3) Using an application of their choosing (MAGE), NGA shall verify the ability to exchange Geographical Information System (GIS) data within the enclave using the Sonim phones.

4) Using an application of their choosing (GLIMPSE), NGA shall verify the ability to transmit real-time video streams within the enclave using the Sonim phones.

- NGA will provide test procedures and identify data captured for each of the four application tests identified above and for any additional tests executed at their request.

Datacasting Enclave Expansion Testing (February 9-10, 2016)

The test team will verify a datacasting communications enclave consisting of a test site in the City Hall Annex, a test site at the University of Houston (UH) Office of Emergency Management (OEM), the transmission capability at Houston Public Media (Television Station KUHT) and a reception capability distributed among selected stakeholders. Most of the systems included in this enclave were deployed and configured in support of the July 2015 test. However, the enclave has been expanded for the February 2016 test to provide more ready access to HPD.

As a result of a live test performed in Houston in July 2015, there is currently an operational datacasting capability in Houston. Figure C4 contains a schematic representation of the components that provide that capability.

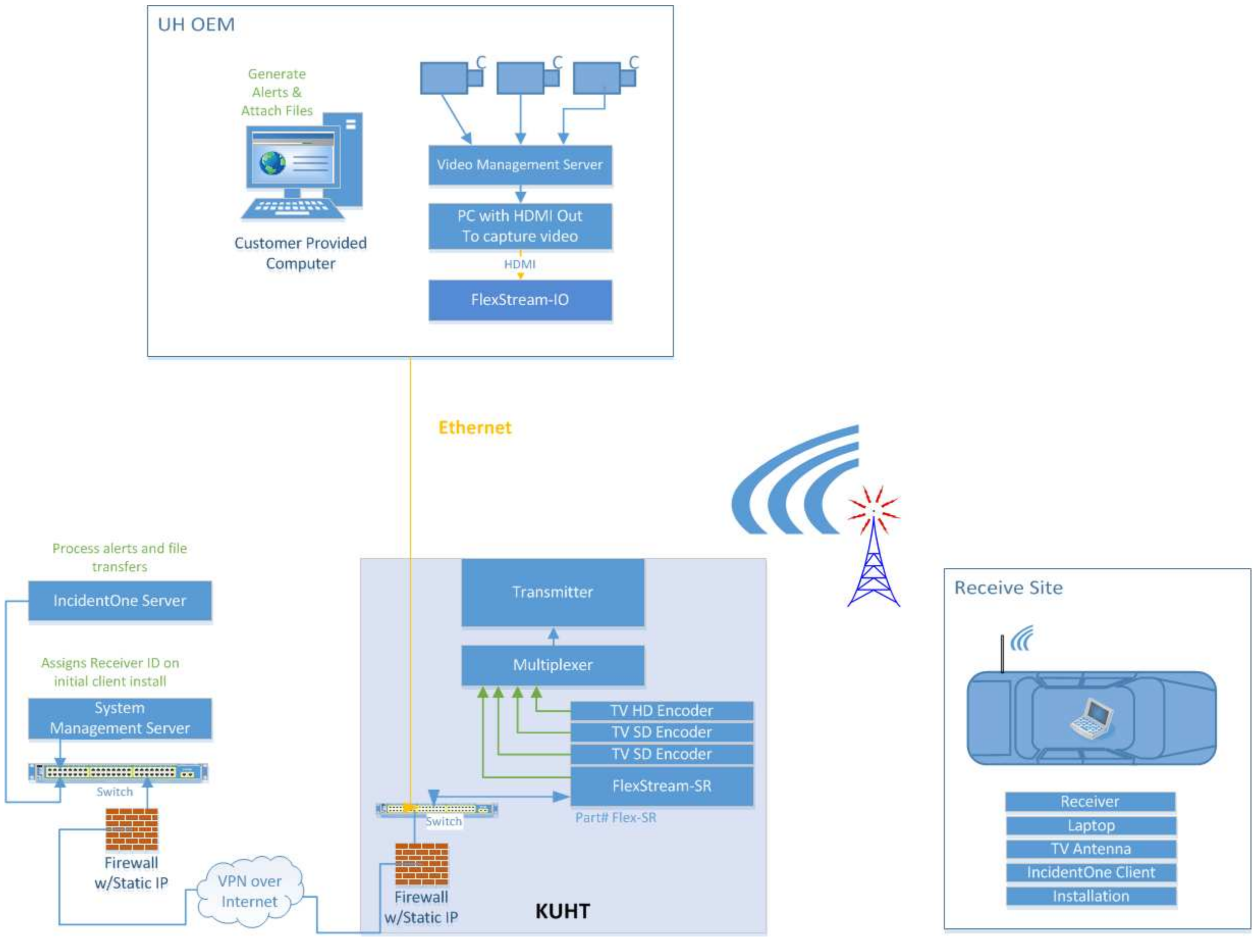


Figure C4: Current Configuration of Datacasting Enclave in Houston

As represented in Figure C4, equipment has been installed within the UH OEM that enables transmission of digital data and live video streaming from the UH OEM Video Management Server (VMS) via KUHT broadcasts. Data encoded in a portion of the KUHT broadcast stream can be received and interpreted by users with the required reception antenna, IncidentOne software and an appropriate registration. Other users, with a static IP address and behind a firewall, can access the system to broadcast data.

For the February 2016 exercise, the datacasting capability will be expanded as shown in Figure C5 to enable data, including streamed video, to be broadcast using datacasting from the City Hall Annex.

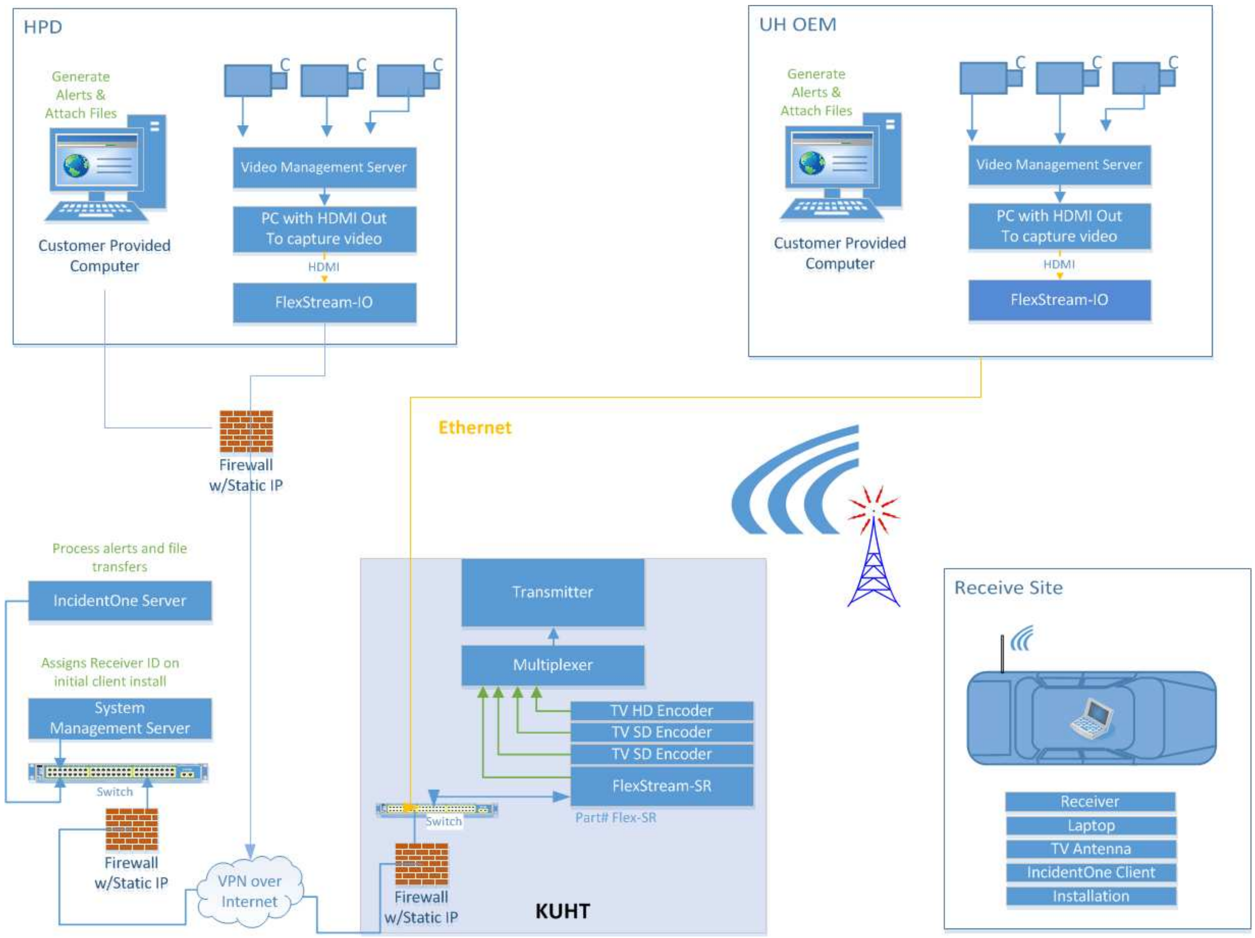


Figure C5: Expanded Datacasting Enclave for February 2016 Test

SpectraRep will configure the datacasting system over the weekend prior to test execution. Basic steps will include the following:

1) Access to the VMS will be provided via the Houston EOC.

2) An interface will be configured to transmit video streams from the Houston EOC to a dedicated computer to be used to initiate datacasting transmissions in the City Hall Annex.

3) A SpectraRep FlexStream Video I/O device will be installed at the selected site.

4) A High Definition Multimedia Interface (HDMI) will be implemented between the dedicated PC and the Flexstream I/O device.

5) A static IP address will be provided and a firewall will be established.

6) A Virtual Private Network (VPN) will be established between the HPD site and KUHT.

7) Data from the dedicated computer, including video streamed from the VMS, can be transmitted from the HPD site to KUHT for inclusion in the datacasting stream.

8) Except for real-time video, data from other terminals behind the firewall can also be included in the datacasting stream.

As mentioned earlier, representatives of JHU/APL will travel to Houston on Monday, February 8. Representatives of SpectraRep will travel on Friday, February 5. Final equipment Checkout is scheduled to be performed on February 9. The Datacasting Enclave Load Test will be performed on February 10. An end-to-end system test is scheduled for February 11. In order to verify the enclave, representatives of SpectraRep and JHU/APL will execute the following procedures:

1. 0900–1000: Test Coordination Meeting. The test team and key stakeholders will meet at the Houston City Hall Annex at 900 Bagby Street, Houston, TX 77002.

2. 0900–1500: A teleconference line will be set up. The open line will support coordination with test members and stakeholders not present at the City Hall Annex. Operators with datacasting receiver equipment can call using the line to request data transmissions.

3. A test team laptop will be installed in the test location at the City Hall Annex. The laptop will have SpectraRep IncidentOne Software and will be a registered recipient for all tests of the datacasting system during the week of February 8-12. Test team members will have the ability to monitor all data transmitted via datacasting to ensure receipt and evaluate quality and delivery time.

4. On February 9, the following tests will be performed:

    a. Connectivity between the City Hall Annex and KUHT will be verified. Data and real-time video will be transmitted via the datacasting system. Transmissions will be configured to target only the laptop in the Annex.

    b. Prospective test participants with a datacasting receiver will call and request data. A test message and additional data will be transmitted upon request and the participant will verify receipt.

    c. Test team members will work with representatives of the City of Houston to identify appropriate surveillance camera video for use in the tests.

    d. Test team members can use the two laptops (i.e., the laptop used to initiate datacasting transmissions and the laptop used to receive datacasting transmissions) to verify performance of the datacasting system. Data delivery times will be quantitatively measured. Test team members will make qualitative evaluation of the relative quality of the input and output video streams.

5. 1100–1900: Representatives of JHU/APL and SpectraRep will "troubleshoot" all receivers failing their final checkout.

6. 1100–1900: Test team members will load non-video data for transmission during the February 10 Datacasting Load Test. Data will be fictionalized to ensure that there are no privacy issues. A similar set of data will be loaded at the UH OEM.

7. 1600–1700: Wrap-up: A wrap-up meeting will be held at the City Hall Annex. The purpose of this wrap-up will be to provide status and to accept questions from Houston and Harris County stakeholders.

8. 1700–1900: JHU/APL and SpectraRep will review checkout results and verify readiness to proceed.

Stage Two Testing: PW LTE Mesh Network Interoperability (February 9-10, 2016)

As part of the test, DHS and NGA will each deploy a portable LTE cellular mesh network developed by PW. Connectivity and interoperability between these two networks (DHS and NGA) will be demonstrated. Figure C6 is a schematic representation of the test configuration for the interoperable LTE enclaves. When connected in proximity to each other, the two enclaves should automatically form a mesh network between CWS200 eNodeBs via Wi-Fi. Stage 2 testing will be executed without Internet connectivity.

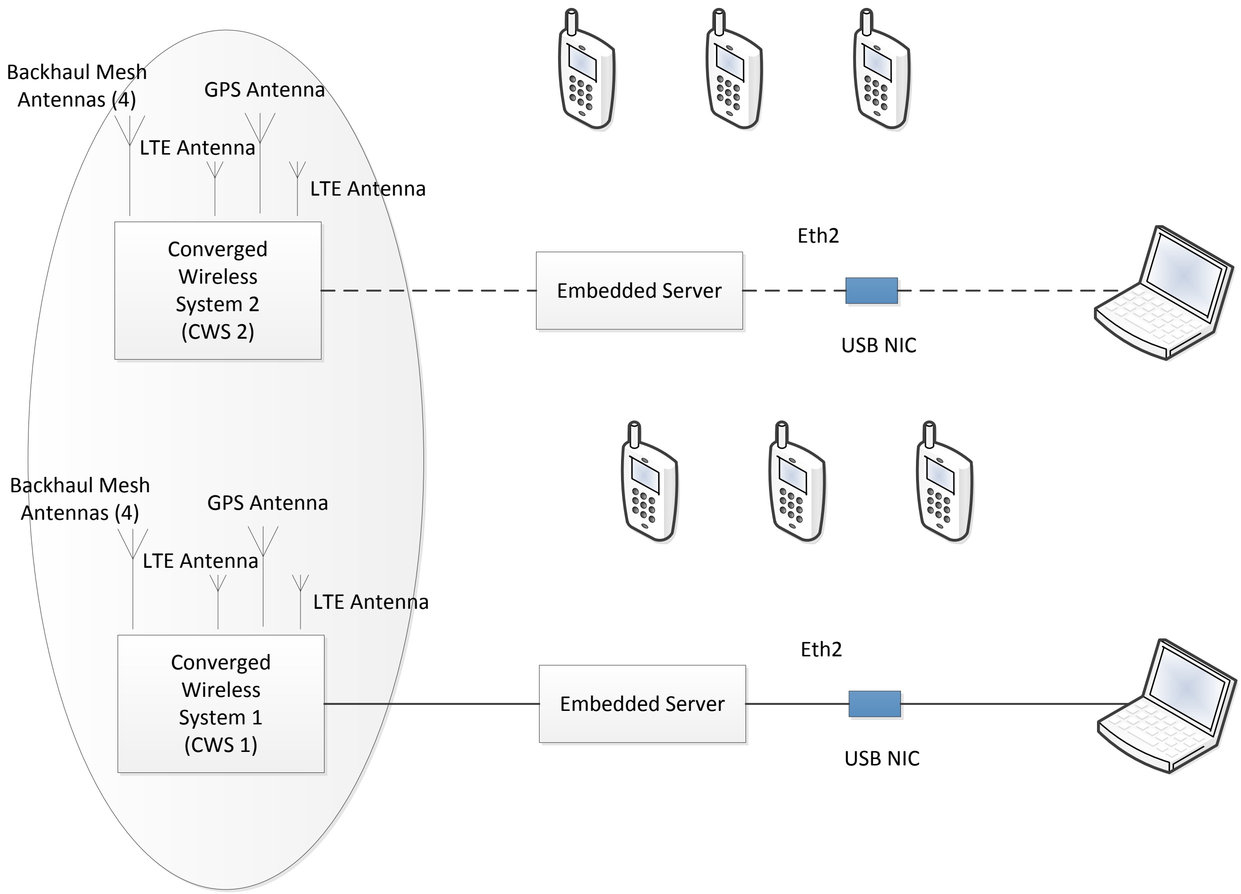


Figure C6: Two Connected Deployable LTE Enclaves

- The location for this test is in the vicinity of NRG Park. To avoid interference with the Harris County Band 14 Public Safety LTE network, the test will need to be conducted in an area outside the coverage area of this existing public safety network. NRG Park should meet this requirement. Space Requirements for the test are dependent on the distance needed by the eNodeBs to connect successfully using Wi-Fi, but should be no more than 2 km from end to end.

- The CWS is configured as follows:

  1. Two LTE antennas are connected to ports L0.0 and L0.1 on the CWS chassis.

  2. A GPS antenna is connected to the GPS Port on the CWS chassis.

3. Connect the CWS to AC power using the power cable and brick provided.

4. Four Wi-Fi backhaul mesh antennas will be connected to Ports P0.0/P0.1 and P1.0/P1.1 on the CWS Chassis.

- One embedded server is configured as follows:

1. Connect the embedded server to an AC power source via the AC Port on the box.

2. Connect the embedded server to a laptop going from a USB port on the laptop to Ethernet connection on the laptop.

3. Connect the embedded server port Eth1 to the CWS port GE1.

   - **Note: The other embedded server is not connected. The Eth1 to GE1 for one PW system shall remain disconnected.

Once the CWS and embedded server are connected, the following procedures are executed to initiate the first enclave:

1. The laptop is configured with the following IP parameters: 10.60.0.1/255.255.0.0

2. The embedded server is powered up. It should take between two and five minutes to complete. The embedded server is a XEN server running four virtual machines. Once the XEN server has finished booting, it will activate the other four virtual machines.

3. On the laptop, connect using PuTTY to each of the four virtual machines using the following credentials:

   a. Root/password.

   b. 10.60.253.249 – XEN Server.

   c. 10.60.254.241 – Content Server.

   d. 10.60.254.231 – Evolved Packet Core.

   e. 10.60.254.228 – LTE/Het-Net Access Controller.

   f. 10.60.253.228 – Element Management System for the HNG.

4. Once the Evolved Packet Core starts (10.60.254.231 – Evolved Packet Core), run the following commands:

   a. Service epc stop

   b. Service epc start

5. Prior to powering up the CWS, perform the following:

a. Plug in the LTE antennas.

b. Plug in GPS antenna.

c. Place Terminators on unused antenna terminals.

6. Power on the CWS. When the blue light stops blinking and remains in a constantly illuminated state, the connection between the CWS and HNG has been established.

7. Check the status of the LTE Cell as follows:

   a. In the PuTTY session opened in step 5, enter the PW command line of the HNG by typing "cli" upon receiving a prompt from the Linux shell.

   b. Enter the following command: "show access nodes cws oper-data"

   c. Four CWS units should be displayed; only one should be in a "*connected*" state.

   d. Enter the following command: "show access nodes cws lte cell oper-data"

   e. Four CWS units should be displayed; only one should be in an "*InService*" state.

8. Power on the Sonim handsets.

Once the LTE cell has been established, the test team will verify the connectivity within the cell. During the test, the following capabilities will be verified:

1. Download VoIP client and make call.

2. Situation Awareness and Collaboration Application (MAGE) Testing:

   a. From an Android (Sonim) handset that does not have the MAGE client installed, visit the MAGE Server URL (check with NGA staff during exercise for assigned URL), go to the "About" page, and click on the "Download the APK" link.

   b. Follow the instructions to complete the application installation.

   c. Follow the usage guide attached to this test plan to use MAGE.

3. Video Streaming (GLIMPSE) Testing:

   a. From an Android (Sonim) handset that does not have the GLIMPSE client installed, visit the GLIMPSE Server URL (check with NGA staff during exercise for assigned URL), go to the "About" page, and click on the "Download the APK" link.

   b. Follow the instructions to complete the application installation.

c. Open the application and configure the GLIMPSE server URL from step 1.

d. On one handset, choose the GLIMPSE application broadcast mode.

e. On a second handset, choose the GLIMPSE application subscribe mode to view the broadcast from the first handset.

Overall Schedule for Stage Two

9:00 Arrive at NRG Park.

9:00–10:00 Coordination Meeting for joint testing with DHS and NGA. Determine suitable locations for testing, and identify and coordinate testing needs in support of the planned exercise.

10:00–11:00 Stage and setup testing configuration and validate the configuration will meet testing requirements.

11:00–16:00 Conduct Planned Testing.

16:00–17:00 Post Test debriefing to share lessons learned.

High-level Joint JHU/APL & NGA Test Plan

Objective: Determine the baseline characteristics of the LTE mesh network.

1) Of the multiple CWS200s, one will be a stationary anchor and the others will be mobile.

2) Ensure that the connection between Eth1 on the embedded server and GE1 on the CWS200 is removed on any mobile configuration. The anchor CWS200 must have the cable connected for this scenario.

3) Activate both enclaves within close proximity to ensure the establishment of a mesh network and verify that both CWSs are transmitting.

4) The establishment of a mesh network is indicated by a solid BLUE status light on the front panel of the Mobile CWS.

5) Once mesh establishment has been verified, proceed to move away from the anchor CWS in a measured fashion (both distance and sufficient wait time) to baseline the distance when the mesh network disconnects. PW will provide the time specification for CWS mesh establishment so that the wait time is long enough to confirm mesh network establishment.

6) A disconnected CWS will be indicated by a blinking status light on the Mobile CWS. Once the status light changes from a solid blue to blinking blue, note the distance and the radiation center between the mobile and stationary CWS. This will be the mesh distance.

7) Once the distance has been measured, continue to move away from the anchor CWS to ensure that the mesh is completely disconnected. Then begin approaching the stationary CWS in a measured fashion (both distance and sufficient wait time) to establish the baseline distance when the mesh network is re-established.

8) Continue to approach the anchor CWS until the blue status light on the mobile CWS turns solid, indicating mesh network establishment.

9) Once the two CWS devices form a mesh network, note the distance of the CWS unit and the radiation center of the antenna. This will be the mesh re-establishment distance.

10) Repeat if necessary, leveraging additional mobile CWS nodes and different antennas (i.e., directional hi-gain Wi-Fi) as appropriate.

Objective: Conduct Functional Tests

11) Using predetermined NGA applications, perform functional testing to validate basic capabilities using the functional verification matrix below.

Test	Result (pass/fail with quality description)
Place VoIP phonecall using Zoiper client of Asterix service between two UEs	
Collect data point in MAGE on one UE and view the collected data point on a second UE	
Visualize a UE's status in MAGE from a different UE	
Capture a video in GLIMPSE on one UE and view that video from a second UE	

12) The DHS XP7 should not be preloaded or preconfigured with NGA applications to assess requirements needed for field deployment.

13) Using the distance from the mesh network baseline, functional verification should be performed within the footprint of the individual CWS and between meshed nodes to verify that, as the End User devices move around the mesh network, service is not interrupted and the HetNET is successfully orchestrating handoffs between nodes.

14) The re-selection within the CWS footprint and CWS mesh should be validated as well.

Datacasting Enclave Load Testing

Enclave Load Testing will involve only the systems indicated in Figure C6. The objective of this part of the test Stage is to demonstrate the ability of the datacasting system to function with input from two independent agencies attempting to use the datacasting system to support simultaneous event responses. As this is a purely technical test, no operational personnel are required to provide support. The following procedures will be executed:

1. 0900–1000: Test Readiness Review. Members of the test team and key stakeholders will meet to review the results of Equipment Checkout and make a "ready to proceed" determination for the system.

2. 1200–1300: Test team and observers will deploy for the test. For this test, the test team will be deployed at the UH OEM and the City Hall Annex. A teleconference bridge will be established to provide participants an opportunity to communicate for the duration of the test.

3. 1300–1700: At approximately 1300, upon determining that all test team members and observers are deployed, the test will begin. At test initiation, test team members at UH OEM and at the City Hall Annex will initiate an event using the SpectraRep IncidentOne software. Both events will be targeted at a limited number of recipients. However, both events will target at least one test team laptop to enable both incidents to be viewed. The following tests will be executed:

    a. Load Test One, Data files:

        i. Upon instruction from the test conductor, both teams will initiate another event.

        ii. As part of the event, test team members at each datacasting test site will affix a pre-loaded set of data files.

        iii. Observers and test team members will confirm receipt of the content.

        iv. Upon instruction of the test conductor, teams will initiate another event with a second larger set of data files affixed.

        v. The process will continue until degradation is observed.

    b. Load Test Two, Video Streaming:

        i. Test team members at each datacasting test site will begin streaming video from one camera via the datacasting signal.

        ii. Observers and test team members will confirm receipt of the video and assess the quality of the video received.

iii. Upon instruction from the test conductor, an additional video stream will be added to the datacasting input.

iv. Observers and test team members will confirm receipt of the video and assess the quality of the video received.

v. The procedures will be repeated until degradation is observed.

4. 1600–1700: Upon completion of the test, the test team and stakeholders will meet for a wrap-up meeting.

Stage Three Testing: Deployable LTE Enclave To Local Carrier Testing (February 10, 2016)

Stage Three testing will verify the ability to connect the PW deployable LTE enclave(s) to a local carrier, either a commercial carrier or preferably the local public safety telecommunications network (i.e., the existing Harris County, TX, 700-MHz LTE network). The team will test both pathways during the test.

Upon completion of Stage One Testing of the PW LTE enclave, there should be sufficient connectivity to transmit data from the LTE enclave to the location at the City Hall Annex where the datacasting test site has been established. Figure C7 contains a representation of this capability.

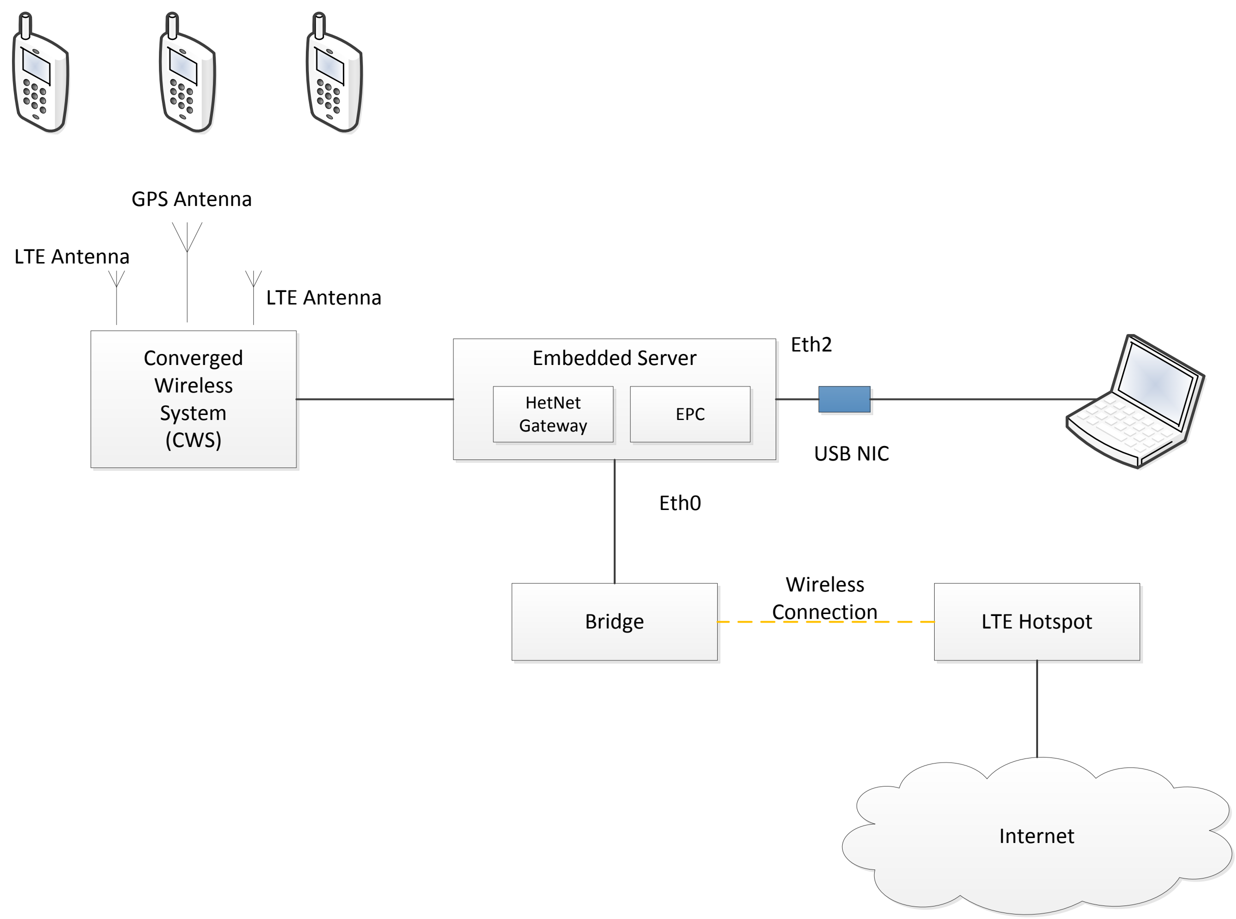


Figure C7: Test Configuration for LTE Enclave to Local Carrier Connectivity Test

The CWS is configured as follows:

1. Internet Routable connection for the DHS PW system will be provided by a wireless bridge connected via Wi-Fi to a commercial LTE Hotspot.
2. Two LTE antennas are connected to ports L0.0 and L0.1 on the CWS chassis.
3. A GPS antenna is connected to the GPS Port on the CWS chassis.

4. Connect the CWS to AC power using the power cable and brick provided.

The embedded server containing an Evolved Packet Core and a HetNet Gateway is configured as follows:

1. Connect the embedded server to an AC power source via the AC Port on the box.

2. Connect the embedded server to a laptop going from a USB port on the laptop to Ethernet connection on the laptop.

3. Connect the embedded server to the bridge via the port labeled Eth0.

4. Connect the embedded server port Eth1 to the CWS port GE1.

Once the CWS and embedded server are connected, the following procedures are executed to initiate the first enclave:

1. The laptop is configured with the following IP parameters: 10.60.0.1/255.255.0.0

2. The embedded server is powered up. It should take between two and five minutes to complete. The embedded server box is a XEN server running four virtual machines. Once the XEN server has finished booting, it will activate the other four virtual machines.

3. On the laptop, connect using PuTTY to each of the four virtual machines using the following credentials:

    a. Root/password.

    b. 10.60.253.249 – XEN Server.

    c. 10.60.254.241 – Content Server.

    d. 10.60.254.231 – Evolved Packet Core.

    e. 10.60.254.228 – LTE/Het-Net Access Controller.

    f. 10.60.253.228 – Element Management System for the HNG.

4. Once the Evolved Packet Core starts (10.60.254.231 – Evolved Packet Core), run the following commands:

    a. Service epc stop

    b. Service epc start

5. Prior to powering up the CWS, perform the following:

    a. Plug in the LTE antennas.

    b. Plug in GPS antenna.

c. Place Terminators on unused antenna terminals.

6. Power on the CWS. When then blue light stops blinking and remains in a constantly illuminated state, the connection between the CWS and HNG has been established.

7. Check the status of the LTE Cell as follows:

    a. In the PuTTY session opened in step 5, enter the PW command line of the HNG by typing "cli" upon receiving a prompt from the Linux shell.

    b. Enter the following command: "show access nodes cws oper-data".

    c. Four CWS units should be displayed; only one should be in a "*connected*" state.

    d. Enter the following command: "show access nodes cws lte cell oper-data".

    e. Four CWS units should be displayed; only one should be in an "*InService*" state.

8. Power on the Sonim handsets.

When the handsets are powered up and connected, enclave performance will be verified as follows:

1. Connect to the Internet from a browser on one of the Sonim handsets.

2. Download VoIP client and make call.

3. Situation Awareness and Collaboration Application (MAGE) Testing:

    a. From an Android (Sonim) handset that does not have the MAGE client installed, visit the public MAGE Server URL (check with NGA staff during exercise for assigned URL), go to the "About" page and click on the "Download the APK" link.

    b. Follow the instructions to complete the application installation.

    c. Follow the usage guide attached to this test plan to use MAGE.

4. Video Streaming (GLIMPSE) Testing:

    a. From an Android (Sonim) handset that does not have the GLIMPSE client installed, visit the public GLIMPSE Server URL (check with NGA staff during exercise for assigned URL), go to "About" page and click on the "Download the APK" link.

    b. Follow the instructions to complete the application installation.

c. Open the application and configure the GLIMPSE server URL from step 1.

d. On one handset, choose the GLIMPSE application broadcast mode.

e. On a second handset, choose the GLIMPSE application subscribe mode to view the broadcast from the first handset.

Overall Schedule for Stage Three

9:00 Arrive at NRG Park

9:00–10:00 Coordination Meeting for joint testing with DHS and NGA. Determine suitable locations for testing, and identify and coordinate testing needs in support of the planned exercise.

10:00–11:00 Stage and setup testing configuration and validate the configuration will meet testing requirements.

11:00–16:00 Conduct Planned Testing.

16:00–17:00 Post Test debriefing to share lessons learned.

High-level JHU/APL Test Plan

Objective: Determine the baseline performance of the connected network and app server access.

1) Measure the throughput of the data connection at the commercial carrier hotspot, wireless bridge, and the Band 14 UE using the commercial Speedtest app and/or Speedtest website, as appropriate.

2) Confirm that sufficient samples are obtained to quantify the performance characteristics of nodes.

3) Perform connectivity and functional test to app clients/services, such as UStream, the SpectraRep app and/or other services.

    a. Connectivity to the UStream and/or SpectraRep app servers or other services will be verified.

    b. Confirm that a live video stream can be sent from the field using the Sonim XP7 device provisioned to work on the PW LTE network to the server associated with the app used to stream the live footage.

    c. Validate that the live video footage arrives at the server for retrieval.

    d. Measure subjective video quality of the video at the server side.

Stage Three Extended Testing: Deployable LTE Enclave to Public Safety LTE Enclave (February 10, 2016)

An NGA LTE Enclave connecting to the Harris County Band 14 Public Safety Network has been proposed. Detailed procedures for this configuration will be provided by PW. Figure C8 contains a schematic representation of the test configuration. NGA will execute configuration of the enclave to support this test. This scenario attempts to demonstrate that a central HetNet Gateway tied into an operator's Evolved Packer Core can connect to remote CWS node(s) and establish a LTE network.

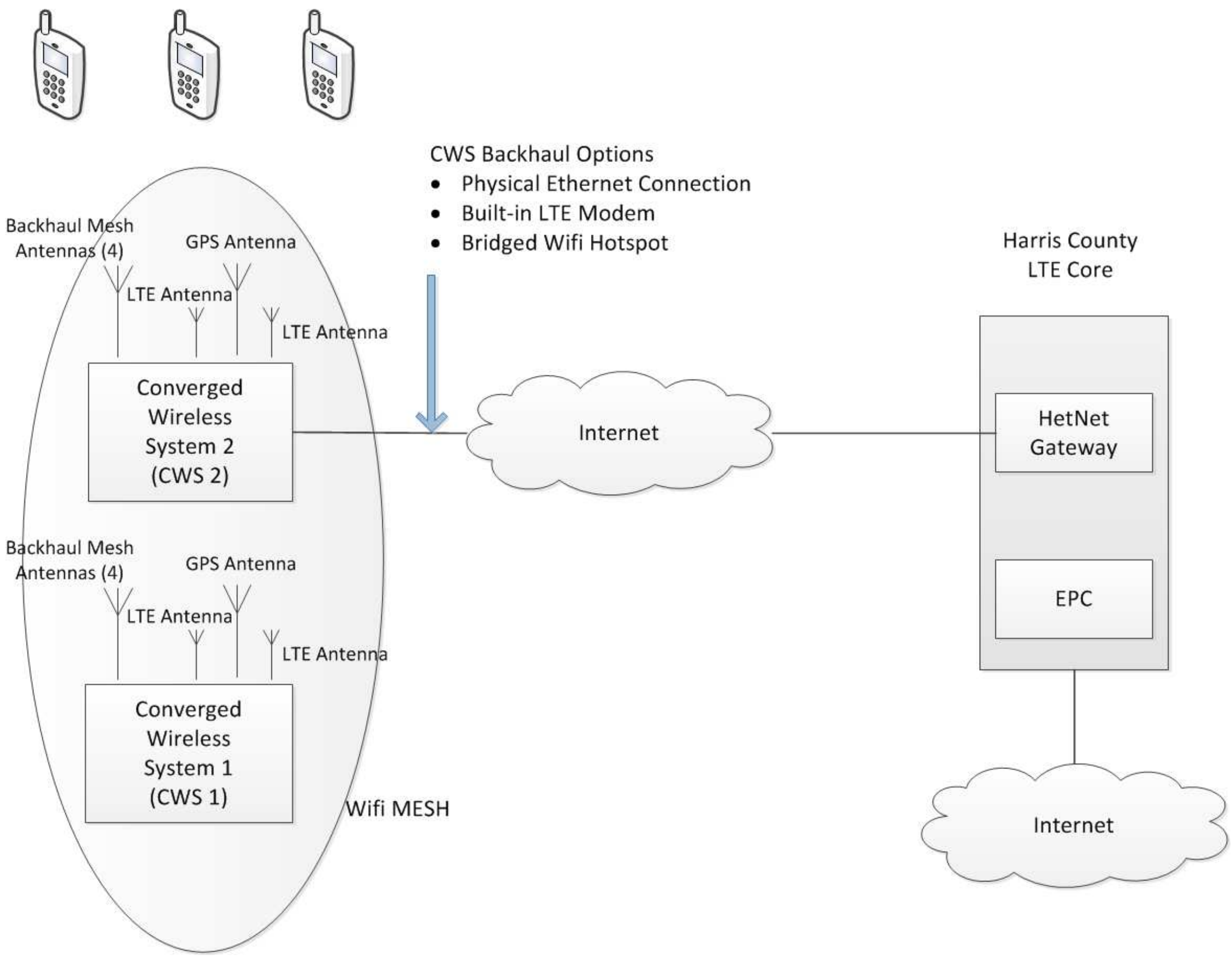


Figure C8: LTE Enclave Connectivity Testing to Harris County Band 14 to HPD Using LTE from Gateway CWS

High-level Test Plan

Objective: Validate connectivity of the remote PW CWS node to the Harris County LTE network using the PW HetNet Gateway located at the Harris County Core. PW will provide instructions of setting up this test configuration.

1) Confirm that the SIM provisioned to be used for the Test Network is installed in the Sonim XP7 under test.

2) Verify that the remote LTE network is connected to the Harris County LTE network.

3) Confirm that the SIM provisioned to be used for PW Test Network is installed. Attempt to attach to the network created by the CWS node. The device under test (DUT) should not attach to a network.

4) Install the SIM provisioned for the Harris County Band 14 LTE network and verify that the DUT attaches to the network (Check for Alpha Tag: XZY).

5) If connection to Harris County LTE core is successfully established, then basic connectivity testing should be performed (Note: May need to manually change APN on the Sonim Device).

    a. Perform connectivity and functional test to app clients/services, such as UStream, the SpectraRep app and/or other services.

        i. Connectivity to the UStream and/or SpectraRep app servers or other services will be verified.

        ii. Confirm that a live video stream can be sent from the field using the Sonim XP7 device provisioned to work on the PW LTE network to the server associated with the app used to stream the live footage.

        iii. Validate that the live video footage arrives at the server for retrieval.

        iv. Measure subjective video quality of the video at the server side.

    b. Situation Awareness and Collaboration Application (MAGE) Testing:

        i. From an Android (Sonim) handset that does not have the MAGE client installed, visit the public MAGE Server URL (check with NGA staff during exercise for assigned URL), go to the “About” page and click on the “Download the APK” link.

        ii. Follow the instructions to complete the application installation.

        iii. Follow the usage guide attached to this test plan to use MAGE.

    c. Video Streaming (GLIMPSE) Testing:

        i. From an Android (Sonim) handset that does not have the GLIMPSE client installed, visit the public GLIMPSE Server URL (check with NGA staff during exercise for assigned URL), go to the “About” page and click on the “Download the APK” link.

        ii. Follow the instructions to complete the application installation.

        iii. Open the application and configure the GLIMPSE server URL from step 1.

        iv. On one handset, choose the GLIMPSE application broadcast mode.

v. On a second handset, choose the GLIMPSE application subscribe mode to view the broadcast from the first handset.

6) If connection to the Harris County LTE core is successfully established, basic HetNet orchestration function of the CWS should be verified.

Stage Four Testing: End-to-end Deployable LTE to Harris County on site LTE to Datacasting Connectivity Testing (February 11, 2016)

The final stage is an end-to-end test of the entire datacasting architecture in an operational context. Figure C9 contains a schematic for the test configuration. Note that three potential "paths" have been identified. Depending on the results of Stage 3 tests, the test team will execute tests using all three paths. However, only one path is required for a successful test.

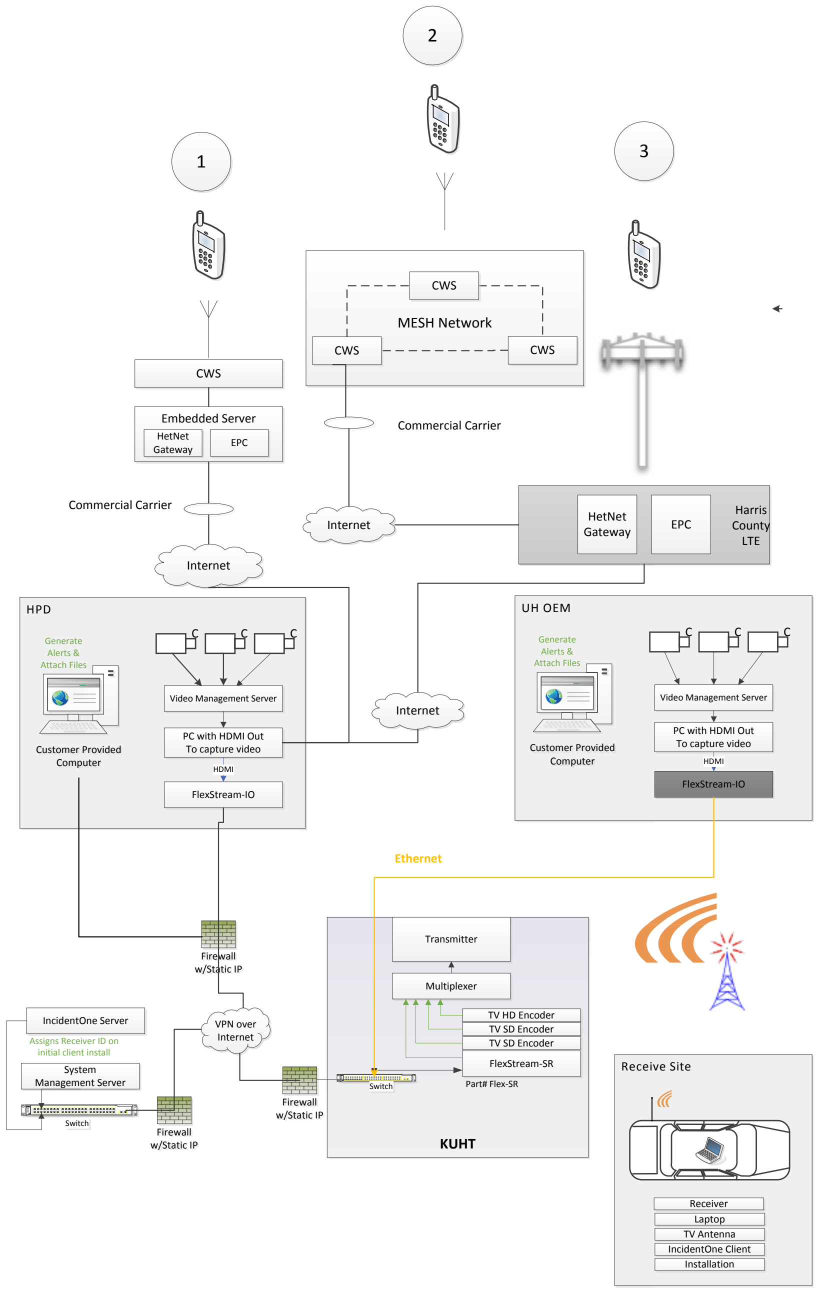


Figure C9: Stage 4 (End-to-end) Test Configuration

The three paths (Figure C9) to be tested are:

1. Handheld to LTE Deployable Enclave to Internet to HPD/Datacasting Enclave to Datacasting Recipients. Instructions for setting up this test configuration are outlined in the Stage One Test procedures.

    a. Test Plan:

        i. Establish the baseline available bandwidth of the commercial LTE connection.

        ii. Load an Application on the DHS XP7 device capable of streaming live footage from the remote PW enclave, from a location away from the Harris County LTE network.

        iii. At a prearranged time, start the streaming application and capture live footage to be transmitted to a location suitable for the datacast system to capture and transmit the footage over the datacast network.

        iv. Test team members at the City Hall Annex will initiate an event using the SpectraRep IncidentOne software. Test team members will append files to the event broadcast. Receipt of the event notification and the attached files will be verified by the test team.

        v. Test team members will broadcast video from the HPD VMS and transmitted via the enclave using the datacasting system. Test team members will verify receipt.

        vi. The test will be repeated as necessary.

2. Handheld to LTE Deployable Enclave to Harris County Band 14 Public Safety Network to HPD/Datacasting Enclave to Datacasting Recipients. Instructions for setting up this test configuration are outlined in the Stage Three Extended Test procedures.

    a. Test Plan:

        i. Load Application on a DHS Sonim XP7 Device capable of streaming live footage from the Harris County LTE Network.

        ii. Replace existing test SIM on the DHS XP7 with that which has been provisioned to work on the Harris County LTE Network.

        iii. At a prearranged time, start the streaming application and capture live footage to be transmitted to a location suitable for the datacast system to capture and transmit the footage over the datacast network.

        iv. Test team members at the City Hall Annex will initiate an event using the SpectraRep IncidentOne software. Test team members will

append files to the event broadcast. Receipt of the event notification and the attached files will be verified by the test team.

v. Test team members will broadcast video from the HPD VMS and transmitted via the enclave using the datacasting system. Test team members will verify receipt.

vi. The test will be repeated as necessary.

3. Handheld to Harris County Band 14 Public Safety Network to HPD/Datacasting Enclave to Datacasting Recipients.

    a. Test Plan:

        i. An officer (or other person designated by HPD/City of Houston) will use a handheld LTE device connected to the Harris County Public Safety Band 14 LTE Network (within the coverage area of Harris County) and begin streaming data to the test team location at the City Hall Annex (900 Bagby Street).

        ii. Test team members at the City Hall Annex will initiate an event using the SpectraRep IncidentOne software. Test team members will append files to the event broadcast. Receipt of the event notification and the attached files will be verified by the test team.

        iii. Test team members will broadcast video from the HPD VMS and transmitted via the enclave using the datacasting system. Test team members will verify receipt.

        iv. The test will be repeated as necessary.

Houston Datacasting/LTE Testing Agenda

Team 1: City Hall Annex – 900 Bagby Street, Houston, TX 77002

	2/8	2/9	2/10	2/11	2/12
0800		Travel to City Hall Annex	Travel to City Hall Annex	Travel to City Hall Annex	Follow-up: No Tests explicitly planned; day reserved for follow-up meetings and tests as required
0900	Travel to Houston	Daily Coordination Meeting	Daily Coordination Meeting	Daily Coordination Meeting	
1000		Datacasting Enclave Testing	Datacasting Enclave Testing		
1100				End-to-End Tests	
1200			Travel to UH OEM		
1300			Datacasting Load Tests		
1400					
1500					
1600	JHU/APL and SpectraRep coordination	Daily Debrief	Daily Debrief	Daily Debrief	
1700					Travel to DC/Baltimore
1800		JHU/APL and SpectraRep coordination	JHU/APL and SpectraRep coordination	JHU/APL and SpectraRep coordination	
1900					
2000					

Team 2: NRG Park – 1 Reliant Pkwy, Houston, TX 77054

	2/8	2/9	2/10	2/11	2/12
0800		Travel to NRG Park	Travel to NRG Park	Travel to City Hall Annex	Follow-up: No Tests explicitly planned; day reserved for follow-up meetings and tests as required
0900	Travel to Houston	Daily Coordination Meeting	Daily Coordination Meeting	Daily Coordination Meeting	
1000		Stage 1 Testing	Stage 2 Testing continued	Travel to NRG Park	
1100				End-to-End Tests	
1200			Stage 3 Testing		
1300					
1400		Stage 2 Testing			
1500					
1600	JHU/APL and SpectraRep coordination	Daily Debrief	Daily Debrief	Daily Debrief	
1700					Travel to DC/Baltimore
1800		JHU/APL and SpectraRep coordination	JHU/APL and SpectraRep coordination	JHU/APL and SpectraRep coordination	
1900					
2000					

Schedule Details:

February 8

0800–1500: Travel to Houston: Representatives of JHU/APL will arrive in Houston on February 8; SpectraRep will arrive in Houston on February 5.

1600–1800: JHU/APL and SpectraRep Coordination: JHU/APL and SpectraRep will meet to coordinate efforts for the remainder of the week. SpectraRep will provide a summary of

progress made during the week. Both JHU/APL and SpectraRep will make modifications to the schedule if required.

February 9

0900: Daily Coordination Meeting: A daily coordination meeting will be held. A phone bridge will be set up to enable the test teams to deploy at both the City Hall Annex and NRG Park.

1000–1400: Stage One Testing at NRG Park: JHU/APL and NGA will execute Independent Enclave Testing of the PW deployable LTE system. (J. Chang, M. Gaither)

1000–1600: Stage One Testing at City Hall Annex: JHU/APL and SpectraRep will execute Independent Enclave Testing of the expanded datacasting enclave. (D. Syed, M. O'Brien)

1400–1600: Stage Two Testing at NRG Park: JHU/APL and NGA will execute mesh Enclave Testing of the PW deployable LTE system. (J. Chang, M. Gaither)

1600–1700: Daily Debrief. A daily debrief will be conducted. All stakeholders will be invited.

1800–2000: JHU/APL and SpectraRep Coordination: JHU/APL and SpectraRep will meet to coordinate efforts for the remainder of the week. The two organizations will make modifications to the schedule based upon the day's results if required.

February 10

0900: Daily Coordination Meeting: A daily coordination meeting will be held. A phone bridge will be set up to enable the test teams to deploy at both the City Hall Annex and NRG Park.

1000–1600: Stage Two and Three Testing at NRG Park: JHU/APL and NGA will execute Independent mesh testing of the PW deployable LTE system and demonstrate connectivity to local networks. (J. Chang, M. Gaither)

1000–1200: Stage One Testing at City Hall Annex: JHU/APL and SpectraRep will execute Independent Enclave Testing of the expanded datacasting enclave. (D. Syed, M. O'Brien)

1200–1300: Travel to UH OEM: JHU/APL representatives will travel to UH OEM to support load tests (D. Syed, M. Gaither)

1300–1600: Datacasting Load Testing at City Hall Annex and UH OEM: JHU/APL and SpectraRep will execute datacasting load tests. (D. Syed, M. Gaither: UH OEM; M. O'Brien: City Hall Annex)

1600–1700: Daily Debrief. A daily debrief will be conducted. All stakeholders will be invited.

1800–2000: JHU/APL and SpectraRep Coordination: JHU/APL and SpectraRep will meet to coordinate efforts for the remainder of the week. The two organizations will make modifications to the schedule based upon the day's results if required.

February 11

0900: Daily Coordination Meeting: A daily coordination meeting will be held. A phone bridge will be set up to enable the test teams to deploy at both the City Hall Annex and NRG Park. However, for this meeting, it is envisioned that the whole team will be assembled.

1000–1100: Members of the test team attending the meeting at the City Hall Annex will travel back to NRG Park. (J. Chang, M. Gaither)

1100–1400: Stage Four Testing at City Hall Annex and NRG Stadium: (D. Syed, M. O'Brien: City Hall Annex; J. Chang, M. Gaither: NRG Park)

1600–1700: Daily Debrief. A daily debrief will be conducted. All stakeholders will be invited.

1800–2000: JHU/APL and SpectraRep Coordination: JHU/APL and SpectraRep will meet to coordinate efforts for the remainder of the week. The two organizations will make modifications to the schedule based upon the day's results if required.

February 12

0900–1500: This time is reserved for any additional testing or meetings required.

1700: Travel to DC/Baltimore: Representatives of JHU/APL will return home.

APPENDIX D: City of Houston Datacasting Deployment in Support of the Republican Presidential Candidates' Debate (February 25, 2016)

Datacasting equipment used to support the February 9-11, 2016, tests remains installed at the Houston Public Media KUHT broadcasting station and at the UH OEM for operational use by their staff. Additional functionality was added to expand its use by HPD and the City of Houston. On February 25, 2016, the University of Houston hosted a Republican Presidential Candidates' Debate. Multiple stakeholders [including UH OEM, the City of Houston Emergency Operations Center (EOC), HPD and Houston Fire Department (HFD)] participated in the coordination of security for this event. During the debate, the SpectraRep datacasting system was used to provide situational awareness to both the UH OEM and the City of Houston. This deployment served as an opportunity to test the system in a "real-world" scenario (including load testing), and to gather feedback on its use and potential improvements. Staff from the Johns Hopkins University Applied Physics Laboratory (JHU/APL) observed datacasting system use and gathered post-event feedback from the end users.

During the debate, the datacasting system was operated independently by (i.e., video was broadcasted from) two organizations: UH OEM and the City of Houston EOC. JHU/APL staff had access to observe operations in the City of Houston EOC only; they did not have access to the UH OEM. The Houston EOC provided targeted real-time video transmissions to three end-users: the City of Houston EOC (via their situational awareness display wall), an HPD mobile command post on site at the UH debate location and an HFD mobile unit. Figures D1, D2 and D3 contain examples of these three end-user displays.

Figure D1: Datacasting Feed as Displayed in the City of Houston EOC

Figure D2: Datacasting Feed as Displayed on the HPD Mobile Command Post Vehicle Laptops

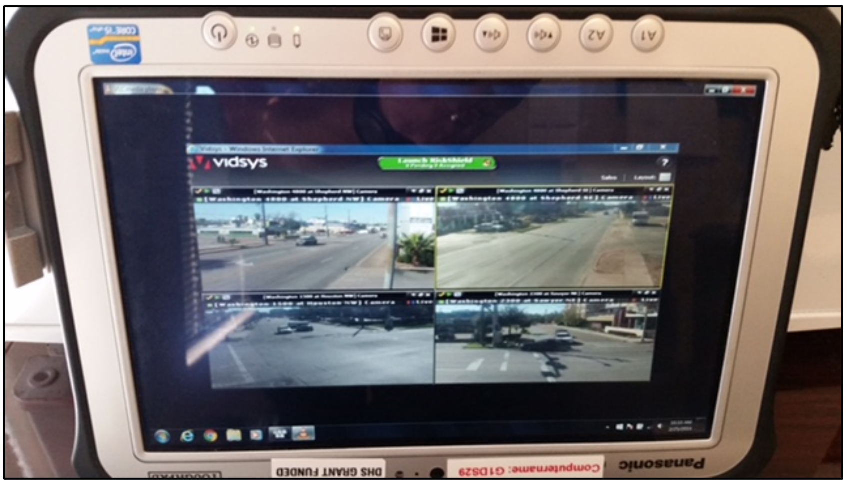


Figure D3: Datacasting Feed as Displayed on the HFD Tablet Device

The City of Houston EOC and the UH OEM independently datacast real-time video streams, each containing four video feeds (for a total of eight feeds) for the majority of the event. The organizations had an existing agreement that allowed for the shared viewing of their independent camera feeds through the SpectraRep software dashboard. Each organization could view the other's datacast camera feeds without having actual control over the other organization's cameras.

In addition to datacasting, SpectraRep had previously implemented a number of pre-processing capabilities to support the February 9-11, 2016 tests, including the ability to re-transmit video streams input to the datacasting system and screen captures of the datacasting dashboard via VPN. As stated earlier, the ability to transmit input video streams was invaluable during testing because it enabled observers at remote locations to readily compare datacasting output to the original input so they could make subjective assessments of datacasting output fidelity. Both capabilities were deemed valuable by representatives of HPD. As a result, SpectraRep enhanced these features prior to the February 2016 tests. During the Republican Presidential Primary Candidates' Debate at

the University of Houston, HPD and City of Houston EOC personnel used these features to augment what they were able to observe.

Prior to the debate, the UH OEM had only planned to exchange video feeds using the web interface. However, concurrent with the debate, there were a number of protests around the UH campus. Although the protests were peaceful (and remained so), UH OEM and HPD monitored their status. Because of this unplanned demand, the web interface became saturated. Therefore, the UH OEM had to quickly configure an additional computer to receive datacasting feeds from the City of Houston EOC. The City of Houston had aerial views of the protest and views of activity on the nearby freeway, and they streamed real-time video from their helicopter and views of freeway activity to the UH OEM. As a result of the added datacasting feed, UH OEM was able to maintain video views of the campus, nearby city streets, local buildings and the freeway, so they could monitor the movement of the protesters. For this event, the use of datacasting was limited to provision of video; no other type of content was transmitted.

Observations

The deployment of this system during the Republican Presidential Candidates' Debate was considered successful by the City of Houston. It added significant situational awareness capabilities that were otherwise unavailable to the end users. Personnel with the City of Houston, the HPD and the HFD were able to view datacast camera footage for cameras for which they did not have access by other means. Datacasting provided the HPD mobile command post with its only video communication capability with either the City of Houston or the University of Houston. The only other available video feeds were from three cameras: the mobile command post/vehicle onboard camera (attached to the vehicle), and two other field-deployable cameras near the vehicle.

City of Houston EOC users noted the ease of system setup and integration, which required minimal equipment and infrastructure and was accomplished in a short timeframe (e.g., less than 24 hours). The mobile command post was easily fitted with a datacasting receiver that allowed video viewing access via two laptops.

Staff at the UH OEM reported that the system was easy to set up and easy to use. They noted that new staff could be taught how to use the datacasting system in as little as five minutes. They also asserted that access to the helicopter video feed during the debate had greatly enhanced their situational awareness and contributed to their ability to maintain a secure environment. The two organizations had not planned to share video prior to the debate, but decided to do so the night before the debate. Even so, this video sharing solution was easily implemented in time. In this case, the presence of a datacasting capability provided rapid inter-organizational coordination and enhanced situational awareness for security personnel at the University of Houston. It also enabled the staff to avoid dispatching additional officers to the site of the protests to monitor what was happening.

There was a point during the debate during which surveillance cameras captured views of two individuals breaking off from the protest. Although UH OEM observers did not react to this event at the time, they noted later that they might have liked to forward images of these two individuals to HPD. In addition to providing an additional potential datacasting

use-case, this highlights the need for pre-existing memoranda of understanding between organizations to facilitate exchanging video data via datacasting or any other communications medium.

Users at the City of Houston EOC and UH OEM expressed a desire for greater “front-end” integration of the system. Specifically, they expressed an interest in tools that would enable them to better manipulate video feeds and more effectively access data prior to transmission. Staff at the City of Houston EOC expressed a desire to be able to switch between views containing multiple video streams and single video views. However, because the videos transmitted via datacasting, videos in the VPN feed are screen captures, so they cannot be effectively manipulated on the receiving end. Staff at the UH OEM expressed a desire to have data for transmission presented to the system in a manner so as to facilitate location of desired data. While this capability does not exist in the pilot configuration implemented in Houston, the fully operational version of the datacasting system operated by the Clark County (Nevada) School District has been fully integrated with school data servers, and a user friendly interface has been developed to enable users in the dispatch to rapidly locate and disseminate data and video during an emergency.

The preceding issues are not specific to datacasting; they are ubiquitous to all telecommunications systems. As public safety telecommunications capabilities are expanded, especially with the potential nationwide adoption of FirstNet, there will be an increased need for capabilities that facilitate access and manipulation of data for transmission. Public Safety agencies need to consider not only the capabilities of their telecommunications technology, but also how it would be integrated into the supporting infrastructure.

The UH OEM staff expressed an interest in installing IncidentOne software on all their computers. They requested more instruction manuals to help train additional staff on the system. Because of the ease of installation and use, UH OEM staff expressed the belief that, with more manuals, they could rapidly train additional staff to use the system. Manuals have not been provided to date because the configuration installed in Houston is still in its pilot state. A permanent installation would require some level of integration to meet UH OEM needs.

SpectraRep is continuing to incorporate end-user feedback into the improvement of its software and system design, and will be supporting additional upcoming events in Houston with the deployment of this datacasting system.

APPENDIX E: List of Acronyms and Abbreviations

3GPP	Third-Generation Partnership Project
3GPP2	Third-Generation Partnership Project 2
4G	Fourth-Generation
8-VSB	Eight-level Vestibule Sideband
AAC	Advance Audio Coding
ACK/NAC	Acknowledged/Not Acknowledged
ANR	Automatic Neighbor Relations
ATSC	Advanced Television Systems Committee
CAP	Common Alerting Protocol
CCTV	Closed-Circuit Television
CDMA	Code Division Multiple Access
CLI	Command Line Interface
COTS	Commercial Off-the-Shelf
CWS	Converged Wireless System
DHS	Department of Homeland Security
DTV	Digital Television
DUT	Device Under Test
EDGE	Enhanced Data Rates for GSM Evolution
eNodeB	Evolved Node B
EPC	Evolved Packet Core

E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FEC	Forward Error Correction
FirstNet	First Responder Network Authority
FRG	First Responders Group
GEOINT	Geospatial Intelligence
GOTS	Government Off-the-Shelf
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HetNet	Heterogeneous Network
HIPAA	Health Insurance Portability and Accountability Act
HNG	Heterogeneous Network Gateway
HPD	Houston Police Department
HSPA	High-Speed Packed Access
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
JHU/APL	The Johns Hopkins University Applied Physics Laboratory
LAC	LTE Access Controller
LAN	Local Area Network
LTE	Long-Term Evolution
MAGE	Mobile Analytic GEOINT Environment

MPEG	Motion Picture Experts Group
MPEG-2	Motion Picture Experts Group 2
NGA	National Geospatial-Intelligence Agency
NPSBN	Nationwide Public Safety Broadband Network
NTIA	National Telecommunications and Information Administration
OIC	Office for Interoperability and Compatibility
PDN	Packet Data Network
P-GW	PDN Gateway
PID	Packet Identifier
PSCR	Public Safety Communications Research Program
PSIP	Program and System Information Protocol
PTT	Push-To-Talk
RAN	Radio Access Network
RAT	Radio Access Technology
RC	Radiation Center
RNC	Radio Network Controller
RSRP	Reference Signal Received Power
S&T	Science and Technology Directorate
SIM	Subscriber Identity Module
SMLA	Spectrum Manager Lease Agreement

SON	Self-Organizing Network
TCP/IP	Transition Control Protocol/Internet Protocol
TDMA	Time-Division-Multiple Access
TV	Television
UDP/IP	User Datagram Protocol/Internet Protocol
UE	User Equipment
UHF	Ultrahigh Frequency
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
VHF	Very High Frequency
VM	Virtual Machine
VMS	Video Management Server
VPN	Virtual Private Network
VQiPS	Video Quality in Public Safety
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access