On The Performance Of CBRS Fixed Wireless Access: Coverage And Capacity Field Study

A Technical Paper prepared for SCTE•ISBE by

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Table of Contents

Title **Page Number**

Table of Contents 2

Abstract 5

Introduction 5
1.1. Citizen Broadband Radio Services CBRS 5
1.2. Fixed Wireless Access (FWA) 6
1.2.1. CBRS FWA Opportunities 6
1.2.2. CBRS FWA Challenges 7
1.3. Charter CBRS FWA Trials and Inverstigations 7
1.4. Paper Structure 7

Network Architecture 8

Technology Description 11
1.1. LTE Equipment Specification 11

Test Results 12
1.1. Denver Trial – Hilly Terrain 12
1.1.1. Coverage in Hilly Terrain 13
1.1.2. Capacity in Hilly Terrain 19
1.2. Tampa Trial – High Foliage 27
1.2.1. Coverage in High Foliage – LTE CBRS 27
1.2.2. Coverage in High Foliage – Proprietary CBRS and 5GHz 31
1.3. Coldwater Trial – Snow and Rain 33
1.3.1. Snow and Rain Effect on CBRS 33
1.3.2. Beamforming Gain – Coverage Test 36
1.3.3. CBRS+5GHz Radio Prototype 37
1.4. Lexington Trial – User Experience 39

Conclusion 39

Abbreviations 40

Bibliography & References 41

List of Figures

Title **Page Number**

Figure 1 – CBRS Band 48 Sharing Framework 6
Figure 2 - LTE Network Architecture 8
Figure 3 - Charter Testing Network Architecture 9
Figure 4 - Charter Custom Built Test Van 10
Figure 5 - Denver Coverage Trial Fixed Locations 13
Figure 6 - Denver Coverage Trial DL Throughput 14
Figure 7 - Denver Coverage Trial UL Throughput 14
Figure 8 - Denver Test Point 3 Elevation Profile 15
Figure 9 - Denver Test Point 5 Elevation Profile 16
Figure 10 - Proprietary Radio DL Throughput at 25 ft CPE 17

Figure 11 - Proprietary Radio UL Throughput at 25 ft CPE 17
Figure 12 - Proprietary Radio SNR Values at 25 ft CPE 18
Figure 13 - Proprietary Radio RSSI Values at 25 ft CPE 18
Figure 14 - Denver Field Trial First Sector........ 19
Figure 15 - Participant With Major Fresnel Zone Blockage 20
Figure 16 - Participant With Minor Fresnel Zone Blockage 20
Figure 17 - Participant First Sector Throughputs 21
Figure 18 - Denver Field Trial Second Sector........ 22
Figure 19 - Participants Second Sector Throughput 23
Figure 20 - Sector Throughput with 10 CPE's at 256QAM 24
Figure 21 - Sector Throughput with 10 CPE's at 64/16QAM 25
Figure 22 - Adding 10 CPE's at 256QAM to Existing Sector - Sector Throughput = 227 Mbps 26
Figure 23 - Adding 10 CPE's at 64QAM to Existing Sector - Sector Throughput = 152 Mbps 27
Figure 24 - RSRP at 12ft and 25ft CPE Height........ 28
Figure 25- SNR at 12ft and 25ft CPE Height 29
Figure 26 - DL Throughput at 12ft and 25ft CPE Height 29
Figure 27 - UL Throughput at 12ft and 25ft CPE Height 30
Figure 28 - Modulation at 12ft CPE Height 30
Figure 29 - Modulation at 25ft CPE Height 31
Figure 30 - Proprietary CBRS and 5GHz Throughput Results for 12ft CPE 32
Figure 31 - Proprietary CBRS and 5GHz Throughput Results for 25ft CPE 32
Figure 32 - Effect of Rain on RSRP at Different CPE Heights – Cell Near 33
Figure 33 - Effect of Rain on SNR at Different CPE Heights – Cell Near........ 34
Figure 34 - Effect of Rain on Throughput at Different CPE Heights – Cell Near 34
Figure 35 - Effect of Rain on RSRP at Different CPE Heights – Mid-cell........ 35
Figure 36 - Effect of Rain on SNR at Different CPE Heights – Mid-cell 35
Figure 37 - Effect of Rain on Throughput at Different CPE Heights – Mid-cell........ 36
Figure 38 - Effect of Beamforming on Throughput at Mid-cell 36
Figure 39 - Effect of Beamforming on Throughput at Cell Edge 37
Figure 40 - Prototype Radio Throughput at 12ft Receiver Height........ 38
Figure 41 - Prototype Radio Throughput at 25ft Receiver Height........ 38
Figure 42 - Various Internet Devices Running Simultaneously........ 39

List of Tables

Title **Page Number**

Table 1 – LTE eNB Equipment Specifications 11
Table 2 - LTE CPE Equipment Specifications 11
Table 3 - Proprietary Equipment Specifications........ 12
Table *4* - Denver Test Points Distance from Base Station 13
Table *5* - Denver Trial First Sector Participants RF conditions and Throughput........ 20
Table 6 - Denver Trial Second Sector Participants RF conditions and Throughput 22

Table 7 - Adding 10 CPE's at 256QAM to Existing Sector 25
Table 8 - Adding 10 CPE's at 64QAM to Existing Sector 26
Table 9 - Tampa Test Points Distance from Base Station 28
Table 10 - Tampa Test Points for Proprietary Equipment 31

Abstract

The rural broadband gap in the U.S. is real and can't be ignored. It's estimated that millions of Americans in rural communities lack broadband internet access, or at best they are underserved with limited connectiviy below the Federal Communications Commision (FCC) definition of broadband. This broadband gap is affecting various aspects of rural community's life style that ranges from lack of internet in schools to less attractive investment opportunities, and lower standard of living.

Charter, being a leader in broadband connectivity, found in the Citizens Broadband Radio Service (CBRS) band a good opportunity to provide rural broadband internet access cost effectively up to 40 miles away from its Fiber network service area.

In the past two years, Charter conducted extensive field testing and studies on CBRS and 5GHz for Fixed Wireless Access (FWA) in different markets to cover varieties of terrain, and environmental impact on the signal propagation. The testing conducted in an end-to-end setup from Customer Premisis Equipment (CPE) to the core network.

In this paper FWA field testing results, best practices, and some techniques to help expand the coverage for rural FWA are presented.

Introduction

1.1. Citizen Broadband Radio Services CBRS

CBRS isn't a new band, rather it's a new framework of using the 3.55 to 3.7 GHz frequencies. Currently the use of 3.55 to 3.7GHz also known as Band 48 is limited due to the existence of legacy users like military, satellite earth stations, and some Wireless Internet Service Providers (WISPs). The FCC made a historical decision in 2015 to expand the use of the 3.5GHz band to other users including but not limited to broadband operators, venues, public and private entities, enterprises, startups, and service providers. Historically, spectrum has been a scarce resource and is auction off to service providers for billions of dollars. The FCC goal is to democratize the band and decrease the barriers of entry for any entity wanting to use the 3.5GHz band, this is expected to spur innovation and keep the Unites States on the leading edge of telecommunications technology.

The CBRS spectrum sharing framework allows users to access the full 150MHz on dynamic basis based on priority tiers. Legacy users retain the right to use the spectrum whenever they need it. Priority Access License (PAL) holders collectively retain access to as much as 70 MHz of spectrum in a license area, with up to 40 MHz of spectrum per PAL holder. They must protect legacy users from harmful interference, but they receive protection from interference by General Authorized Access (GAA) users. GAA users collectively have access to spectrum not being used by legacy users and PAL holders in a given area, which is as much as 150 MHz of bandwidth. GAA users do not receive interference protection from legacy users or PAL holders. Spectrum Access Systems (SASs) have been created to dynamically monitor and authorize use of specific spectrum resources for PAL and GAA users based on this priority order, using geolocation databases and policy management servers[1].

The CBRS sharing framework enables multiple users to share the CBRS spectrum, and while doing so, each has use of its assigned channel based on the priority of the tier the user is in. The SASs authorize users to use the spectrum and ensure that sharing among users is fair and try to decrease interference as much as possible.

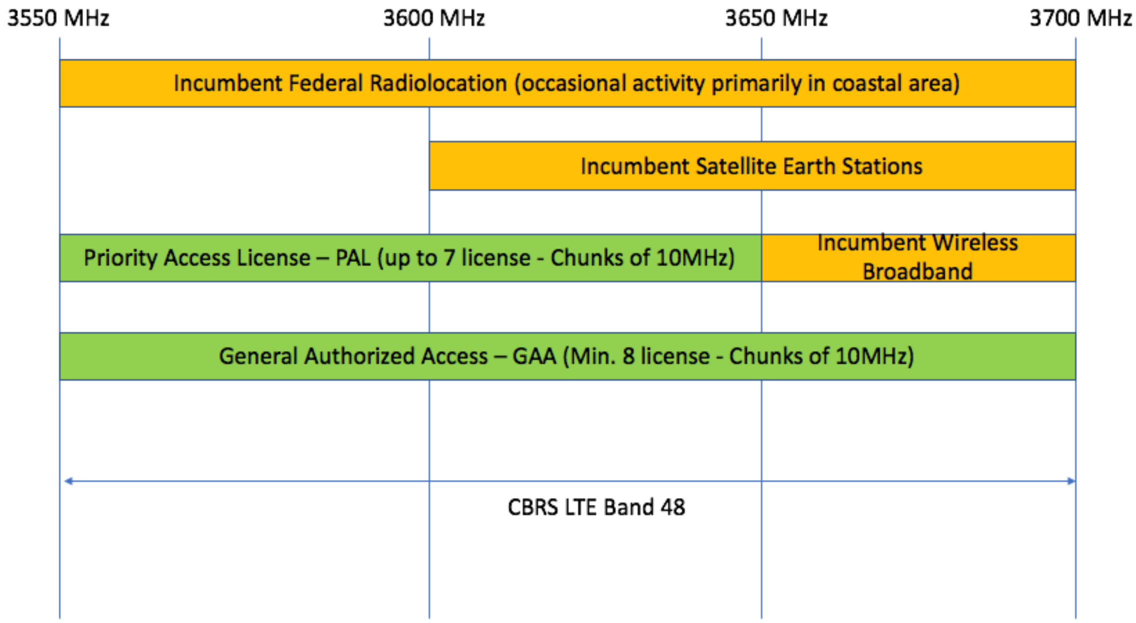


Figure 1 – CBRS Band 48 Sharing Framework

1.2. Fixed Wireless Access (FWA)

CBRS spectrum sharing has many use cases, in this paper we are focusing on FWA use case due to its relevance and importance to Charter as a leading broadband provider in the United states.

The first logical target market for FWA is rural households especially that millions of them lack broadband internet speeds. The FCC made it one of its priorities to close the digital gap in the country using various technologies. CBRS band is positioned to play a major role in closing this digital gap. The idea of FWA is simply to deliver high speed internet using wireless technologies, in the case of CBRS it's LTE or 5G or a proprietary technology. A radio is installed on a tower that delivers high speed wireless internet to CPE attached on the outside of the customers' house. The CPE has to be oriented towards the radio and acts like a cellular device in the sense that it needs a Subscriber Identification Module (SIM) card to operate.

1.2.1. CBRS FWA Opportunities

To understand the business case of FWA CBRS we have to know what's meant by rural community and broadband service. While there are many definitions for rural the U.S Census bureau defines rural as area with population density less than 100 people per square mile[2]. According to the FCC, broadband speeds are 25Mbps downlink and 3Mbps uplink[3], it's expected that the definition of broadband will increase over time to account for all the new applications and use cases requiring higher data rates.

Charter is well positioned to capture this FWA opportunity because of the vast fiber rings Charter owns cross country, the big number of Charter owned towers, and the Charter – Spectrum brand equity. The fiber will be used for backhaul while the towers used to install radios on them. The existence of fiber and towers in charter's portfolio will decrease the cost and time to roll out FWA service.

1.2.2. CBRS FWA Challenges

As with any new opportunity some challenges arise. The challenges for the CBRS FWA are creating the appropriate framework for spectrum sharing which the CBRS Alliance (OnGo) and WinnForum are addressing. Another challenge is the spectrum management by SAS, with incumbent protection and coordination for GAA and for the PAL. Ecosystem is a challenge in terms of equipment and vendors availability and variability but we are seeing big improvements with many companies interested in bringing forward CBRS equipment and competitive roadmaps. The CBRS Alliance OnGo certification created a framework for vendors certification that helps in accelerating the equipment ecosystem. Another major challenge is the limited reach of the 3.5GHz signal.

It's worth noting that CBRS FWA is not the only answer to close the digital gap and connect all underserved in this country, rather it should be one of the tools available for service providers to extend their network reach. Depending on the house hold density different options are more economic viable. For example, in dense area with high household population density fiber is more appropriate means to deliver broadband internet and in areas of very low population density and very few households solutions based on sub GHz like TV White Space (TVWS) would be more viable. Operators should have a toolbox of solutions to serve their customers and CBRS FWA should be in this toolbox.

1.3. Charter CBRS FWA Trials and Inverstigations

For the past two years Charter has been running trials across the country to investigate the opportunities and challenges of the CBRS band. The idea is to provide FWA in rural areas meeting the FCC definition of broadband. FWA isn't here to replace fiber rather to complement it.

Multiple technology including standards based and proprietary in both CBRS band and 5GHz using different morphologies have been evaluated.

The FWA trials were performed in the hilly suburbs of Denver, high foliage areas north of Tampa, mixed terrain of Bakersfield, snowy conditions in Northern Michigan, and rural farms of Kentucky. Proving that 25Mbps on the downlink and 3Mbps on the uplink can be achieved in a cell radius equal to and greater than 5 miles using Long Term Evolution (LTE) and wireless proprietary technologies.

Multiple features have been tested including carrier aggregation, multi user Multiple Input Multiple Output (MIMO), and beam forming for cell performance and capacity.

1.4. Paper Structure

The rest of this paper is organized as follows; section 1 the FWA network architecture is presented, section 2 details the technology and equipment used in the trials. In Section 3, coverage and capacity results are presented for testing in hilly terrain, high foliage, and snow and rain conditions with detailed analysis and discussion on findings. Section 4 concludes with the lessons learned from Charter FWA testing, followed with some recommendations.

Network Architecture

In this section we describe the FWA network architecture which is very much like the regular LTE network architecture as shown below. There is an Evolved Packet Core (EPC) and Radio Access Network (RAN) portions and instead of the User Equipment (UE) a CPE will be installed on the outside of the customer's home pointing towards the radio.

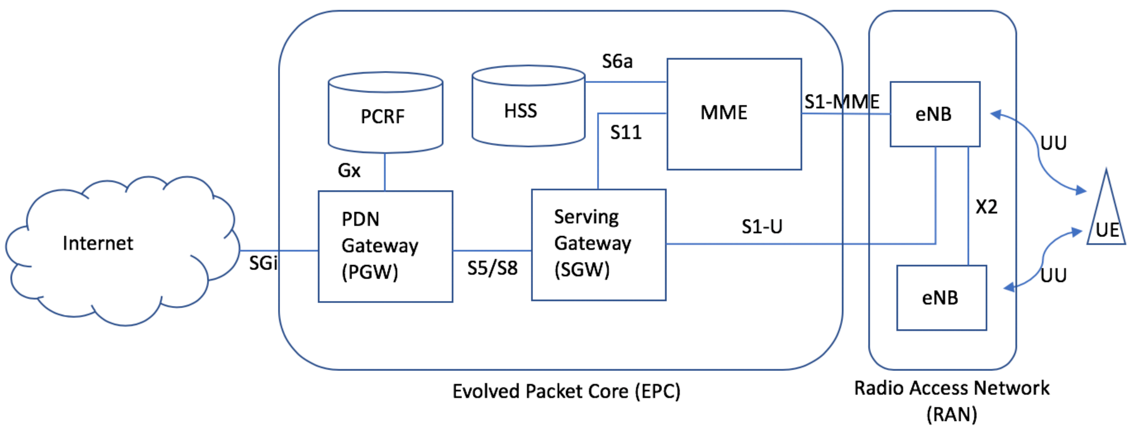


Figure 2 - LTE Network Architecture

Unlike mobile networks, some setting won't be necessary like thresholds for handovers and load balancing on X2 since the CPE will never change location.

For our testing we installed the EPC in one of Charter's data center and used Charter owned fiber as front haul to the radio as well as backhaul to the internet. In all our testing the radios were installed on Charter towers or on top of a Charter buildings. A high-level network diagram of our testing is shown below.

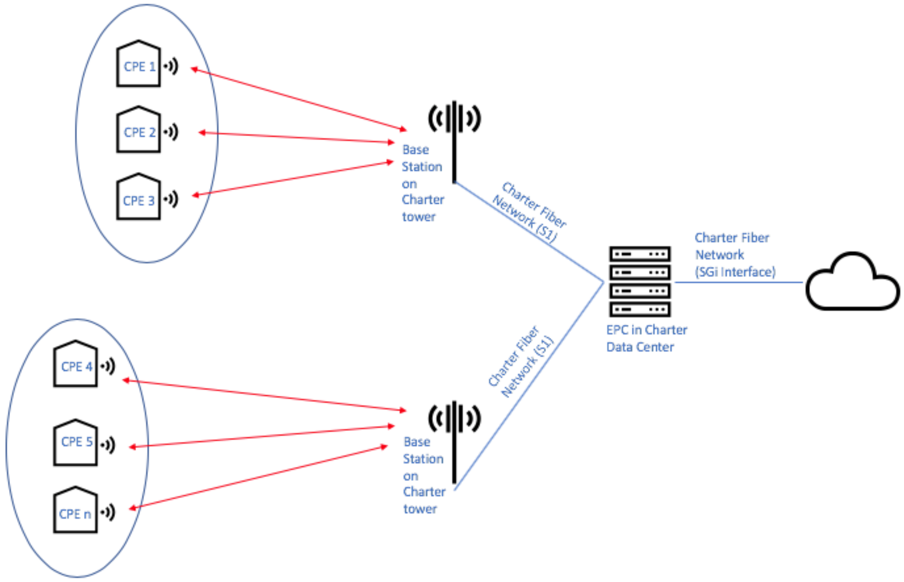


Figure 3 - Charter Testing Network Architecture

During field testing we used two custom-built test vans with hydraulic mast that goes up to 45 ft high. Each van was equipped with a test station containing state of the art computer running CPE debugging software. This software reads information from the CPE's chipset and records it, the information included Radio Frequency (RF) signal strength, Signal-to-noise ratio, Quadrature Amplitude Modulation (QAM), throughput at various layers, signaling messages, neighboring cells, frequencies, etc.

The vans were used to simulate various house heights at different locations. For the Denver employee field trial, the vans were instrumental in checking the RF signal at participants' homes prior to CPE installation. Below is a picture of one of the test vans.

Figure 4 - Charter Custom Built Test Van

To run throughput tests we used two methods; the first method is installing iperf, which is an industry standard traffic pushing software, in the data center and on mini-PC's connected to the CPE's. This setup allowed us to push downlink and uplink as Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) whenever needed and for as long as we wanted. This method accounted for the latency in the core and RAN.

The second method is using an industry standard hardware plugged into the CPE, when the hardware detects that the CPE is not being utilized for a while it runs speed tests towards a server in the internet. This second method was used only in the Denver employee field trial because the employees were using the FWA service and we didn't want to interrupt their use. This hardware ended up being useful to run speed tests when employees weren't using the FWA service. This method accounts for latency in the core, RAN, and internet.

In few instances we wanted to test the capacity of a loaded network so we forced the iperf method while employees were using the service in the peak hour.

In this paper we present the results of our testing in Denver where the terrain was very rough with many hills, in Tampa where the high trees foliage didn't allow the signal to travel far, in Cold water where we wanted to study the effect of extreme weather on the RF signal, and finally in Lexington where we ran a multi-user demo showcasing a typical household environment.

Technology Description

In this section we present the technology used in our field testing. In the CBRS band we used both LTE 3rd Generation Partnership Project (3GPP) compliant equipment and non-3GPP proprietary equipment from multiple vendors. In the unlicensed band testing we used non-3GPP proprietary equipment transmitting in the 5GHz Unlicensed National Information Infrastructure (U-NII) band.

1.1. LTE Equipment Specification

For the LTE equipment vendors, the objective was to test the technology given the different stage of CBRS equipment development. We started testing with Band 42 and 43 then finally moved to band 48 equipment.

Table 1 – LTE eNB Equipment Specifications

Specification	Value
Product	LTE Macro eNB
Band Support	B48 (3.55 – 3.7 GHz)
Carrier Aggregation	Up to 3 CA
MIMO	2x2
Frame Configuration	TDD Frame Configuration 2 Special Sub Frame 7
IBW/OBW	150 MHz / 60 MHz
Output Power	2 x 10 W
Antenna	Built-in 11dBi OR utilize external antenna
Modulation QAM DL/UL	256 / 64
BF Capability	No
CBRS Classification	CBSD CAT B

For our field testing we used both the built-in 11dBi antenna and an external 17dBi antenna at different instances. Each time we ran tests we made sure to adjust the radio power output in order to stay in compliance with the FCC power limitation rules of 47dBm/10MHz for CAT B Citizen Broadband Radio Service Device (CBSD)[4][5].

The CPE used for testing was an outdoor CAT B CBSD-CPE, in 2019 this CPE became OnGo CBRS and FCC certified, it's worth noting that when we started our trials in 2017 there was no certification process in place. The specifications of the CPE used is presented in the below table.

Table 2 - LTE CPE Equipment Specifications

Specification	Value
Product	CPE
Setup	Outdoor Mounted
Band support	B42, B43, B48
Chipset	GCT
Carrier Aggregation DL/UL	4CA / 2 CA
MIMO	Up to 4x4
LTE Category	CAT 15
Output Power	23 dBm
Antenna Gain	10 dBi

Specification	Value
Modulation QAM DL/UL	256/64
CBRS Classification	CBSD-CPE CAT B

The total Equivalent Isotropically Radiated Power (EIRP) of this CPE is 33dBm which is less than the 47dBm/10MHz FCC rules. During testing we faced some coverage limitations because we were uplink challenged. A higher power CPE would have allowed successful RACH channel at further distances from the radio thus increasing the coverage of the tested eNB. This topic is further discussed in the next section, Test Results.

The proprietary equipment used for testing came in two different version. One version works in B48 (3.55-3.7GHz) and the other in the U-NII band (5.1-5.9GHz). The proprietary equipment spec's is presented in the below table.

Table 3 - Proprietary Equipment Specifications

Specification	Value
Product	Proprietary Wireless Equipment
Band Support	B48 and U-NII 5GHz
MIMO	4x4
Duplex	TDD 50:50
EIRP	CBRS: 43 dBi 5GHz: 33 dBi
Modulation QAM DL/UL	Up to 512/512 QAM
BF Capability	Digital Beam Forming 16 active RF chains
CBRS Classification	CBSD CAT B
5GHz Classification	Point-to-Multi-Point

This equipment transmitted as point to multi-point without the need of an EPC or Core. The transmitter and receiver acted as a layer 2 switch passing the data. The EIRP in the CBRS was 43dBm/20MHz which is short of the maximum allowed by the FCC. In the U-NII band the EIRP was 33 dBm as allowed by the FCC[6]. Both transmitter and receiver had the same specifications. Modulation QAM 1024 was also tested but was hard to achieve for locations far from the transmitter due to drop in Signal to Noise Ratio (SNR).

Test Results

In this section we present the field test results from different markets we been to. We also present the reasoning of choosing to test CBRS in these markets and the purpose behind the executed testing.

1.1. Denver Trial – Hilly Terrain

The first test market was Denver, CO. The terrain in Denver is hilly with high percentage of Fresnel zone blockage which made it very challenging for coverage.

We executed two sets of tests, the first is to study the coverage in the hilly terrain environment and the second is to investigate the capacity in the same environment.

1.1.1. Coverage in Hilly Terrain

CBRS radio was mounted on the rooftop of one of Charter's building at 45 ft height and 7 test points were selected to reflect different terrain profile as per the below table. Only point 1 had Line Of Sight (LOS) to the radio and the rest were non-Line Of Sight (nLOS).

Table 4 - Denver Test Points Distance from Base Station

Test Point	Distance From Radio (Miles)
Point 1	0.22
Point 2	0.87
Point 3	1.27
Point 4	2.04
Point 5	2.47
Point 6	2.87
Point 7	3.21

The below map shows the seven test points and the radio location. We used one channel of 10MHz bandwidth to transmit. The EIRP used was 47dBm since were using one channel only. All points were chosen to fall within the 65 degrees 3dB horizontal bandwidth of the antenna.

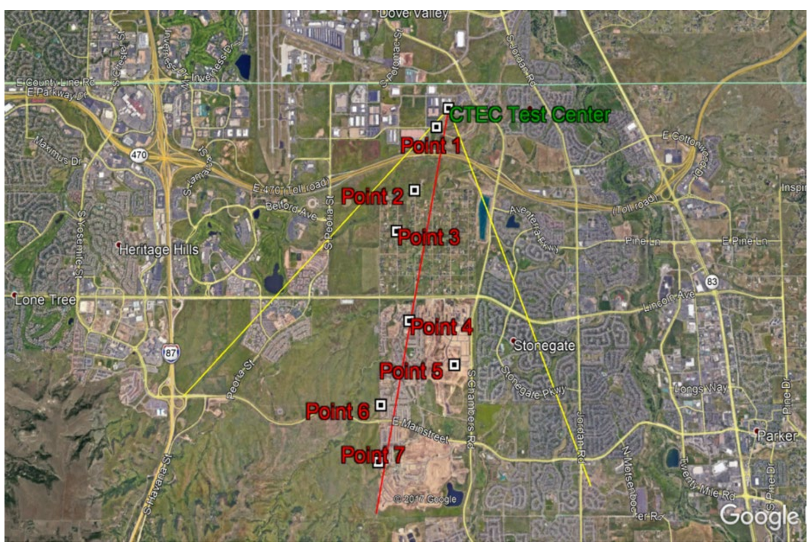


Figure 5 - Denver Coverage Trial Fixed Locations

At each test point we tested the CPE at two different heights, 12 ft and 20 ft. These two heights were chosen to mimic a one- and two-story house.

At 12 ft CPE high the CPE couldn't attach at points 5 and 7. At 20 ft CPE high the CPE couldn't attach at point 5. We had the qRexLevMin set to 128 dBm which is the minimum Reference Signal Received Power (RSRP) values measured by the UE in a cell to be able to get unrestricted coverage-based service in that cell. This means at points 5 and 7 (12 ft CPE) the CPE detected RSRP lower than 128 dBm.

The figures below show the Downlink (DL) throughput, and Uplink (UL) throughput at all test points for 12ft and 20ft CPE height.

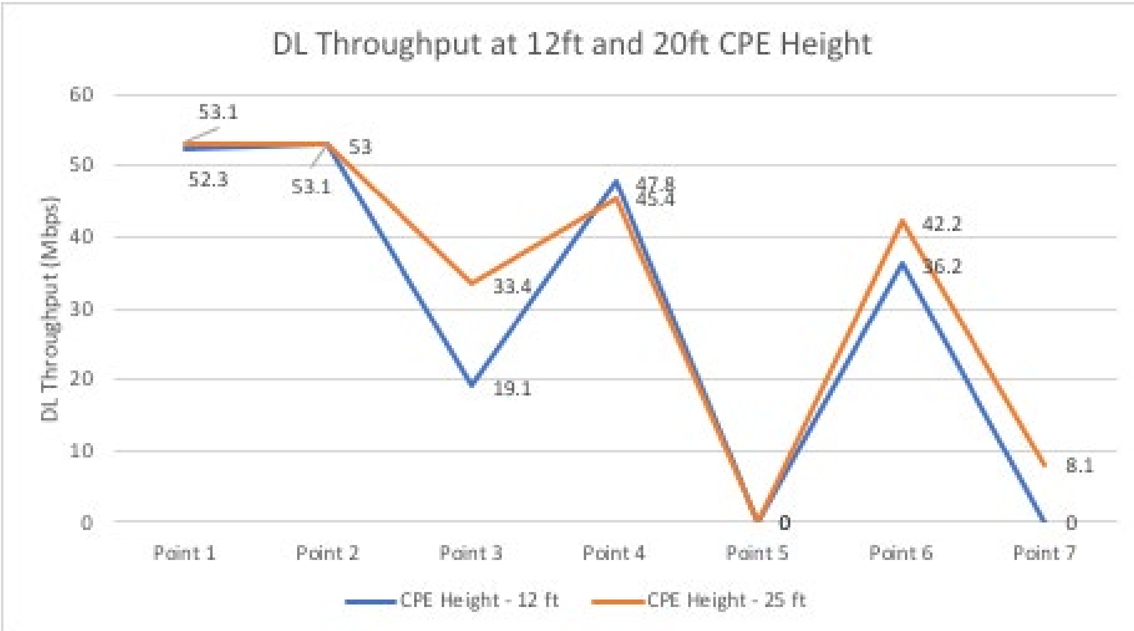


Figure 6 - Denver Coverage Trial DL Throughput

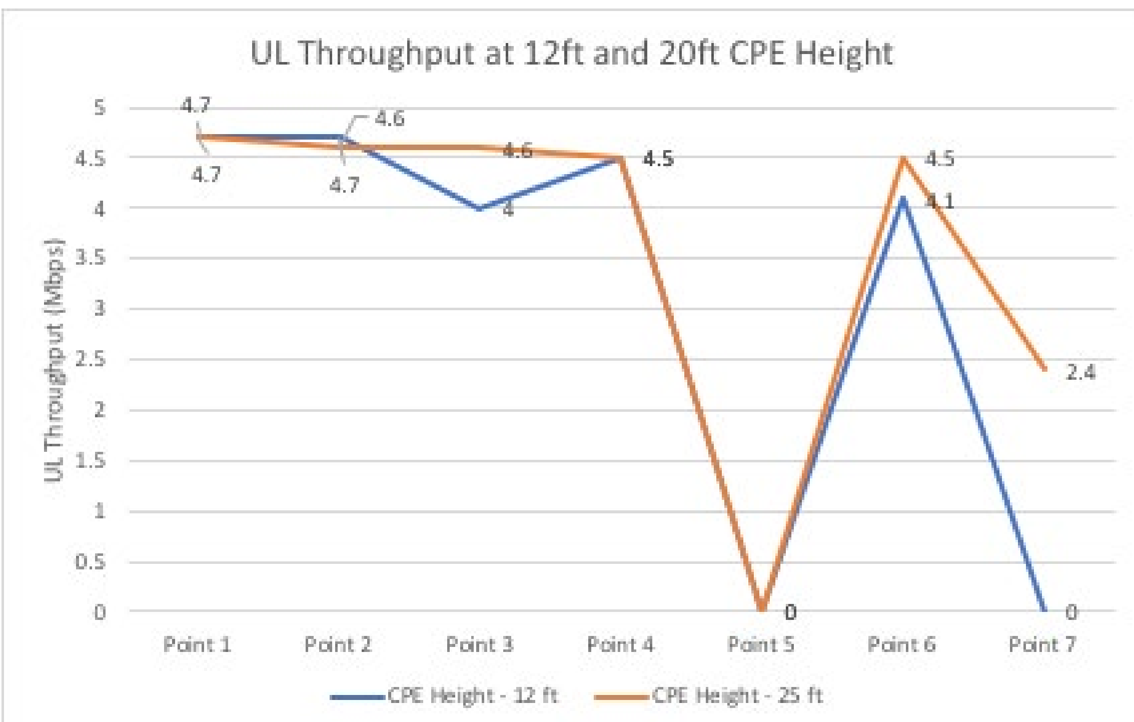


Figure 7 - Denver Coverage Trial UL Throughput

When we raised the CPE to 20 ft height, the CPE could attach at point 7 while still cannot attach at point 5. The RF conditions improved and the throughput increased due to raising the CPE.

At 12 ft high CPE the QAM modulation varied between 64QAM and 16QAM with point 3 mostly 16QAM. At 20 ft high CPE we saw 64QAM most of the times at all points except point 7 where we saw mostly Quadrature Phase Shift Keying (QPSK) modulation which explains the big dip in throughput at point 7.

For both CPE heights we saw a dip in RF conditions at point 3 and no attach at point 5. Looking at the terrain profile for both points we can see the test points are at a much higher elevation than the radio with a lot of terrain blockage. Figure 9 shows the elevation profile for the fixed point 3.

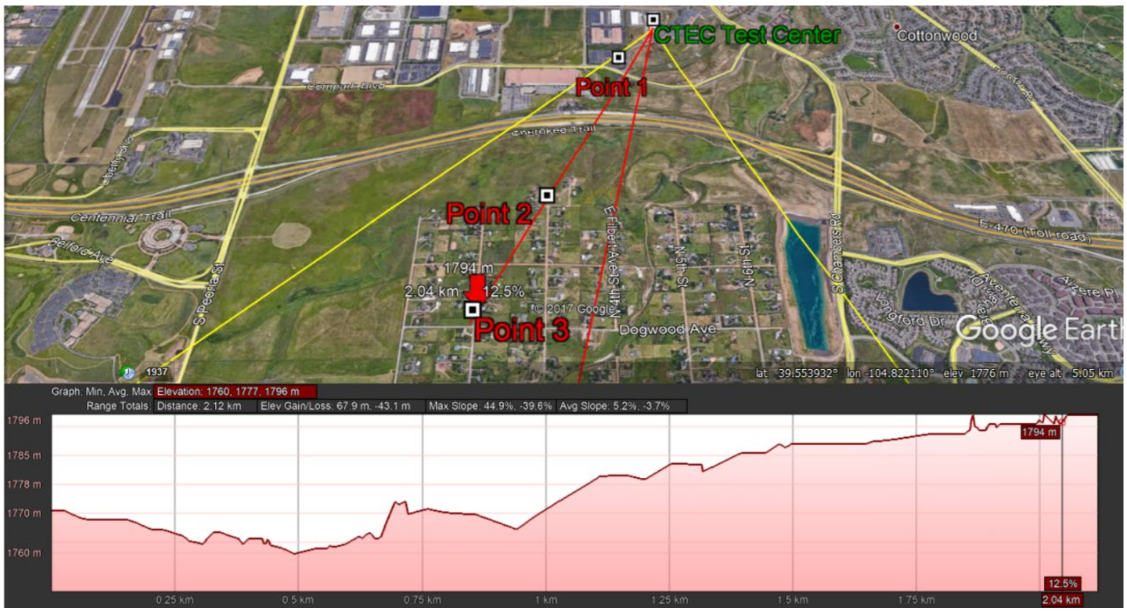


Figure 8 - Denver Test Point 3 Elevation Profile

Point 3 was in an open area with few houses and high trees up to 20 ft high. Figure 10 shows the elevation profile for point 5.

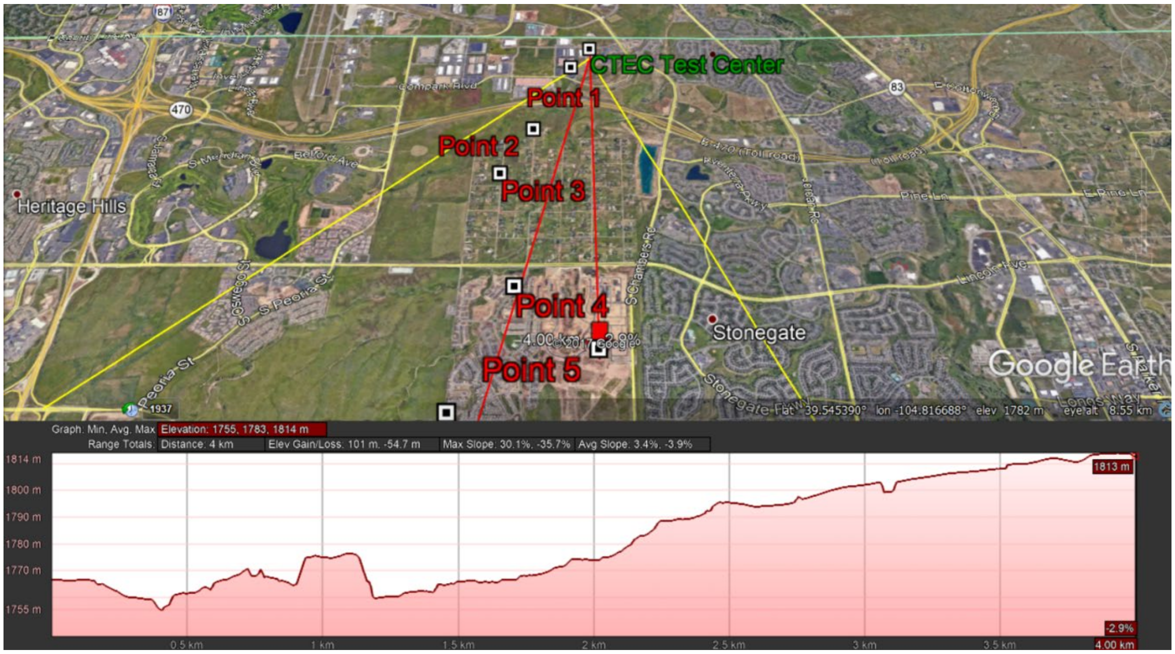


Figure 9 - Denver Test Point 5 Elevation Profile

Point 5 was in a residential area with some mid-rise buildings.

The inability for the CPE to attach at point 5 made us think of the need to use different technologies to attach at hard to reach urban areas. At the time of testing there was no available LTE beam forming radios in band 48 so we turned to proprietary technology.

We installed a non-3GPP proprietary radio on the top of the Charter building instead of the macro eNB, and took the receiver to all 7 test points to test at 12 ft and 20 ft heights same as we did with the LTE CPE. The main differences between the proprietary equipment and the LTE is the proprietary supported digital beam forming with 16 active RF chains, transmitted at 43 dBm/20 MHz which is short of the FCC rules of maximum EIRP, and the receiver also transmitted at 43 dBi vs 33 dBi for the LTE CPE. The channel bandwidth was 20MHz and the frame configuration was set to 50:50.

With this setup we didn't expect UL challenges due to the high-power CPE also and wanted to understand the effect of beam forming in the CBRS band.

The below figures show the throughput, SNR, and Received Signal Strength Indicator (RSSI) at all test points for 12 ft and 20 ft high CPE.

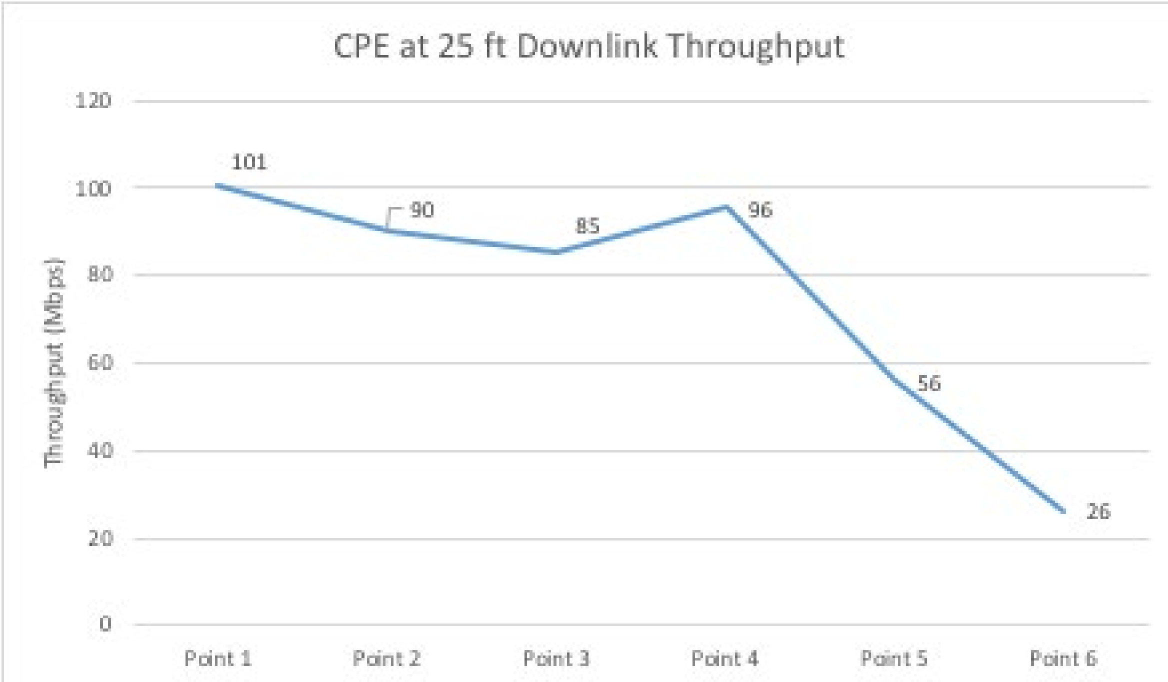


Figure 10 - Proprietary Radio DL Throughput at 25 ft CPE

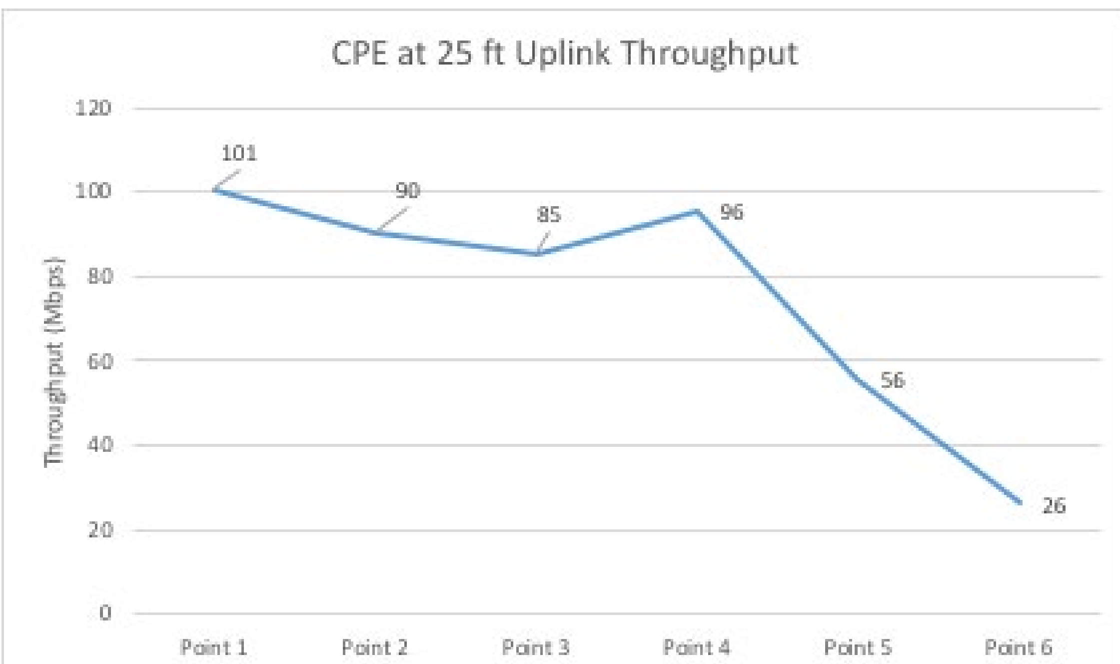


Figure 11 - Proprietary Radio UL Throughput at 25 ft CPE

Note the downlink and uplink are almost identical, that's because the equipment used TDD frame configuration 1:1 meaning half the resources are used for downlink and the other half used for uplink.

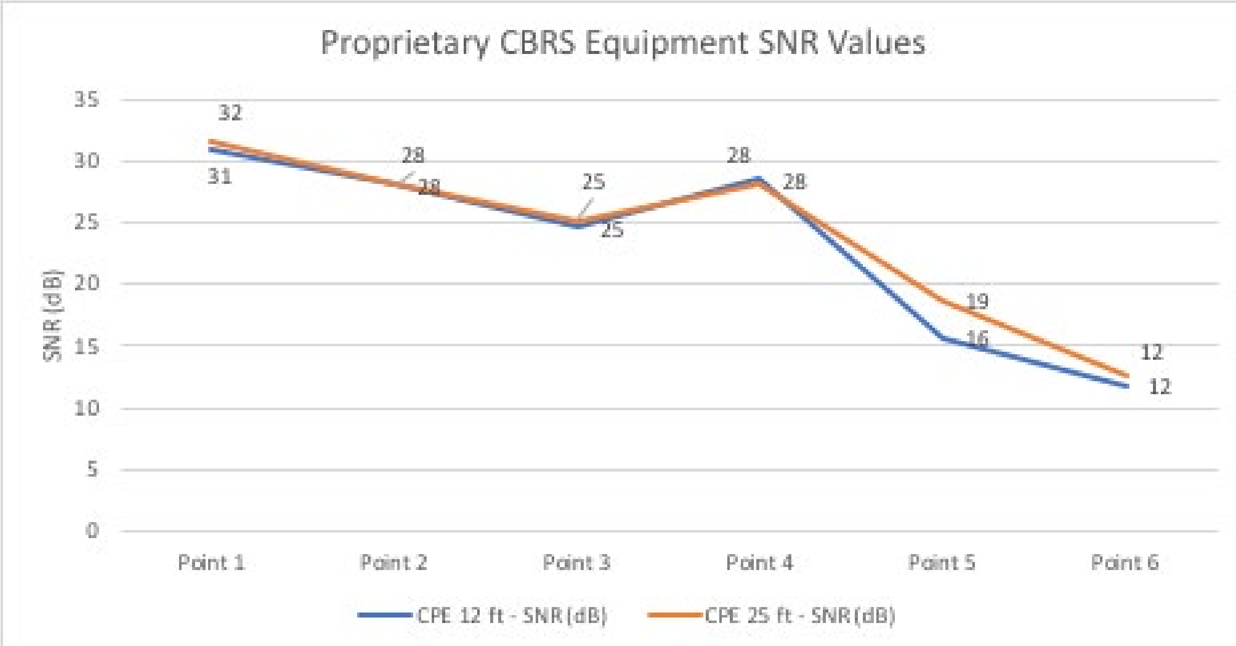


Figure 12 - Proprietary Radio SNR Values at 25 ft CPE

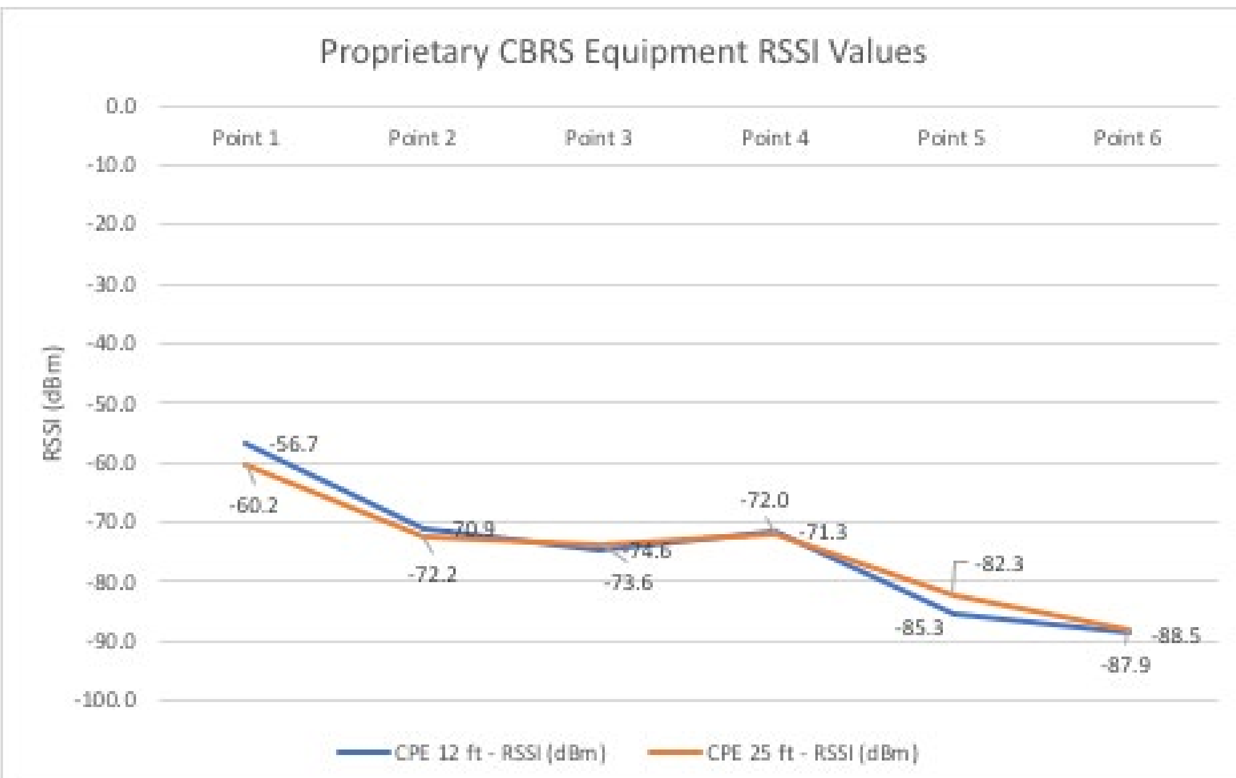


Figure 13 - Proprietary Radio RSSI Values at 25 ft CPE

With the proprietary CBRS equipment we saw the same dip in RF conditions at point 3 similar to the LTE equipment tested earlier. The two interesting observations we saw was the CPE connected at point 5 and RF conditions at 12ft and 25 ft weren't very different except at point 5.

We concluded that due to beam forming effect we could connect at point 5 between the mid-rise buildings. This conclusion encouraged us to work with the 3GPP LTE vendors to get beam forming LTE CBRS equipment to test various scenarios in residential areas.

1.1.2. Capacity in Hilly Terrain

After we determined the CBRS coverage in Denver, it was time to study the capacity. We are conducting an employee field trial in Denver where we provided broadband speeds of minimum 25Mbps downlink and 3Mbps uplink. Many employees signed up to be part of the trial and agreed to have CPE's installed on their houses. In the Denver employee trial, we used the LTE CBRS equipment and had several sectors serving the employees, here we focus on the results of two sectors only.

The first sector was installed on Charter's building rooftop used earlier in the coverage testing. At the time of writing this paper this sector was used to serve 7 employees with more being added as shown in the below figure.

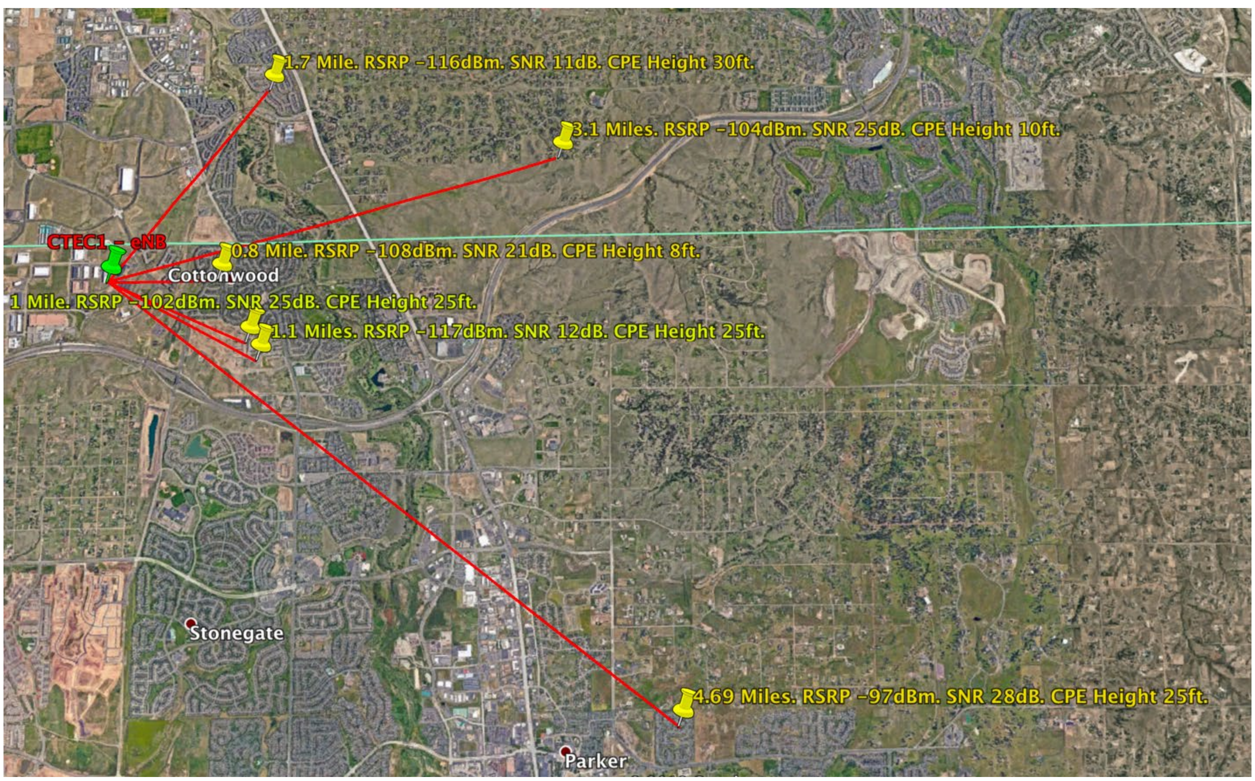


Figure 14 - Denver Field Trial First Sector

This sector served employees ranging from 0.8 mile to 4.7 miles away from the radio. The below table shows each house's distance from the eNB along with the RF conditions and throughputs.

Table 5 - Denver Trial First Sector Participants RF conditions and Throughput

Distance from eNB (miles)	RSRP(dBm)	SNR(dB)	CPE Height (ft)	Downlink (Mbps)	Uplink (Mbps)
0.8	-108	21	8	174	4
1	-102	25	25	58.4	2.8
1.11	-117	12	25	38.2	2.3
1.7	-116	11	30	91	3.8
3.1	-104	25	20	204	10.5
4.69	-97	28	25	243	10.3

The employee field trial data showed us some very interesting insights for example there is a participant at 1.1 mile from the radio with CPE installed at 25ft getting worst RF conditions than a participant at 4.7 miles away with CPE also at 25ft high.

The below is a screenshot from a propagation modeling tool showing the CPE in this participant house 1.1 mile away from the radio. The model shows blockage of the Fresnel zone which in turns explains the CPE is getting RSRP -117dBm and SNR 12dB although fairly close to the radio.

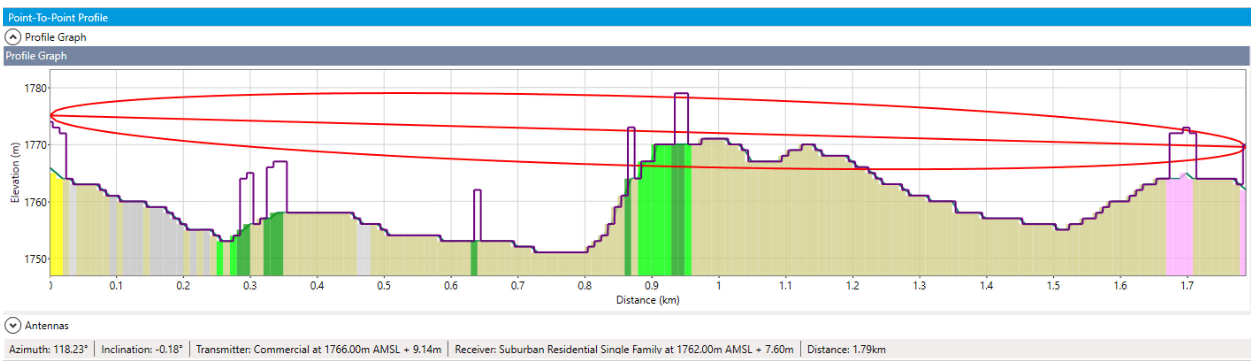


Figure 15 - Participant With Major Fresnel Zone Blockage

The same tool showed the CPE in a participant house 4.7 miles away has little to no Fresnel zone blockage. That explains the good RF conditions RSRP -97dBm and SNR 28dB at 4.7 miles away from the radio.

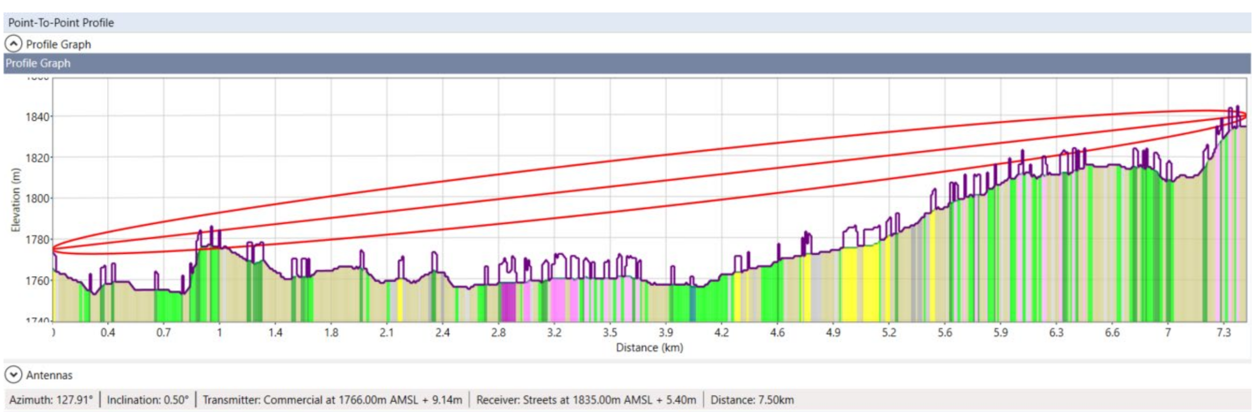


Figure 16 - Participant With Minor Fresnel Zone Blockage

The throughputs the employees were getting are shown in the below graph. The graph shows the throughputs they were getting when the sector wasn't loaded and when the sector was fully loaded.

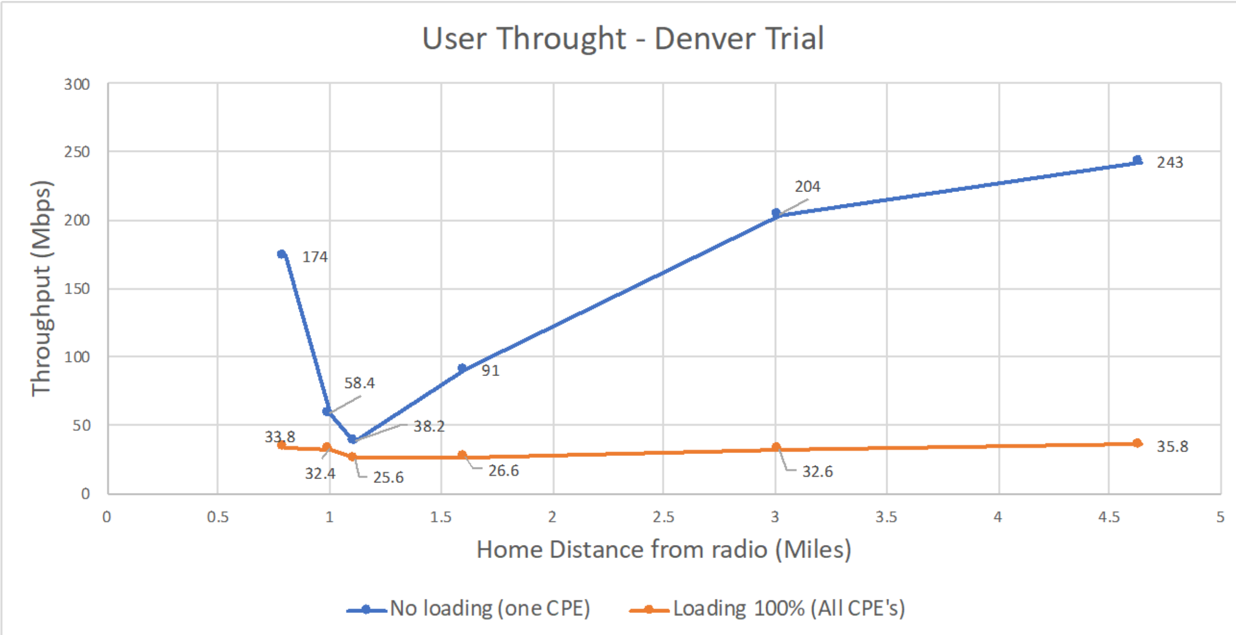


Figure 17 - Participant First Sector Throughputs

The blue line represents the throughput of each CPE performing maximum download for its location one CPE at a time while the orange represents the throughput when all CPE's are performing maximum download at the same time. There were different scheduler settings for the eNB to serve multiple CPE's simultaneously but we decided to keep it at proportional fair to guarantee fair resources distribution to all CPE's.

The second sector we focus on in this paper was installed on another Charter building at 125 ft and is currently serving 11 employees, more are being added. This sector served employees ranging from 0.6 mile to 5 miles away from the radio as shown in the below figure.

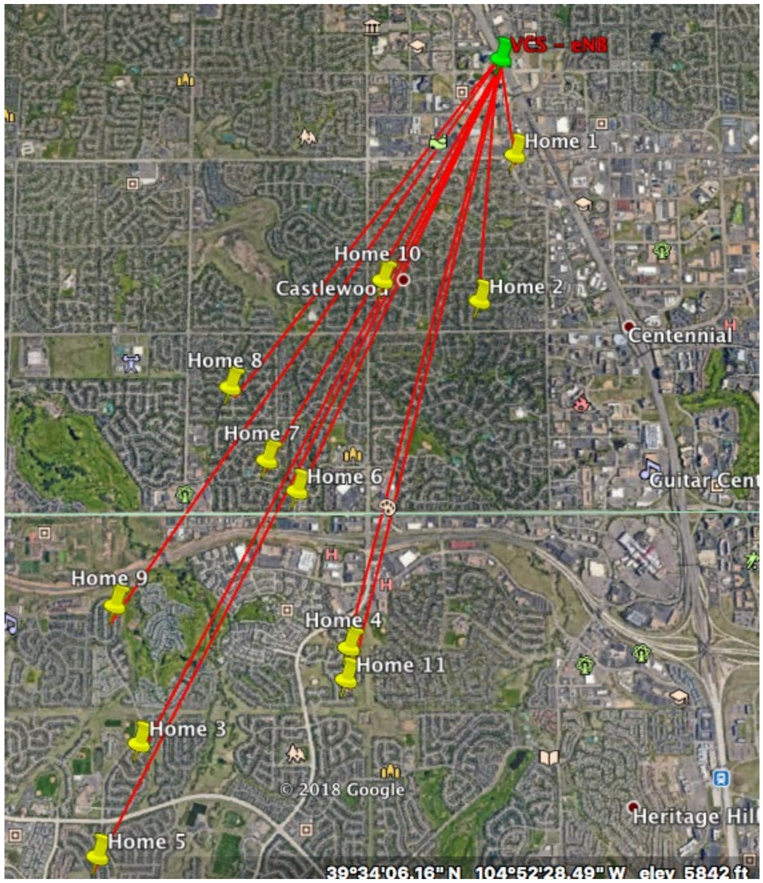


Figure 18 - Denver Field Trial Second Sector

Since this sector was at a higher elevation than the first sector we expected better performance in terms of CPE RF conditions.

RF conditions of most participants were good due to the radio installed on a high building. For example, there is a participant at 5 miles away getting RSRP -114dBm, SNR 24dB and another participant at 4.3 miles getting RSRP -99 dBm, SNR 29dB. The RF conditions along with throughputs of the CPE's are shown in the below table.

Table 6 - Denver Trial Second Sector Participants RF conditions and Throughput

Distance from eNB (miles)	RSRP(dBm)	SNR(dB)	Downlink (Mbps)	Uplink (Mbps)
0.6	-112	16	153	4.31
1.4	-110	19	210	5.13
1.4	-118	12	155	6.16
2.4	-116	13	121	1.29
2.6	-106	21	192	5.56
2.7	-95	29	248	10.2
3.4	-100	26	270	12

Distance from eNB (miles)	RSRP(dBm)	SNR(dB)	Downlink (Mbps)	Uplink (Mbps)
3.5	-113	15	146	3.49
3.8	-99	26	273	13.9
4.3	-96	28	257	11.9
5	-112	15	165	6.28

The throughputs the employees were getting are shown in the below graph. The graph shows the throughputs they were getting when the sector wasn't loaded and when the sector was fully loaded.

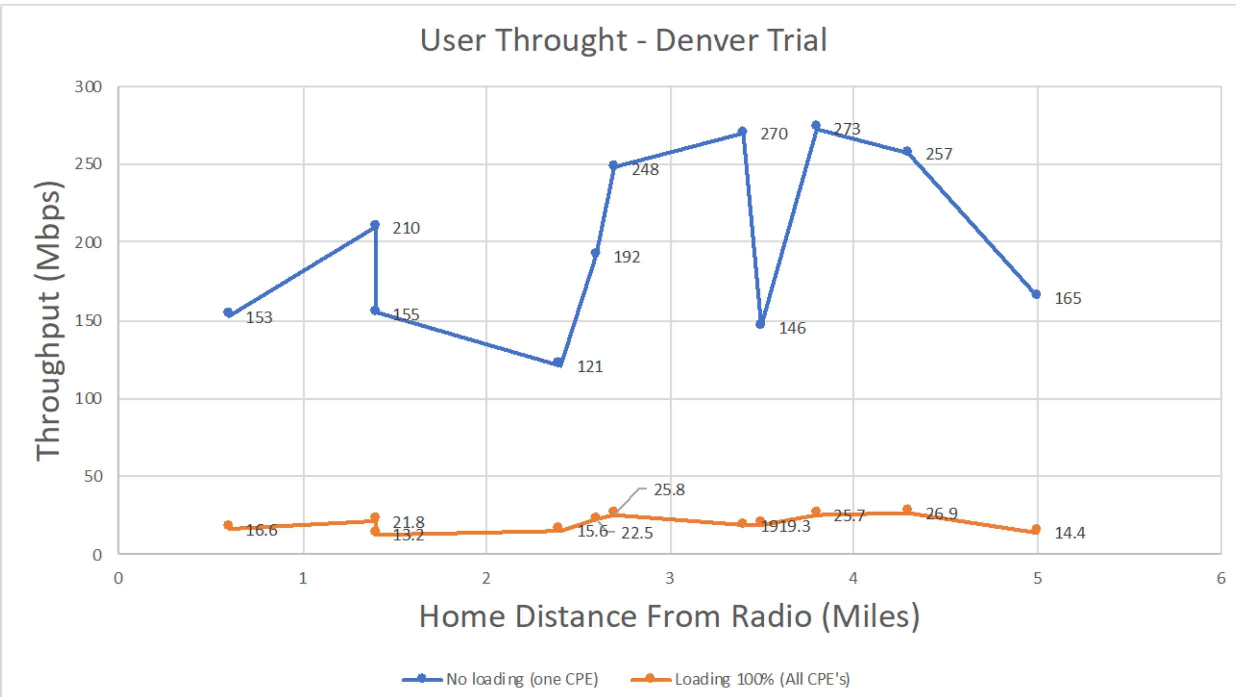


Figure 19 - Participants Second Sector Throughput

When loading all CPE's at once the LTE resource blocks were shared among CPE's thus some CPE's downlink fell below 25Mbps which was expected. During network planning there is a factor called over subscription which basically means that not all subscribers will be doing maximum throughput simultaneously even at peak hours. This over subscription factor differs from a network to another and is used to make sure the network is fully utilized while at the same time ensuring subscribers experience a high quality of service. Network planners have to carefully pick the over subscription factor in order not to affect users experience.

For the sake of sector capacity, we calculated that theoretically a 40MHz LTE CBRS channel can achieve around 300Mbps sector throughput at 256QAM. In the lab we got a maximum 285Mbps at perfect RF conditions. We turned to the field and ran a couple of test cases where we had 10 CPE's at 256QAM and measured the sector throughput, then moved the 10 CPE's away from the eNB till they dropped to 64/16QAM and again measured the sector throughput.

With all 10 CPE's at 256QAM and doing maximum downlink simultaneously the sector throughput was 253.9 Mbps as shown in figure 20.

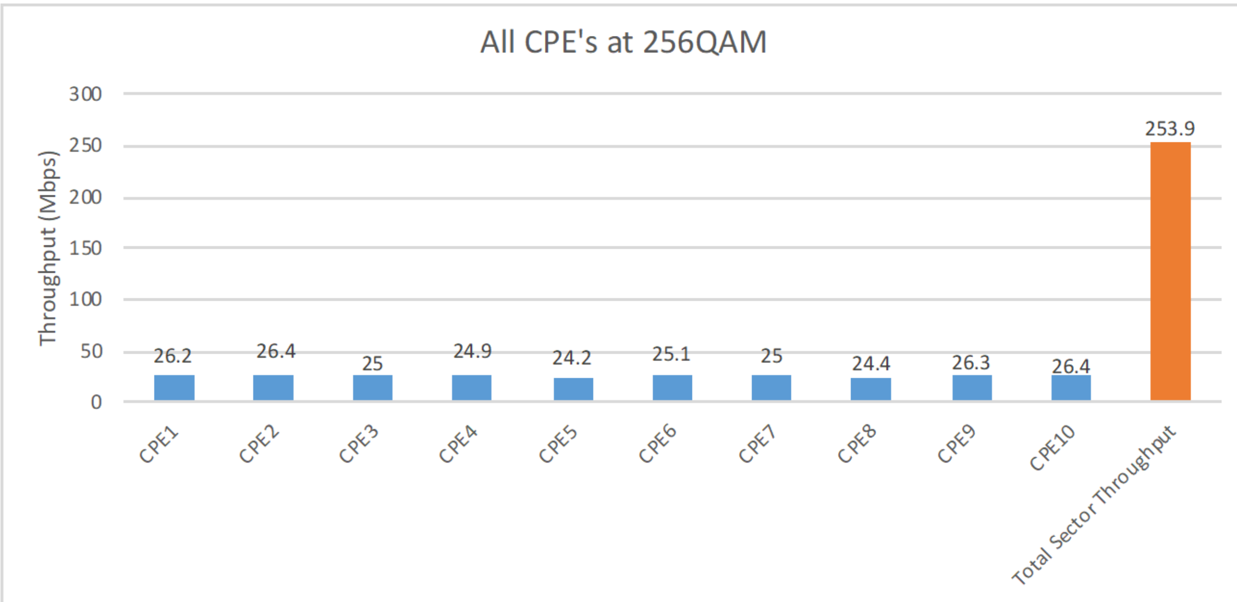


Figure 20 - Sector Throughput with 10 CPE's at 256QAM

With all 10 CPE's at 64/16QAM and doing maximum downlink simultaneously the sector throughput dropped to 111.6 Mbps as shown in figure 21.

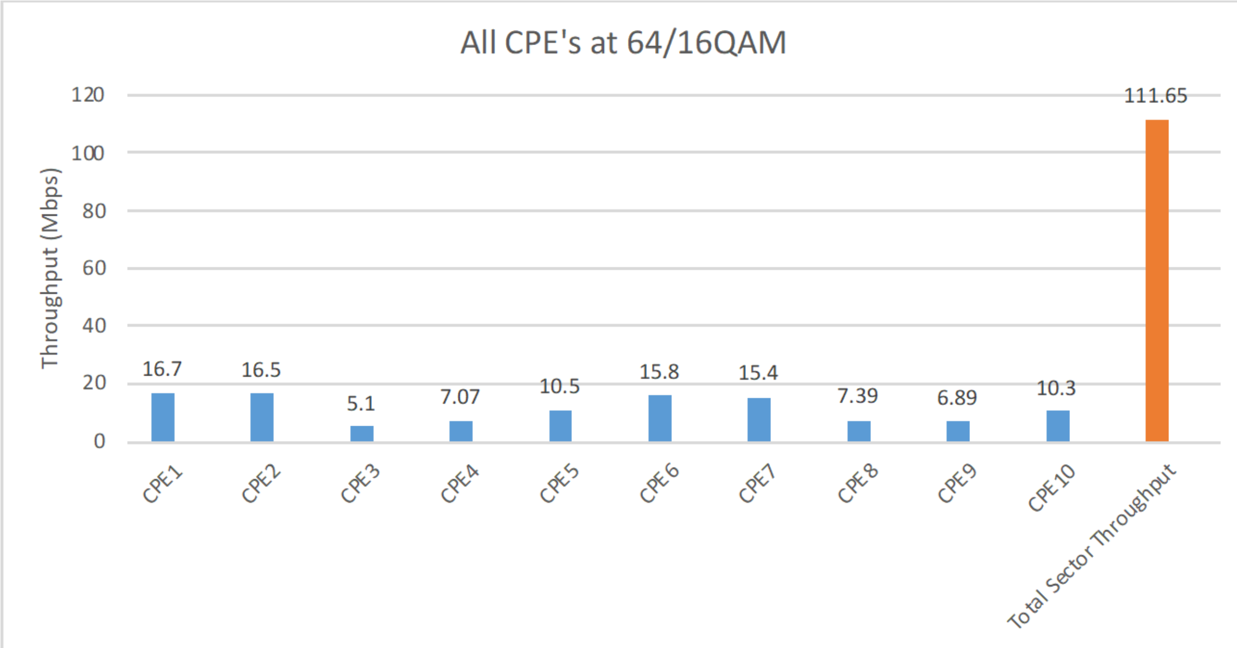


Figure 21 - Sector Throughput with 10 CPE's at 64/16QAM

The conclusion here is that the location and subsequently RF conditions of the CPE's will greatly affect the sector throughput because CPE's at bad RF conditions consumes more resource blocks. This is a point of consideration when designing FWA networks since CPE's will always be at the same location and their RF conditions can be pre-determined before installation.

To further understand the sector throughput in commercial deployments we turned to our Denver field trial to the sector serving 11 subscribers. On that sector we did the same previous couple of tests where we added 10 CPE's at 256QAM to the sector and measured the sector capacity then added 10 CPE's at 64QAM and measured the sector capacity. We felt these two tests are a better representation of a real-world scenario because we had several subscribers at various RF conditions.

Figure 22 shows the Denver trial sector when adding 10 more subscribers to it all at 256QAM, we ended up having 14 CPE's at 256QAM, 3 CPE's at 64QAM, and 4 CPE's at 16QAM. The calculated sector throughput was 227 Mbps. This can be considered an ideal scenario sector because most subscribers are at 256QAM.

Table 7 - Adding 10 CPE's at 256QAM to Existing Sector

QAM Modulation	Number of CPE's
16	4
64	3
256	14

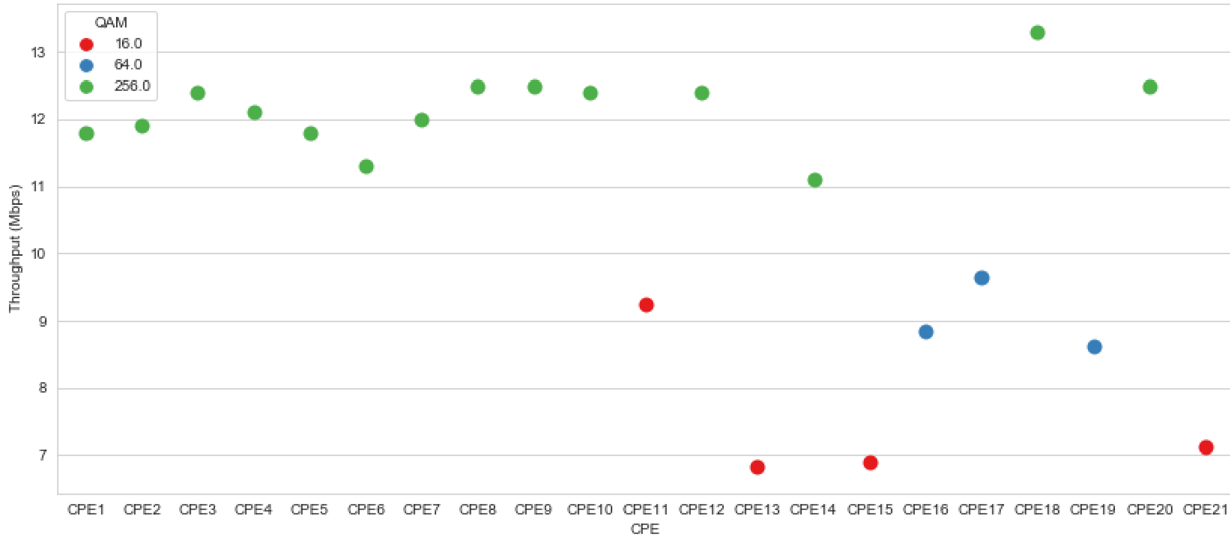


Figure 22 - Adding 10 CPE's at 256QAM to Existing Sector - Sector Throughput = 227 Mbps

Figure 23 shows the Denver trial sector when adding 10 more subscribers to it all at 64QAM, we ended up having 4 CPE's at 256QAM, 13 CPE's at 64QAM, and 4 CPE's at 16QAM. The calculated sector throughput dropped significantly to 152 Mbps. This can be considered a realistic scenario sector because most subscribers are at 64QAM.

Table 8 - Adding 10 CPE's at 64QAM to Existing Sector

QAM Modulation	Number of CPE's
16	4
64	13
256	4

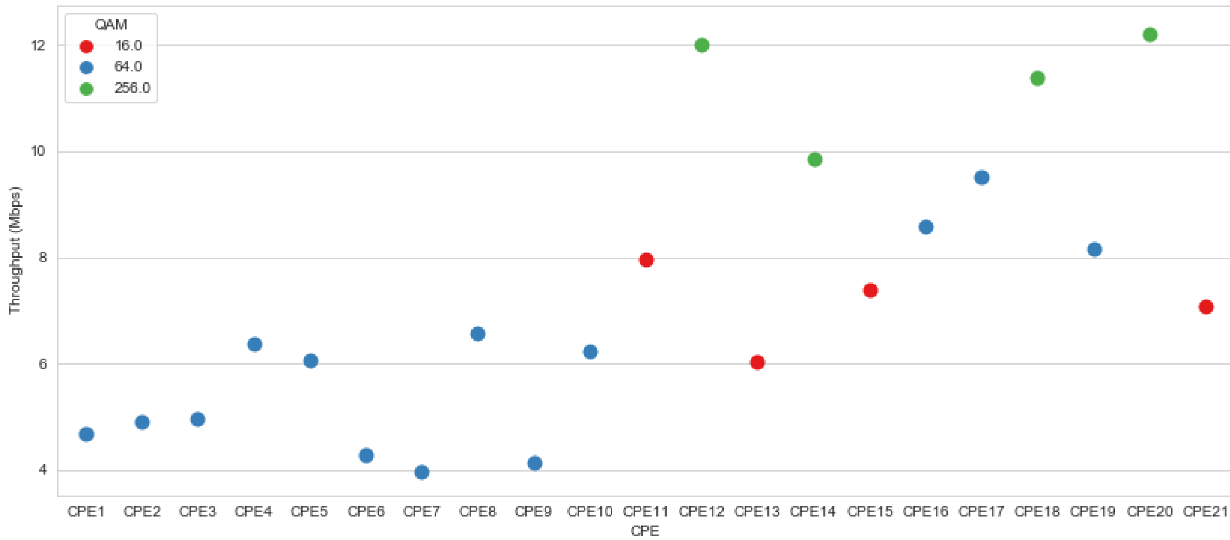


Figure 23 - Adding 10 CPE's at 64QAM to Existing Sector - Sector Throughput = 152 Mbps

These tests show the importance of FWA network planning for capacity purposes because the distribution of subscribers will affect the sector throughput and quality of service. Also, the theoretical maximum sector throughput will likely not be seen in the field. Ideally FWA network planners will want all subscribers at 256QAM which is not realistic because the cell radius will likely be small. A cell radius vs capacity tradeoff has to happen to ensure a good size cell radius with reasonable throughputs, most likely the majority of subscribers will have to be on 64QAM with very few on 256 and 16QAM.

We got a lot of learning from the Denver trial for example how to find the perfect place on the house to install the CPE, plan LTE CBRS network, and monitor various network components' performance. Also, to consider oversubscription when planning a FWA commercial network, and keeping in mind that sector throughput will vary depending on the subscriber's locations and RF conditions. We also learned the higher we install the radio the better RF coverage we can achieve.

1.2. Tampa Trial – High Foliage

After testing CBRS in Denver which is considered an urban hilly environment, we decided to study the effect of high foliage on CBRS coverage. We wanted to understand how can CBRS be used in rural areas to close the digital gap in the country. Our choice was New Port Richey which is north of Tampa, FL.

The test market had high dense trees going up more than 25 ft. One of the reasons we chose New Port Richey is because Charter owned a 140ft tower which made it a perfect environment to test CBRS FWA.

1.2.1. Coverage in High Foliage – LTE CBRS

To understand the CBRS coverage in foliage, we decided to use both the LTE and the proprietary equipment.

We started with the LTE CBRS radios and installed it at 130ft on the Charter owned tower. We used one channel 10MHz bandwidth and set the radio EIRP to 47dBm.

Test points were chosen as per the below table. All test points were non-line of sight. One at a time we took the test van to each test point and setup the CPE at 12ft and 25ft to test how far the radio can cover.

Table 9 - Tampa Test Points Distance from Base Station

Test Point	Distance From Radio (Miles)
Point 1	0.32
Point 2	0.58
Point 3	1.06
Point 4	1.24
Point 5	1.68
Point 6	2.67
Point 7	3.21

The RF and throughput results for both CPE heights are shown below graph.

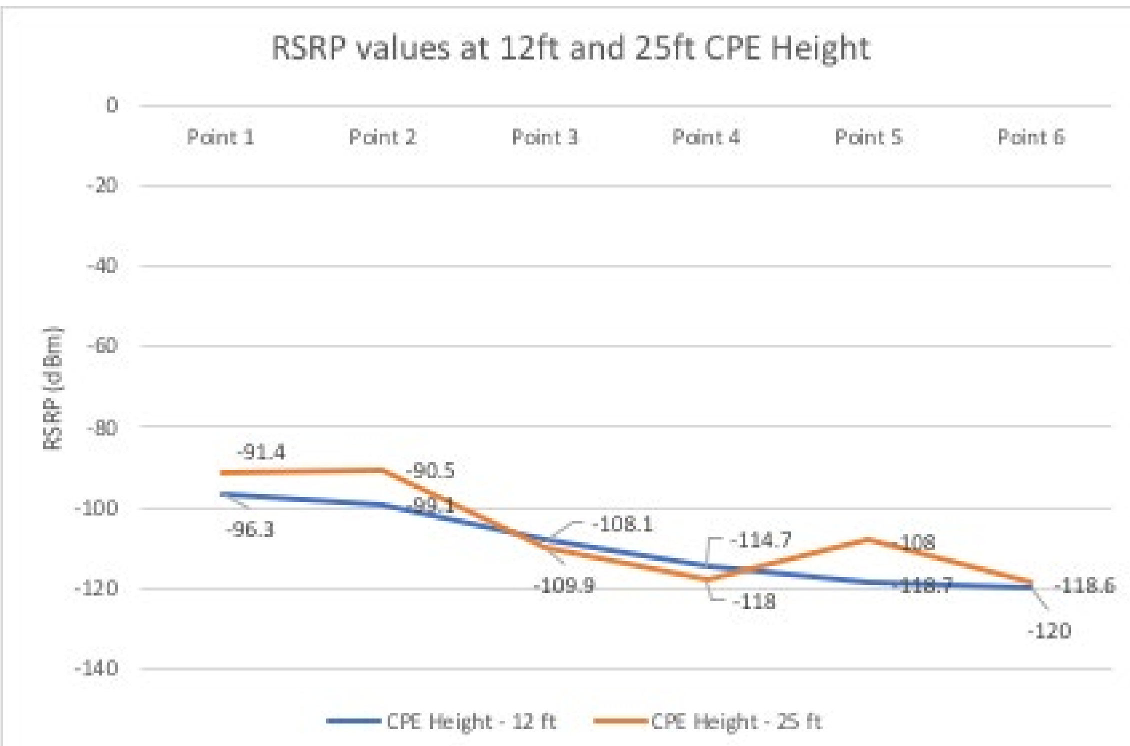


Figure 24 - RSRP at 12ft and 25ft CPE Height

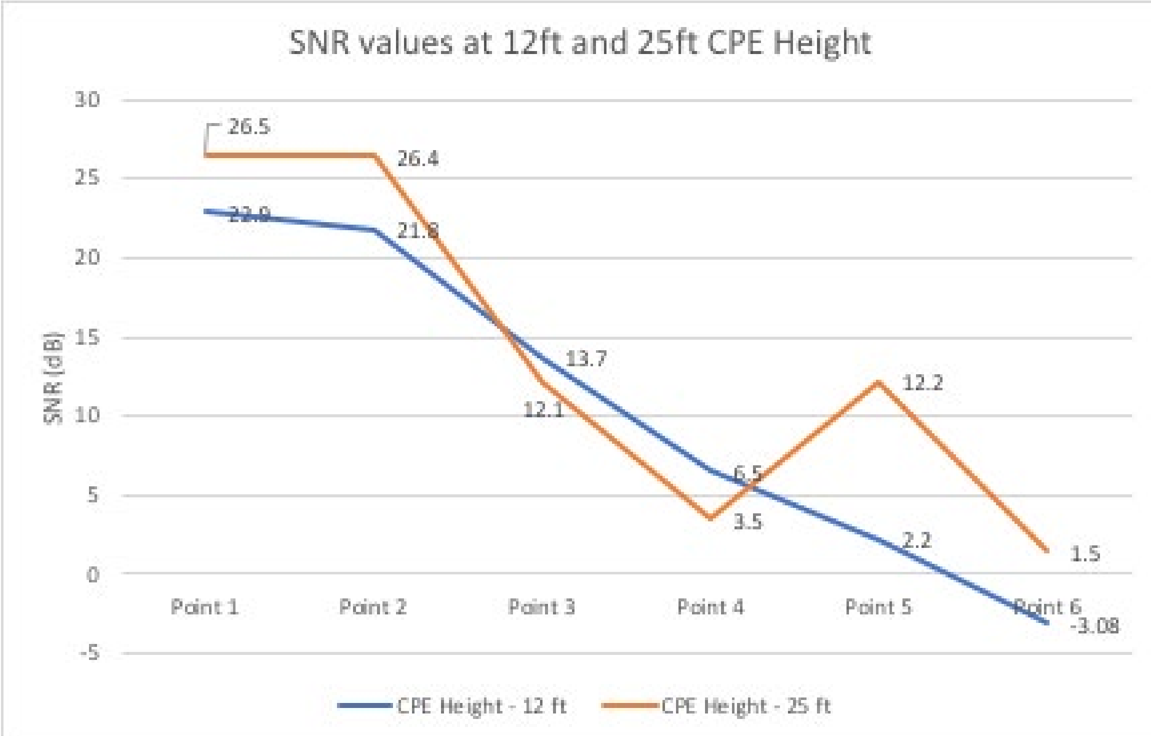


Figure 25- SNR at 12ft and 25ft CPE Height

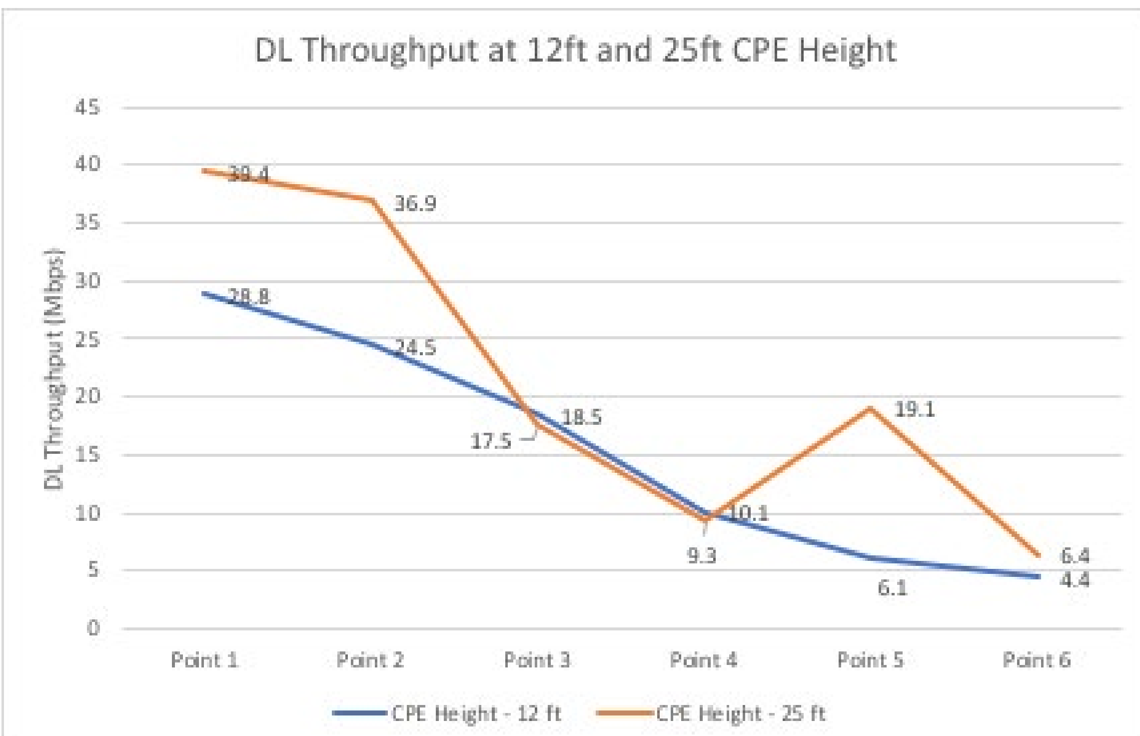


Figure 26 - DL Throughput at 12ft and 25ft CPE Height

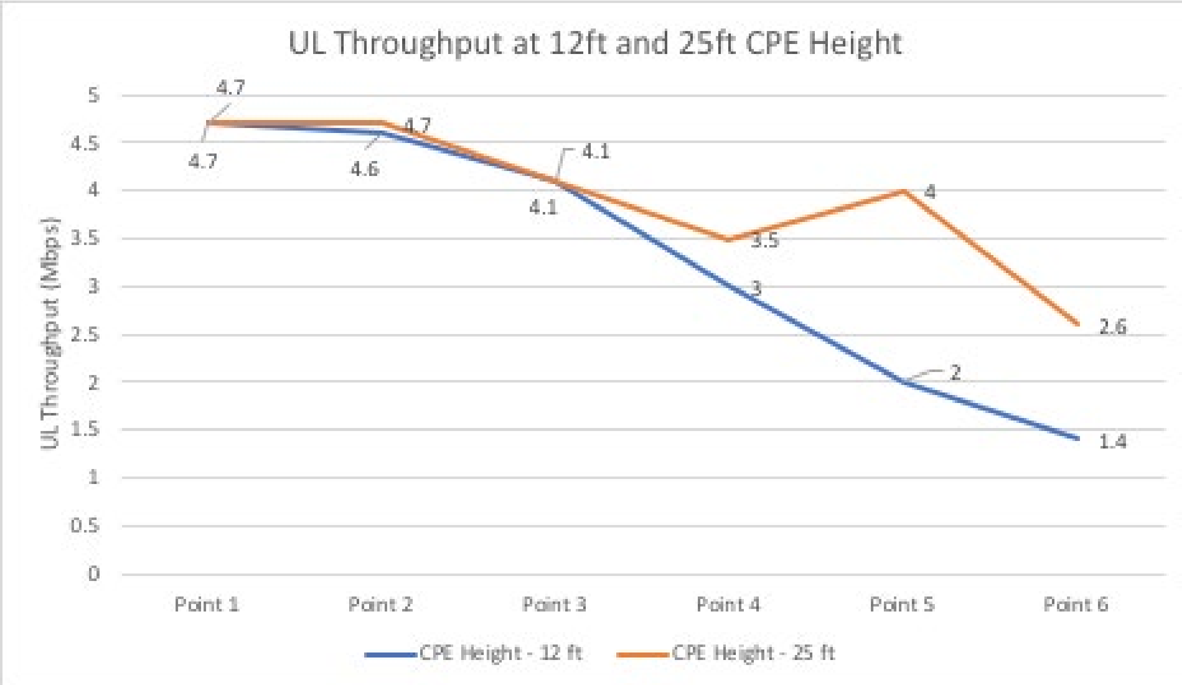
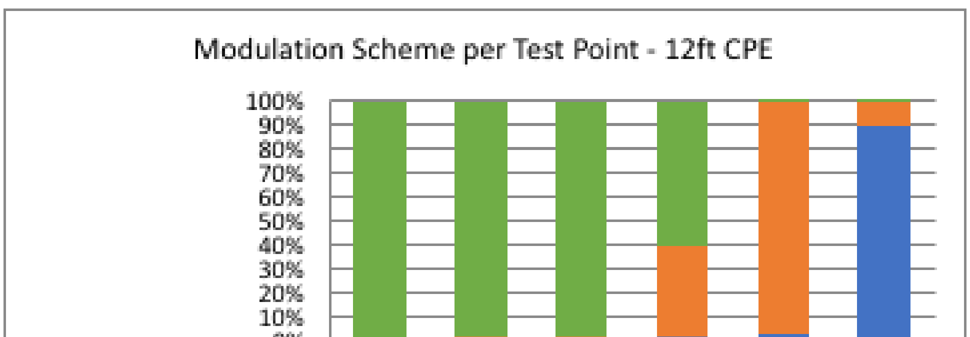


Figure 27 - UL Throughput at 12ft and 25ft CPE Height

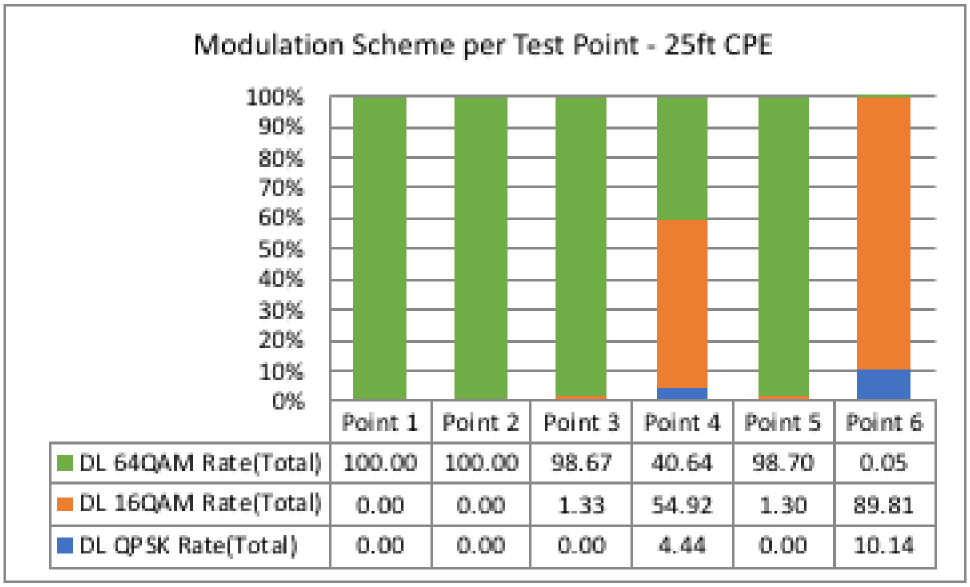
An interesting observation is at points 3 and 4 as the height of the CPE didn't make much of a difference in terms of throughput. That's due to RF conditions being very similar at both CPE heights due to the high dense trees blocking the signal, going above tree line would have made the RF conditions better.

The below figures show the QAM modulation values at all test points for both CPE heights.



	Point 1 (0.51 Km)	Point 2 (0.93 Km)	Point 3 (1.63 Km)	Point 4 (1.92 Km)	Point 5 (2.71 Km)	Point 6 (4.3 Km)
DL 64QAM Rate(Total)	99.86	98.63	98.39	60.23	0.00	0.12
DL 16QAM Rate(Total)	0.14	1.37	1.61	38.15	96.79	10.19
DL QPSK Rate(Total)	0.00	0.00	0.00	1.61	3.21	89.68

Figure 28 - Modulation at 12ft CPE Height



	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
DL 64QAM Rate(Total)	100.00	100.00	98.67	40.64	98.70	0.05
DL 16QAM Rate(Total)	0.00	0.00	1.33	54.92	1.30	89.81
DL QPSK Rate(Total)	0.00	0.00	0.00	4.44	0.00	10.14

Figure 29 - Modulation at 25ft CPE Height

From the above modulation scheme graphs we see points 3 and 4 at both CPE heights are very similar which again explains the similar throughput at both heights.

Looking at point 5, It's clear that increasing the CPE height made the RF conditions better, thus changed from 16QAM at 12ft CPE height to 64QAM at 25ft CPE height.

The CPE couldn't attach at point 7 (3.2 miles) and beyond. We concluded the high foliage limited our sector coverage and to get good RF conditions the CPE must be installed above tree line.

We went beyond 3.5 miles and raised the CPE 45ft high and could connect, however, 45ft high CPE isn't practical in real live deployment scenarios. We wanted our testing to mimic a CPE installed at one- or two-story buildings.

1.2.2. Coverage in High Foliage – Proprietary CBRS and 5GHz

We then moved to test the proprietary equipment and did two sets of testing. First, we tested the CBRS proprietary equipment then we tested the unlicensed 5GHz version. We mounted both CBRS and 5GHz radios at 130ft height on the tower. The CBRS maximum EIRP was 43dBm which is a bit short of the FCC maximum EIRP CBRS rules. The 5GHz radio used maximum EIRP 33 dBm which is the maximum power allowed for U-NII by the FCC. Both radios used 20MHz channels and TDD frame configuration 50:50.

Since these proprietary radios used beam forming technology and performed well in the Denver trial, we decided to challenge them. We chose a different yet more challenging test point set as below.

Table 10 - Tampa Test Points for Proprietary Equipment

Test Point	Distance From Radio (Miles)
Point 1	0.6
Point 2	1.7

Test Point	Distance From Radio (Miles)
Point 3	2.7
Point 4	3.2
Point 5	4
Point 6	5

At 12ft high CPE, the CBRS radios connected at points 1, 2, and 6. The 5GHz radio connected as points 1 and 6 only. It was expected to get better performance with the CBRS radio vs. the 5GHz radio because of the high power of the CBRS radio and lower frequency of CBRS compared to the 5GHz.

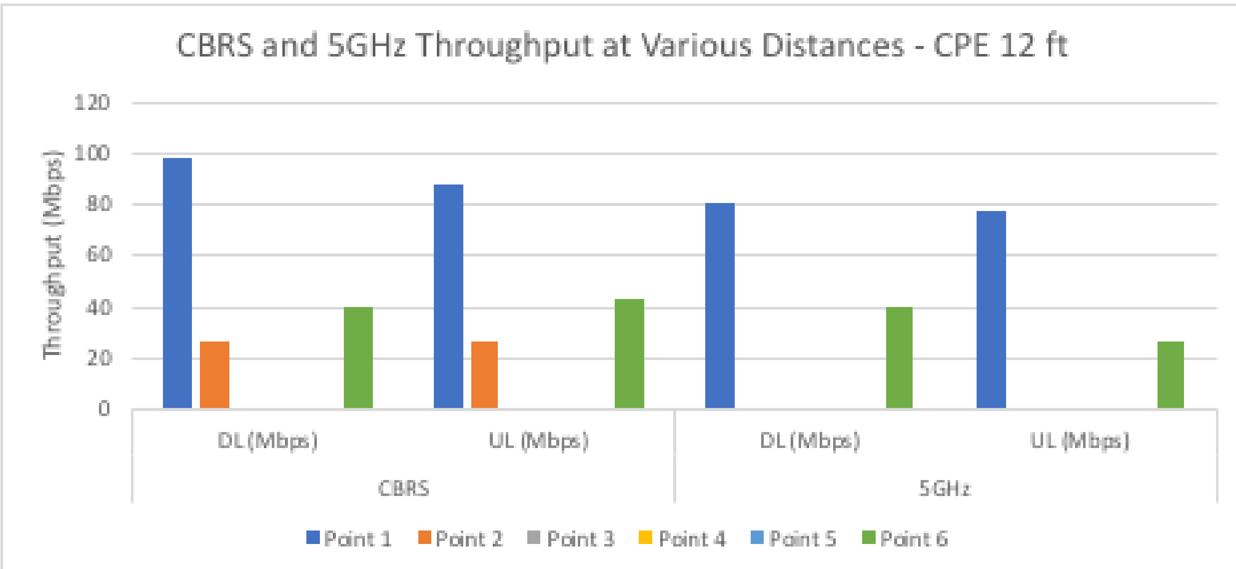


Figure 30 - Proprietary CBRS and 5GHz Throughput Results for 12ft CPE

Raising the CPE to 25ft high gave better performance for both the CBRS and 5GHz radios. The CBRS radio connected at all points except point 4, while the 5GHz radio connected at points 1, 2, and 6 only.

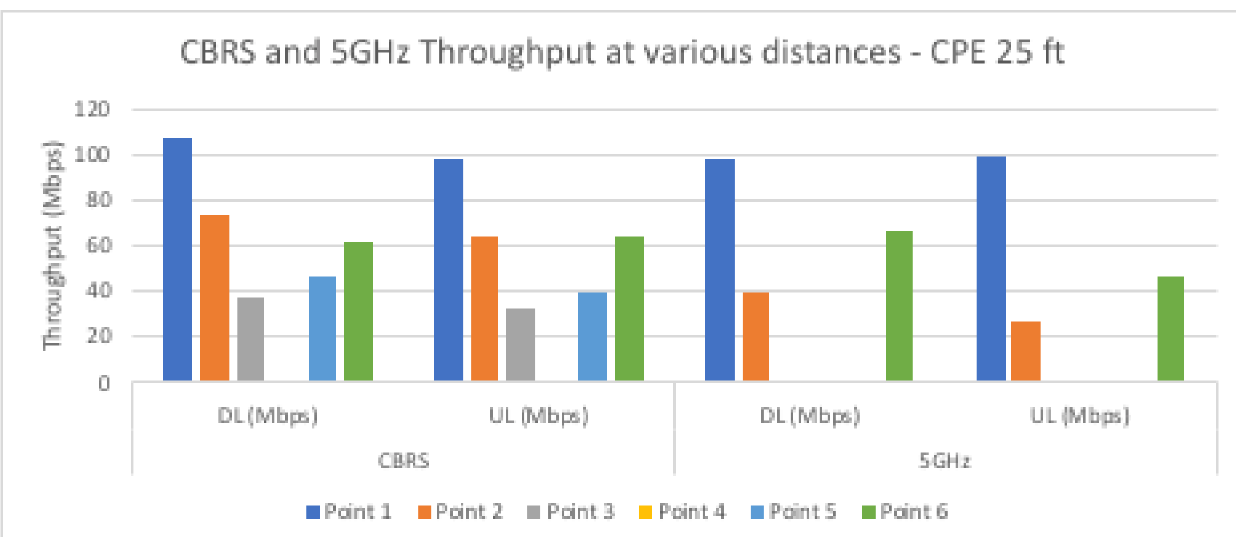


Figure 31 - Proprietary CBRS and 5GHz Throughput Results for 25ft CPE

The interesting points here were points 5 and 6 which are 4 and 5 miles away from the radio. Raising the CPE to the clutter height above the tree line resulted in the CPE connected with decent throughputs.

We concluded that in FWA scenarios when using a high tower to install the radio we can still connect in high foliage environments if the CPE is above the clutter height.

Also, the 5GHz CPE connecting at 5 miles away from the radio was interesting and encouraged us to think of building a prototype CBRS+5GHz combined radio.

1.3. Coldwater Trial – Snow and Rain

After testing CBRS in the high foliage environment of Florida, we went to Coldwater, MI to study the effect of snow and rain on CBRS RF conditions. We also had just gotten massive MIMO LTE CBRS equipment and wanted to understand the effect of LTE beam forming gain on coverage. Finally, we wanted to test the idea of combining CBRS with 5GHz radio.

Charter owns a tower in Coldwater, MI and we used it to install the radios at 130ft height. Similar to the other test markets we chose test points varying from 0.3 to 5 miles.

1.3.1. Snow and Rain Effect on CBRS

We went to test in January some days were raining and snowing while other days were just gloomy without snow or rain, it was the perfect environment to understand if snow or rain had any effect on CBRS signal. We picked two test points at 0.8 and 1.4 miles from the radio and tested the LTE CBRS radio on two different days to capture the effect of rain. At both days we tested the CPE at 12ft and 25ft high.

At 0.8 mile from the tower the maximum fluctuation in RSRP was 3dBm, SNR 3dB, and DL throughput 2Mbps as seen in the below graphs.

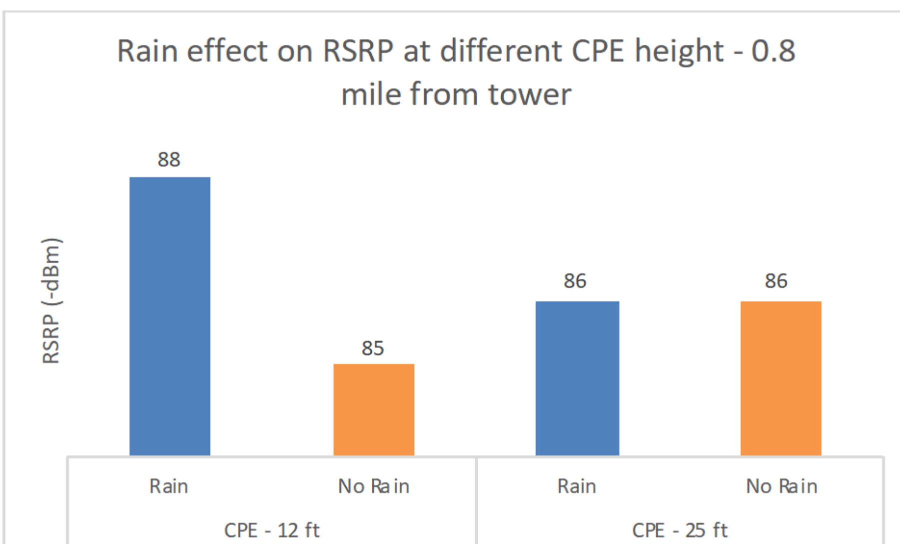


Figure 32 - Effect of Rain on RSRP at Different CPE Heights – Cell Near

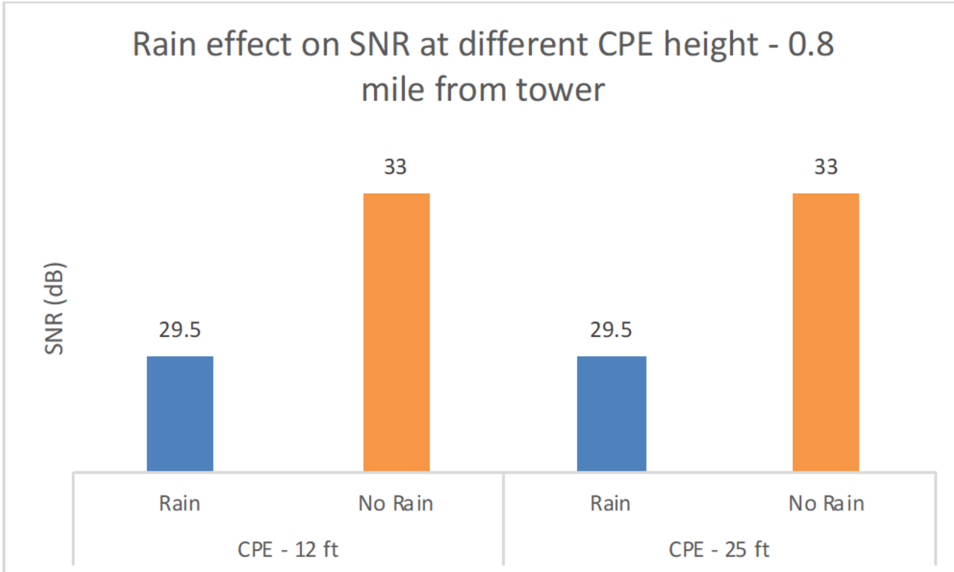


Figure 33 - Effect of Rain on SNR at Different CPE Heights – Cell Near

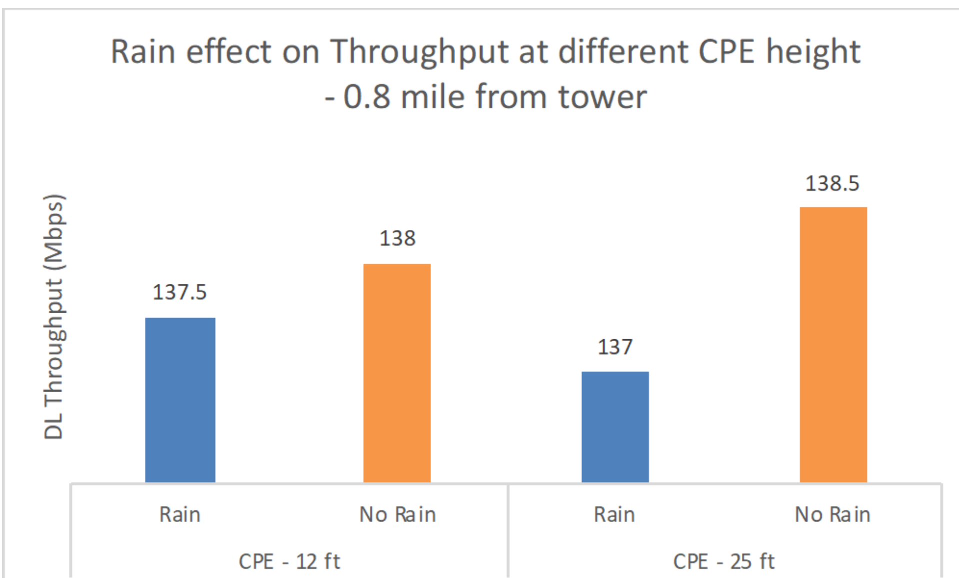


Figure 34 - Effect of Rain on Throughput at Different CPE Heights – Cell Near

At 1.4 mile from the tower the maximum fluctuation in RSRP was 4dBm, SNR 5dB, and DL throughput 6Mbps as seen in the below graphs.

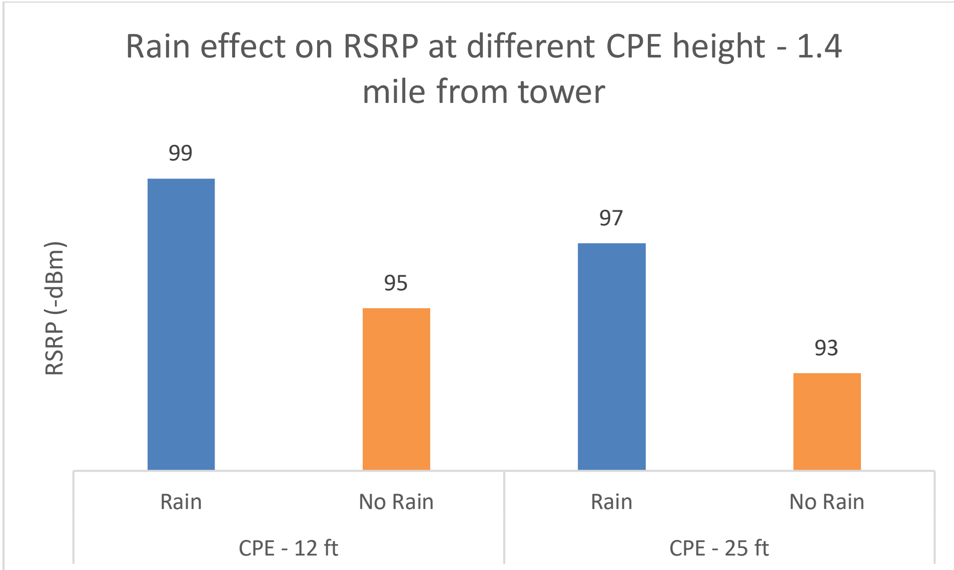


Figure 35 - Effect of Rain on RSRP at Different CPE Heights – Mid-cell

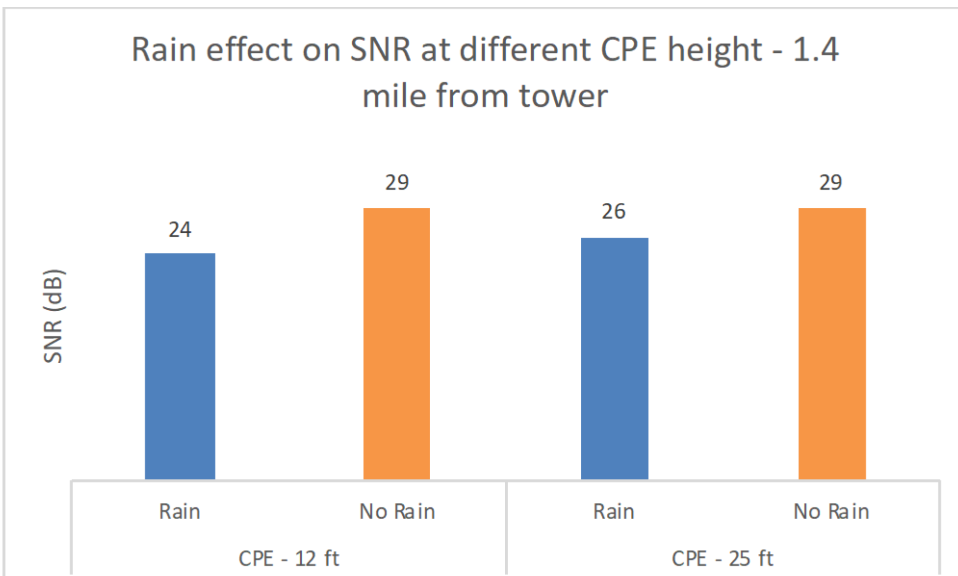


Figure 36 - Effect of Rain on SNR at Different CPE Heights – Mid-cell

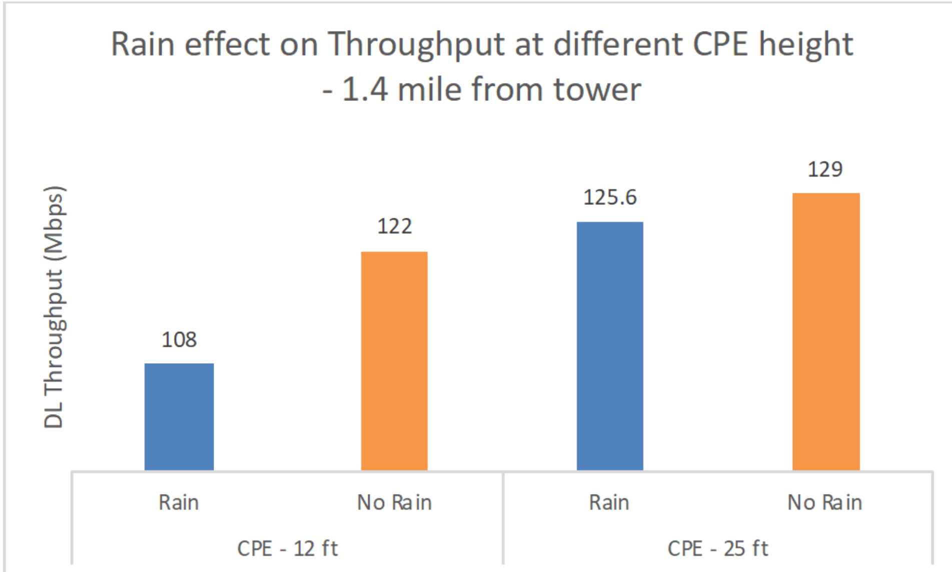


Figure 37 - Effect of Rain on Throughput at Different CPE Heights – Mid-cell

From the above graphs we concluded that unlike mmWave signal the rain had little to no effect on the LTE CBRS signal. The RF fluctuation was in the normal fluctuation range.

1.3.2. Beamforming Gain – Coverage Test

To understand the LTE CBRS beam forming gain effect on coverage we used a massive MIMO 64Tx64R at two test points and compared the results to the regular macro at the same test points.

We chose test points to represent cell middle and cell edge at 2.5 and 5 miles away from the tower. The RSRP's were -109dBm and -130dBm respectively. The macro was set to use open loop Transmission Mode (TM) TM 3 while the massive MIMO was set to use Single User MIMO (SU-MIMO) TM7.

As seen in the below graph, the macro performed better in terms of throughput at cell middle. However, at cell edge the beam forming gain gave 35% more throughput than the macro.

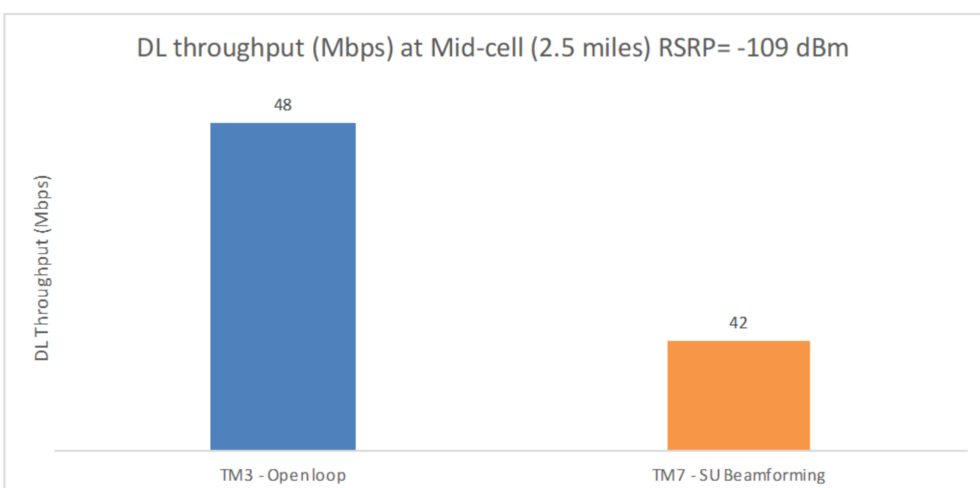


Figure 38 - Effect of Beamforming on Throughput at Mid-cell

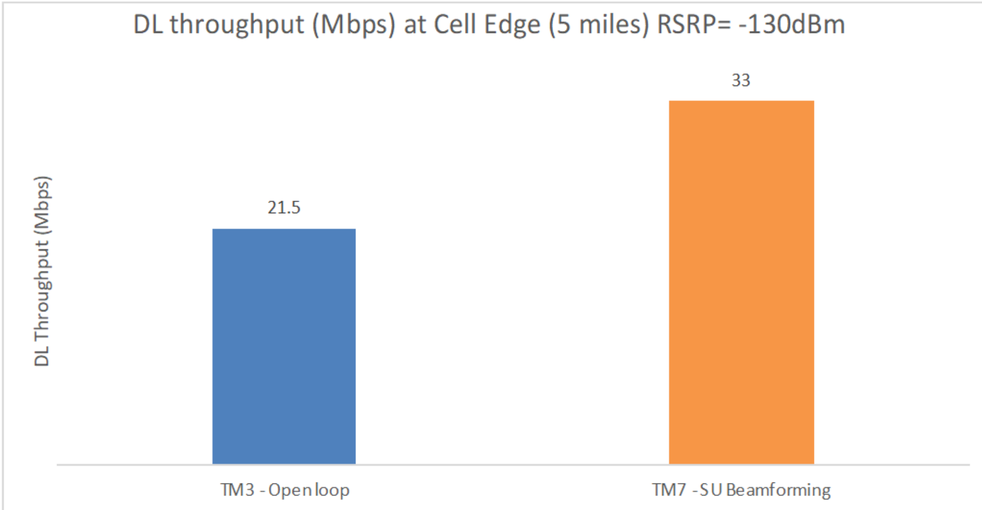


Figure 39 - Effect of Beamforming on Throughput at Cell Edge

We concluded that beam forming gain using SU-MIMO TM7 can help users at cell edge to get better throughput but not at cell middle conditions. This encouraged us to run more tests in the future to further understand the effect of various transmission modes on coverage and capacity.

1.3.3. CBRS+5GHz Radio Prototype

Using the proprietary equipment, we built a prototype of CBRS + 5GHz by aggregating the radios using a layer 2 switch. We did the same aggregation method to the receiver using a layer 2 switch. Since this was just a prototype this wasn't carrier aggregation between both bands rather just aggregating both radios at each end together.

Our goal was to make the link more reliable in case one of the technologies link goes down the other will stay up and also to increase the throughput delivered to the receiver.

We used two channels each is 20MHz, one for the CBRS and the other for the 5GHz. We noticed that the 5GHz didn't connect at one test point for the 12ft receiver but the CBRS did.

The below graphs show the aggregate maximum throughput we got from our prototype unit and also the breakdown of each radio on its own.

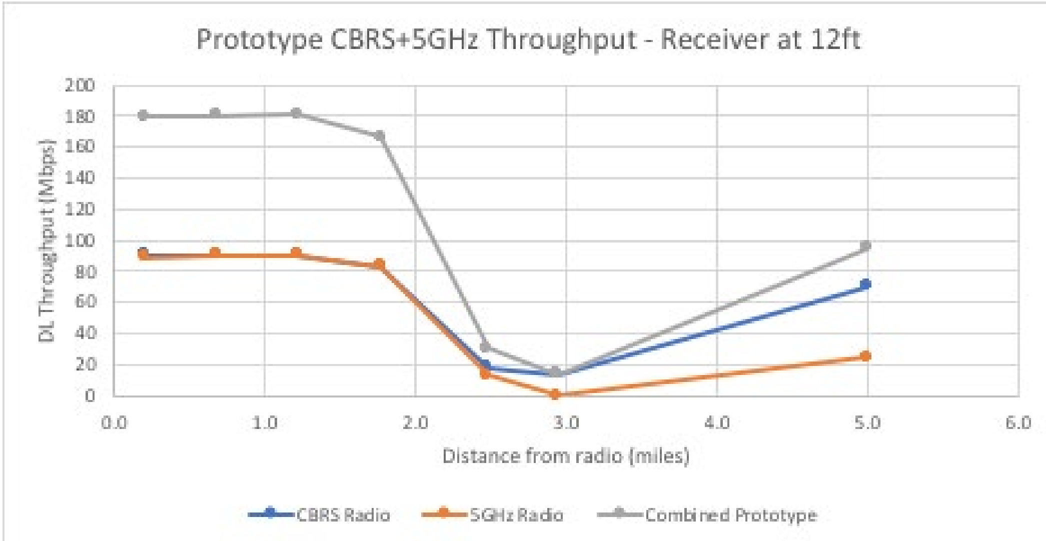


Figure 40 - Prototype Radio Throughput at 12ft Receiver Height

Notice at 3 miles away from the tower at 12ft CPE the 5GHz radio didn't connect but the CBRS did.

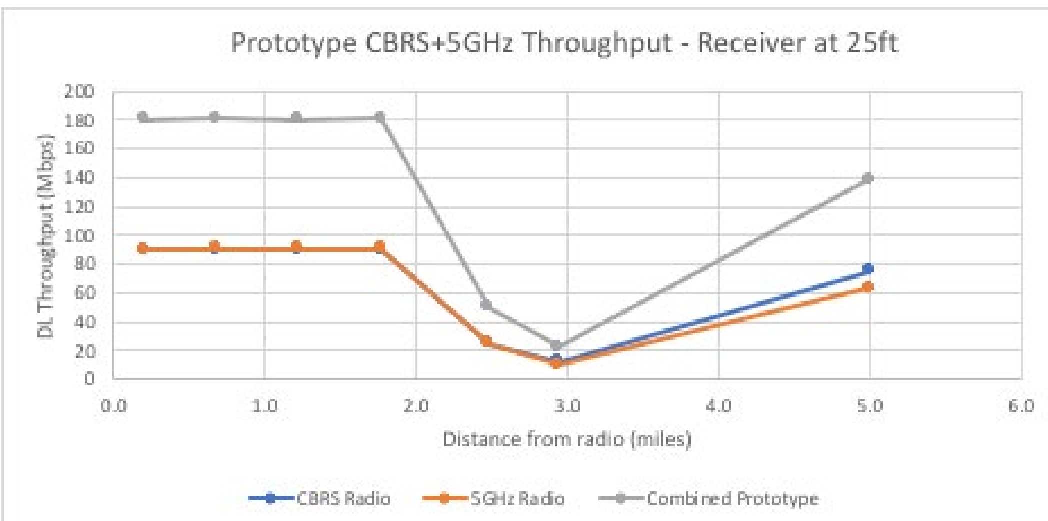


Figure 41 - Prototype Radio Throughput at 25ft Receiver Height

It's worth noting that at 3 miles the test point was heavily obstructed due to surrounding buildings and at 5 miles we were testing in an open area. That explains the dip in throughput at 3 miles from the tower then better performance at 5 miles from the tower.

The prototype combined radio delivered high throughput at all test points due to the aggregation of both bands also it showed reliability where one radio couldn't attach but the other did.

The prototype encouraged us to think of more innovative ways to aggregate different bands in order to provide a more reliable and faster link. Also, this directed us to explore 3GPP technologies like Licensed Assisted Access (LAA) where a licensed and unlicensed band are combined together.

1.4. Lexington Trial – User Experience

From all the previous trials we got a pretty good understanding of CBRS equipment coverage and capacity. What we didn't explore was how much throughput was enough for a typical household usage.

We were out in Lexington, KY for LTE CBRS vendor testing and decided to see if 50Mbps was enough for a typical household usage.

We had a test site at 1.6 miles away from the radio with no line of sight to the CPE. We throttled the speed to 50Mbps and ran all of the following at once: 4K TV running on demand streaming service, tablet running 4K online video service, gaming console playing online game, IP camera, and several laptops browsing the internet and watching online videos. The figure below is from the Lexington demo showing various devices running at the same time simulating a typical household.

Figure 42 - Various Internet Devices Running Simultaneously

We found that none of these services were affected or buffered while all running simultaneously on 50Mbps downlink speed. We monitored the CPE and found the throughput will spike to 50Mbps then drops and few seconds later peaks again, that's because all the mentioned video services have buffering capabilities and are not continuously requested maximum speeds all the time.

We concluded that 50Mbps is more than enough for the typical household needs.

Conclusion

Over the past couple of years, Charter team conducted several CBRS trials to further understand the coverage and capacity of this new band for FWA. It is concluded that a typical cell radius can be 3.5 to 5 miles depending on the terrain and morphology. It is also concluded that foliage negatively affects the CBRS signal and in such areas the CPE's should be installed at or above clutter height. Snow and rain have almost no effect on CBRS signal, and that 50Mbps can run what a typical household family need. SU-MIMO would help give better throughput results for users at cell edge. However, more investigations are needed for massive MIMO technology capacity and how it can be used to further enhance FWA service. It's important to aggregate unlicensed band with CBRS to have a more reliable and faster link.

Finally, we conclude that CBRS can be used for FWA to bridge the digital divide in the nation and help connect millions of users in rural America. CBRS can't replace fiber but will definitely complement it and help reach the last mile users. Charter is in a very good position to use CBRS to extend its broadband offering and reach customers that couldn't be reached in the past due to the high cost of laying fiber. Charter can leverage not only its huge fiber network but also the towers it owns nationwide to reach new customers and provide them with FWA broadband internet speeds. Moreover, Charter could also provide IPTV services over the FWA to customers.

FWA on CBRS represent a very good opportunity for Charter to capture new customers and a new way to utilize Charter's current assets.

Charter will keep investing latest technologies in CBRS and other bands to help connect millions of Americans in rural areas and to provide better services to current customers.

Abbreviations

3GPP	3rd Generation Partnership Project
CBRS	Citizens Broadband Radio Service
CBSD	Citizen Broadband Radio Service Device
CPE	Customer Premisis Equipment
DL	Downlink
EIRP	Equivalent Isotropically Radiated Power
EPC	Evolved Packet Core
FCC	Federal Communications Commision
FWA	Fixed Wireless Access
GAA	General Authorized Access
LAA	Licensed Assisted Access
LOS	Line Of Sight
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
nLOS	non-Line Of Sight
PAL	Priority Access License
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RF	Radio Frequency
RSRP	Reference Signal Received Power
RSSI	Received Signal Strength Indicator
SAS	Spectrum Access System
SIM	Subscriber Identification Module
SNR	Signal to Noise Ratio
SU-MIMO	Single User MIMO
TCP	Transmission Control Protocol
TM	Transmission Mode
TVWS	TV White Space
UDP	User Datagram Protocol
UE	User Equipment
UL	Uplink

U-NII	Unlicensed National Information Infrastructure
WISP	Wireless Internet Service Provider

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