Wireless Access Network Strategies

Lessons Learned On 3.5 GHz CBRS Network Trials

A Technical Paper prepared for SCTE•ISBE by

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1. Introduction

Considering adding a wireless footprint to your network? Hear about the lessons which we have learned over the past three years of CBRS network researches, trials and how we are building a wireless network. What are the key challenges that have been overcome and the areas that need to be considered? As networks converge, wireless technology is becoming another tool to provide additional services and expand the network.

2. Utilization of CBRS Shared Spectrum

2.1. Citizens Broadband Radio Service

On recommendation of President's Council of Advisors on Science and Technology (PCAST) board advisory to lead innovation in wireless technology services, the U.S. government directed National Telecommunications and Information Administration (NTIA) to collaborate with Federal Communications Commission (FCC) to find possibilities for the commercial use of additional spectrum, which held by Federal and non-federal users. In 2015, the FCC adopted rules for commercial use of 3.5 GHz frequency spectrum in the range from 3550 to 3700 MHz for shared wireless access. The commission established Citizens Broadband Radio Service (CBRS) and created three-tier framework to accommodate shared frequency band for the commercial use. CBRS network devices use the LTE standards for radio access and core network as regular LTE devices. The main difference between traditional LTE and CBRS LTE operation is the spectrum access method that devices use. In normal LTE operation, wireless service operators buy license LTE spectrum and utilize the spectrum for an access. In CBRS LTE, a central spectrum assignment mechanism used to manage the spectrum utilization and access. This new central spectrum assignment mechanism known as a Spectrum Access System (SAS)

2.2. A novel three-tier paradigm, an industry first with CBRS

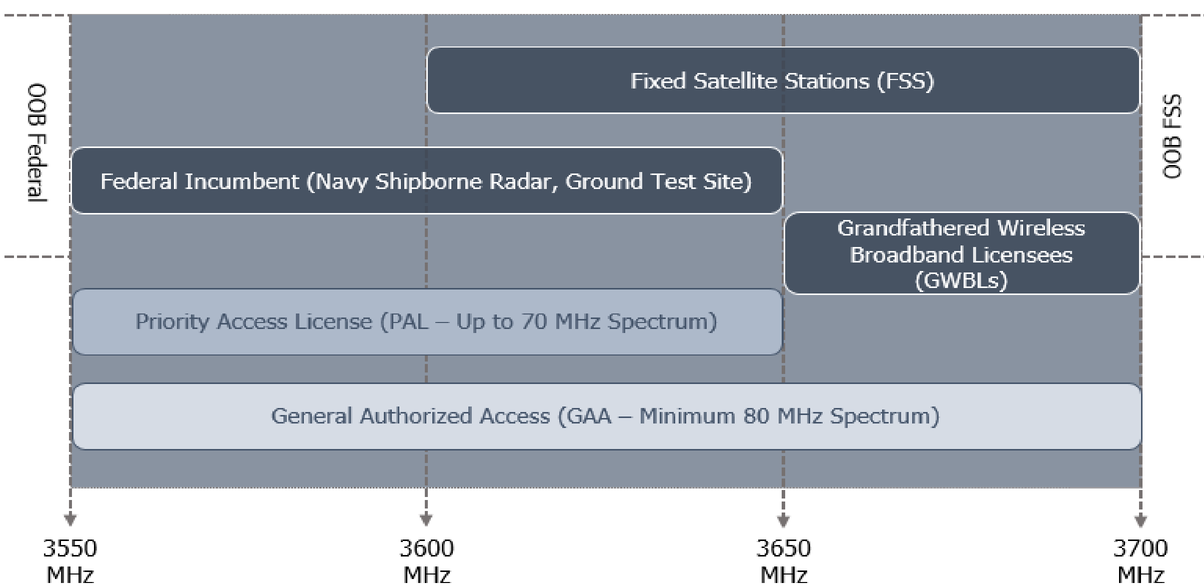


Figure 1 CBRS 3.5 GHz Frequency Band

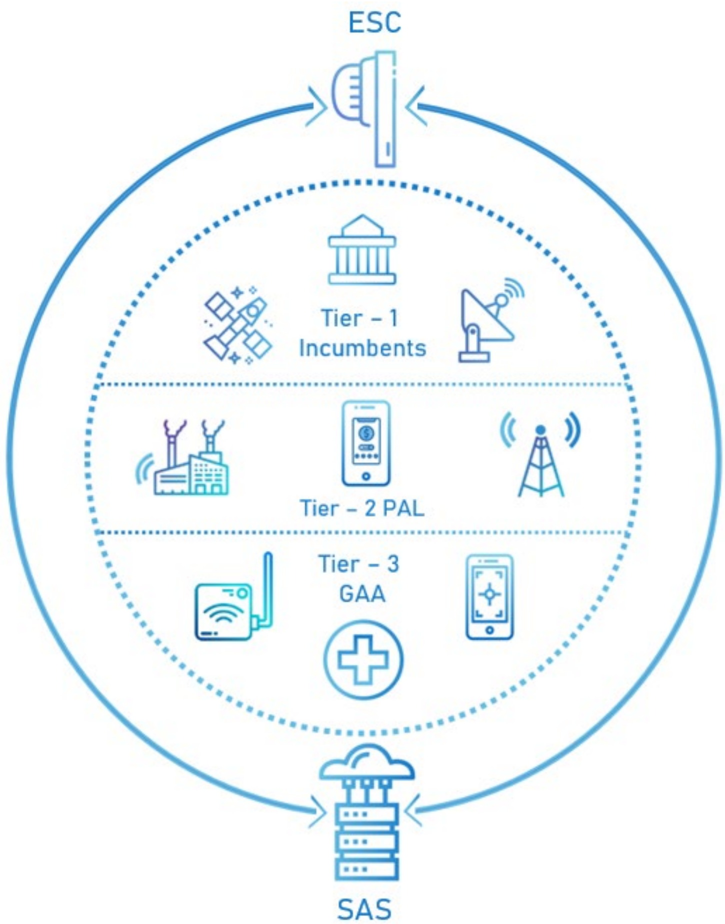


Figure 2 3-Tier CBRS Structure

A three tier-sharing framework, SAS enforced prioritization at all times.

Incumbents: US Military Radar/DoD, Fixed Satellite Station (FSS), Grandfathered Wireless Broadband Licensees (GWBLs) Highest priority access over PAL and GAA users.

PAL: Priority Access License, licensed tier. Licenses awarded via FCC Auction 105 for 3.5 GHz. Priority access to 70 MHz. Must register with SAS. Interference protected from GAA users.

GAA: General Authorized Access, unlicensed tier. Minimum of 80 MHz with an ability to float up to 150 MHz if PAL licenses are unoccupied. Must register with SAS. No interference protection. Opportunistic use, null priority rights.

2.3. Spectrum Access System

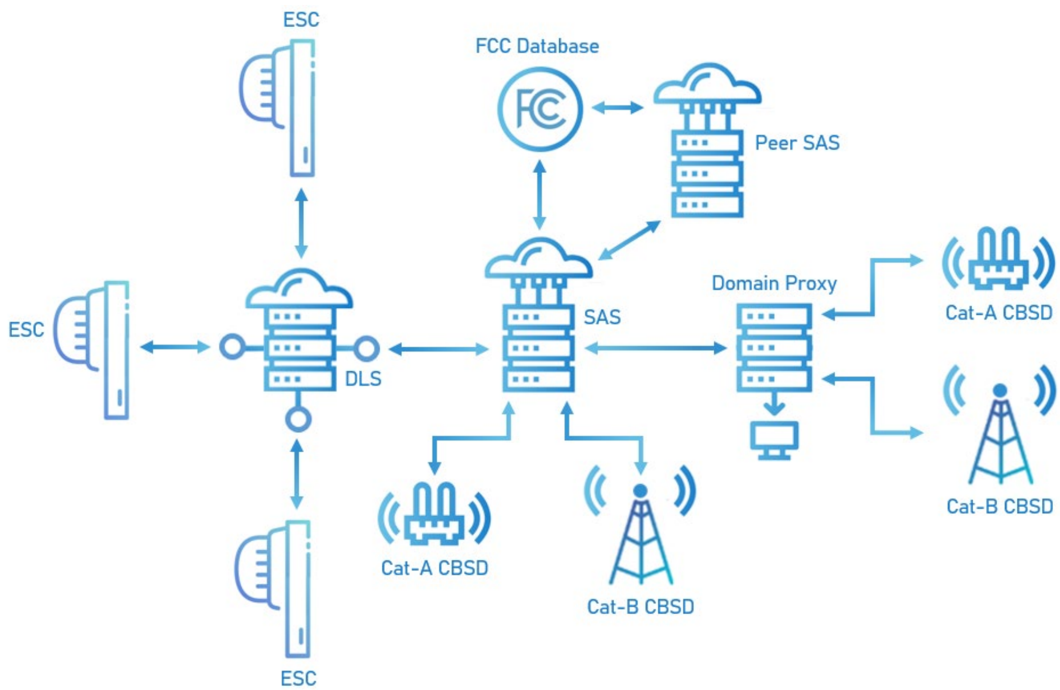


Figure 3 Spectrum Sharing Ecosystem

ESC: Environmental Sensing Capability
DLS: Decision Logic System
SAS: Spectrum Access System
CBSD: Citizens Broadband Radio Service Device

Spectrum Access System (SAS) is an entity authorized by the Commission to operate in accordance with the rules of part 96. It manages the assignment and distribution of spectrum to the users based on permissible frequencies at their location. Depending upon the user location, SAS controls and permits maximum transmission power level to protect higher tiers incumbent users and PAL users. All category CBSDs must register, authenticate identification and report its location with the SAS. An individual CBSD may directly communicate with SAS or CBSDs composed of a network may employ a system (Domain Proxy) for aggregating and communicating all required information exchange between CBSDs and SAS. On exchange of all necessary CBSD's information with the SAS, the SAS verifies requestor CBSD's FCC identifier with a FCC database and verifies CBSD's identity prior to authorizing the state where CBSD can start providing services. SAS is capable to determine available channels for users at any given geographic location and on the request of Spectrum Inquiry from CBSDs; SAS shall respond back to CBSDs with available spectrum for the requesting CBSD's geo location so CBSD can proceed with Grant request to SAS. CBSD would look for a channel grant from SAS by providing its maximum EIRP capability per MHz and on conforming to CBSD's EIRP capability with FCC database; SAS shall approve or reject Grant for requesting CBSD. For any new requesting CBSD, on successful Grant response, SAS would put CBSD in IAP pending until next Coordinated Periodic Activates among SASs (CPAS) window before giving Authorization to such CBSD. CPAS runs through every night from 12am PST to 3am PST. Post CPAS window; granted CBSD would be authorized to transmit by SAS followed by conditional exchange of heartbeats between CBSD and SAS at every 200 seconds time interval.

2.4. Environmental Sensing Capability

Environmental Sensing Capabilities (ESCs) sensors used to detect operation of Federal Incumbent in 3550 to 3700 MHz frequency band and it provides incumbent information back to SAS upon detection of any activity on any of the channels in the band. On receiving Incumbent detection information from ESC, SAS shall direct CBSDs for channel change or cease CBSDs transmission by suspending active grants of CBSD in order to protect federal incumbent's operation. On active Grant suspension by SAS, CBSD shall relinquish that grant and request new Grant for alternate channel recommended by SAS for immediate authorization. If no alternate channel available then SAS shall cease CBSD transmission by suspending its last active grant. On suspended grant, CBSD may continuously send heartbeats to SAS for suspended grant and resume operation when it receives success code (Code "0") from SAS in any of the heartbeat responses from SAS. In Release-1 of CBRS specifications, ESCs only monitor activity of Federal incumbent in 3550 to 3650 MHz of spectrum. ESC is a non-federal entity commonly operated by approved SAS administrators. Due to ESC's importance of detecting federal incumbents, SAS also protects ESCs against harmful interference which may be caused by surrounding CBSDs.

2.5. Incumbents

Incumbents are Tier-1 users of the CBRS frequency spectrum with highest priority over PAL and GAA users. There are Federal and Non-Federal incumbents. Federal incumbents are U.S. Navy's Shipborne Radar System that operates on any frequencies between 3550 to 3650 MHz. Federal incumbents also include some inland radar operation sites operating on any frequencies between 3500 to 3650 MHz. Non-Federal incumbents include Fixed Satellite Stations (FSSs) and Part-90 Grandfathered status Wireless Internet Service Providers. They are called as Grandfathered Wireless Broadband Licensees (GWBLs). FSSs are receive only earth stations operating on frequencies between 3600 to 3700 MHz. There are a few Out-of-Band (OOB) Registered for protection earth stations, i.e. TT&C (Telemetry, Tracking and Command) FSSs operate on frequencies between 3700 to 4200 MHz. GWBLs operate only on upper 50 MHz of CBRS spectrum, i.e. 3650 to 3700 MHz. These are all Tier-1 incumbents in CBRS shared model eligible for interference protection by SAS. Spectrum controller system retains information about these Federal as well as Non-Federal incumbents and their protection and exclusion zones in accordance with the rules of part 96. Depending upon CBSD's geo location and relation between non-federal incumbents (location of FSS and GWBL's active transmitter), SAS shall determine if the deployed CBSD location is an exclusion or protection zone for that CBSD to protect that non-federal incumbent from harmful interference. SAS also retains information about list of Exclusion Zones (EXZs) published by NTIA and shall not allow CBSD operation within 40kms radius of defined locations.

2.6. Protection of Federal Incumbents

Federal incumbents are-protected by SAS through the method of Dynamic Protection Area (DPA) activation. There are two types of DPAs. E-DPA and P-DPA. E-DPA is an ESC-DPA and an always-on DPA, monitored by ESC network. NTIA has provided the list of E-DPAs along the coastal boundary in the east and west coast of U.S. geography. Other than coastal areas, the additional list of E-DPAs provided by NTIA also covering the areas of Alaska, Hawaii, Puerto Rico and Guam. When federal Navy's radar system turn on its operation then SAS administrator's ESC sensor detects the active channel of radar system and the DPA zone where Navy ship operates. Upon detection, ESC provides that DPA ID and channel information to SAS. So within 300 seconds SAS shall re-assign CBSDs those are operating on the same channel as Navy's radar system and are under the protection zone of that DPA if there is any alternate channel available in that geographical area or may even cease those CBSDs' operation if no alternate channel available in order to protect federal incumbent from harmful interference. In order to protect in-land federal incumbents, P-DPAs (Portal-DPAs) are used. There are few P-DPAs published by NTIA for federal's ground based radar test sites operate on frequencies in the range of 3500 to 3650 MHz. Also known as "Informing incumbents" where SAS gets testing schedule of ground based radar system 24 hours in advance. In order to protect in land federal incumbent, SAS shall re-assign CBSDs operating on the same channel as ground radar system's channel and located under that P-DPA zone.

2.7. Protection of Non-Federal Incumbents

Non-Federal incumbents such as FSSs and Part-90 GWBLs protected by SAS from harmful interference caused by low tiered users through the method of aggregate interference calculation as per rules defined in part 96. Aggregate interference calculations consider CBSDs within 40 to 150 kms radius depending on the type of protected entities and type of CBSD.

2.8. Commercial SAS Trial Obervations in New York City, NY

Charter deployed a cluster of 21 FCC certified Category-B outdoor CBSDs in New York City, NY area. All CBSDs are configured with single 20 MHz LTE channel transmitting at max power per Category-B CBSD limit defined in part 96 under general radio requirements. New York City, NY county area is within 150 kms radius of one of the registered for protection "Fixed Satellite Station" (FSS) located in The Bronx, NY. There is an unexpired GWBL's transmitter located within 40 kms radius of this FSS. Hence, this relation between FSS and GWBL makes the area of 150 kms radius of the FSS an "Exclusion Zone". Therefore, upper 50 MHz of spectrum found to be unavailable for CBRS services by SAS until the expiration of active GWBL's license. So CBRS services can only be operational in the spectrum between 3550 to 3650 MHz in the New York City county geographical area. As per NTIA's defined protection zones, the deployed geographical area covered by five E-DPAs and four P-DPAs. CBSD grant suspension observed by any of these five E-DPA activations whenever there is any incumbent activity detected by ESC network in these E-DPA zones. The only channel suspended by SAS where Navy's radar system is operating on. Due to unavailability of alternate channel re-assignment feature on SAS now, CBSD could not get instantaneous new grant authorization from SAS. CBSD stayed in grant suspended state while Navy's radar system was in operation and resumed its services back when SAS gets no further information from ESC about incumbent activity.

2.9. Conclusion

CBRS is technology agnostic so it's not only good for LTE services but also one of the best option to deploy 5G services today in mid-band range of spectrum because of possibility to have wider channel bandwidth up to 100 MHz in 5G as per FR1 specs of 3GPP. Use of CBRS will provide platform for high performance deployments of diverse use-cases. It can be as simple as point to point or point to multipoint deployments for a small networks to large complex networks. These use-cases can be fixed, mobility and even advanced standalone networks. Other than mobile and cable service providers, many other market verticals such as Medical, Industrial, Agricultural, Retail, Oil & Gas, Energy, Power utility, Transportations, Airport and Educational institutions can utilize CBRS spectrum and make best use of it for their private network, Internet of Things (IoT), Security and surveillance and much more.

3. Implications to the deployment strategies

This section covers the details of how Charter has leveraged it's all possible physical assets such as Cable strand, Towerstream buildings and valued SMB locations for strategic deployment of its wireless mobility network in CBRS across 5 different markets. The deployed networks have been fully utilized for Charter's extensive in depth testing of MVNO data offload use case.

3.1. Attached Mount Deployment (Rooftop)

47 dBm/10 MHz allowable power limit applies to this deployment type and it can support larger antennas e.g. 64T64R Massive-MIMO antennas, one CBSD can have multiple sectors, typically get mounted on the rooftops and connect to Charter's DOCSIS serving the building.
Application: Attach mount unit can be installed more strategically than strand mount or SMB to clear obstructions or point to a targeted hotspot with required down-tilts without limitations like the other two types (Strand, SMB). Attached mount will be more effective when advanced features like Antenna Beamforming, Sector Virtualization, and Dynamic Load Balancing etc. are tested. This type of deployment provides larger coverage and capacity than strand and SMB scenarios.
Cost: Attach mount deployment and radio costs are most expensive than other three types of deployment. High cost for this type of deployment due to site surveys, A&E (structural analysis, construction drawings, LPC, transit or any other permit required) and entering into lease agreement with landlord. Site installation and commissioning, city inspection and close-out.

Figure 4 Attached Mount (Rooftop) Outdoor Deployment

3.2. Strand Mount Deployment

Strand mount is the most cost effective solution for Charter where aerial cable strand lines exist. The size and power are lower than Attached mount CBSDs, but their biggest bottleneck is power consumption from

the HFC plant power supply. Charter's mandating vendors to stay under 100W, some vendors have come up with strategies like powering down the CBRS amp until traffic picks up to keep plant power consumption low.
Application: Another bottleneck of strand unit is the mounting orientation – It has to be always along the strand and thus hotspot-targeted deployment in this case might be challenging. To mitigate this, Charter has requested Quasi-Omni strand design that has dual sectors with two sets of antenna covering NE and SW directions. Their height is always 18ft and typically, comes with 2x2 MIMO capability.
Cost: Utilizing existing assets to mount, connect to, maintain and operate make these the most cost efficient and expedient deployment type for outdoor Cat-B CBSDs.

Figure 5 Strand Mount Outdoor Deployment

3.3. Small Medium Business (SMB) Deployment

Indoor low power Category-A devices have been installed as part of Charter's CBRS wireless trial on Charter business customer's premises. Mainly used to provide pedestrian coverage. This deployment type can provide blanket coverage when deployed every 400 - 500 ft. A Strand or Attach mount usually compliments SMB coverage by serving as an umbrella cell and fill in for any coverage holes. Charter has requested vendors for Tri-Star config which adds a third sector to cover indoor and two sectors pointing outside the stores from behind a glass window. Charter makes use of this deployment type where applicable to form a uniform layer of CBRS coverage targeting AOI's and have run trials confirming seamless connectivity and performance between the outdoor coverage and the indoor coverage.

Inside Out: Charter's initiative to provide outdoor / pedestrian street coverage utilizing business customers' locations tested to serve as a contingent layer of indoor Category-A devices under outdoor high power Category-B umbrella cell. Below is a snapshot of three different locations where Indoor units installed with different heights and attenuation after the glass within 100ft was observed to be least at 18ft. This resulted in a larger footprint and relatively sustained coverage of the three scenarios.

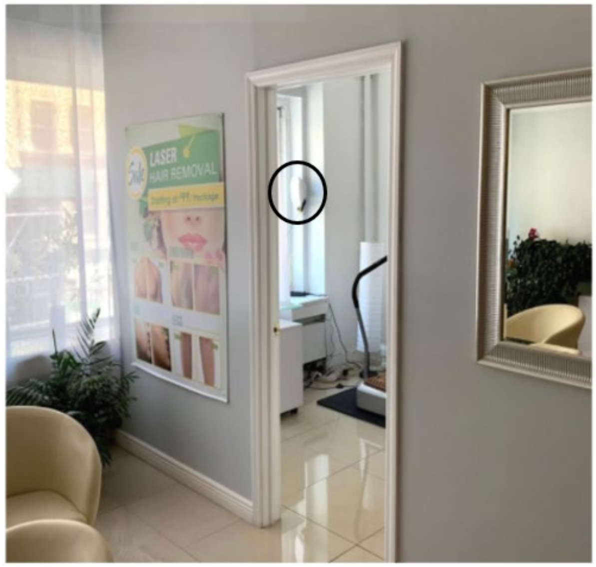


Figure 6 Indoor CBSD Deployment in SMB

Figure 7 Inside-Out Deployment in Spectrum Stores

Table 1 Inside-out Testing

Inside-Out Testing	Manhattan Spectrum Store	Astoria Spectrum Store	7th Floor Charter Office
Coverage Radius	1000 ft.	485 ft.	495 ft.
Throughput Outside	67 Mbps / 19 Avg.	74 Mbps / 17 Avg.	49 Mbps / 9 Avg.
Throughput Inside	77 Mbps	74 Mbps	72 Mbps
RSRP within 100ft.	-78 dBm	-95 dBm	-102 dBm
Height	18 ft.	8 ft.	70 ft.
Clutter Type	Dense Urban	Urban	Dense Urban
Glass Type	Standard	Double glass panel	Standard

Conclusion: Inside-out strategy requires optimal height (around 15 ft.) non-reflective and non-metal coated glass type and strategic placement of CBSD behind the glass in SMB location.

One of the most frequent issue noticed on SMB type indoor small cell is TDD time synchronization using external independent GPS antenna due to unreliable GPS signal with low SNR level in dense urban and urban locations in New York City and Los Angeles. It has been observed that small cells keep going into a GPS holdover state and out-of-sync state followed by out of service very frequently. It is unrealistic to use IEEE 1588PTP solution with independent grand master clock on each and every SMB locations. SMB small cells are wired using DOCSIS3.1 indoor CM for backhaul connectivity and hence it will be essential to have DOCSIS Timing Protocol (DTP) on such locations to mitigate timing sync related issues. DTP has been described in detail in section 8.1 of this document.

Outside-In Tests: The nature of the 3.5 GHz wave makes it less reliable when coverage target area is indoor and CBRS cell deployed outside. We conducted tests with a few types of inbuilding locations with an outdoor CBRS serving cell on Strand. Our tests include, location with Brick Wall and no windows in corridor, location with windows but obstructed for outside signal and location with windows and no obstructions to outside signal.

Figure 8 Outside-In Test Locations

Table 2 Outside-In Testing

Outside-In Testing	High School (Inside)	Grocery Store (Inside)	Restaurant (Inside)
RSRP (dBm)	-112 dBm (best), -135 dBm (worst)	-118 dBm to -135 dBm (outside -99 dBm)	-105 dBm (outside -100 dBm)
Throughput (Mbps)	9 Mbps (avg), 0 Mbps (min)	8 Mbps (outside 39 Mbps)	30 Mbps (outside 39 Mbps)
Coverage Limiting Factor	Uplink timeout	20-30 dBm Loss of RSRP	Glass type
Structure Type	Brick walls	Glass window + wall	Full glass windows
Clutter	Residential/Urban	Commercial/Urban	Commercial/Urban
Will Outside-In strategy work?	No	Weak	Yes (Rare case)

Conclusion: Providing the coverage inside the building from outdoor CBSDs will not work effectively. If Area of Interest (AOI) is inbuilding then it has to be targeted within the building.

4. Performance Characteristics of CBRS LTE Network

CBRS is a beneficial platform to bridge the gap between low spectrum carriers and mmWave challenges. Below are some of the characteristics Charter has observed in their CBRS trails.

4.1. Characteristics of CBRS Wave

3.5 GHz electromagnetic waves are subject to increased propagation losses than say the signals of AWS 1700 MHz or GSM at 800 MHz in a cellular network. The CBRS wave is 8.5 cm in wavelength, compared to 17 cm (AWS) and 37.5 cm (GSM) at the above frequencies. Thus, a CBRS cell gets- 2 times more propagation loss from 1.7 GHz carrier and 4.4 times higher propagation loss from 800 MHz frequencies. Extrapolating these values, if we suppose 3.5 GHz Category-B CBSD's Cell Radius in a dense urban clutter is 1/4th mile (1320 ft.) would yield cell radius of AWS radio at about ½ mile (2650 ft.) and about 1.1 miles (5808 ft.) for GSM keeping same EIRP.

Antenna size advantage: CBRS has a cutting-edge advantage over low band carriers making it more favorable to rollout. Due to smaller wavelength, antenna size is typically 12" – 15" long and weighs 2 lbs. This has opened-up deployment possibilities /strategic venues that were not an option in lower band rollouts from an acquisition standpoint. Image below shows CBRS 3.5 GHz antenna to the left and 600 MHz antenna on the right on one of Charter's trial sites. CBRS antenna is 14.3" long, wights 2 lbs compared to 600 MHz antenna's 8 ft length and more than 100 lbs weight.

Frequency Range	MHz	3300 - 3800MHz
Polarisation	Degree	+/-45° Slant Linear
Gain	dBi	12.5
Azimuth Beamwidth	Degree	65°
Azimuth Beam Squint	Degree<	3°
Elevation Beamwidth	Degree	22°
Electrical Downtilt	Degree	T0°
Electrical Downtilt Deviation	Degree<	1°
Impedance	Ohms	50
VSWR	<	1.5
Return Loss	dB>	14
Isolation	dB>	25
Front to Back Ratio: Total Power +/-30°	dB>	28
Upper Sidelobe Suppression, Peak to 20°	dB>	18
Cross-Polar Discrimination	dB>	16
Maximum Effective Power Per Port	W	50

Figure 9 CBRS 3.5GHz Antenna Properties

Decreased Obstruction Resistance: CBRS wave is seen to incur abrupt attenuation when obstructed compared to AWS and GSM that could refract around obstructions, form a shadow and resume coverage in good RSRP range. CBRS however is observed to be very prone to obstructions. This can be seen in drive data when the cell is obstructed the coverage takes an abrupt hit i.e. 20-30 dBm attenuation.

3.5 GHz coverage reliability: CBRS wave is affected to a higher degree relatively when deployed in high foliage areas, hilly terrain obstructing antenna beam, downtowns or vertically layered dense urban clutter that obstructs the beam.

Figure 10 Dense Urban Morphology

4.2. mmWave Comparison

If an operator doesn't already own spectrum, then there are a few options which can be considered. The next auction which will be happening is the C-BAND auction. This spectrum will have very similar characteristics to CBRS and should be viewed in a similar manner. The other option is to look at mmWave. mmWave has two distinct advantages. The first advantage is large blocks of bandwidth which can be utilized versus sharing 150 MHz among many parties. The second advantage is the ability to radiate at higher powers due to the restrictions the FCC has placed on CBRS. Both of these are strong advantages for mmWave; however, mmWave has a major issue. It does not propagate very far, and it is easily obstructed by foliage, buildings, and windows. To show the differences, a theoretical comparison was performed between 5G CBRS and 5G 28 GHz mmWave. Table 3 below shows the baseline assumptions for the comparison and Figure 11 shows the results.

Table 3 5G CBRS vs 5G 28 GHz mmWave Assumptions

	mmWave gNB	Sub-6 gNB	mmWave UE	Sub-6 UE
Combined transmission power (dBm)	28	34	16	23
Antenna gain (dBi)	23	23	11	0
Total EIRP (dBm)	51	57	27	23
BW (MHz)	800	100	800	100
Frequency (GHz)	28	3.5	28	3.5
Height (m)	40	40	1.5	1.5
DL/UL max layers	2/2	8/4	2/2	2/2
Propagation Model	Rma Rural NLOS	Rma Rural NLOS	Rma Rural NLOS	Rma Rural NLOS

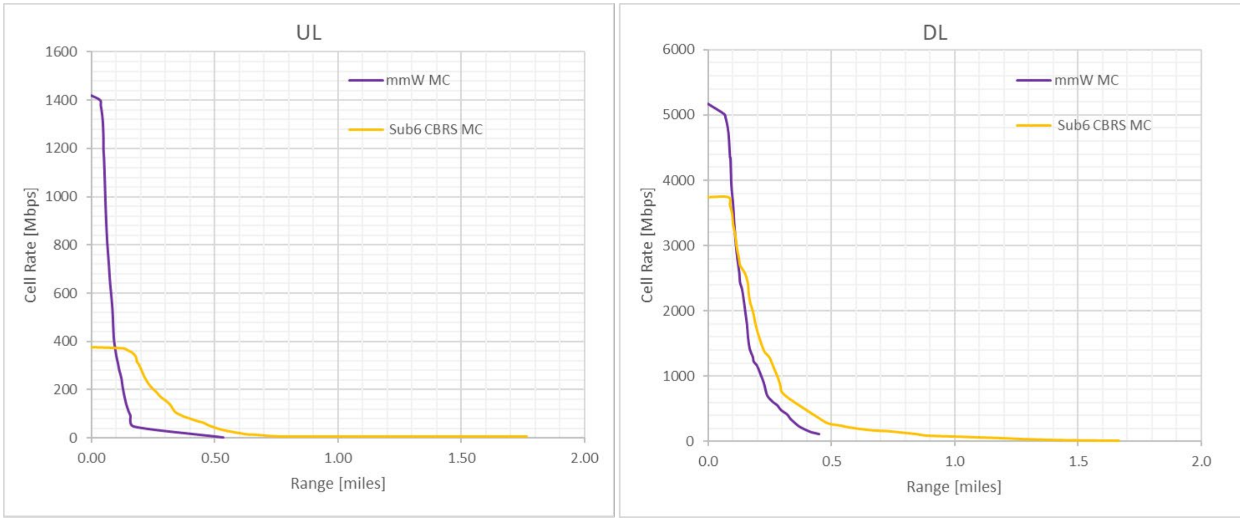


Figure 11 5G CBRS vs 5G 28 GHz mmWave Results

Key takeaways from the results: DL throughput is not significantly higher for the 28 GHz mmWave transmission versus the 5G CBRS product even though the bandwidth is 8X. 5G CBRS gets significantly more coverage (1.7 miles versus 0.5 mile); however, UL connectivity is very low just pass 0.5 mile. UL capacity below 0.2 mile is significantly greater in mmWave.

4.3. 5G CBRS vs 4G CBRS

Outside of the hype, does it make sense to deploy a 5G CBRS network versus a 4G CBRS network? There are many areas which need to be explored before making this decision. For the purposes of this paper, a short review of a few of the technical aspects will be performed.

From a theoretical comparison, spectral efficiency for 5G is slightly better due to a leaner carrier design which corresponds to roughly 15% improvement. Very similar improvement for 5G is also seen with Pathloss calculations.

General comparison between LTE and 5G –

Table 4 LTE vs NR Comparison

	LTE	NR
Frequency Range	Sub-6 GHz	Sub-6 GHz and mmWave
Maximum CC BW	20 MHz	100 MHz or 400 MHz depending on frequency band
Subcarrier Spacing	Fixed 15 kHz	Scalable 2^µ 15 kHz
Waveform	DL: CP-OFDM UL: DFT-s-OFDM	DL: CP-OFDM UL: CP-OFDM/DFT-s-OFDM
TTI	14 OFDM symbols in fixed 1ms	14 OFDM symbols with scalable 1/2^µ ms
Channel Coding	Data: Turbo coding	Data: LDPC Control: Polar code

	Control: Tall biting convolutional coade	
Initial Access	Broadcast	Unicast
MIMO	8 layers codebook and non-codebook precoding	8 layers non-codebook precoding
Reference Signal	CRS, DMRS, CSI-RS, SRS	DMRS, CSI-RS, PTRS, SRS
Duplexing	FDD, Static TDD	FDD, Dynamic TDD
HARQ	Synchronous/Asynchronous with 8 processes	Asynchronous with 16 processes and CBG retransmission

4.4. CBRS Coverage Reliability from Field Tests

Charter conducted tests to observe CBRS behavior and coverage reliability in different clutter types. It has been noted that CBRS is more prone to obstructions and cell radius is affected when path is obstructive. Phenomenon like refraction and scattering do not aid CBRS wave in an obstructed path.

Figure 12 Field Drive Test Plot

Site data shown in the Figure 12 where street to the north is obstructed. It has been observed the RSRP cannot sustain obstruction and degrades to sub -120 dBm zone very quickly right after (138 ft). Unobstructed path to the west is 736 ft. SINR also shows similar trend to RSRP degradation. This is typical behavior of CBRS 3.5 GHz wave when obstructed and reduces effective cell radius in non-LOS conditions.

4.5. Factor affecting throughput in CBRS network – Field Assessment

Charter tested various factors to observe effects on throughputs. Below is the analysis of data gathered. From the field we observed DL throughput has high dependency on RSRP. As CBRS RSRP fluctuates the affect is translated directly to the streaming UE. As seen from test results, depending on morphology of the clutter, below a certain RSRP the SINR takes a hit and throughputs plunge to single digits.

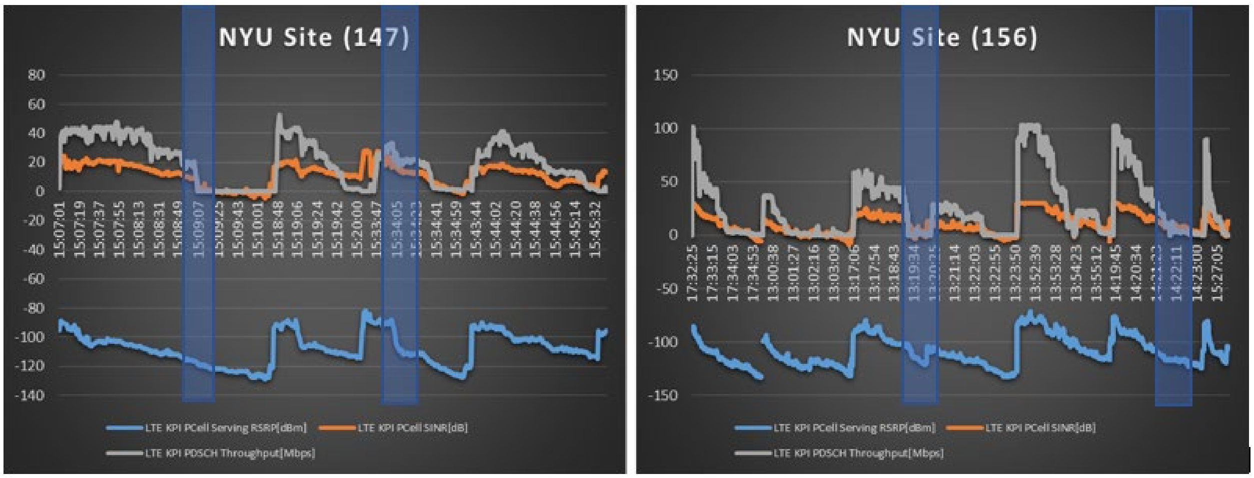


Figure 13 Field Single Site Performance Stats

In the left graph: As highlighted, when RSRP (blue) drops below -115 dBm, the DL Throughput is seen taking an abrupt hit (gray) to single digits. It rises again as RSRP goes up and again below certain RSRP the throughput nose dives. The second highlighted region from left to right, shows obstruction in coverage as RSRP taking a steep gradient downward, the throughput degrades but doesn't drop down to minimum until RSRP crosses neg 115 dBm. For this morphology, neg 115 dBm seems to be the point below which decent throughputs cannot sustain. In the right graph: In the second site region the throughput shows same trend as first region, as shown in highlighted area, as RSRP (blue) dips below neg 100 dBm, the SINR drops and Throughput take a steep slope downward to single digits (gray). As soon as RSRP exceeds -100 dBm, both SINR and throughput rise showing direct correlation. The second highlighted area shows similar trend when RSRP drops.

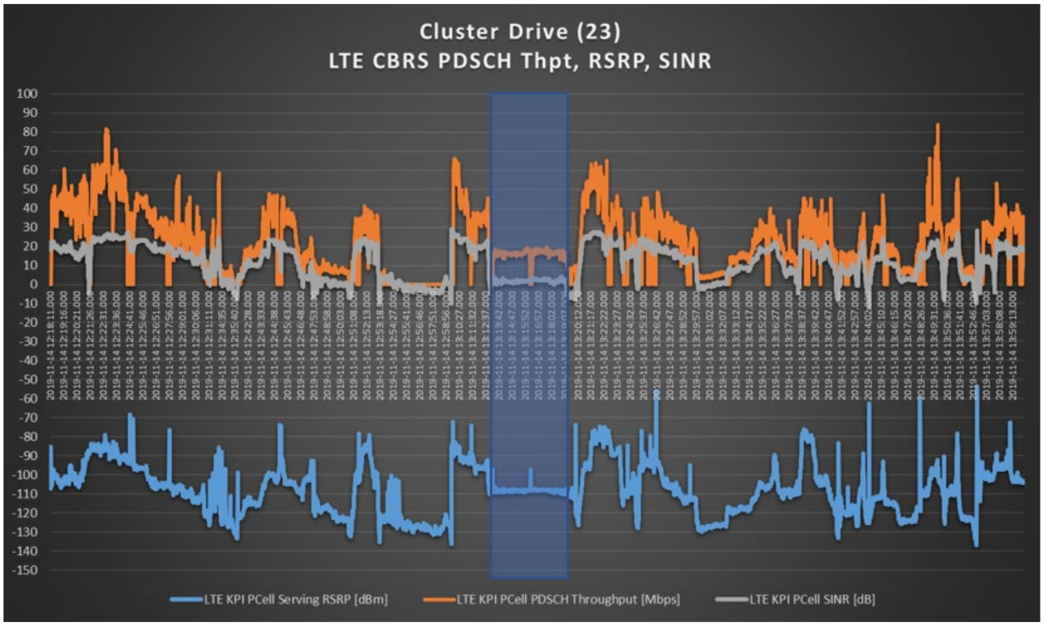


Figure 14 Field Cluster DL Performance Stats

In another area cluster drives were observed to show instances (left highlighted portion above) where RSRP stayed between -110 dBm to -112 dBm and throughputs were not severely affected even when SINR dropped to single digits. The right highlighted portion shows an abrupt drop in DL throughput as RSRP plunges but it regains and trends alongside RSRP rising trend.

Also this area was deployed with a different vendor equipment than the previous area so the chipset or equipment's receive sensitivity or processing power could be the factors differentiating from other area. In addition to this, this clutter morphology is denser with more shadowing, reflections, refractions and beam scattering phenomenon(s) coming into play.

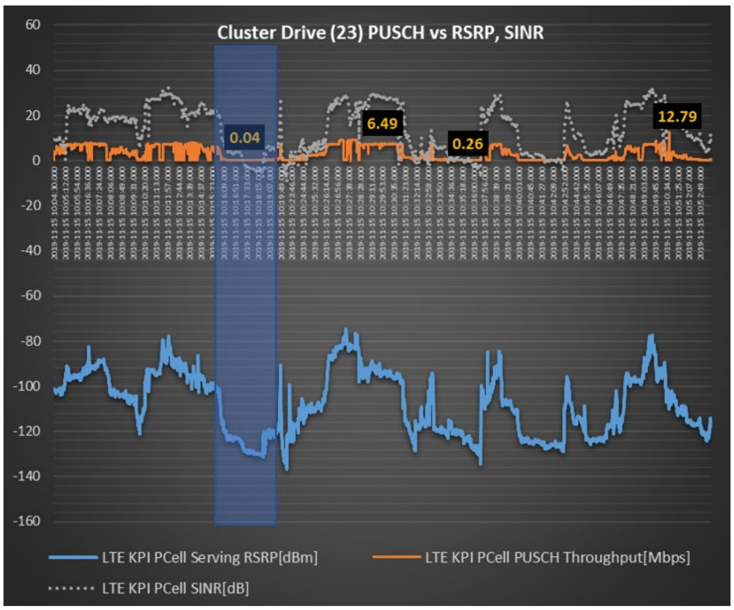


Figure 15 Field Cluster UL Performance Stats

In this graph UL throughput data is shown, collected during a field trial. It can be seen UL is more susceptible to degrade as RF conditions deteriorate. When DL RSRP dips below -100 dBm, the UL throughput lowers to under 1 Mbps. Although DL RSRP is uncorrelated to UL but the path loss scenario's are the same in both directions most of the time, as highlighted in the graph above show.

4.6. LTE Performance KPIs Observation from Field Trials

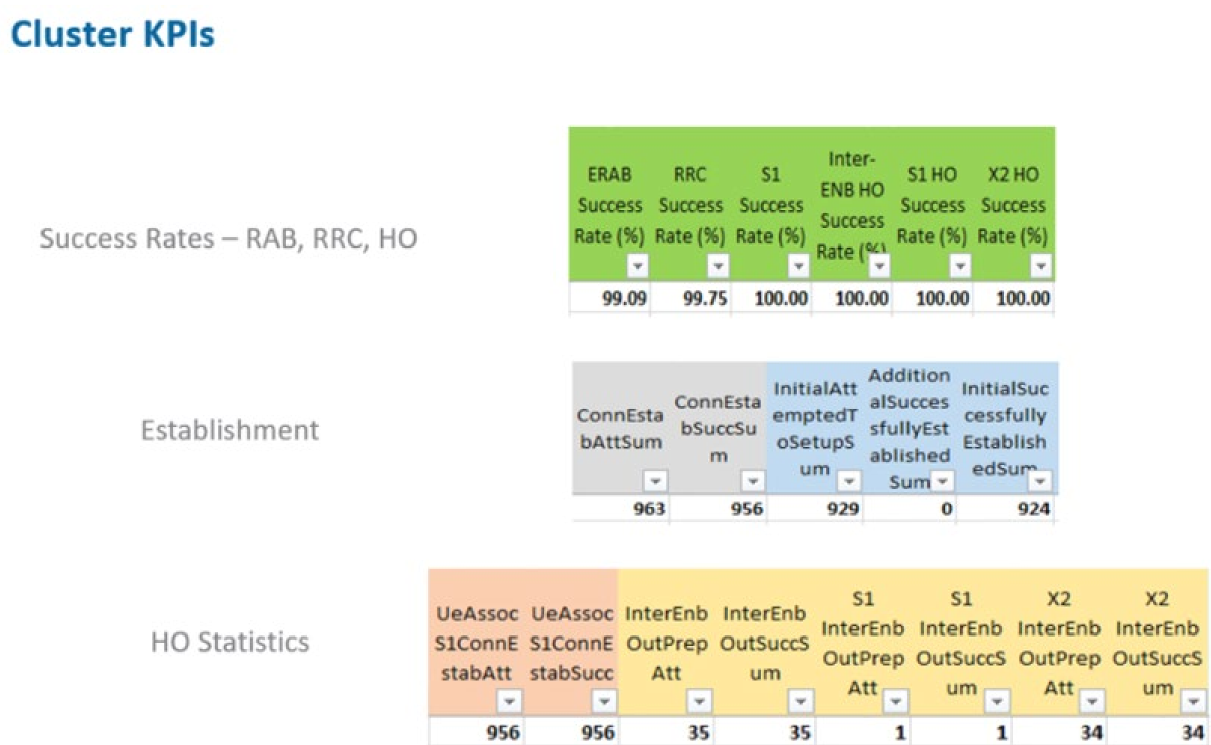
Performance KPIs for Strand network when tested yielded following –

Up to 14 Simultaneous UEs connected in dedicated mode, 14 GB Tonnage carried with 1% Drop Rate and 99% Establishment Rate and X2 HO Success rate of 95%

Table 5 Cluster Performance KPIs

Strand CBRS Cluster KPIs	Max UEs Connected	Drop Rate (%)	ERAB Success Rate (%)	RRC Success Rate (%)	S1 Success Rate (%)	Tonnage (GB)
	14	1	99	99	100	14

Attached mount cluster field tests showed following –



Cluster KPIs

Success Rates – RAB, RRC, HO

ERAB Success Rate (%)	RRC Success Rate (%)	S1 Success Rate (%)	Inter-ENB HO Success Rate (%	S1 HO Success Rate (%)	X2 HO Success Rate (%)
99.09	99.75	100.00	100.00	100.00	100.00

Establishment

ConnEstabAttSum	ConnEstabSuccSum	InitialAttemptedToSetupSum	AdditionalSuccessfullyEstablishedSum	InitialSuccessfullyEstablishedSum
963	956	929	0	924

HO Statistics

UeAssocS1ConnEstabAtt	UeAssocS1ConnEstabSucc	InterEnbOutPrepAtt	InterEnbOutSuccSum	S1 InterEnbOutPrepAtt	S1 InterEnbOutSuccSum	X2 InterEnbOutPrepAtt	X2 InterEnbOutSuccSum
956	956	35	35	1	1	34	34

Figure 16 Attached Mount Cluster KPIs

In a single session 5.9 GB network tonnage was handled with 43 HO attempts in between 3 sites, 8 Sectors and 16 Carriers. Up to 14 UEs, 5 simultaneously attached to the network, peak data rates of

103 Mbps observed. 963 connection establishment attempts, ERAB setup rate, RRC Success rate, S1 & X2 HO Success rate and Inter-eNB success rates were all greater than 97%.

RSRP	Percentage of Drive (%)	DL Thpt Avg (Mbps)
> -90 dBm	11	41
> -100 dBm	17	35
> -110 dBm	37	25
> -120 dBm	21	16
> -130 dBm	14	5

Figure 17 Cluster Drive RSRP and Throughput

RSRP is the key driver of performance. Below graph is a plot of DL throughput per dBm and the steepest gradient is at -104 dBm. We've observed depending on clutter type and morphology the throughput is more affected as RSRP degrade from -104 dBm and drops to single digits as it nears -120 dBm as shown in 'Factor Affecting Throughput in a CBRS Network – A Field Assessment' section.

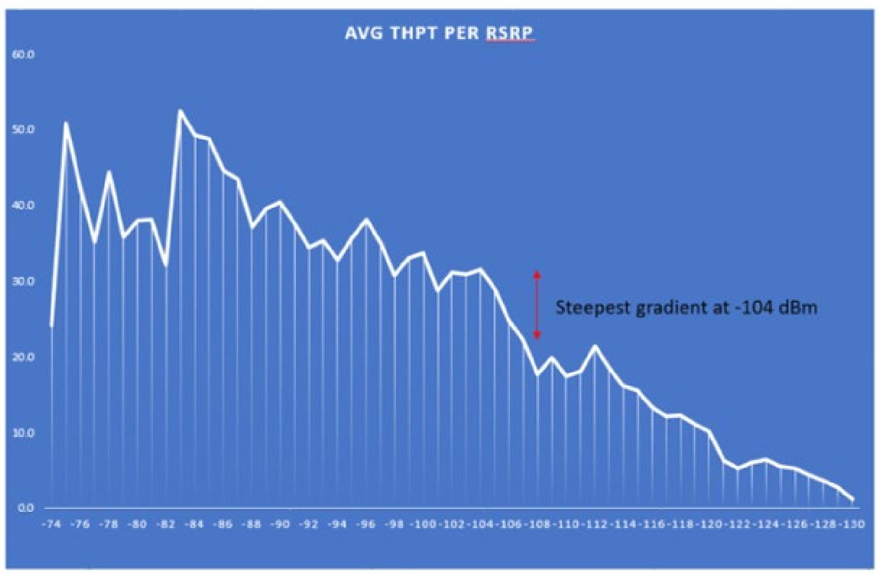


Figure 18 RSRP to Throughput Function

4.7. Capacity Testing

Charter conducted a field trial in Tampa, FL to test CBRS load bearing capability and effect on cell performance throughput. Field trial done at three distinct locations from the cell based on RSRP values referred as Cell Near, Cell Mid and Cell Edge.

Figure 19 Load Test Setup on Field

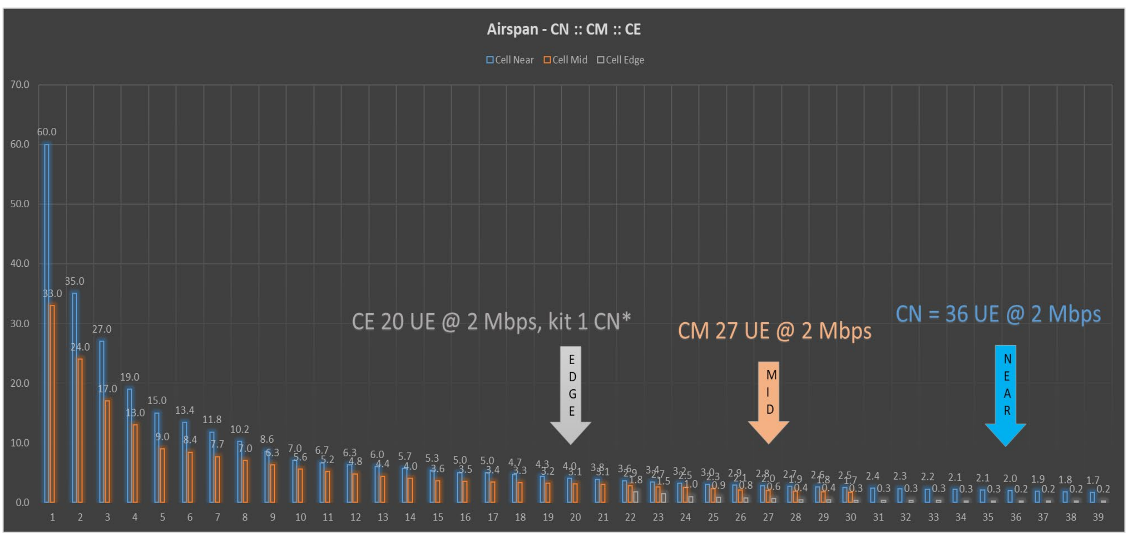


Figure 20 Load Test DL Performance Stats

In the graph above, when one UE attached at Cell Near location, the Downlink throughput was 60 Mbps. When second UE was fired up the Downlink throughput dropped to 35 Mbps Avg. Third one joined, and the throughput reduced to 27 Mbps and so on (blue). At the Cell Near location, up to 36 UEs simultaneously streamed above 2Mbps. At the Cell Mid location (orange), throughputs started at 33 Mbps and up to 27 UEs could stream above 2Mbps simultaneously. Lastly, at the Cell Edge (gray) location, 20 Simultaneous UEs could stream at and above 2 Mbps. Testing of another vendor showed slightly different results, consolidating all in the table below shows Cell Near of 34 and Cell Edge of 13 UEs maintaining 2 Mbps at all times.

Table 6 DL Load Testing

DL Throughput	# UEs at Cell Near	# UEs at Cell Edge
> 20 Mbps	4	0
15 – 20 Mbps	2	0
10 – 14 Mbps	4	0
5 – 9 Mbps	7	4
2 – 4 Mbps	**34**	13
0 – 1 Mbps	0	**33**

Majority of UEs stayed within 2 – 4 Mbps at Cell Near.
Majority of UEs stayed under 1 Mbps at Cell Edge

In addition, from observation in the Field trials that as UEs are loaded up, the 2Mbps boundary threshold (DL) reduced virtually. Our test results shown in the table below:

Table 7 Load Effect on Cell Radius

Loading effect on Geographical Radius of 2 Mbps DL boundary		
# of Simultaneous UEs	**2 Mbps Radius (m)**	**% Loss of Radius**
1	342	
5	277	19%
15	205	40%
30	64	81%

4.8. Busy Hour Traffic Analysis

Busy hour changes dynamic of the cell, grade and quality of service. Below is a theoretical analysis of how busy hour affects end user throughputs. Input parameters in this calculation have been taken from our capacity testing field trial.

We assumed average throughput per user is 50 Mbps DL / 10 Mbps UL in non-busy hour. Using capacity trial results, we get average of 34 Cell Near and 13 Cell Edge, giving an average of 23.5 UEs Cell Mid for 20 MHz. At 40 MHz we took 1.5 times 23.5 UEs = 35 UEs per cell. Assuming 80% of users at busy hour, this comes to 28 UEs per cell in BH. Combining rates for different QAMs, throughput per user in BH comes out to be 5.8 Mbps. From 50 Mbps to 5.8 Mbps is the effect of busy hour on a CBRS cell. This analysis is theoretical.

Table 8 Assumptions for Busyhour (BH) effect on Throughput

Per CBRS Cell 40 MHz BH Analysis	DL	UL	Unit	Remark
Avg. Throughput per UE (Product)	50	10	Mbps	20% UL based on FC2
# of UEs per Cell	35		Avg	Per testing in 20 MHz: CN 35 + CE 12 = 23.5 Avg UEs * 1.5 for 40 MHz = 35.2 UEs
BH Users	28		UEs	80% of estimated total UEs
Peak Throughput BH (256 QAM)	300		Mbps	
Peak Throughput BH (64 QAM)	220	35	Mbps	
Peak Throughput BH (16 QAM)	150	23	Mbps	
Peak Throughput BH (QPSK)	75	12	Mbps	

Peak Throughput BH (Consolidated)	164	17	Mbps	(Based on drive data: 30% for each DL Modulation except 10% for 256 QAM)
Throughput per User (BH)	5.8	0.6	Mbps	
Total Tonnage per User (BH)	2.6	0.3	GB	
Total BH Tonnage per Sector	73.6	7.5	GB	

Table 9 Busyhour (BH) Traffic Analysis - Strand Mount

BH Traffic Analysis – Strand	**DL**	**UL**	**Unit**
Avg. Throughput per UE (Product)	50	10	Mbps
# of UEs per Cell	35		Avg
BH Users	28		UEs
Peak Throughput BH (Consolidated)	164	17	Mbps
Throughput per User (BH)	5.8	0.6	Mbps
Total BH Tonnage per Sector	73.6	7.5	GB
Total BH Tonnage per Strand Site	147.2	15.0	GB

Table 10 Busyhour (BH) Traffic Analysis - Attached Mount

BH Traffic Analysis – Attached	**DL**	**UL**	**Unit**
Avg. Throughput per UE (Product)	50	10	Mbps
# of UEs per Cell	35		Avg
BH Users	28		UEs
Peak Throughput BH (Consolidated)	164	17	Mbps
Throughput per User (BH)	5.8	0.6	Mbps
Total BH Tonnage per Sector	73.6	7.5	GB
Total BH Tonnage per Attached Site	220.7	22.5	GB

Table 11 Busyhour (BH) Traffic Analysis - SMB

BH Traffic Analysis – Attached	**DL**	**UL**	**Unit**
Avg. Throughput per UE (Product)	50	10	Mbps
# of UEs per Cell	17		Avg
BH Users	14		UEs
Peak Throughput BH (Consolidated)	164	17	Mbps
Throughput per User (BH)	12.0	1.2	Mbps
Total BH Tonnage per Sector	73.6	7.5	GB
Total BH Tonnage per SMB Site	220.7	22.5	GB

Average DL User throughput drops from 50 Mbps to 5.8 Mbps as traffic spike hits 80% of cell capacity. Cell overlap along with advanced load and spectrum sharing and congestion mitigation techniques can be employed to reduce this impact.

4.9. Conclusion

CBRS is more suited for hot-spot targeted and pocketed coverage applications with redundancy to fall back to alternate technology when needed like Charter's MVNO in DSDS configuration with the ability to transition to MVNO network to mitigate customer impact. In the event of blanket / cluster wide coverage requirement the ISDs will have to be no more than 1000 – 1400 ft. apart.

CBRS LOS vs non-LOS coverage, the loss beam incurred when subjected to obstruction due to its high propagation loss characteristics, makes CBRS radius shrink to a greater extent than low band spectrum carriers.

5. CBRS Radio Devices and RF Design of CBRS Network

5.1. CBRS Radio Devices

In CBRS terminology, an LTE eNodeB or base station is called Citizens Broadband Radio Service Device (CBSD). As per Code of Federal Regulation, Part 96, there are two categories of CBSDs defined, Category-A and Category-B devices. All CBSDs must register with and authorized by SAS prior to their initial service transmission. They must operate at or below the maximum power level authorized by SAS and must be in compliance with their FCC equipment authorization. For Category-A CBSD, the maximum EIRP and maximum PSD limits are 30dBm/10MHz and 20dBm/MHz respectively and generally deployed indoors. For Category-B CBSD, the maximum EIRP and maximum PSD limits are 47dBm/10MHz and 37dBm/MHz respectively and deployed outdoors.

5.2. CPE for Fixed Wireless Access

Selection of optimal Customer Premise Equipment (CPE) for Fixed Wireless Access (FWA) application is very crucial. High power, high antenna gain CPE device helps in network design for better uplink user performance perspective. Today, there are many OnGo certified, part 96 compliant CPEs available in the market to choose from for various different form factors for Fixed Wireless network application in CBRS. Charter has done FWA rural broadband trial in North Carolina with a couple vendor's CPE devices with capability of 1x4 and 2x4 MIMO configurations and high power up to 26 dBm and 15 dBi high gain antenna for better user experience. Their 3GPP device category information is very important and used to allow the eNodeB to provide compatible user services more efficiently. In other words, the user equipment category defines the overall performance and the capabilities of the UE. There are different UE categories that have a wide range of features supported for enhanced end user performance experience. Some of them are only capable of supporting SISO; some of them support 2x2 and 4×4 MIMO. The UE category defines a combined uplink and downlink capability as specified in 3GPP TS36.306

Table 12 CPE Category

User Equipment Category	Downlink (Mbits/s)	Max # of DL MIMO Layers	Uplink (Mbits/s)	3GPP Release
1	10.3	1	5.2	Rel. 8
2	51	2	25.5	
3	102	2	51	
4	150.8	2	51	
5	299.6	4	75.4	

User Equipment Category	Downlink (Mbits/s)	Max # of DL MIMO Layers	Uplink (Mbits/s)	3GPP Release
6	301.5	2 or 4	51	Rel. 10
7	301.5	2 or 4	102	
9	452.2	2 or 4	51	Rel. 11
10	452.2	2 or 4	102	
11	603	2 or 4	51	
12	603	2 or 4	102	

5.3. RF Design

Various different strategic CBRS trials have been performed over the last couple of years. Extensive Continuous Wave (CW) tests performed in different morphological geography to understand 3.5 GHz signal propagation characteristics in all different areas like dense urban, urban, sub-urban and rural. Results have been studied thoroughly, data utilized for RF design model tuning to create our own optimal propagation model for each different morphological area. For an accurate and realistic RF design, the recommendation is to use 3D modeling with accurate and high definition 3D geo data for a better result. Foliage data consideration into RF design would give result that is more accurate. For the best RF design and propagation model tuning, adopt an advanced method to collect CW data with better equipment. The advanced method such as dead reckoning giving location information that is more accurate. This will be crucial for markets such as NYC, LA and Dallas or any downtown areas with high-rise buildings.

5.4. Conclusion

Plenty of RF drive tests and walk tests performed on the field on different types of small cells from multiple vendor equipment deployed on strand, rooftop and indoor locations. An average cell radius provided by strand mount small cell is approximately 300 meters. This is line of sight (LOS) radius and not a uniform radius of circular coverage as strand mount CBSDs usually deployed below clutter at 18 feet radiation point. The cell radius for line of sight coverage from an Attached mount (Rooftop) small cell is at least 1500 meters, diameter of cell coverage is 3000 meters. However, the overall non line of sight radius depends on height of attached mount CBSD and is relative to clutter and can vary from 300 meters to 700 meters radius (600 meters to 1400 meters diameter).

6. Introduction of 3GPP Virtual RAN Split Options

Virtual Radio Access Network (vRAN) is a new network deployment architecture that reduces the operational and capital expenditures of wireless network deployment. vRAN network architecture consists of mainly three parts, 1- Central Unit (CU), 2- Distributed Unit (DU) and 3- Radio Unit (RU). Each of these parts can execute different layer(s) of network communication protocol, and this is classified as ‘Split Options. In this part of white paper, we will explain what different split options are, and why Charter has selected split option 2 for DOCSIS based 5G CBRS wireless network deployment.

6.1. Split Options

In vRAN deployment model, there are seven main protocol split models used to execute different parts of protocol layers at Distributed Unit (DU) and at Central Unit (CU). Here is the list of protocol split options used today.

- Option 1: RRC/PDCP split
- Option 2: PDCP/RLC split
- Option 3: Intra-RLC split based on a split of the RLC functionality such that the entire RLC is located in the central unit hosted in the cloud
- Option 5: Intra-MAC split
- Option 6: MAC/PHY split
- Option 7-1: This split where the IFFT and cyclic prefix insertion/removal performed at the remote radio unit (distributed unit) and IQ samples in frequency domain exchanged over the Fronthaul interface
- Option 7-2 & 7-2a: These splits have the additional benefit that pre-coding and digital beamforming, or parts thereof, are performed at the remote radio unit (distributed unit)
- Option 7-3: This split option considered only for the downlink, further reduces bandwidth requirements on the interface as coded user data exchanged before modulation.

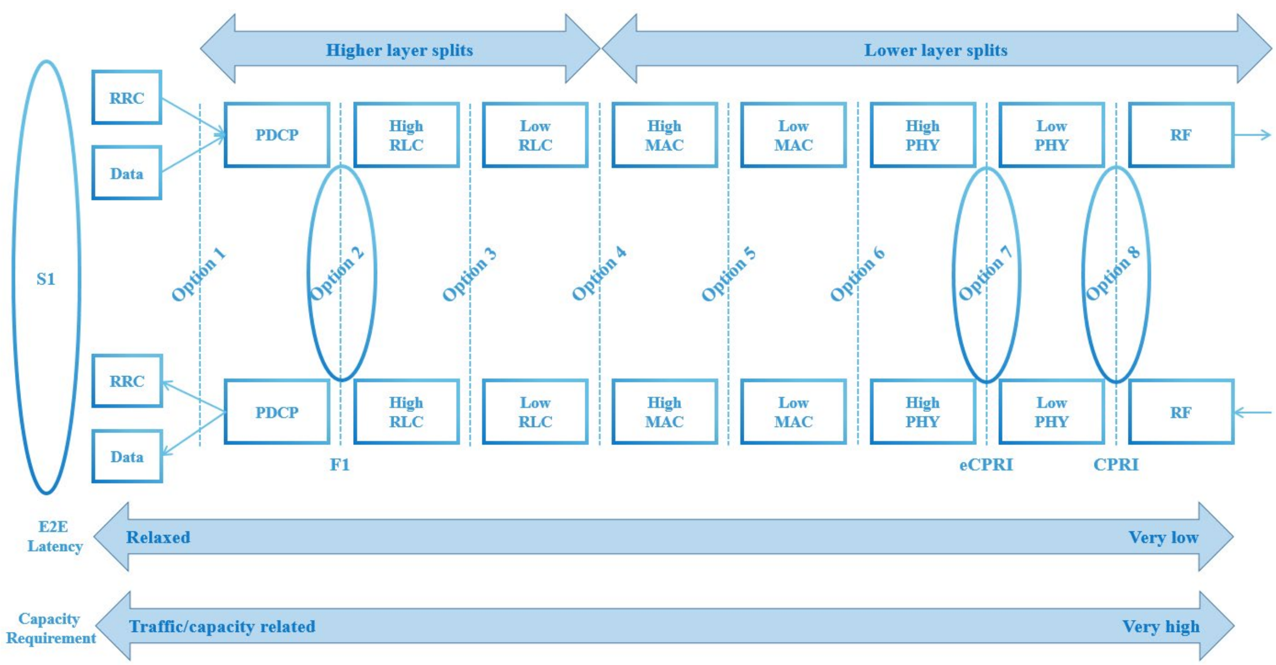


Figure 21 Protocol Split Options

Each protocol layer has a number of processes that perform the tasks of that protocol layer. In addition, these processes represented by the processing blocks. In Physical layer (PHY) of LTE standard, there are nine processing blocks and split options 7.1, 7.2 and 7.3 created based on splits between processing blocks.

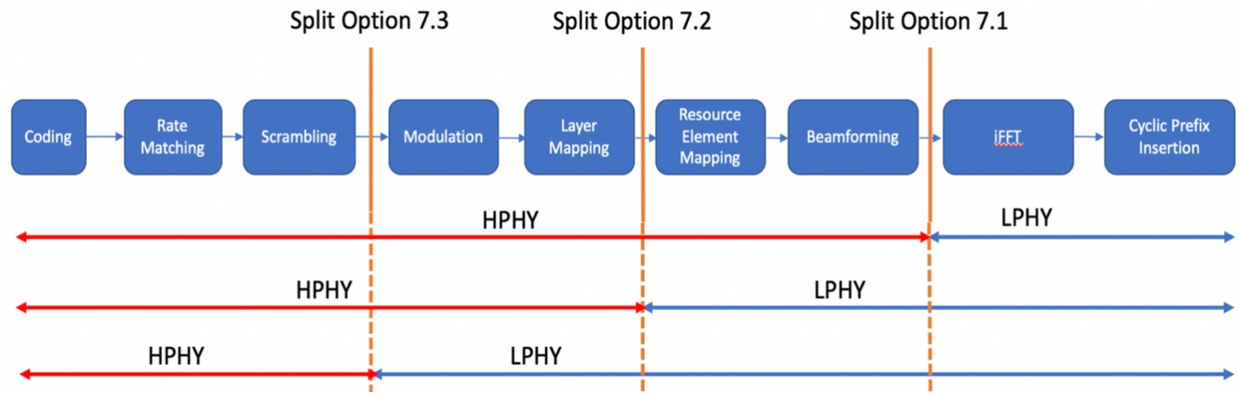


Figure 22 Sub-splits for Split Option 7

Processing blocks below split point are called Lower Physical Layer (LPHY) and processing blocks above split point is called Higher Physical Layer (HPHY). LPHY is executed in RU and HPHY is executed in DU.

6.2. Split Options and Latency Requirements

Latency requirements on the interface in general become tighter the further down in the protocol stack the split is, though one can classify two levels of latency requirements. For 3GPP, Split Option 1-3, where all RAN functionality that has to operate synchronously to the radio (i.e. in real time), the interface latency requirements are rather relaxed. Latency requirements are much more stringent for the other options where RAN split cuts in between synchronous functionalities. Recommendation to have Split Option 7-3 for CRAN deployment. Split Option 2 or Option 3 is preferred for deployment with DOCSIS since latency requirements is rather relaxed.

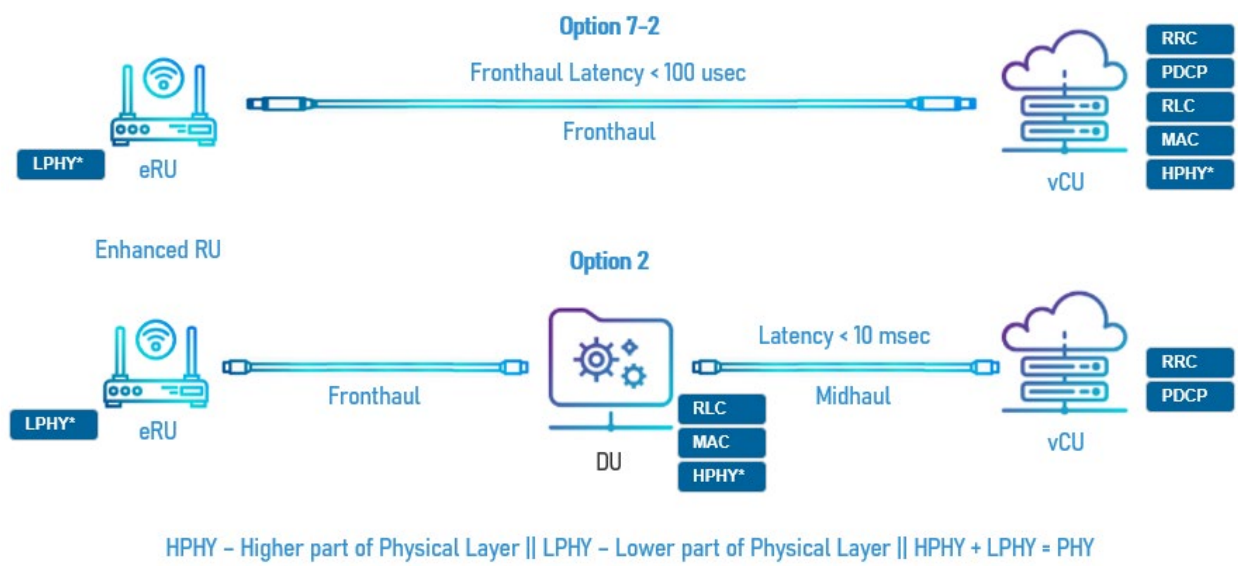


Figure 23 Sub-splits Option 7-2 vs Split Option 2

6.3. Split Option 2 vs Option 7-2

Split Option 2: As Charter, we selected split option 2 model for vRAN deployment over our widely available DOCSIS network. Split option two model has a separation at RLC layer, executes PHY, MAC and RLC layers at DU and RRC and PDCP layers at CU. Data transmission latency requirement for split option 2 is at most 10 msec. Any latency value of more than 10 msec. will degrade the quality of service delivered to our subscribers.

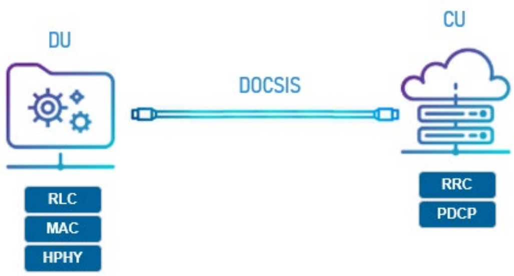


Figure 24 Split Option 2

Split option 2 has latency advantage over split option 7.2 in addition to the following advantages such as Mobility support. Handover between DUs will be similar to current intra-sector handover since DUs served with the same CU (same RRC layer). Link latency between DU and CU will affect the RRC messaging (required for HO) latency. No fiber requirements. Lower scheduling delay since scheduler runs in DU.

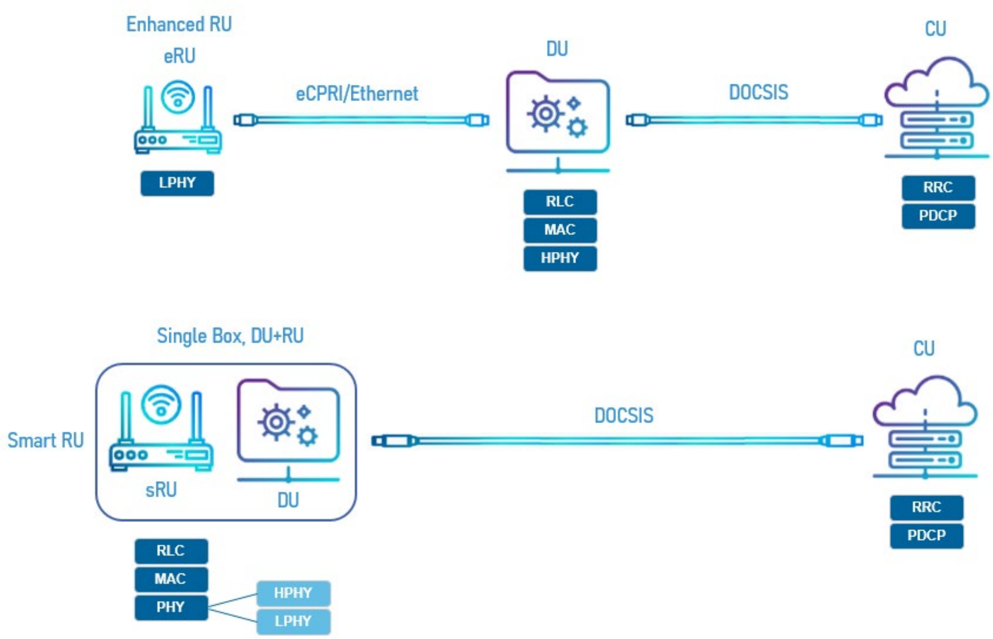


Figure 25 Split Option 2 over DOCSIS

Charter has selected combined RU and DU model for cable strand DOCSIS deployment. In this model, DU and RU is combined in a singled box executing PHY, MAC, HPHY (higher part of PHY layer) and LPHY (lower part of PHY layer) protocol layers.

Split Option 7-2: This model requires fiber deployment and we are considering using this split in markets where we have the required fiber coverage. Data latency requirement is 500 microseconds. Certain advantages of this split model are, but not limited to, Interference Management through Coordinated Multi-

Point (CoMP) and Inter-cell Interference management. SON features will benefit from central processing, and scheduling. Since eCPRI is not used, cost of CU will be lower.

Figure 26 Split Option 7-2 over Fiber

6.4. Conclusion

Charter has selected Split Option-2 for its vRAN based 5G CBRS wireless network deployment over DOCSIS because of its data transmission latency advantages. Also, since DOCSIS network provides advanced latency reduction features such as Bandwidth Report (BWR), Charter is ready to leverage these features to further ease of its 5G CBRS wireless network deployment on cable strand. We will keep monitoring the latest advancements in vRAN field, and latest releases of 3GPP standards together with oRAN initiative to fine tune our vRAN network deployment strategies.

7. DOCSIS Backhaul

Near ubiquitous availability of Cable and DOCSIS assets in urban and suburban areas is one of the significant factors driving Charter's and more broadly cable industry's interest in Small Cell deployments for many years.

In anticipation of DOCSIS use as backhaul for wireless, the wireless technical leadership at Charter and CableLabs have been busy adding several critical and innovative features in DOCSIS.

In this section of the paper, we discuss these features.

7.1. Low Latency Xhaul (LLX)

LLX aims to reduce the latency for mobile traffic on the DOCSIS network to as low as 1–2.5ms. It uses mobile and DOCSIS scheduler pipelining to achieve lower latency. CableLabs issued LLX specification in 2019 in a document titled Low Latency Mobile X-haul over DOCSIS® Technology. As shown in the picture, LLX introduces a new interface called Bandwidth Report (BWR) for exchange between the scheduling functions of the mobile and DOCSIS networks, which produces the effect of one pipelined system rather than two independent systems.

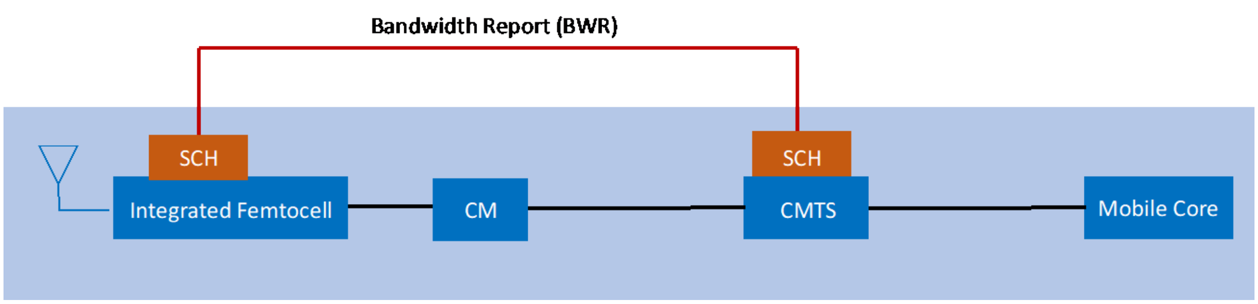


Figure 27 Low Latency Xhaul

The Bandwidth Report (BWR) is sent by the eNodeB scheduler to the DOCSIS scheduler and provides information about the amount of bytes eNodeB scheduler expects for some specific time in the future for the data transmission before the arrival of the actual traffic. Current LTE-DOCSIS systems do not have BWR and have a cumulative latency. The latencies of the eNodeB and CMTS systems are additive. Latency increases further with network congestion.

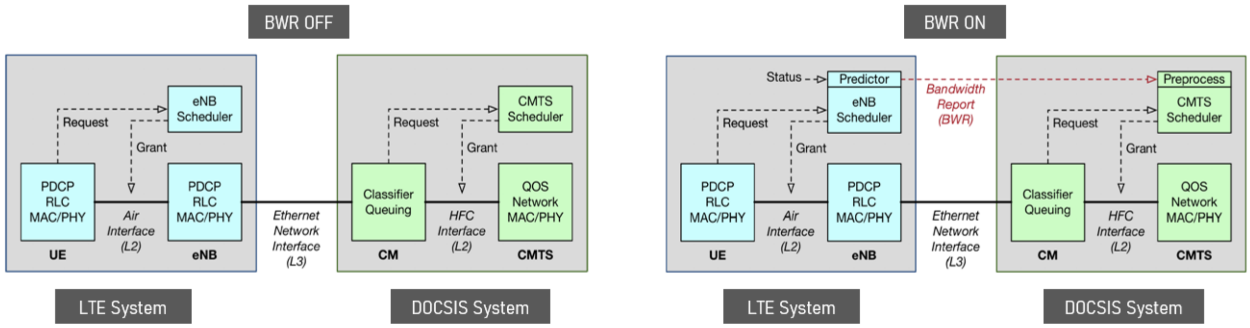


Figure 28 Bandwidth Report OFF/ON

For example, a 4G eNB or 5G gNB provides a future traffic profile through the BWR message, allowing the CMTS to make QoS and granting decisions earlier than it normally would. As a result, we can observe significant reduction in the variability in Jitter, improvement in average latency and smoothening of latency curve when BWR is ON. BWR works in 5G-NR similarly to the way it works in LTE for the majority of 5G traffic that employ larger slot sizes. 5G-NR URLLC (Ultra Reliable Low Latency Communication) latency requirements are 1-2ms. Using BWR the CMTS scheduler will have to predict the number of grants required per queue, verify this a few milliseconds later when the BWR arrives, and adjust as necessary.

7.2. Low Latency DOCSIS (LLD)

LLD is a CableLabs specification developed with vendors and operators. It focuses on lowering the latency by reducing queuing delay and media acquisition delay. The queuing delay is, lowered by using a different logical path for queue building vs. non-queue-building application traffic. In addition, the media acquisition delay is, lowered by using proactive scheduling mechanisms. LLD targets a reduction in round-trip latency in the DOCSIS network to below 5ms. It also targets a reduction in delay variation on the DOCSIS network by a factor of 100 compared to what is typical today. As a result, LLD promises to deliver significantly improved user experience for consumer applications, such as online gaming. Very importantly, the existing DOCSIS 3.1 equipment can include support for LLD with a software upgrade and without requiring hardware change.

7.3. Conclusion

Although Low Latency DOCSIS (LLD) and Low Latency X-Haul (LLX) have similar-sounding names, they are two different technologies with different objectives. While LLX reduces the latency for mobile user traffic on the DOCSIS network used as mobile X-haul (backhaul, mid-haul, or Fronthaul), the LLD reduces the latency in general on the DOCSIS network.

As the interest in Small Cell deployments is gaining momentum, operators are actively analyzing the LLX technology and inquiring the SmallCell vendors to support it. To operators' relief, the mobile eNB/gNB and the DOCSIS CMTS can add support for LLX via software upgrade without requiring hardware change.

As the Smallcell and CMTS vendor implementations of LLX become available in the next year, Charter looks forward to evaluating the technology in the lab and field.

8. Timing and Synchronization

Unlike Wi-Fi, the 4G LTE and 5G NR require stringent synchronization (Phase and Frequency) of wireless transmission to avoid interference between uplinks and downlinks. Since the CBRS is a shared band, the clock synchronization across basestations of the same and different operators is critical for full realization of the spectrum and avoid unwanted interference. As laid out in the table below, the synchronization requirements for TDD LTE and 5G NR are specially stringent.

Table 13 Frequency and Phase Synchronization Requirements

	Frequency	Phase
4G LTE TDD	±50 ppb	±1.5 µs
5G NR TDD	±50 ppb	±1.5 µs

These synchronization requirements are documented in 3GPP specifications – TS 36.133, TS 36.922, and TS 38.104.

As discussed earlier in this paper, Charter is pursuing both indoor and outdoor deployment of CBRS Smalcells. The acquisition of accurate phase and frequency for outdoor Smallcel deployment is rather straight forward and Charter is planning to use GPS.

On the other hand, the acquisition of accurate phase and frequency for indoor wireless deployment is much more complex and requires evaluation of multiple options.

As shown in the table, there are a number of options for timing and synchronization. For outdoor deployments, GPS is the most widely used timing source. However, for indoor applications such as Femtocell, the combination of PTP and DTP ranks higher on the list and is carefully studied and tested.

Table 14 Synchronization Types - Advantages and Disadvantages

	Advantages	Disadvantages
DOCSIS Timing Protocol (DTP) with PTP	• Supports LTE TDD and 5G timing precision requirements [2] • Timing from our Charter owned and operated network • CableLabs standard promoted by cable vendors	• Requires significant changes to DOCSIS infrastructure, including hardware upgrade to CM • Grand Master clocks in each headend • Regular network calibrations may be required
Over-The-Top PTP	• No upgrades to DOCSIS network required	• Timing synchronization not precise enough for TDD LTE even with DOCSIS QoS. (5-10 millisecond range) • Performance is negatively impacted with network loading and uplink packet delay variation (uplink BW limited)
Network Listen/Macro Sniffing	• No upgrades to DOCSIS network required	• Reliance on Macro network for timing • Availability everywhere is an issue • Out-of-band listen requires dedicated radio – additional cost & more space
Global Positioning System (GPS)	• No upgrades to DOCSIS network required • Supports LTE TDD timing precision requirements	• Receive challenges indoors, susceptible to jamming • Placement not in the control of the operator • Installation and operation cost external antennas
Over the top Network Time Protocol (NTP)	• No upgrades to DOCSIS network required	• Timing synchronization not precise enough (100 millisecond) even with dedicated QoS on DOCSIS
TV Broadcast Listen	• No upgrades to DOCSIS network required	• Need a receiver for TV broadcast • Femtocell must know location – own & TV tower

8.1. DOCSIS Timing Protocol (DTP)

DTP is part of CableLabs' DOCSIS 3.1 specifications and further enhanced in CableLabs CM-SP-SYNC specification. DTP carries the IEEE 1588v2 protocol over the DOCSIS network without the influence of jitter from network buffering. Additionally, DTP accounts for plant and path asymmetry that over-the-top

PTP may not. Furthermore, DTP provides timestamp and determines the downstream timing offset, which PTP uses to calculate precise timing and synchronization.

The picture below shows the application of DTP and PTP when DOCSIS network is used as backhaul for the mobile traffic. As shown, the DTP used between the CMTS and CM and PTP is between the grandmaster clock and CMTS and between the CM and eNB. CMTS and CM essentially convert PTP to DTP on the DOCSIS link. Sync E makes the frequency synchronization performance of PTP better. In case of loss of the master clock, Sync E also helps eNB keep clock running longer in holdover mode without losing precision.

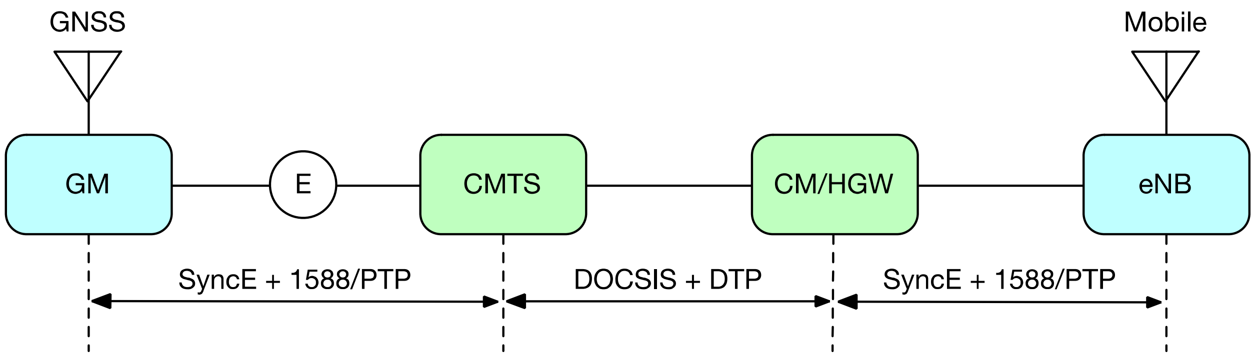


Figure 29 DOCSIS Timing Protocol

DTP is a new protocol and is currently not widely implemented or deployed. However, there is a keen interest in it from cable operators exploring indoor Small Cell deployments. Operators need a reliable source of precise timing and synchronization for both 4G TDD LTE and 5G NR deployments.

8.2. Assisted GPS

For indoor deployments, Charter is also evaluating “Assisted” GPS technology, which claims to provide accurate phase and frequency in challenging RF environments (e.g., building basement). In an “Assisted” GPS enabled system, DOCSIS backhaul could be used to feed the small amount of data carried by the satellite signals. This process makes it unnecessary for the “Assisted” GPS receiver to demodulate the data, allowing the system to provide accurate phase and the frequency at significantly low GPS signal levels.

8.3. Conclusion

The engineering teams at Charter are actively testing both PTP/DTP and “assisted” GPS technologies in collaboration with CableLabs and Cisco. We hope to publish results from our study in the next Cable-Tec-Expo for the benefit of the industry.

9. Wrap-Up

The rollout of a wireless network is a significant challenge. The wireless engineering team at Charter has dedicated the past three years to understanding the characteristics which are important to a successful wireless deployment. In this paper, we have covered the important deployment scenarios which should be understood for every deployment – Strand Mount (Outdoor Aerial Strand), Attached Mount (Outdoor, non DOCSIS), and Indoor Deployments. Strand Mount utilizes all of the advantages of the HFC/DOCSIS network such as power availability, wide coverage, and quick deployments. This does need to be countered with the additional power load on the network. The Attached Mount deployments are utilized for strategic applications such as hot spots which can not be reached via the HFC network. The most important consideration of an Attached Mount is power and permitting which can eat up months of time getting a unit deployed. Key to success though is ultimately the indoor coverage. A drawback of CBRS is the EIRP power limits imposed by the FCC. This significantly reduces the ability of a 3.5 GHz signal to enter most building structures; therefore, it is important to have a strong indoor coverage plan. Charter has found a significant advantage with an Indoor/Outdoor strategy where two sectors cover the street outside of a building and the third sector is for indoor coverage.

It is important to understand the RF properties of CBRS. The 3.5 GHz signal is in a sweet spot for new wireless spectrum. It has the advantages of small form factor versus lower frequency spectrum while still getting reasonable coverage versus mmWave spectrum. From our research, RSRP is critical to monitor and manage. An RSRP value which drops below -110 / -115 dB causes a significant drop in throughput. It is important to rely on accurate 3D modeling to make sure a reasonable RSRP is maintained throughout the network. With the timeline of a wireless network deployment, it is important to consider 5G in your decision. Most significant deployments of a wireless network will start in 2-3 years which will give time for the initial higher cost of 5G to align with present day 4G deployment costs. Organizations like ORAN are helping drive 5G costs down quicker through standards and interoperability.

With the deployment of a DOCSIS network, it is important to consider Split 2 versus Split 7.2. Our research and testing has shown that Split 2 or a full gNB is a more practical option for a DOCSIS network primarily due to the amount of capacity required to support Split 7.2. Latency is a challenge, but it can be managed for a Split 7.2 configuration via adoption of technologies such as Low Latency Xhaul (LLX) and Low Latency DOCSIS (LLD).

For indoor and dense urban environments, timing will be a challenge. There is research and new technology in development focused on supporting better timing in both of these environments. Our current focus is on DOCSIS Timing Protocol and Assisted GPS. Both technologies have proven to support a better timing signal indoors.

It is hard to put three years of research into a single paper. The focus of this paper has been on the technologies which we feel have the strongest impact on a new wireless network on a modern day HFC plant. Best of luck with your wireless deployment.

Abbreviations

3GPP	3rd Generation Partnership Project
AOI	Area of Interest
AWS	Advanced Wireless Services
BH	Busyhour
bps	bits per second
BWR	Bandwidth Report
CBRS	Citizens Broadband Radio Service
CBSD	Citizens Broadband Radio Service Device
CE	Cell Edge
CM	cable modem
CMTS	cable modem termination system
CN	Cell Near
CPAS	Coordinated Periodic Activates among SASs
CRAN	Centralized Radio Access Network
CU	Central Unit
CW	continuous wave
DL	downlink
DLS	Decision Logic System
DOCSIS	Data Over Cable Service Interface Specifications
DPA	Dynamic Protection Area
DSDS	Dual SIM Dual Standby
DTP	DOCSIS Timing Protocol
DU	Distributed Unit
E-DPA	ESC Dynamic Protection Area
EIRP	Effective Isotropic Radiated Power
ESC	Environmental Sensing Capability
EXZ	Exclusion Zone
FCC	Federal Communications Commission
FEC	forward error correction
FSS	Fixed Satellite Station
FWA	Fixed Wireless Access
GAA	General Authorized Access
GHz	gigahertz
GM	Grand master
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GWBL	Grandfathered Wireless Broadband Licensee
HD	high definition
HFC	hybrid fiber-coax
HO	Handover
HPHY	Higher Physical layer
Hz	hertz
IFFT	Inverse Fast Fourier Transform
LLD	Low Latency DOCSIS

LLX	Low Latency Xhaul
LOS	line of sight
LPHY	Lower Physical layer
LTE	Long Term Evolution
MAC	media access control
Mbps	Megabits per second
MHz	megahertz
MIMO	Multiple Input Multiple Output
MVNO	Mobile Virtual Network Operator
NTIA	National Telecommunications and Information Administration
NTP	Network Time Protocol
OOB	Out of Band
PAL	Priority Access License
PCAST	President's Council of Advisors on Science and Technology
PDCP	Packet Data Convergence Protocol
P-DPA	Portal Dynamic Protection Area
PDSCH	Physical Downlink Shared Channel
PHY	Physical layer
PPS	pulse per second
PSD	power spectral density
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QOS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RF	radio frequency
RLC	Radio Link Control
RRC	Radio Resource Control
RSRP	Reference Signals Received Power
RU	Radio Unit
SAS	Spectrum Access System
SCTE	Society of Cable Telecommunications Engineers
SINR	Signal to Noise and Interference Ratio
SMB	small medium business
TT&C	telemetry, tracking and command
UE	user equipment
UL	uplink
vRAN	Virtual Radio Access Network

Bibliography & References

Code of Federal Regulations, Title 47, Part 96
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