Overlaying Mid-Band Spectrum Backhaul/Fronthaul onto HFC

A Symbiotic Convergence of Cable & Wireless

A Technical Paper prepared for SCTE by

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1. Introduction

Cable 10G and Wireless 5G may seem to be at odds. However, when combined, they offer an evolutionary strategy with much synergy.

5G uses a collection of different frequency bands, each with unique characteristics. Recent developments in C-band, CBRS (Citizens Broadband Radio Service) and Wi-Fi provides some new mid-band spectrum (i.e. 3 - 6 GHz) that is offering a middle ground that may be the future wireless workhorse. Its reach covers a significant number of mobile users with substantial data rates. But its deployments may need many more densely packed cell sites than current 4G LTE macro-cells. This presents an opportunity for MSOs to leverage their existing HFC infrastructure for providing both backhaul and power to those new cell sites.

The paper presents a basic tutorial on mid-band wireless technologies in the 3-6 GHz range that includes C-band, CBRS and Wi-Fi 6E. It covers MIMO antenna systems from 2T2R to 64T64R and when and where each is appropriate. ORAN (Open Radio Access Network) standards help to virtualize the 5G infrastructure, identifying backhaul, midhaul and fronthaul interface options.

The many choices for the mid-band wireless system can vary bandwidth requirements from 100's Mbps to many 10's Gbps. The paper shows which configurations can easily be supported on DOCSIS 3.1 while others might require DOCSIS 4.0 and some may need direct fiber connect.

Some case studies are provided where potential mid-band small cells are mapped to actual HFC networks. Results from a CBRS design show its potential reach. This data is used to map cells to several existing HFC nodes. The nodes under study vary from dense urban nodes (i.e. >250 HP/mile) down to sparse rural nodes (i.e. <40 HP/mile). Various trade-offs are considered in cell site placement on the HFC.

HFC appears to be ideally suited to support this Mid-band xHaul infrastructure. A strategy is laid out for cable plants of varying densities. D3.1 midhaul can be leveraged extensively in the early days to get wide coverage quickly. Very dense urban areas will eventually require complex antenna/MIMO systems with fiber fronthaul. This integrates nicely with an N+2 fiber deep strategy. But even then, cells with DOCSIS xHaul will be needed to fill the holes and hotspots. D4.0 then enables even higher capacities at these cable cell sites.

In the end, Cable and Mid-band wireless (C-Band, CBRS, Wi-Fi 6E) are much stronger together and are at the core of a next gen converged network evolution.

2. 5G Midband and Wireless for Cable Dummies

For many cable operators, wireless in general and 5G in particular is a brand new, if not foreign, technology. This section provides a tutorial to help educate cable technologists in this area.

Mobile Wireless Services have been deployed since the mid-1980s through a succession of generations:

- **1G**: 1980s – Analog signals, typically 1 Tx port and 1-2 Rx ports on the radio (diversity improved signal reception). Frequency bands were 850 MHz in US and 900 MHz RoW (rest of world). Voice only
- **2G**: early 1990s – Digital signals, typically 2 ports on radio one for Rx, one for Tx/Rx. Initially Voice only but later technologies such as GPRS and EDGE allowed data to be encoded as if it were voice for early data transmission. First introduction of mid-band spectrum 1900 MHz in the US, 1800 MHz RoW. Fairly quickly all existing 1G services were converted to 2G.
- **3G**: 2000 – Digital signals, designed for data transmission, again 2 ports on the radio, only one doing Tx. New frequency bands were added, specifically at 2100 MHz (slightly different bands in US and RoW)
- **4G**: 2009 – (a.k.a. LTE, Long Term Evolution) Digital signals, designed for data transmission. MIMO introduced (Multiple Input Multiple Output) which improved data capacity by using multiple transmitters and receivers. In general, radios had 2 or 4 ports with all ports capable of Rx and at least 2 Tx ports. New frequency bands including 700 MHz and 2600 MHz in the US, 800 MHz, 2300 MHz and 2600 MHz RoW. VoLTE (Voice over LTE) encoded voice as data (similar to VoIP) to allow 4G systems to handle voice traffic. This allowed the decommissioning of 2G and 3G networks to commence.
- **5G**: ~2020 – Digital. Improved efficiency compared to 4G. In addition, 5G is meant to be more flexible, so that it could in theory replace not only existing mobile wireless communications standards (e.g. 4G) but also those for fixed wireless, vehicle anti-collision radar, Wi-Fi, Bluetooth, etc. To date 5G has really only been applied to achieve faster mobile wireless, but other Use Cases remain to be explored.

There are several aspects in which mobile wireless networks differ from fixed wireless networks such as Wi-Fi. Mobile wireless networks are designed such that a service area is broken up into a collection of cells and the network transitions the user from one cell to the next automatically and seamlessly as the user moves geographically. Therefore, mobile wireless is often referred to as cellular service. With Wi-Fi this transition is handled manually.

Another key difference is that Wi-Fi uses shared spectrum. This results in limits in terms of both antenna gain and maximum transmitted power, as well as their sum EIRP (Effective Isotropic Radiated Power). EIRP is connected to coverage – higher EIRP means that the signal strength will be adequate for data transmission over a wider area.

Most mobile wireless spectrum is licensed within geographic regions and within the region the license holder has exclusive use of the spectrum. This means that the license holder does not need to worry about interfering with other users. This enables them to achieve much higher EIRP levels. For example the UNII bands (which includes the 5 GHz spectrum that Wi-Fi uses) has a maximum allowed EIRP of 36dBm while most mobile wireless networks deploy radio and antenna systems with maximum output in the range of 65-75dBm (so a factor of 1,000 to 10,000 higher EIRP). The new CBRS band is a unique case. The spectrum is shared, but the power levels are higher, with a maximum of 47dBm EIRP per 10 MHz channel.

2.1. 5G Midband – What is all the hype?

5G is a collection of different frequency bands, each with unique characteristics. Recent developments in C-band, CBRS & Wi-Fi provides some new mid-band spectrum (i.e. 3 - 6 GHz) that is offering a middle ground that may be the future wireless workhorse. Its reach covers a significant number of mobile users with substantial data rates. But its deployments may need many more cell sites then current LTE macro-cells.

Citizens Broadband Radio Service (CBRS) is a first-of-its-kind effort to get maximum utilization out of spectrum. It refers to 150 MHz of spectrum in the 3550 MHz to 3700 MHz range that the FCC has designated for sharing among different tiers of users. The 3.5 GHz band has been identified as a critical band for wireless mobility. This frequency is low enough to have good propagation characteristics, particularly in comparison to extremely high frequency millimeter waves (mmWave). But it is also high enough so that advanced antennas using M-MIMO (massive multiple input multiple output) technology are small enough to meet zoning restrictions and be deployed.

However, once 3.5 GHz was proposed for usage for mobile wireless, the US found itself with a problem. The spectrum right around 3.5 GHz was already being used, by the US military in coastal regions and by incumbent Wireless Internet Service Providers (WISPs) inland. Most countries would have given up on this spectrum, but the FCC came up with a clever plan to maximize usage involving a 3-tier hierarchy.

The highest priority tier goes to US military applications and (for now) other legacy incumbents. SAS (Spectrum Access System) serves as a traffic cop, telling other users to shut down when the US military is using the spectrum. However, since the US military application is primarily ship-borne radar, the usage is mostly confined to coastal regions, particularly a few spots where US naval ships are based and even in those regions the usage is sporadic.

The second priority tier goes to PAL (Priority Access License) license holders who have paid to have exclusive use of 10 MHz channels within a specific geographic region (for CBRS these regions are counties). In any county, a single entity can own up to 4 PAL licenses which guarantees 40 MHz out of the 70 MHz available for PAL license holders.

The lowest level priority tier is General Authorized Access, GAA. GAA users have free access to the spectrum on a first-come, first-served basis. Since no more than 70 of the 150 MHz can be licensed under PAL, GAA users are assured that at least some spectrum will always be available for GAA use.

Since GAA usage is free, this allows end users to build and run mobile wireless networks for a fraction of the cost that would be required if licensed spectrum were being used. This puts CBRS into the same category as other free spectrum services such as Wi-Fi or Bluetooth. However, since CBRS has a EIRP cap of 47dBm instead of 36dBm, individual sites can cover a much larger area then Wi-Fi. This can be very advantageous in a campus or office park setting. And since CBRS typically is deployed with mobile wireless technology (usually 4G or 5G, though some radios use proprietary systems), true mobile wireless service is available, and handoffs can be managed automatically. This gives CBRS a further advantage over Wi-Fi.

In 2020, several mobile network operators (MNOs), primarily Verizon, AT&T and T-Mobile, spent over $80 billion purchasing C-Band spectrum (3.7 – 3.98 GHz) at the U.S. Federal Communications Commission (FCC) auction. Based on an accelerated clearing schedule, 100 megahertz of the auctioned spectrum will be cleared in 46 of the top U.S. markets by December 2021. Verizon and AT&T won 60 MHz and 40 MHz, respectively, of the earliest available C-band "A" blocks. Verizon's deployment plans initially call for turning up spectrum at existing macro sites focused on 46 markets. Rural fill-ins, small cells and in-building are part of the picture down the line. By December 2023, the remaining 180 megahertz in these same 46 markets, as well as the full 280 megahertz in the other markets, will be cleared for use by 5G services.

Comparing C-Band with CBRS, the C-Band EIRP limits are much higher – the combined antenna and radio may generate 76dBm. But none of the spectrum is free and in fact the licenses for C-band were much more expensive on average than CBRS PAL licenses.

Meanwhile in the United States and other countries, 1.2 GHz of spectrum from 5.9 to 7.1 GHz has been set aside as unlicensed spectrum that is being used in Wi-Fi 6E. However, the higher 6 GHz frequency band and lower transmit powers will limit the outdoor range for Wi-Fi 6E.

2.2. Antenna 101 – Success starts with the Antenna

Outdoor wireless network success starts with the antenna. It is the equivalent of the speaker/headphones for an audio system. Specifically, the antenna transforms the guided RF (Radio Frequency) energy generated by the radio and carried by transmission lines into free space electromagnetic waves that propagate through the atmosphere.

It should be noted that base station antennas (BSAs) are not intended for point-to-point communications. The goal of a base station antenna is to provide relatively uniform coverage in an area where coverage is desired (inside the cell area) with a minimum of excess energy going outside the cell area.

2.2.1. Omni vs. Sectored Antenna

There are different types of cell arrangements from the perspective of the base station equipment. In the 1G systems and even today in rural areas or for small cell applications, the site where the base station equipment is located will provide wireless coverage in all directions around the site using an omni-directional antenna. This is considered a single-sector site.

Note that in the wireless field, “omni-directional” refers only to the pattern in the azimuth plane. This is in contrast to academia where “omni-directional” is often thought of as identical to “isotropic” which indicates that energy is uniformly radiated throughout the 4π steradians of space. So in mobile wireless, one common antenna type is a “high gain omni” which marries an omni-directional azimuth pattern with a narrow, highly-directive elevation pattern.

The most common cell configuration today is a 3-sectored site (Figure 2). In this case the area surrounding the base station tower is divided into 3 120-degree sectors, each with its own set of radios and antennas. Typically, the antennas used will have a HPBW (half power beamwidth) of roughly half the sector size, so in this case 65° azimuth HPBW antennas are usually used. Since modern cellular systems have 100% frequency re-use, a 3-sectored site offers 3 times the data capacity of a 1-sectored site for the same geographic area.

Finally, in cases where very high capacity is required, a commonly chosen option is a 6-sectored site (Figure 2), which can offer up to twice the capacity of a 3-sectored site. For these sites, typically antennas are used with a 35° azimuth HPBW. In many cases operators will use special “twin-beam” antennas, where a single antenna is designed to provide coverage for two of the 60-degree wide sectors. This minimizes the amount of clutter at the top of the tower. Images of antennas for 1-sector, 6-sector and 3-sector sites are shown in Figure 1.

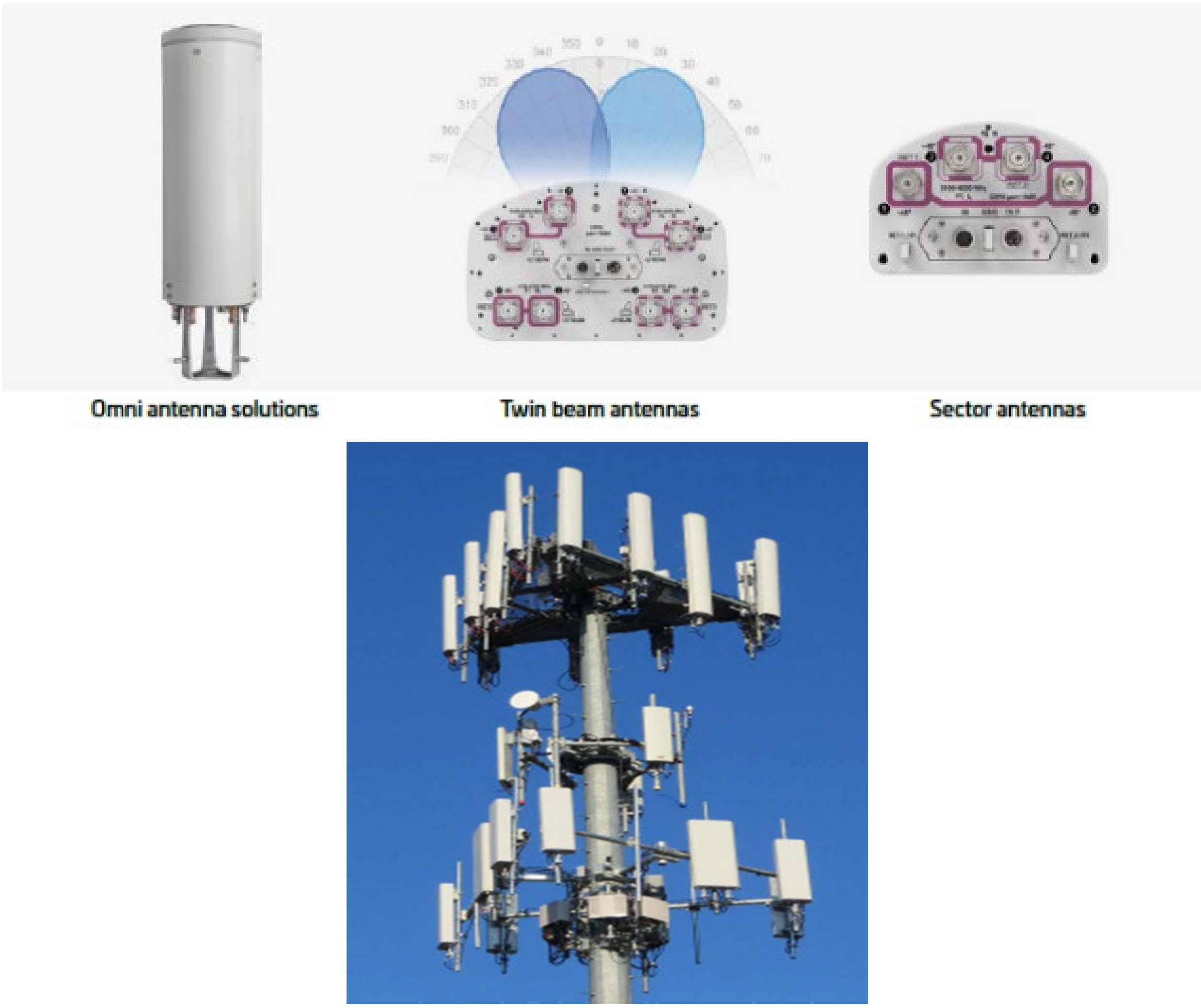

Figure 1 – Antenna technologies

Figure 2 – Sector antennas – Three to Six Sectors

Note that the full theoretical capacity may not be realized due to the overlap of radiated energy between sectors causing interference. In a cellular network there is always a balance that must be maintained between coverage and capacity. If there is too little overlap in coverage of the individual sectors, then holes in coverage may appear. But if there is too much overlap then interference builds to a level where capacity is reduced. Capacity generally is a function of SINR (Signal to Interference and Noise Ratio) which measures this level of interference relative to the primary signal strength. So, a goal of antenna designers is to make antennas that maximize the amount of energy that goes into the sector relative to energy going outside the sector. And the goal of an RF planner (network designer) is to deploy the antennas in such a way to further improve focusing of energy into the sectors.

2.2.2. EIRP considerations

A unique feature of CBRS is the medium level EIRP cap of 47 dBm. In Wi-Fi systems with a 36 dBm cap, it is typically assumed that the antenna gain will be quite low as well as the transmitted power. In other licensed bands, such as C-band, the EIRP cap is so high that it is effectively never reached, and both passive and active antenna systems are designed without any concern for the EIRP cap. The only limit on gain is the fact that the antenna must cover a certain region and so a very narrow fixed beam might not be appropriate.

For macro cell applications, C-band radios can offer up to 320W RF power and 21-25 dBi antenna gain, implying EIRP in the 78 dBm range. In a small cell or strand mount application, the radio power might be 40W (i.e. 4 channels @ 10W) with a 10-12 dBi antenna, so more like 58 dBm EIRP. This makes CBRS competitive for small cell applications, especially since the CBRS cap is per 10 MHz channel. Therefore, if 40 MHz of spectrum is available, the actual cap is 53dBm, not 47dBm.

EIRP equals the sum of transmitted RF power and antenna gain. It describes the energy density level of transmitted signals and is distance agnostic. However, given EIRP, one can calculate energy density at a specific distance from the site.

For wireless communications, one often talks about the link budget, which is the calculation of energy that makes it from the transmitter to the receiver. Per Figure 3, the link budget is positively influenced by transmitter power P_{TX}, transmit antenna gain G_{TX}, and receive antenna gain G_{RX}. It is negatively affected by path loss L_{FS} and other system losses L_{OTHER}. The first two terms P_{TX} and G_{TX} make up the definition of EIRP. Given that EIRP is limited, one can only improve the link budget further by increasing the receive antenna gain G_{RX} or reducing path loss (e.g. install antennas at a taller height to help eliminate blockages).

Let us digress for a moment to discuss antenna gain. Gain is a measure of an antenna's ability to focus the radiated energy in a particular direction. Typically, this is measured in dBi, dB relative to an isotropic radiator, which uniformly radiates energy in every direction. Since the antenna may radiate different amounts of energy in each direction, this is expressed as a bi-variate function Directive Gain = $D(\theta,\varphi)$ where θ and φ are variables describing one's angular position relative to the antenna. Since this relative to an isotropic radiator if the antenna has high Directive Gain at some values of (θ,φ) then it must have low values (< 0dBi) in many other directions. The maximum value of Directive Gain is called Directivity. Finally, antenna gain = Directivity – Antenna Losses. Examples of antenna patterns with low gain and high gain are shown in Figure 4.

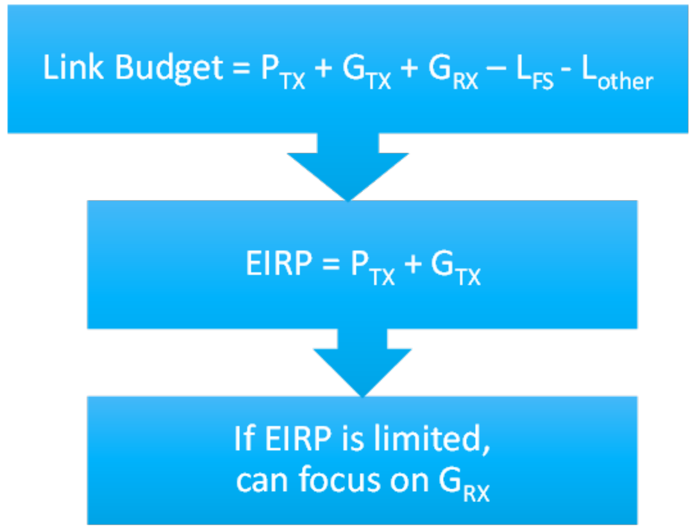

Figure 3 – Link budget vs EIRP

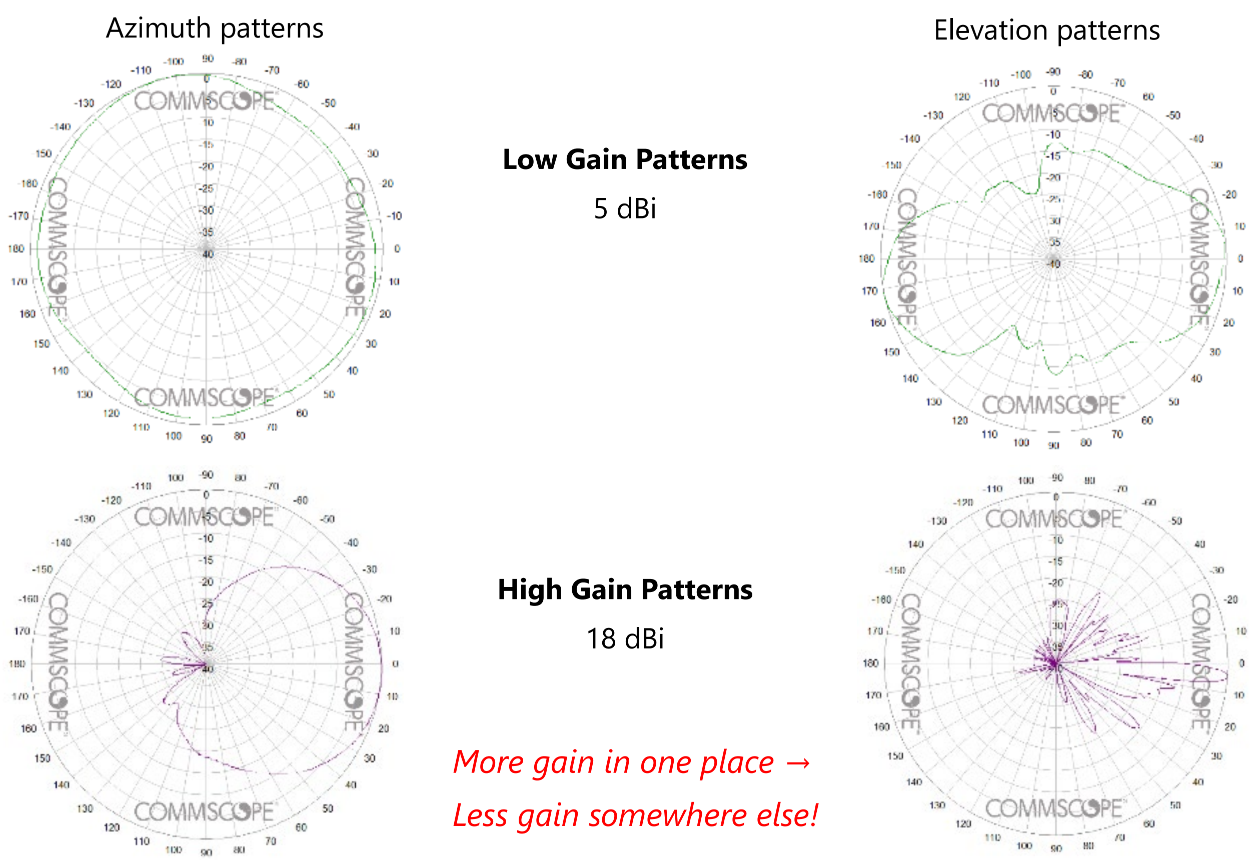

Figure 4 – Antenna Gain

The link budget equation is normally applied to point-to-point antennas which are aimed so that each has its maximum directive gain pointed at the other antenna. But as mentioned earlier, base station antennas cover an area and at the various points in the area the link budget between the base station antenna and the User Equipment (UE) antenna is better described by

$$P_{TX} + D(\theta,\varphi)_{TX} + D(\theta,\varphi)_{RX} - L_{FS} - L_{other}$$

Since antennas with high gain by necessity must have low values of $D(\theta,\varphi)$ at many angles, one can see that it is not necessarily a good thing for the antenna gain to be high.

From the perspective of the downlink, it is better to have higher input power and lower antenna gain since this implies that the energy is more evenly spread across the sector of coverage. However, from the perspective of the Uplink, both the UE transmit power and the UE gain are quite limited. So, the only way to improve the link budget is by increasing G_{RX}, the gain of the receive antenna, which for the uplink is the base station antenna. Thus, the optimal antenna design depends on whether CBRS is used only for the downlink, or for both downlink and uplink. Note – if the CBRS band is only used for the downlink, then the UE is most likely using a low band for the uplink. The low band has less path loss L_{FS} which helps the UE link budget with lower P_{TX} and G_{TX}.

2.2.3. Antenna arrays

The word antenna can refer to a single radiating element or a collection of radiating elements, called an array that are fed from a common input. Antenna arrays can be one dimensional (e.g. a single column of radiating elements) or two dimensional (e.g. a rectangular array with M rows and N columns). Most MIMO base station antennas use a single column as the array.

The size of these arrays can vary substantially, for example from 2T2R to 64T64R. The larger arrays tend to be used at macro towers and in conjunction with massive MIMO (M-MIMO). The technology enables features such as beam forming in 3-dimensions (e.g. vertical for tall office buildings). Small cells, such as strand-mount and streetlight locations, will tend to have much smaller antenna arrays due to their location restrictions.

2.3. Pattern impact on capacity

To verify the above, CommScope ran some RF simulations. Three different antennas with varying levels of gain were examined for a 3-sector grid.

1. 17.3 dBi gain, 5.4° EL HPBW, 4° tilt
2. 16.7 dBi gain, 9.0° EL HPBW, 6° tilt
3. 13.8 dBi gain, 17.0° EL HPBW, 8° tilt

The simulation was repeated for inter site distances (ISD) of 1 mile and 0.5 mile and for three different rad center heights (the height of the antenna above ground) of 45, 100 and 150 feet. The antennas were sited at the far corners of the 3 sectors and pointed towards the center of the area so that the impact of interference between cells could be taken into account. The layout for the 1-mile cell radius case is shown in Figure 5.

For this layout, each sector covers 5 square kilometers. The environment of the three sectors can be described as follows:

- Sector 3 (top): moderate/high density, residential/light industrial

- Sector 4 (right): open, flat, rangeland/airport
- Sector 5 (left): sparse/moderate density, industrial

Figure 5 – One-mile cell radius suburban scenario

The small triangles represent the locations of the sites. In particular, consider the case with 1-mile ISD and 45-foot rad center height. The simulation looked at three parameters:

- Downlink coverage (RSRP)
- Downlink capacity (RS-CINR)
- Uplink capacity (UL Allocated bandwidth throughput)

Since the results vary depending on the placement of the User Equipment (UE) in the sector, they are typically portrayed statistically via a Cumulative Distribution Function (CDF). The 3 CDF curves are shown in Figure 6. Note that for all 3 graphs, better performance is indicated by data points that are higher (same level of performance over a larger area in the sector) and further to the right (higher level of performance over the same area in the sector).

From a downlink coverage perspective, the best results come from the antenna with the lowest gain (the green curve). This is because the EIRP is capped. The lowest gain antenna G_{TX} can use higher transmit power P_{TX} and overall provides more even coverage across the sectors. The middle gain antenna provides the next best coverage (red curve) and the highest gain antenna provides the worst overall coverage (the blue curve).

For downlink capacity, the order is the same, with the lowest gain antenna performing the best and the highest gain antenna performing the worst. However, the results change for uplink capacity. Now the mid-gain antenna performs the best, the highest gain antenna performs nearly as well, and there is a large gap separating the performance of the low gain antenna from the other two antennas. The key difference is that for the downlink the transmit power could be increased to compensate for the 3.5dB difference in gain. But for the uplink capacity case the UE transmit power will be unchanged, so the higher gain becomes more important. Note that for mobile wireless systems, the Uplink path is always the weaker one because the base station radio can transmit at much higher power levels than the UE.

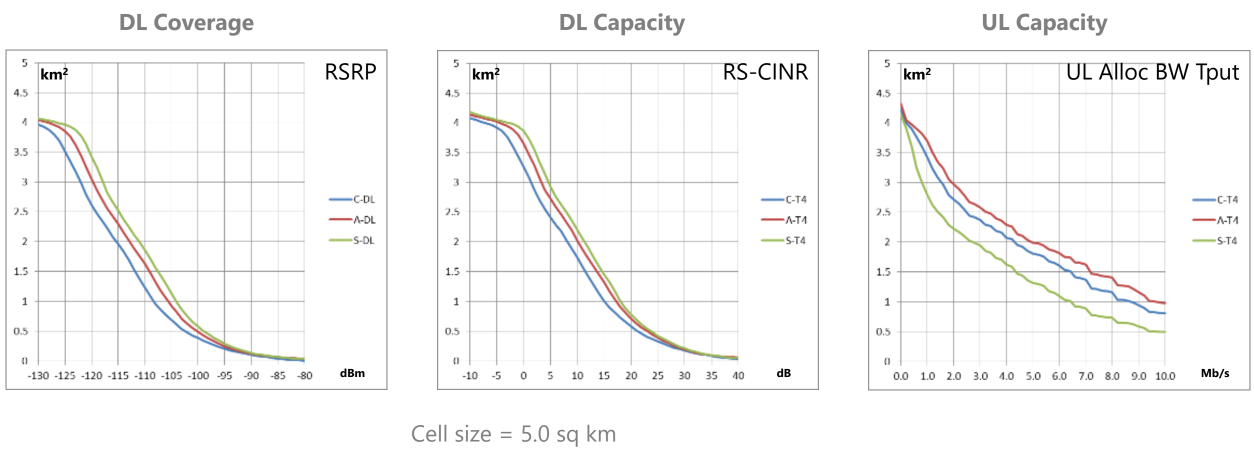

Figure 6 – One-mile cell radius suburban scenario - 45' Height Antenna

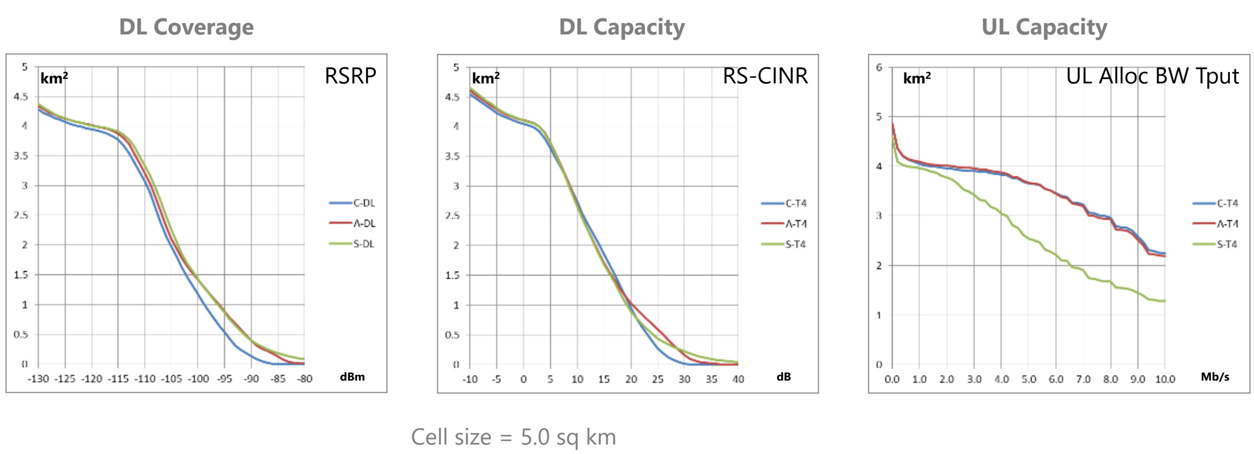

Figure 7 – One-mile cell radius suburban scenario - 150' Height Antenna

In Figure 7, the same 3 CDF plots are shown for the 1-mile ISD with a 150 foot rad center height. The results are generally the same except that the performance gap for DL coverage and DL capacity. The mid-gain and high-gain antennas perform identically for UL capacity, but there is a huge gap in performance between those two antennas and the low gain antenna.

Summarizing these results lead to the following conclusions:

If using CBRS for supplemental downlink:

- Meet the EIRP limit by using more radio power with lower gain antenna
- More even coverage due to fatter elevation pattern → higher RSRP and SINR
- **Depending on site specifics, optimal EL HPBW ~ 15–20°, optimal gain 12–14 dBi**

If using CBRS for uplink and downlink:

- Uplink thruput increased with higher gain BSA
- **Elevation HPBW 5–10° brings improved performance, optimal gain 15–18 dBi**
- Assumes 3 sectors, 65° Az HPBW
- Can get increased gain/capacity via sectorization

2.4. Small Cell Coverage

For cable operators, the most enticing use case that takes advantage of their HFC infrastructure is the small cell deployment. Perhaps the two most obvious applications will be strand mounted small cells on aerial coaxial plant and small cells mounted on streetlights. Streetlights may be the best/only option for underground plants. Streetlights also have an advantage over strand mount as they are at a higher elevation (e.g. 45’ vs. 30’) which enhances the reach of the antenna.

Table 1 provides some small cell range estimates for C-Band, CBRS and Wi-Fi 6E. As shown previously, the coverage is also impacted by the transmit power which varies quite a bit between technologies. Wi-Fi 6E is also at a disadvantage as it is using the 6GHz which has higher path losses than the 3.5 to 4.0 GHz bands used by CBRS and C-Band.

Table 1 – Small Cell & Strand-mount Coverage Range Estimates

Mid-band Small Cell Ranges	EIRP	Mounting Location	Reasonable Range (more Urban)	Stretch Range (more Rural)
C-Band	52-58	Streetlight	600m (~2000’)	900m (~3000’)
		Strand	425m (~1400’)	640m (~2100’)
CBRS	47-53	Streetlight	340m (~1150’)	500m (~1650’)
		Strand	240m (~800’)	360m (~1200’)
6GHz Wi-Fi 6E	36	Streetlight	70m (~240’)	100m (~325’)
		Strand	50m (~175’)	70m (~240’)

Note that the above table contains several assumptions:

1) The C-band radios are 4 x 20W and the antennas are about 12dBi gain. Some variation in EIRP is allowed given that the antenna gain may vary.
2) Note that the actual antenna gain depends on whether an omni or directional antenna is used and the height of the antenna
3) Directional antennas normally have a higher gain than omni antennas, but you need 3 of them to cover a site for 360 degrees. So nominally the directional antennas take a 5dB hit in terms of coverage.
4) CBRS EIRP is shown as a range since the cap is per 10 MHz channel, so a user with more channels can increase their EIRP.
5) Small cell array length can be as high as 24" (600mm) for a streetlight antenna, but strand-mount arrays are normally under 8" (200mm) in height. Thus, assumed that in general the strand mount system would have 3dB less EIRP than a streetlight system. The difference in height might have a slight difference in propagation, but we assumed that this was negligible.
6) Propagation loss goes as the square of distance. So, assume that a 6dB increase in EIRP corresponds to a doubling of the range.
7) The range is for outdoor UE. There can be significant additional path loss when trying to penetrate inside buildings depending on building materials.

2.5. Backhaul, Midhaul, Fronthaul RAN Interfaces

Given the many diverse requirements that 5G networks must support such as high data rates, low latency and high reliability, the implementation of the Radio Access Network (RAN) has been under constant debate. Early proposals focused on the idea of Cloud-RAN with a dense network of cells. However, the 3GPP's 5G-R RAN2 specification included eight different functional split options. A discussion on these different interface options are detailed in [LARSEN_2018] and [ORAN_2020].

The functional splits for the different interface options from [ORAN_2020] are shown in the lower half of Figure 8. The industry has evolved to supporting a distributed RAN architecture that includes a Central Unit (CU), a Distributed Unit (DU) and a Radio Unit (RU) that might also be called a Remote Radio Unit (RRU). This architecture is shown in the top half of Figure 8. The term fronthaul refers to the interface between the DU and the RU/RRU. Midhaul refers to the interface between the CU and the DU.

Today, most 5G industry focus is on one of two options:

- Option 2: a high-level centralized unit (CU) and a distributed unit (DU) split which is essentially a separated control and user plane. In this implementation the DU and remote radio unit (RRU) are often combined into a single entity as a self-contained access point.

- Option 7.2 Cat A: a low-level split that allows for high reliability and low latency communications and near-edge deployment. This split takes place between the Hi-PHY (Physical Layer) and Low-PHY. In this split, only the Low-PHY and RF functions are in the access point.

With more complex antenna arrays (e.g. 64T64R) and massive MIMO (M-MIMO), the processing requirements for the DU increase significantly. Using Option 7.2x allows the DU to be moved to a more optimum location and it reduces the size and power requirements at the antenna site.

With simpler antenna arrays and reduced MIMO levels, the DU becomes simpler and can be more easily integrated with the RU/RRU. Small cells are a perfect example of this.

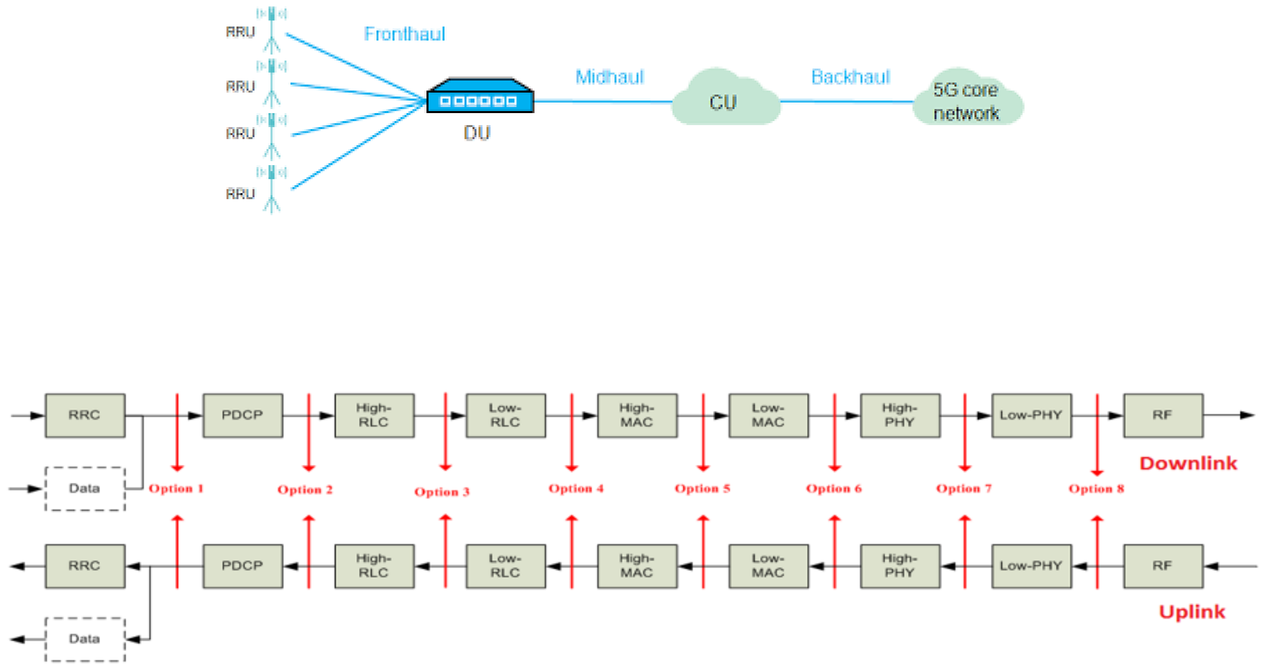

Figure 8 – Backhaul, Midhaul, Fronthaul RAN Interfaces

3. Capacity Planning for Midhaul or Fronthaul Cells

3.1. Midband Backhaul & Fronthaul Interface Capacity Requirements

The amount of capacity required for wireless xHaul varies significantly based on several factors. It becomes a function of the number of antennas, MIMO level, channel bandwidth, number of sectors per cell and the RAN interface used (e.g. Midhaul or Fronthaul). Table 2 shows some capacity examples for various configurations that could be seen from HFC-based small cells to Macro tower base stations.

Table 2 – xHaul Capacity Estimates for various Antenna configurations

Antenna	MIMO	Location	Channel Bandwidth	Sectors per cell	Midhaul DL	Midhaul UL	Fronthaul DL	Fronthaul UL
2T2R	2x2	Strand or Streetlight	40MHz, DL only	1	525 Mbps	-	1.9 Gbps	-
			40MHz	1	420 Mbps	62 Mbps	1.9 Gbps	2.0 Gbps
4T4R	4x4	Strand or Streetlight	40MHz, DL only	1	1050 Mbps	-	3.8 Gbps	-
			40MHz	1	840 Mbps	125 Mbps	3.8 Gbps	4.1 Gbps
			100MHz	1	2.2 Gbps	320 Mbps	9.7 Gbps	10.6 Gbps
8T8R	BF 2x2	Mini-Macro	40MHz	3	0.6 – 1.1 Gbps	90 – 165 Mbps	2.8 – 5.0 Gbps	3.1 – 5.5 Gbps
	4x4		40MHz	3	1.3 – 2.2 Gbps	180 – 333 Mbps	5.7 – 10 Gbps	6.2 – 11 Gbps
	4x4		100MHz	3	3.3 – 5.8 Gbps	500 – 850 Mbps	15 – 26 Gbps	16 – 28 Gbps
64T64R	8x4	Macro	100MHz	6	10 – 23 Gbps	0.7 – 1.7 Gbps	44 –104 Gbps	24 – 56 Gbps

The above table assumes that the downlink (DL) is operating at its best modulation of 256-QAM. This may be generous given real-world conditions, but wanted to show a worst case capacity estimate. The uplink (UL) is assumed to be operating at 64-QAM modulation. For NR-TDD, it is possible to configure the mix between DL and UL. Most of the rows use a DL:UL ratio of 80:20. Two of the small cell rows are configured for 100% DL operation only. In these scenarios, it is assumed that the weaker UL signal is using more robust Low-band frequencies (e.g. <1 GHz).

As can be seen by this table, the Option 2 Midhaul interface has significantly lower bandwidth capacity requirements then the Option 7.2 Cat A Fronthaul interface. Capacity requirements also increases with the channel bandwidth and the number of sectors per cell. As added data point, using an IPv6 backhaul with IPSec would consume about 10% more capacity than the midhaul; while actual UE data consumption would be about 89% of the midhaul capacity.

3.2. CBRS RF Simulation Case Study

A recent case study performed a CBRS RF simulation analysis for a North American metro area. This analysis covered a region with approximately 40K addresses, and roughly 800 radios.

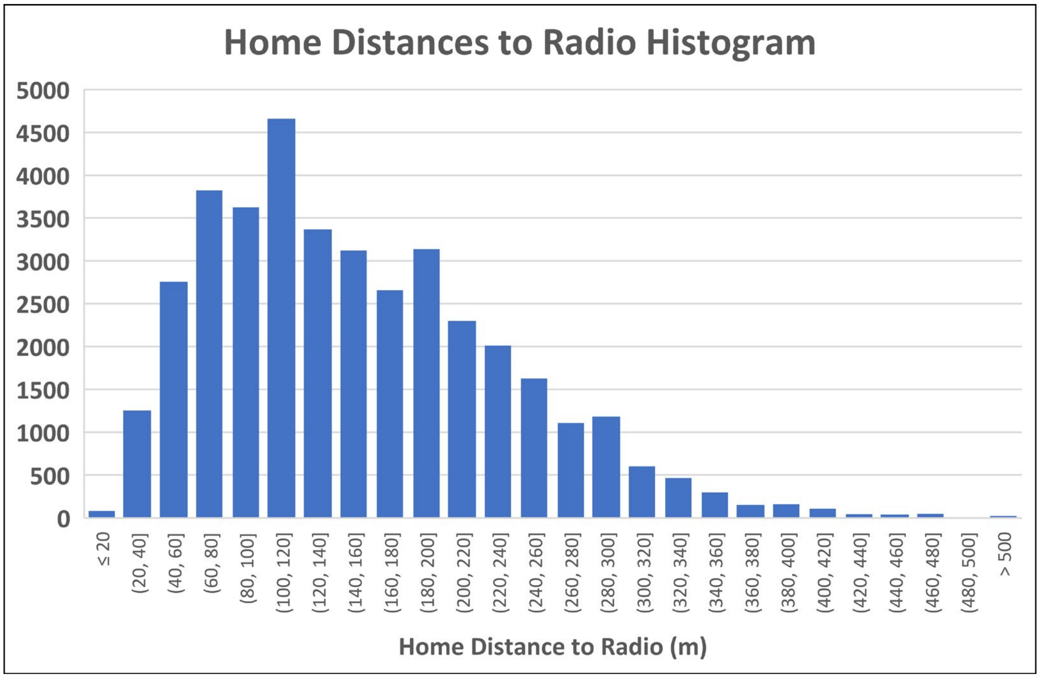

Figure 9 – CBRS Metro area Study – Home Distances to Radio histogram

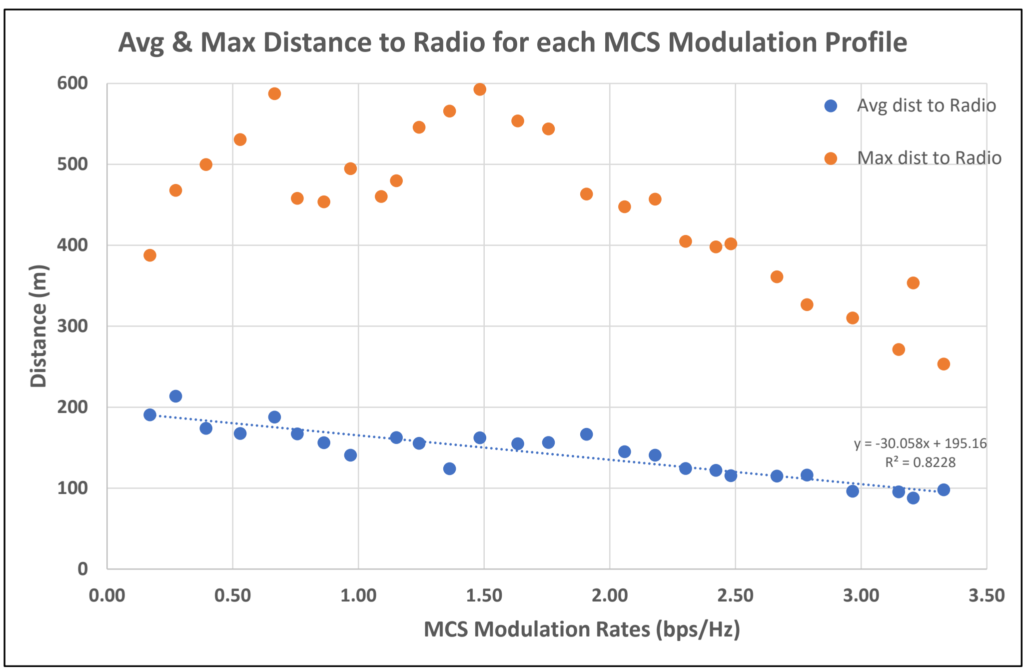

Figure 10 – Average & Max Distance to Radio for each MCS Modulation profile

Some of the key statistics from the study around the distribution of home addresses to the radio include:

Address Distances to Radio:

- Average = 153m
- Maximum = 592m
- Median = 140m
- 95% ≤ 300m
- 99% ≤ 385m

Figure 9 shows that most home addresses are within 200m of a radio and 95% are within 300m. However, there are still several addresses that could be up to 600m away.

Figure 10 shows the average and maximum distance to the radio as a function of the Modulation Coding Scheme (MCS) modulation rate. As the MCS modulation rate increases, there is a linear drop in the average distance to radio and an even more substantial in the maximum distance. For the best MCS rates, the max distance tends to be less than 300m.

Figure 11 is the inverse of Figure 10 where the average and maximum MCS rates are mapped as a function of the distance to the radio. The Max Distance for a given profile is stable up until ~1.5 bps/Hz but drops quickly above that. For distances up to 300m, average modulation (bps/Hz) drops with distance while max stays to MCS 27. Above 300m, average MCS rates stay flat while maximum MCS rates decline quickly with distance.

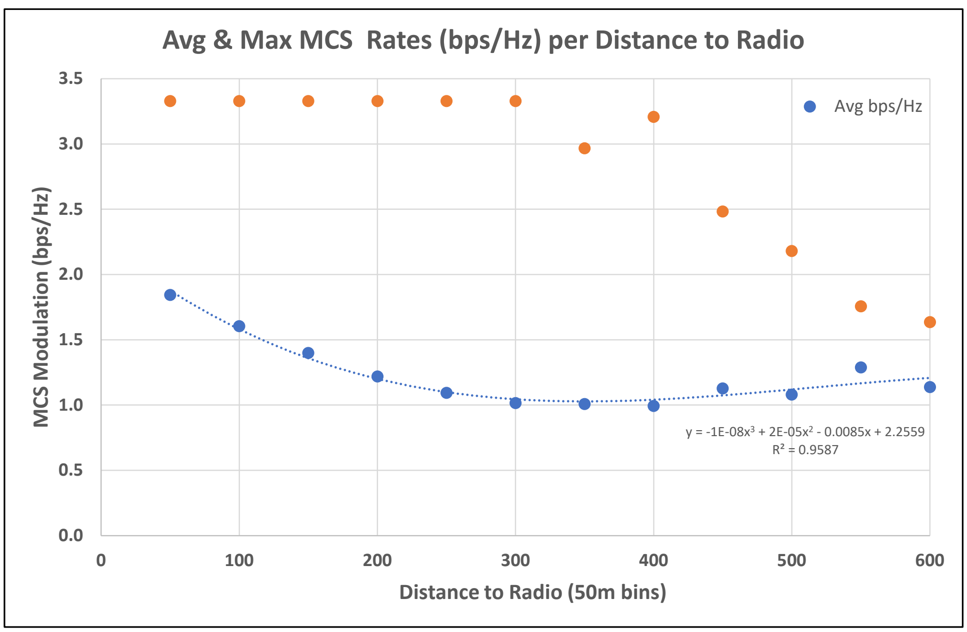

Figure 11 – Average & Max MCS Rates per Distance to Radio

Another observation from the CBRS case study was that in dense areas with >200 home addresses per radio, maximum distance was mostly <300m. Meanwhile, serving radios with fewer addresses (e.g. <60) have a wide range of max distances, even to 600m. Most Radios have fewer than two dozen addresses >300m, while a handful of radios (i.e. <1%) have 40-80 addresses >300m.

In general, the results from this case study reenforce the CBRS range estimates as shown in Table 1.

3.3. HFC Network Capacity Planning

3.3.1. DOCSIS 3.1 Capacities

DOCSIS 3.1 introduced OFDM/OFDMA technologies and increased frequency spectrum of up to 1218 MHz downstream and 204 MHz upstream. This means that the maximum capacity of an DOCSIS 3.1 HFC network could reach 9 Gbps downstream and 1.5 Gbps upstream. This assumes that the operator has retired most or all of its legacy video spectrum (i.e. converted to IPTV or SDV) and replaced most 2.0/3.0 modems with the newer D3.1 modem technology.

From an HFC perspective, the streetlight and strand-mount small cells with an Option 2 midhaul interface shown in Table 1 can be supported by a DOCSIS 3.1 system with an 85MHz mid-split. A 40 MHz DL could fit within 96 MHz OFDM channel or even multiplexed with the residential downstream data. And by accounting for some statistical multiplexing gains, it might even be possible to put a couple midhaul based small cells on a single DOCSIS 3.1 service group (SG). A 100 MHz DL:UL small cell with 2.2 Gbps DL and 325 Mbps UL capacity might fit better on a 1218/204 MHz HFC plant.

Implementing a fronthaul interface on the small cell is much more challenging. A 40 MHz DL-only 2x2 small cell could consume an entire 192 MHz OFDM channel. A 40 MHz DL-only 4x4 small cell then requires two 192 MHz OFDM channel. Turning on the UL will require multiple Gbps upstream capacity. This would require DOCSIS 4.0 as discussed in the next section.

3.3.2. 10G™ Capacities

10G was first announced in 2019 as a vision, or lighthouse beacon, to guide our industry roadmaps towards 10 Gbps services. Much progress has been made in the last 2-3 years. 10G includes multiple technologies including enhanced fiber optics as well as DOCSIS 4.0 technologies.

Figure 12 from [CableLabs_10G] shows the 10G vision for DAA services operating over cable, FTTP and wireless technologies while sharing a common converged fiber optical network through an aggregation node. [CableLabs_10G] states:

> *"The 10G optical network is the backbone of the distributed access architecture and will provide the industry with opportunities for true service convergence that leverages the flexibility and tremendous capacity provided by fiber optics. This year, CableLabs released an update to the 100 Gbps point-to-point coherent optics specification and released a new 200 Gbps specification – both intended to support the aggregation requirements of the distributed access architecture. While operators currently deploy 10G passive optical network technology (PON) where fiber to the premise is preferred, the IEEE standard for next-generation 25G-PON and 50G-PON technology remains on track for mid-2020 completion."*

As can be seen in the figure, 10G has the vision of supporting Mobile Backhaul/Fronthaul and Fixed Wireless Access (FWA) over the service provider's optical infrastructure. The P2P Coherent optics has the reach (up to 80km) and the capacity (to 200 Gbps) to support these applications. It even supports the fronthaul capacity requirements for the Macro cell shown in Table 2.

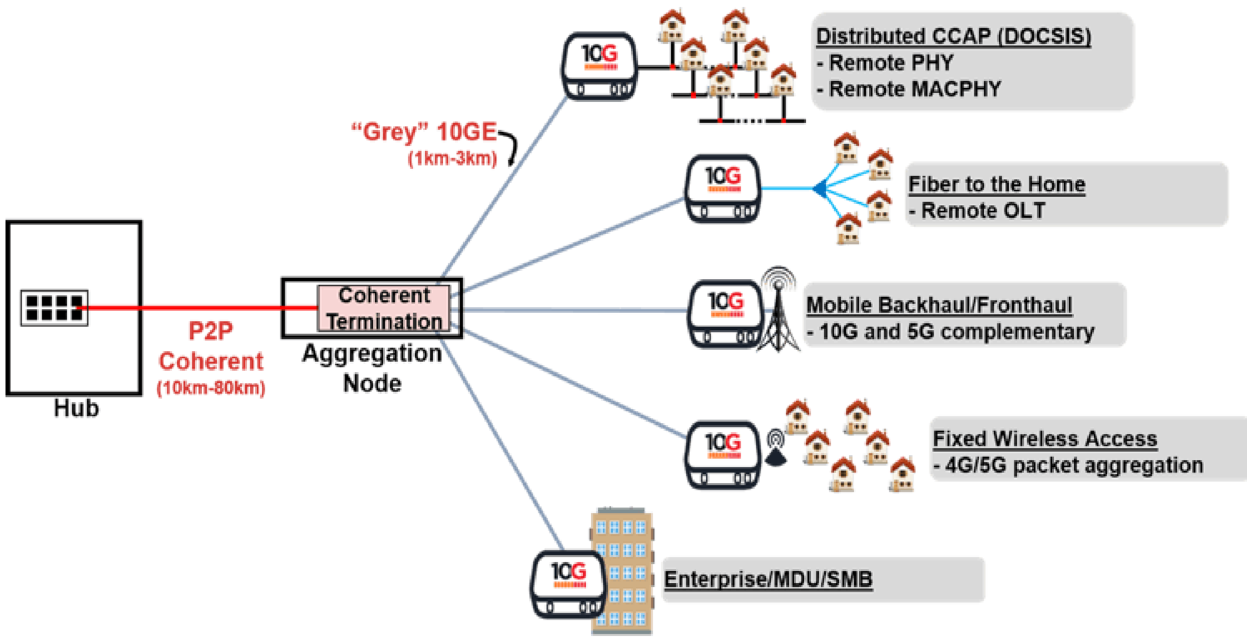

Figure 12 – 10G™ Converged Optical Network – Distributed Access Architecture vision

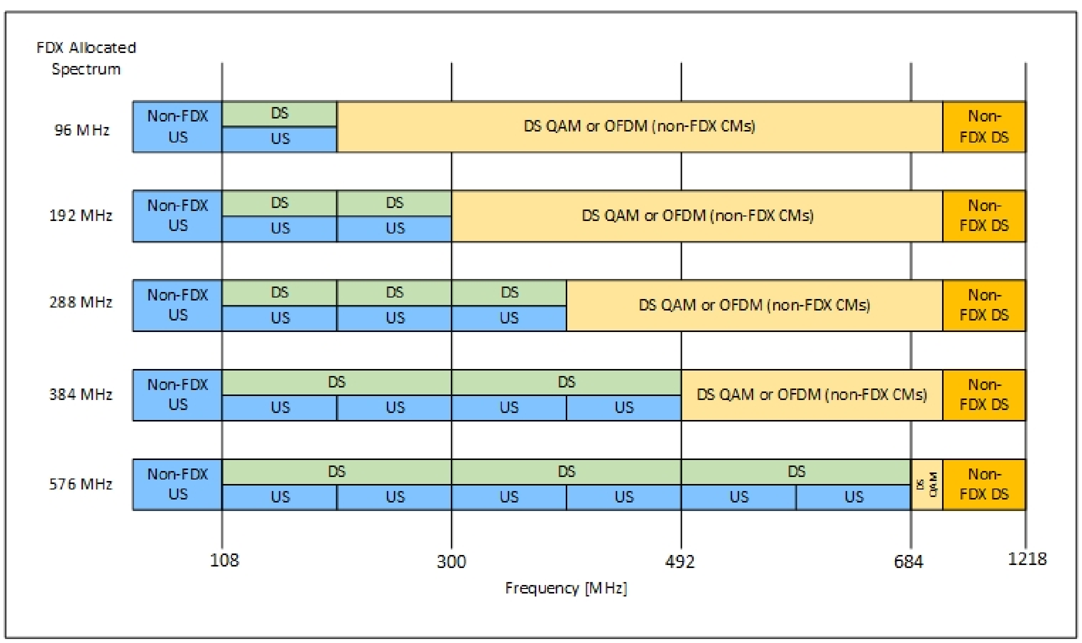

Figure 13 – Full Duplex DOCSIS (FDX) Spectrum Band Options

However, it may not always be possible to co-locate the small cell or mini-macro cell adjacent to the HFC fiber node or along the fiber path. This might result in the cells being connected to the coax portion of the HFC. For small cell RRU with fronthaul interfaces, this might necessitate the use of DOCSIS 4.0. [ULM_2019-1] discusses the capacities that DOCSIS 4.0 can enable and the migration path to 10G.

One area of focus at CableLabs is a technology called Full Duplex DOCSIS (FDX). FDX leverages echo canceller technology to allow simultaneous upstream and downstream operation in the FDX band. FDX is targeted at a fiber deep Node+0 DAA environment. FDX is now part of the new DOCSIS 4.0 specification [FDX_PHY].

The FDX capability offers a fundamental benefit that permits upstream spectrum expansions to occur without causing reductions in downstream spectrum. FDX proposes to have downstream and upstream transmissions occurring in the same frequency band at the same time. In the FDX specification, the overlapping frequency bands are shown in Figure 13.

On a fiber deep Node+0 plant, the upstream OFDMA channel might net capacity of as much as 8-10 Mbps per MHz. This means that a full spectrum 108-684 MHz FDX system might support ~5 Gbps US.

With the Node+0 architecture, the fiber node is now within 300m to 500m of every home. This means the need for using FDX over coax may be minimized.

The other facet of DOCSIS 4.0 is Extended Spectrum DOCSIS (ESD) which supports 1.8 GHz plant with different potential upstream splits in a Node+X plant. In this scenario, the fiber node may be a couple kilometers from the furthest home so it may become necessary to put small cells on the coax.

The extended 1.8 GHz downstream adds much needed DL capacity that could be used for fronthaul RRU devices. The upstream split can then be adjusted based on the desired UL capacity.

So, fronthaul RRU small cells might make a good early use case for DOCSIS 4.0, especially ESD.

4. Using Outside HFC Plant for 5G – considerations and logistics

[ULM_2019-2] took an in-depth look into supporting High band mmWave cells over HFC. At these high frequencies, the wireless cell is limited to very short distances on the order of <100m to 200m which creates coverage issues. The following sections highlight some of the HFC findings from that paper.

Across all the various wireless options, there is a driving need for much smaller cell sizes. To make this happen requires an infrastructure that supports both *the power and the backhaul* to the small cells. The cable industry Hybrid Fiber Coax (HFC) networks are ideally positioned to support this. The HFC networks might support the addition of attached in-line small cells at various demarcation points on the HFC plant. These cells can be added to the DOCSIS network to support 5G, Wi-Fi and/or CBRS/LTE over the HFC.

Figure 14 shows the additional level of density variability that must be considered in cell placement. This example is from a suburban city in New England. In Figure 14, lot sizes vary from 1 acre on the left, ½ acre lots in the middle to <¼ of acre on the right. Cell placement must also account for open spaces and office campus space too.

Figure 14 - New England suburb, illustration for variability of lot sizes within

5. HFC Case Study for N+3 nodes of varying Homes Passed densities

The HFC case study in [ULM_2019-2] considered 5 node examples that varied from low homes passed density in a rural area to a high urban node with many homes. Table 3 provides the key statistics for each of the five nodes. In general, these are N+3 nodes, except the highest density node being N+2. The homes passed per coaxial mile (HP/mile) ranges from 37 to 274. This paper now investigates the implications of mid-band small cells overlaid onto these same HFC nodes.

5.1. Mapping Mid-band Small Cells to N+3 HFC Plant

This section looks at mapping mid-band small cells to HFC N+3 nodes of various densities. The first step is to co-locate the small cell with the fiber node to ensure that the small cell has fiber backhaul. This gives the operator the flexibility to choose whether to implement Option 2 midhaul interface or the Option 7.2x fronthaul interface. If the operator is also implementing a DAA strategy with either a Remote PHY Device (RPD) or Remote MACPHY Device (RMD) in the node, then the small cell can potentially share the 10G long haul Ethernet link as well. After that, additional scenarios may be shown by adding other small cells located on the coax segment adjacent to one of the HFC plant active components.

For High and Med-High density nodes, a cell radius in 250m to 350m range is used. For Low and Med-Low density nodes, a cell radius can stretch to 500m range for handful of homes. This aligns with the CBRS small cell ranges from Table 1. Note that C-band small cells would have an even bigger coverage area due to their increased power budget.

Table 3 – Statistics of 5 HFC N+3 nodes of various densities

N+3 NODE Case Study:	Low	Med-Low	Medium	Med-High	High
Coax Plant Mileage	4.17	6.16	3.54	2.51	1.90
Aerial	0.82	4.72	3.44	2.18	1.72
Underground	3.35	1.44	0.10	0.33	0.18
Total Actives	21	30	21	19	14
Actives/Mile	5.0	4.9	5.9	7.6	7.4
Cascade	N+3	N+3	N+3	N+3	N+2
Total Passings	153	352	398	469	520
Aerial Passings	27	269	383	200	500
UG Passings	120	83	0	0	0
Comm/MDU passings	6	0	15	269	20
HP/Mile	37	57	112	187	274

5.1.1. High Density Node Example

The high-density node example shown in Figure 15 is N+2 with 520 total homes passed (HP) with a density of 274 HP/mile. The fiber node is located on the top side of the area. But even with that, most of the homes are easily within the 250m inner radius.

In this example with the node at one edge of the area, it may make sense to use a 180-degree directional antenna rather than an omni-directional antenna. This can provide some added gain for reaching the outer fringes of the node area.

In Figure 16, the CBRS small cell is placed on the coax adjacent to the first level amplifier. This provides a very central location for an omni-directional amplifier. Almost all of the homes are within 200m of the small cell. The only drawback might be that this limits the small cell to use an Option 2 midhaul interface.

5.1.2. Med-High Density Node Example

The medium-high density node in Figure 17 is N+3 with 469 total HP and 187 HP/mile. While most of the homes are within the 250m radius of the small cell, there are still a good number of homes that are in the 250m to 350m range. This means that the CBRS small cell might better be streetlight mounted for the extra elevation and coverage rather than strand-mount.

So again, it appears that this density node can be serviced by a single CBRS small cell that is co-located with the fiber node.

5.1.3. Medium Density Node

The medium density suburban node in Figure 18 is N+3 with 398 total HP and 112 HP/mile. This is an oddly shaped node, unlike the nicely packed previous two examples. Because it is so stretched, it cannot be covered by a single CBRS small cell. We do use this example to show how an operator might place four small cells scattered within this node to give coverage to both this node and neighboring nodes. One small cell is co-located with the fiber node and the other three are on the coax.

Note – if this node also implements a 2x2 RMD/RPD, then it is possible to arrange the CMTS service groups such that there are no more than two small cells on any given DOCSIS network.

This node shows why an operator needs to look holistically across a multi-node region when deciding on small cell placements.

5.1.4. Med-Low Density Node Example

The medium-low density node in Figure 19 is in a residential development and has N+3 with 352 total HP and 57 HP/mile. Because this is a more rural setting, the figure also now includes a 500m radius for the enhanced range for a streetlight mounted CBRS small cell.

The 500m radius appears to cover a majority of the homes in the node. This may be acceptable if the goal is to off-load as much traffic as possible without the requirement for 100% coverage. If the operator has partnered with a C-band MNO to deploy C-band small cells, a single cell should cover this entire node area.

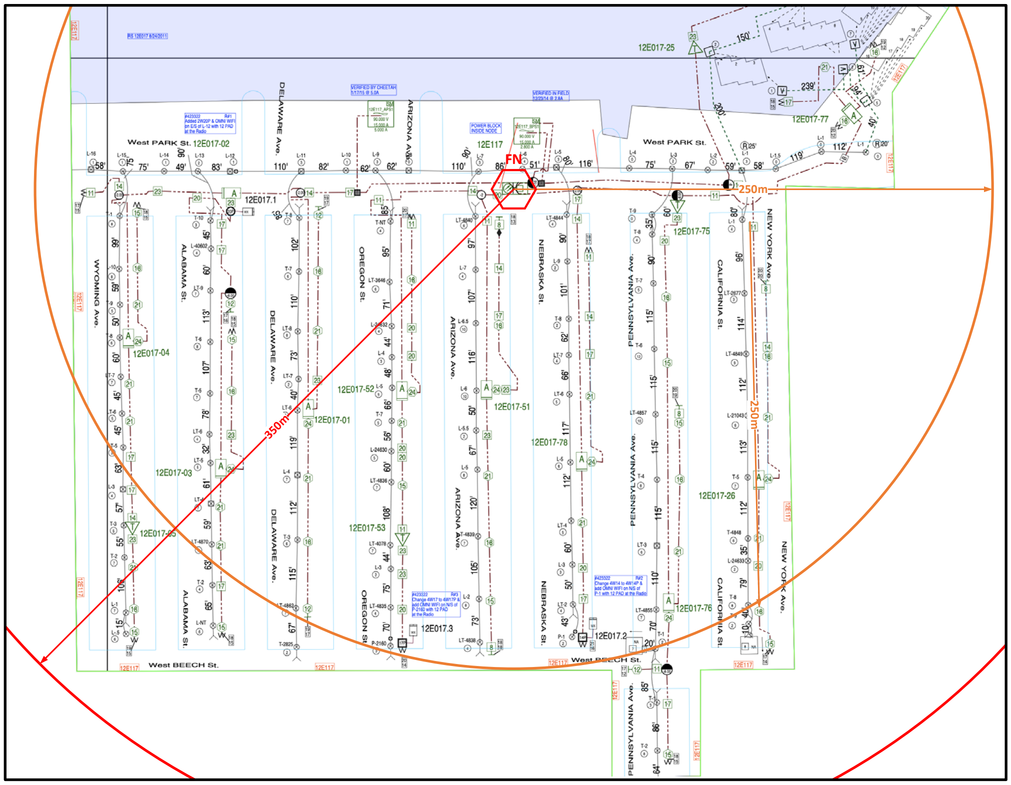

Figure 15 – High Density Node (274 HP/mile) with Small cell at Fiber Node

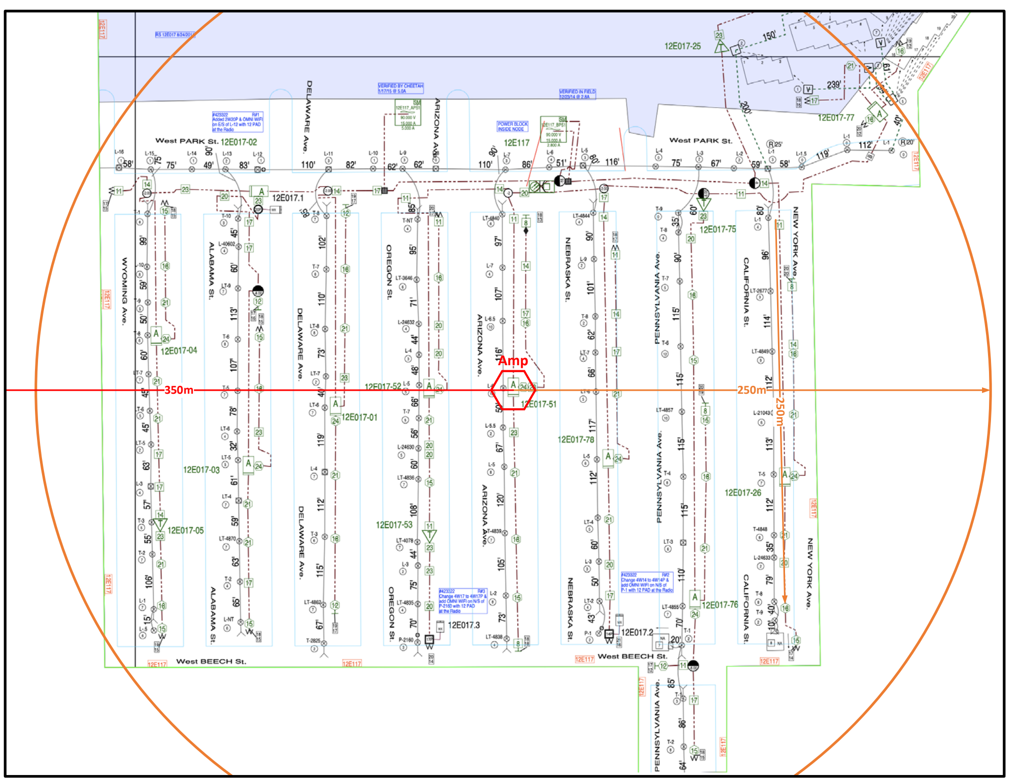

Figure 16 – High Density Node (274 HP/mile) with Small cell at HFC Amp location

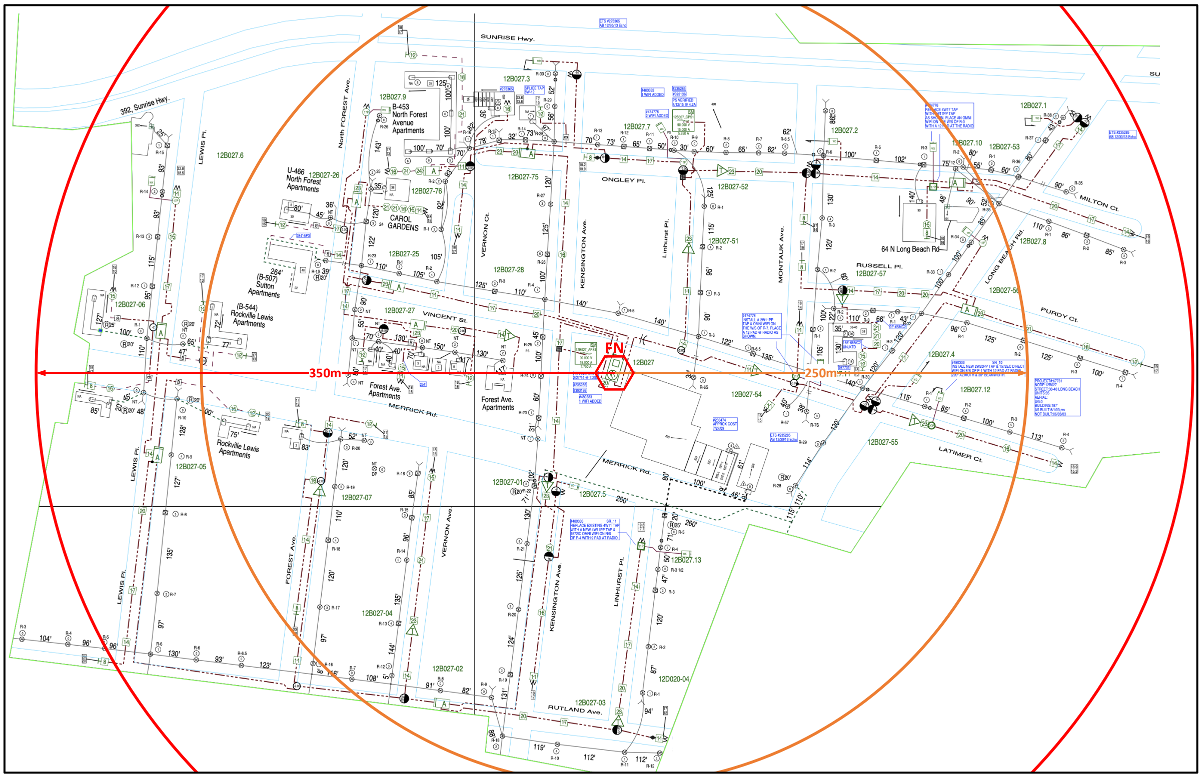

Figure 17 – Med-High Density Node (187 HP/mile) with Small cell at Fiber Node

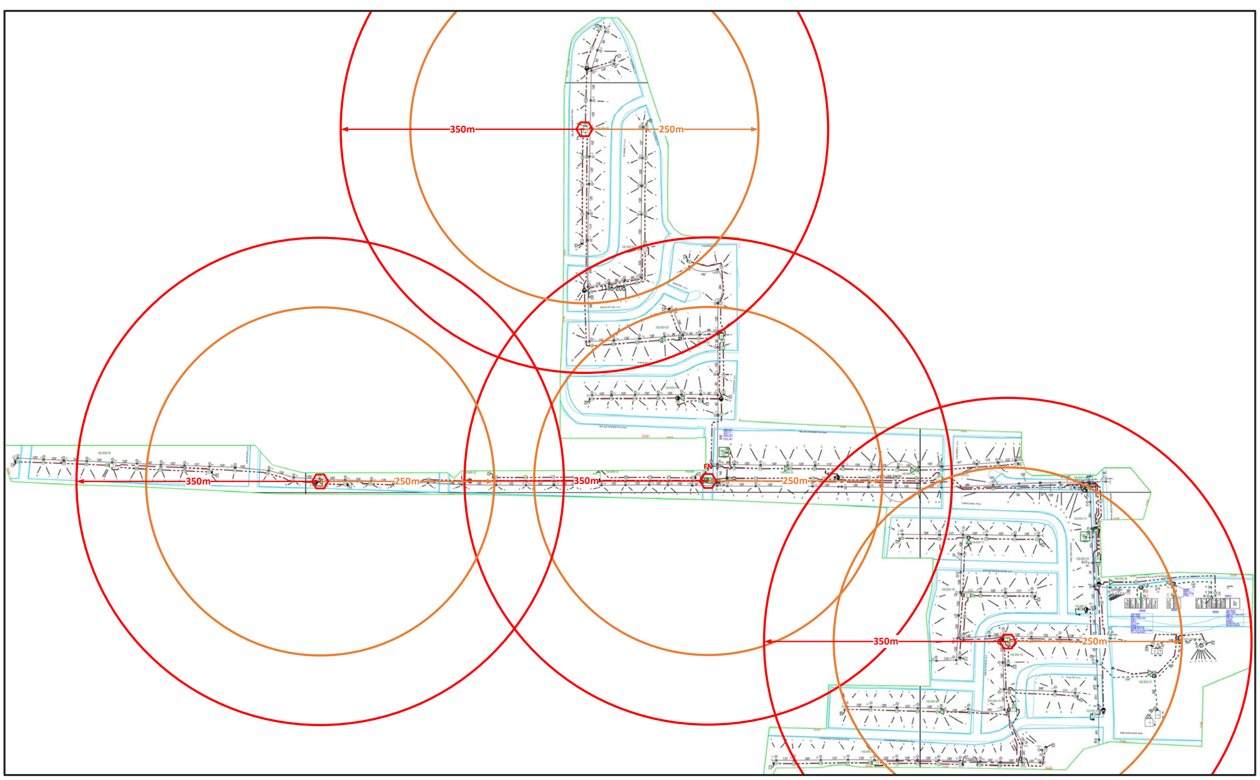

Figure 18 – Medium Density Node (112 HP/mile) with Small cell at Node + HFC Amps

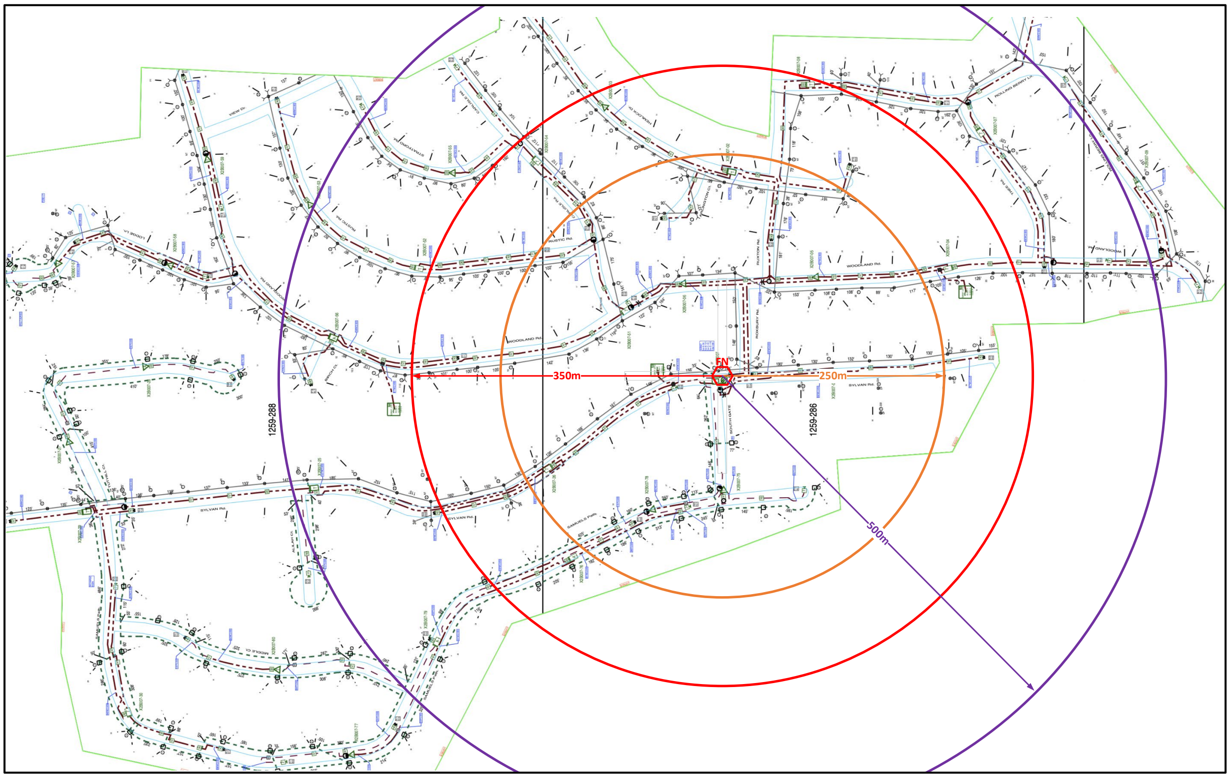

Figure 19 - Med-Low Density Node (57 HP/mile) with Small cell at Fiber Node

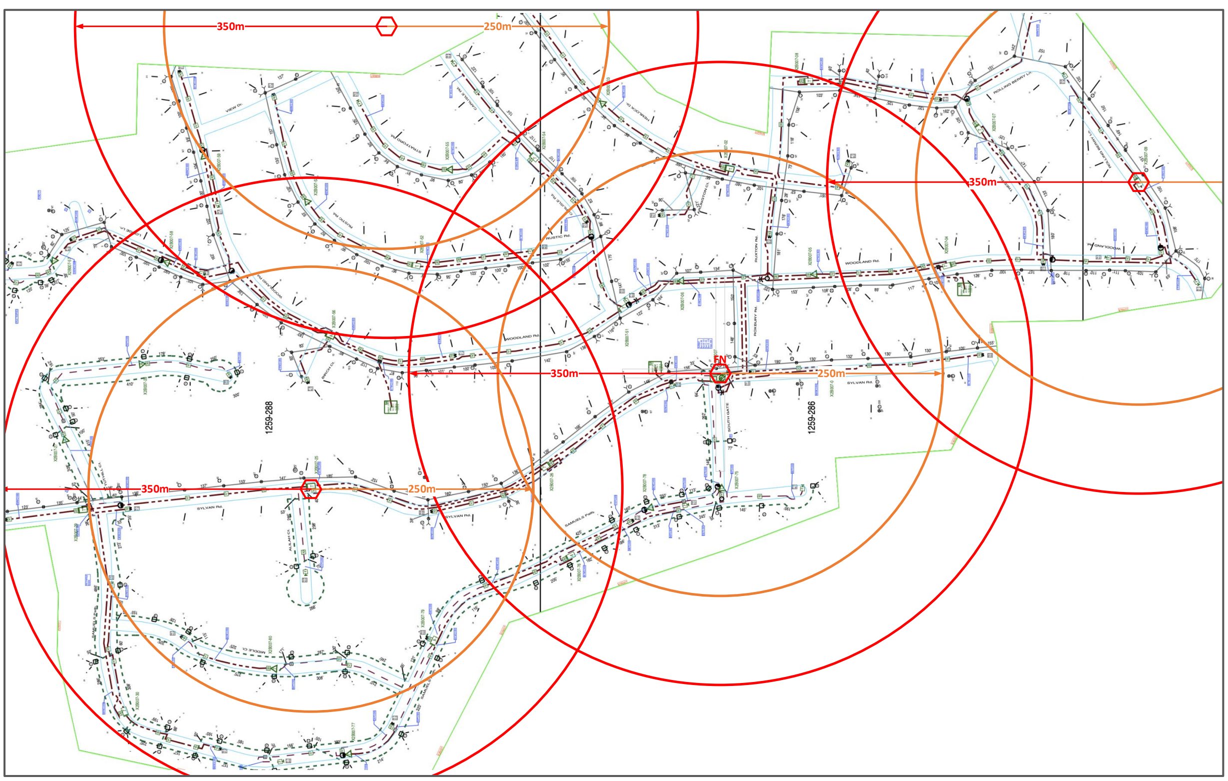

Figure 20 - Med-Low Density Node (57 HP/mile) with Small cells at Node + HFC Amps

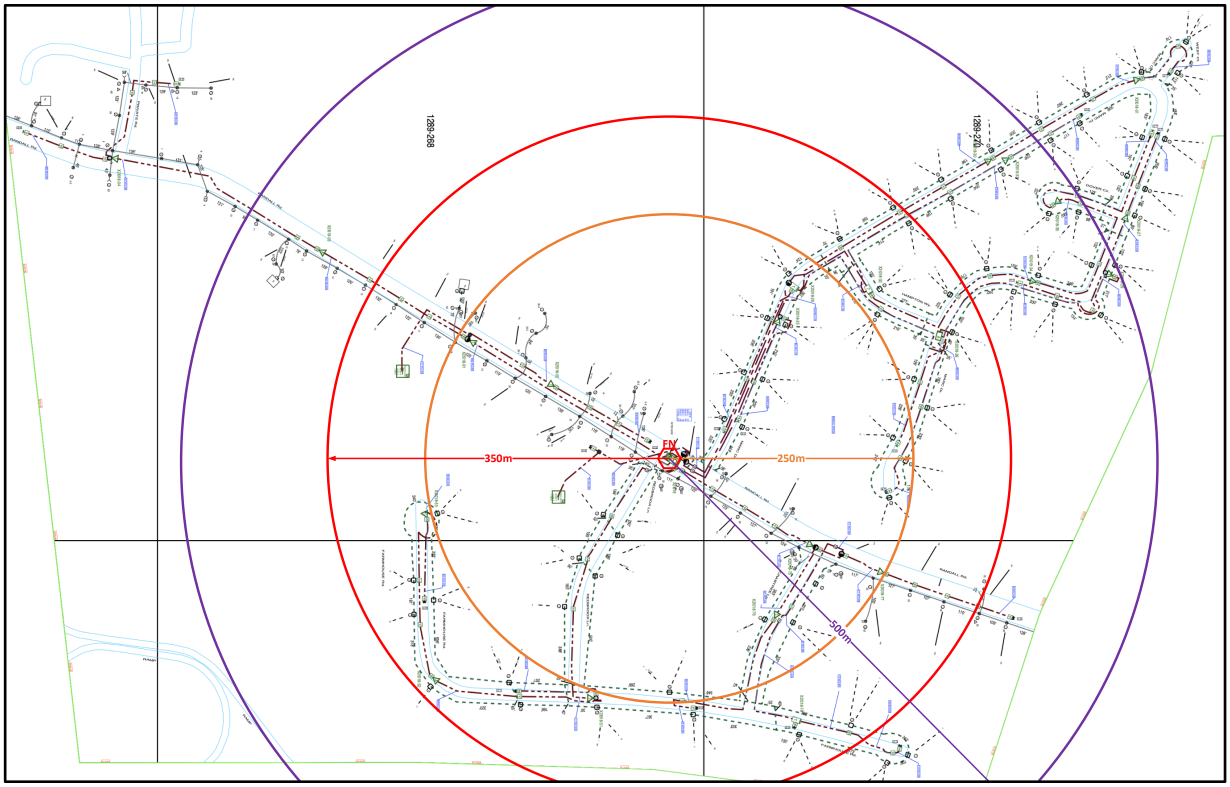

Figure 21 – Low Density Node (37 HP/mile) with stretched Small cell at Fiber Node

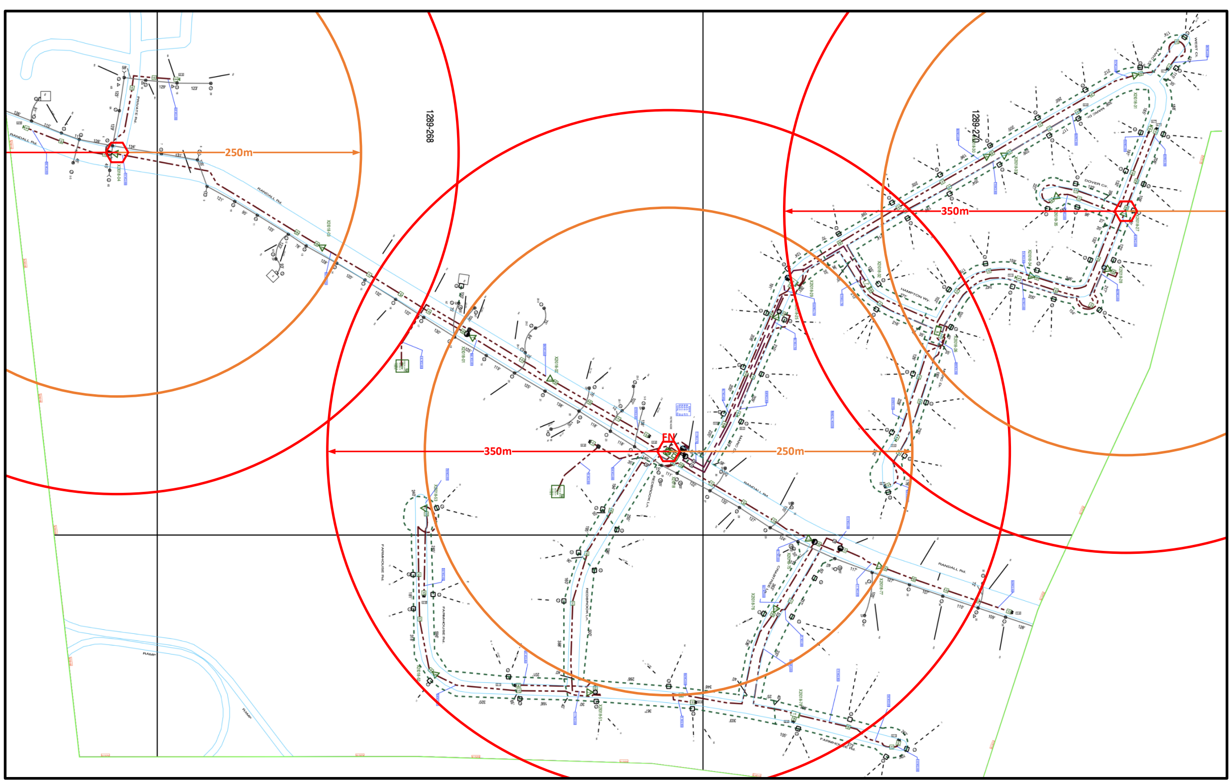

Figure 22 – Low Density Node (37 HP/mile) with Small cells at Fiber Node + HFC Amps

Figure 20 shows a couple of additional CBRS small cells added to the node. If these are all strand-mounted, then maybe their reach will be limited to the 250m to 350m range. In this example, one small cell has fiber access while the other two have coax backhaul. With a 2x2 RMD/RPD, they could be on separate DOCSIS networks.

5.1.5. Low Density Node Example

The low-density rural node in Figure 21 is N+3 with 153 total HP and 37 HP/mile. A streetlight mounted CBRS small cell with ~500m radius does a good job of covering most of the node area, but it still needs some help at the fringes. A C-band small cell should cover this node area without any problem.

Figure 22 shows some strand mounted CBRS small cells with 250m to 350m range. One is co-located with the fiber node while the other two or on the coax in opposite directions (i.e. probably separate RF legs and potentially separate DOCSIS networks.

5.2. Summary – Mapping Mid-band Small Cells to N+3 HFC Plant

After looking across an extremely wide range of homes passed densities (i.e. from 37 to 274 HP/mile), a single CBRS small cell that is co-located with the fiber node is sufficient to cover most of the homes in N+3 plant. For those nodes that need some additional small cells to achieve full coverage, this could be accomplished with only one or two small cells per DOCSIS networks.

Operators with larger HFC cascades (e.g. N+5, N+6) will obviously need additional small cells to achieve their coverage. But this case study shows that N+2/N+3 might be an optimal HFC design target for operators thinking of 5G mid-band convergence. As time progresses and bandwidth needs continue to rise, an operator might want to migrate from a DOCSIS based backhaul to a fiber backhaul. So, the operator might consider how they will eventually pull fiber to these small cells on the HFC coax plant as part of their overall fiber deeper strategy.

6. Mapping Mid-band Small Cells across multiple N+6 Fiber Nodes

6.1. Multi-node N+6 case study

The previous case study had certain limitations. First, many plants have longer amplifier cascades such as N+5/N+6 with fiber not as deep as the N+3 case study. Second, the expanded range with the mid-band small cells now potentially covers parts of multiple nodes at a time. The previous N+3 study gave us a wide range of densities, but only viewed a single node at a time. The next case study expands this to look at a much larger area from a North American metro suburban area to measure the impact across a multitude of nodes with varying densities.

Table 4 shows statistics for a ~3.5 square mile area consisting of 9 adjacent nodes. In addition to the statistics for the entire area in column one, the next four columns show the statistics for some select nodes: i.e. the highest and lowest density ones, as measured by number of homes passed per mile.

Table 4 – Statistics of Metro-suburban HFC N+6 nodes of various densities

N+6 Case Study:	Overall Area (9 nodes)	Node #1 Low Density	Node #2 Low Density	Node #3 High Density	Node #4 High Density
Coax Plant Mileage	**59.6**	9.56	6.58	4.3	2.24
Aerial	**36.1**	3.87	5.39	3.34	1.59
Underground	**23.5**	5.69	1.19	0.96	0.65
Total Actives	**381**	61	45	32	13
Actives/Mile	**6.4**	6.4	6.8	7.4	5.8
Cascade	**N+3 – N+6**	N+6	N+5	N+4	N+3
Total Passings	**5,740**	724	502	628	370
HP/Mile	**96**	76	76	146	165

Figure 23 displays the entire area. The node boundaries are shown on the map with magenta lines. The green lines show the HFC fiber routes. In addition to connecting the nine nodes to the hub site, the fiber backhaul also connects to two Macro tower base stations in the upper quadrant.

6.1.1. CBRS Small Cells at Fiber Nodes Only

Figure 23 also displays nine CBRS small cells located next to or near a fiber node. This location provides access to power and fiber backhaul in case the operator wants to use the Option 7.2x fronthaul interface. The small cell range is roughly shown as concentric circles of 250m and 350m coverage radius. This corresponds roughly to the coverage area of strand-mount and streetlight mount respectively.

Note that two of the fiber nodes were within 250m of each other. Putting a small cell at each node site would have resulted in too much overlap and interference. Rather than eliminating a small cell, we chose to move them a short distance away from the node (i.e. 500’ and 860’). The small cells are still on the fiber backbone and hardline coax to get access to power plus fiber backhaul. Again, the fiber backhaul allows for a fronthaul option 7.2 Cat A interface to be used if desired.

Figure 23 – N+6 Suburban area with Small cells at Fiber Node

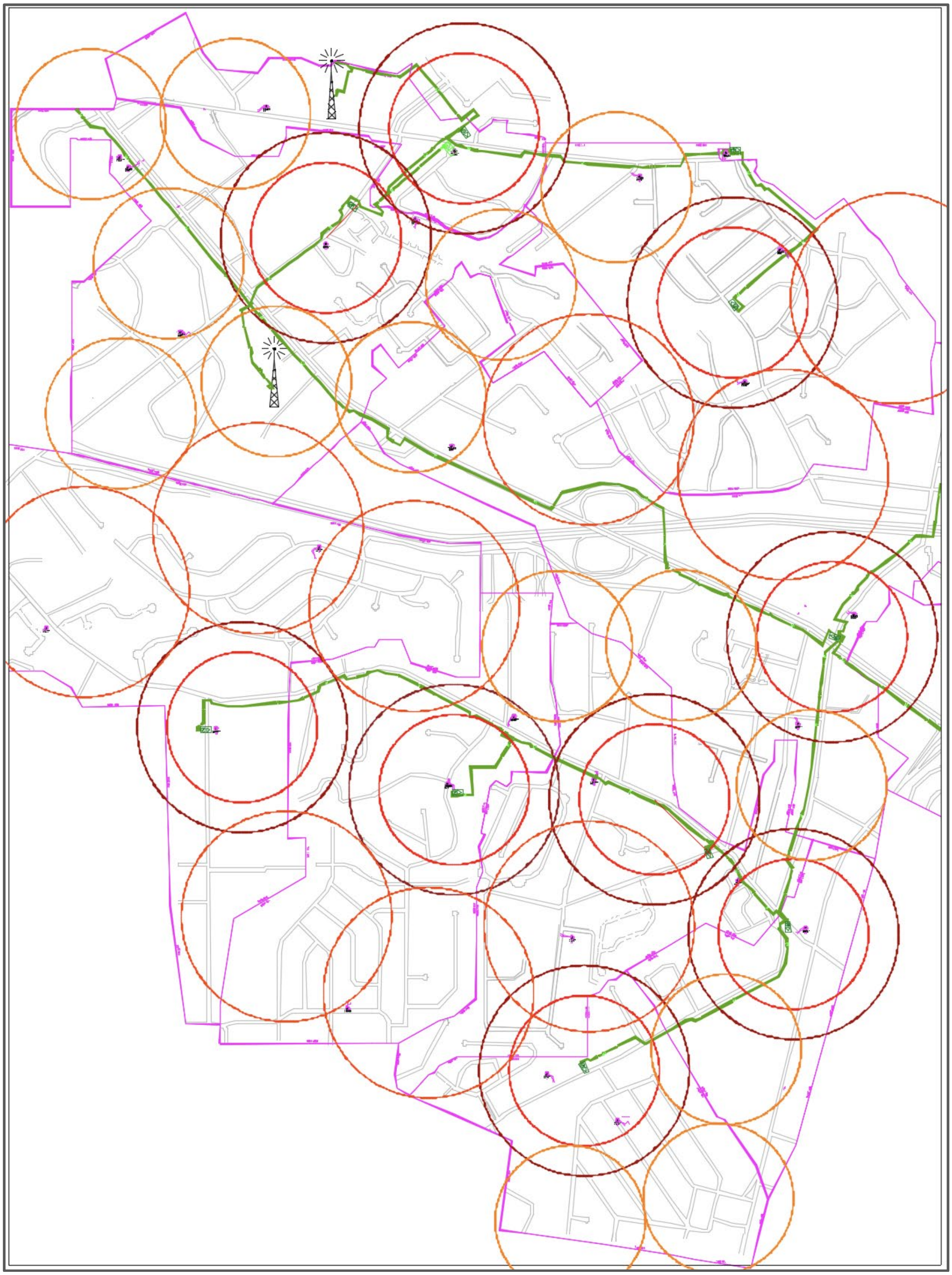

Figure 24 – N+6 Suburban area with Small cells at Fiber Node + HFC coax

The rectangle captured in Figure 23 and Figure 24 is about 1.9 x 2.6 miles (~ 5 square miles), while the actual area covered by our 9 nodes is ~3.5 square miles. As can be seen in Figure 23, less than half of the area has coverage, even with the extended 350m streetlight range. If the operator's goal is just to off-load some mobile data onto their network, this might be good enough. Also note how this coverage on N+6 plant is significantly less than the coverage seen on N+3 plant in the previous section.

6.1.2. CBRS Small Cells at Fiber Nodes and Coax locations

The next step is to fill in the area coverage with strand-mount CBRS small cells with ~250m to ~350m range. This is shown in Figure 24. These small cells would use a DOCSIS backhaul. For this analysis, any lower density nodes with <85 HP/mile were assumed to support ~350m cell range, while higher densities >85 HP/mile would only get ~250m range.

This requires 23 additional small cells to get reasonably complete coverage with a small number of residences just outside the cell radius. Care is taken that these small cells are centered either on the hardline coax strand or on a pole. Note that using streetlight mounting increases the coverage area to 350m to 500m and might eliminate a third of these coax-connected cells.

Overall, there are roughly three to four small cells for every fiber node in this N+6 HFC example. But this can vary quite a bit from node to node. Some nodes only have a single coax-based small cells while others need four more coax-based cells. It turns out that this is a function of the node's homes passed density.

Figure 25 – A zoom-in into one of the high-density nodes

Figure 25 zooms in into the two highest density nodes (i.e. Node #3 and #4 from Table 4). These are located in the lower-right corner of Figure 24 and have densities of 146 – 164 HP/mile. The high-density nodes tend to have shorter cascade lengths and only need one coax-based small cell in addition to the one at the fiber node to cover their area. It took a total of 4-5 cells total to cover this two-node area.

Figure 26 zooms into the lowest density nodes (i.e. Node #1 and #2 from Table 4) in the middle-left of Figure 24. These nodes have a density of 76 HP/mile. These low-density nodes need five coax-based small cells (with expanded 350m coverage) in addition to the two at the fiber node cells to complete the coverage of the 2 nodes' area. Even though there are many more small cells on the DOCSIS network, it should not stress the capacity of the system. The five DOCSIS small cells on low density nodes covers roughly the same number of homes passed as the two DOCSIS small cells on the high-density nodes. So, it is expected that the total DOCSIS load would be similar between both scenarios.

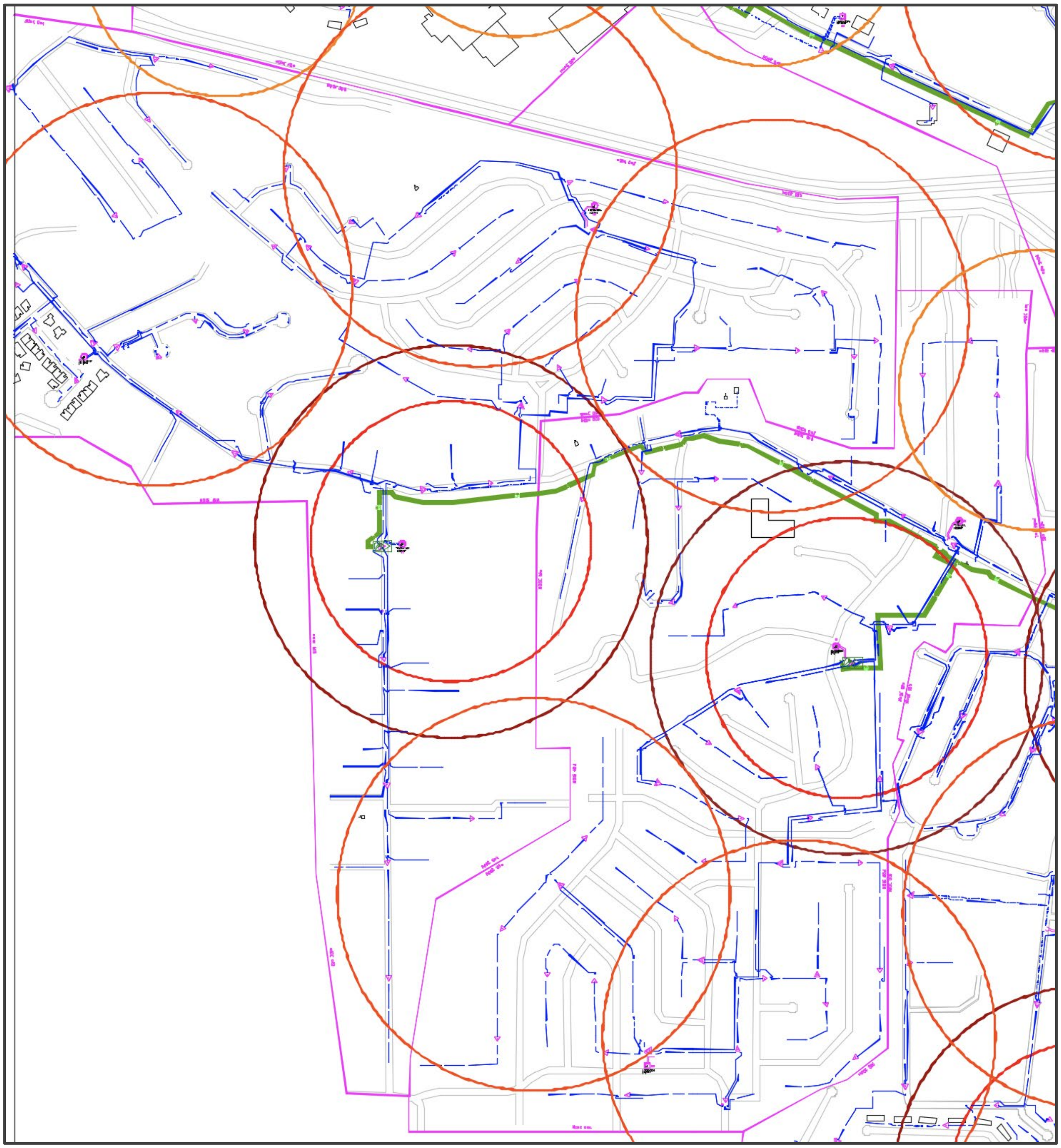

Figure 26 – A zoom-in into one of the lower-density nodes

One strategy that an operator might consider is to go to a lower 2x2 MIMO (instead of 4x4) to extend the cell reach and reduce the total number of small cells needed. The operator is effectively trading off coverage versus user capacity.

Note – In Figure 25 and Figure 26, hardline coax is shown in blue; and actives are visible as well.

6.2. N+0 Upgrade case study

The CommScope HFC design team did a N+0 upgrade design for this case study area. Table 5 shows the statistics for the N+0 upgrade compared to the original N+6 HFC plant. This upgrade pushes fiber much deeper into each node area. Total fiber mileage for this area would increase from 8.55 miles to 24.8 miles.

Figure 27 shows an update to the small cell placement from Figure 24. Note the additional fiber runs shown in green. As it turns out, fiber now passes next to 17 of the original 23 coax-based small cells. The remaining 6 cells are now within 100m – 150m of fiber. With a little additional effort, every CBRS small cell could eventually have a direct fiber connection. Note in the N+0 design that there are now 110 fiber nodes compared to a total of 32 small cells for this area.

In general, N+0 upgrades tend to be relatively expensive because of the amount of fiber being pulled. As shown, N+0 designs also push the fiber much deeper than is needed for CBRS small cell coverage. Our estimates are that an N+2 upgrade might have fiber node placements that align nicely with CBRS small cell placements. An interesting future study would be to look at a more economical N+2 upgrade to see how it aligns with the CBRS small cells.

Table 5 – Statistics of Metro-suburban HFC N+6 nodes vs. N+0 Upgrade

N+6/N+0 Case Study:	N+6 (original area)	N+0 (upgraded area)
Total Fiber Nodes	9	110
Total Fiber Mileage	8.55	24.8
Coax Plant Mileage	59.6	
Aerial	36.1	
Underground	23.5	
Total Actives	381	110
Actives/Mile	6.4	1.85
Cascade	N+3 – N+6	N+0
Total Passings	5,740	5,740
HP/Mile	96	96

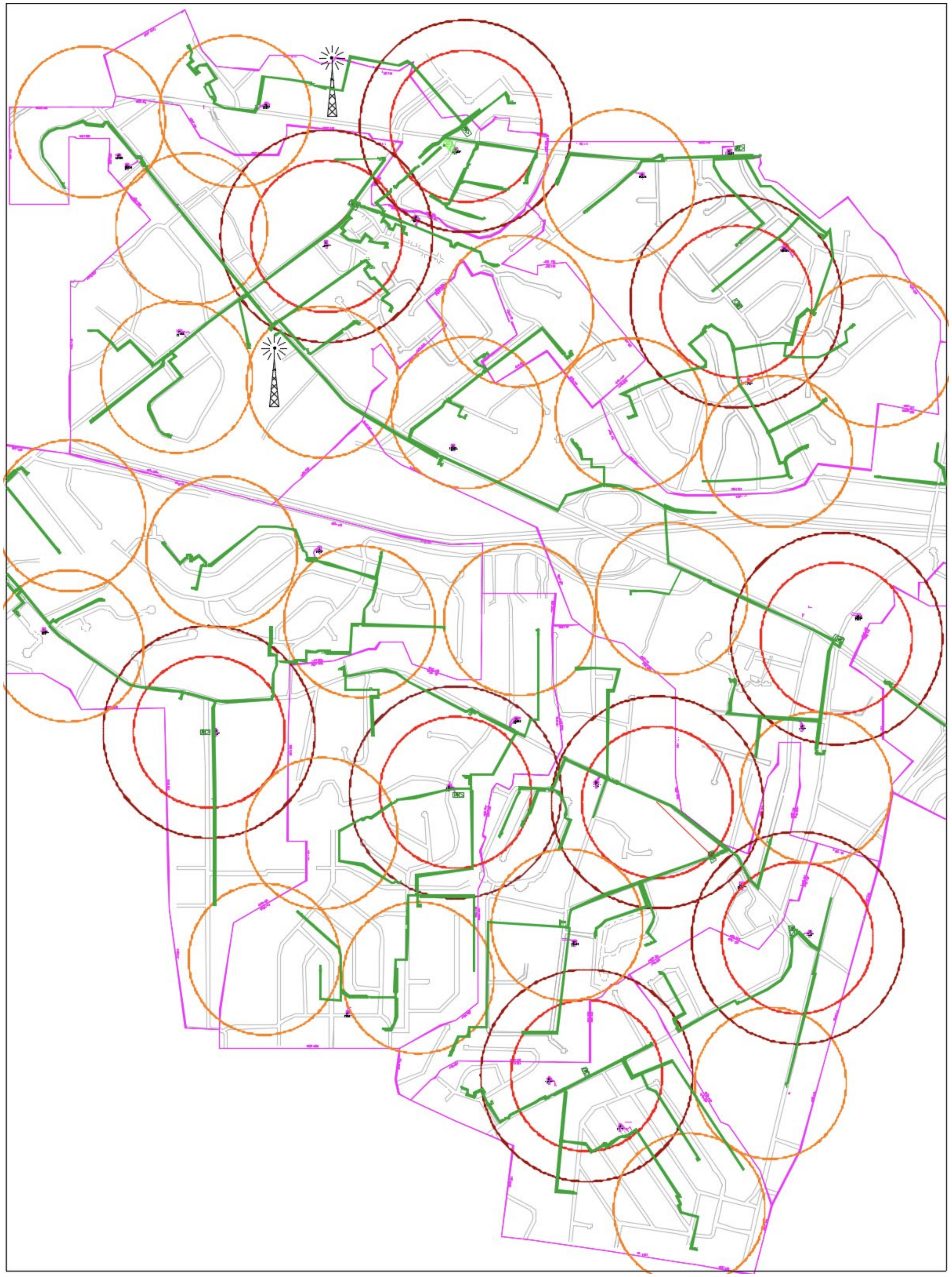

Figure 27 – Suburban area with N+0 fiber upgrade, Small cells at Fiber Nodes

7. Summary

Combining Cable 10G and Wireless 5G can offer an evolutionary strategy with much synergy. Recent 5G developments in C-band and CBRS provides some new mid-band spectrum (i.e. 3.5 – 4 GHz) that is offering a middle ground that may be the future wireless workhorse.

The paper presented a basic tutorial on mid-band wireless technologies; looks at the 5G mid-band capacity requirements; and then showed several case studies on how CBRS small cells might overlay various HFC nodes of varying homes passed densities.

The many choices for the mid-band wireless system can vary bandwidth requirements from 100's Mbps to many 10's Gbps. The paper shows which configurations can easily be supported on DOCSIS 3.1 while others might require DOCSIS 4.0 and some need direct fiber connect.

Two case studies are provided where potential mid-band cells are mapped to actual HFC networks. The nodes under study vary from dense urban nodes (i.e. >250 HP/mile) down to sparse rural nodes (i.e. <40 HP/mile). Various trade-offs are considered in cell site placement on the HFC.

7.1. Lessons Learned

Here is a collection of key takeaways from this paper:

7.1.1. Mid-Band Small Cell Coverage Range

- Small cells will most likely have a 2T2R or 4T4R omni-directional antennas supporting either 2x2 or 4x4 MIMO.
- CBRS strand-mount small cells might have approximately 240m reach in an urban setting with a greater reach (e.g. 360m) in a more rural setting.
- CBRS small cells on top of a streetlight have increased reach, perhaps up to 340m reach in an urban setting with a greater reach (e.g. 500m) in a more rural setting.
- C-Band small cells have even further reach then CBRS small cells thanks to its higher EIRP.
- Wi-Fi 6E range will be hampered to less than 100m reach due to its higher 6 GHz frequency and lower transmit powers. However, it is still expected to rule inside the home as the Mid-Band frequencies may struggle getting inside buildings.
- Some 5G small cells might be downlink (DL) only, using more robust Low-Band frequencies for the weaker uplink (UL) signals

7.1.2. Small cell Midhaul/Fronthaul capacity requirements

- Option 2 Midhaul interface substantially reduces bandwidth capacity requirements compared to Option 7.2 Cat A Fronthaul interface.
  - Option 2 requires more electronics at the radio site (i.e. DU + RU combined)
  - Option 7.2x allows for more sophisticated algorithms (e.g. beam forming) to be done in the edge cloud.
- In general, Option 7.2 Cat A interface would need a direct fiber connection
  - TBD whether DOCSIS 4.0 could meet all of the capacity and strict timing requirements for the Fronthaul interface
- DOCSIS 3.1 capacity appears to comfortably handle Mid-Band small cells with Option 2 Midhaul interface
  - 100 MHz of Mid-Band spectrum might need 1218/204 MHz HFC

7.1.3. Mapping Mid-band Cells to HFC – Key Takeaways

- Locate first small cell at or near the fiber node to leverage both power and fiber backhaul.
    - Maximum flexibility, including the choice of using Option 7.2x Fronthaul interface
- Add additional small cells with Option 2 Midhaul interface as needed along the HFC coax to access power plus DOCSIS network.
    - Over time, can pull fiber to any small cells whose capacity outgrows DOCSIS
- N+2 HFC appears to align nicely with CBRS small cells at fiber node location
- Higher density areas (in HP/mile) tend to require fewer coax-based small cells
- Lower density areas (in HP/mile) tend to require several more coax-based small cells
    - But capacity requirements are also lower due to smaller HP/mile
    - Optionally could support a lower 2x2 MIMO (instead of 4x4) to extend cell reach and reduce number of small cells needed.

7.2. DAA Synergies

- Small cells near fiber node can share 10G Ethernet connection with RMD/RPD.
- A distributed DU in the field that aggregates 6-12 small cells with Option 7.2x interfaces fits nicely into the CableLabs 10G DAA architecture
    - DU in the field greatly reduces the long range backhaul bandwidth capacity requirements (e.g. from 100's of Gbps down to 10's of Gbps)
    - Aggregation node with CableLabs coherent optics provides plenty of bandwidth capacity for the Mid-Band wireless network distribution.
- RMD works best for distributed DU in the field
    - RPD would require DOCSIS MAC core to be located near DU, not in the cloud

7.3. Potential Mid-Band Business Opportunities for Cable Operators

Considering these lessons, what makes sense for HFC service providers? CBRS/C-Band small cell reach covers a significant number of mobile users with substantial data rates. But its deployments need many more cell sites then current LTE macro-cells. This presents an opportunity for MSOs to leverage their existing HFC infrastructure for both backhaul and power.

First considering rural locations, MNOs have typically used Low-Band frequencies to maximize the distances between their macro tower base stations. This spacing may not be suitable for C-Band delivery from the tower to reach the entire community. As 5G bandwidth needs increase, MNOs may decide that deploying C-Band small cells is more economical than building more macro towers. The cable operator can provide the location (i.e. strand-mount) along with power and backhaul as a service to the MNO that owns the C-Band spectrum.

Alternatively, the cable operators might want to deploy their own 5G mobile network leveraging CBRS over their own infrastructure. In rural locations, there is a good probability that the cable operator can get access to a decent chunk of the 150 MHz CBRS spectrum via GAA.

If the cable operator is also acting as a virtual MNO (vMNO) by partnering with one of the leading MNOs, it might choose to place a handful of CBRS small cells in the busiest locations as an off-load strategy. Or the cable operator might build out the CBRS small cells across its HFC for more complete coverage of the area. Note that 100 MHz of spectrum can enable UE data rates of 2 Gbps down by 300 Mbps up. Very impressive.

In urban settings, 4G capacity needs have already forced the MNOs to locate macro towers much closer together. So, they will be in a much better position to offer C-Band from macro towers leveraging sophisticated antenna arrays (e.g. 64T64R) and beam forming algorithms. The need for C-Band small cells will be much smaller; but it may still be needed in hot spots to help reduce congestion.

Therefore, the CBRS small cell will be key for cable operators in urban settings. But there will potentially be many others competing to get CBRS spectrum in these settings. Comcast, Charter and Verizon have all been active in acquiring CBRS PAL licensing so they can be guaranteed their share of the 150 MHz spectrum. Remember that PAL license holders can only consume up to 70 MHz total (up to 40 MHz per single PAL license holder), so at least 80 MHz will still be available for GAA users.

7.4. Conclusion

In conclusion, HFC is ideally suited to support this Mid-band xHaul infrastructure. A strategy is laid out for cable plants of varying densities. D3.1 midhaul can be leveraged extensively in the early days to get wide coverage quickly. Very dense urban areas may eventually require complex antenna/MIMO systems with fiber fronthaul, which integrates nicely with an N+2 fiber deep strategy. But even then, cells with DOCSIS xHaul will be needed to fill the holes and hotspots. D4.0 then enables even higher capacities at these cable cell sites.

In the end, Cable and Mid-band wireless (C-Band, CBRS, Wi-Fi 6E) are much stronger together and are at the core of a next gen converged network evolution.

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Abbreviations

3GPP	3rd Generation Partnership Project
4G, 5G	4th, 5th generation (wireless)
10G	10 gigabit platform (cable)
AP	access point
BSA	base station antennas
bps	bits per second
BW	bandwidth
CAPEX	Capital Expense
CBRS	Citizens Broadband Radio Service
CDF	Cumulative Distribution Function
CMTS	Cable modem termination system
CPE	Consumer Premise Equipment
CU	Central unit
DAA	Distributed Access Architecture
DOCSIS	Data Over Cable Service Interface Specification
DL	Down link
DS	Downstream
DU	Distributed Unit
EIRP	Effective Isotropic Radiated Power
EM	Electro-magnetic
ESD	Extended spectrum DOCSIS
FCC	U.S. Federal Communications Commission
FDX	Full Duplex (i.e. DOCSIS)
FTTP	Fiber to the Premise
FWA	Fixed Wireless Access
GAA	General authorized access
Gbps	Gigabits Per Second
GHz	Gigahertz
HPBW	half power beamwidth
HFC	hybrid fiber-coax
HP	Homes Passed
Hz	Hertz
IPTV	Internet Protocol Television
ISBE	International Society of Broadband Experts
IEEE	Institute of Electrical and Electronics Engineers
LOS	Line of sight
LTE	Long term evolution
MAC	Media Access Control interface
Mbps	Megabit per second
MCS	Modulation Coding Scheme
MDU	Multiple Dwelling Unit
MHz	Megahertz
MIMO	multiple-input and multiple-output
M-MIMO	Massive MIMO
MNO	Mobile Network Operator
MSO	Multiple System Operator

MVNO	Mobile Virtual Network Operator
N+0	Node + 0 actives
N+X	Node + X actives where X = 1 or greater
NCTA	National Cable and Telecommunications Association
nLOS	Near line of sight
Nsub	Number of subscribers
OFDMA	Orthogonal Frequency Division Multiplexing Access (Upstream)
OFDM	Orthogonal Frequency Division Multiplexing
OPEX	Operating Expense
ORAN	Open Radio Access Network
P2P	Point to point
PAL	Priority access license
PHY	Physical interface
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation
RAN	Radio Access Network
RF	Radio frequency
RMD	Remote MAC-PHY device
RoW	Rest of world
RPD	Remote PHY device
R-PHY	Remote PHY
RRU	Remote Radio Unit
RU	Radio Unit
Rx	Receive
SAS	Spectrum Access System
SCTE	Society of Cable Telecommunications Engineers
SDV	Switched Digital Video
SFU	Single family unit
SG	Service Group
SINR	Signal to Interference and Noise Ratio
TDD	Time division duplexing
Tx	Transmit
UE	User Equipment
UL	Up Link
US	Upstream
VoLTE	Voice over LTE
WISP	Wireless Internet Service Providers