Small Cell Traffic Engineering

How Many Small Cells are Needed for Proper Coverage?

A Technical Paper prepared for SCTE•ISBE by

John T Chapman
CTO Cable Access, Fellow
Cisco Systems
300 East Tasman Drive, San Jose, CA
408-526-7651
jchapman@cisco.com

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1. Introduction

The world as we know it in cable is about to change.

Today's cable operators are tomorrow's mobile operators

This is being driven by a multitude of factors. For one, it is a way of significantly increasing revenues. All the cable broadband customers have cell phones and are often paying two different service providers, one for wireline and one for wireless. Does that really make sense?

Remember the telephone network? That country wide collection of twisted pair copper and T1 lines? It does not exist anymore. Telephony is an application that runs over an IP network. There is no Wi-Fi network. Wi-Fi is a radio gateway that exists at the end of an IP network that provides end point connectivity.

Today, we still have separate and distinct mobile and cable networks. But not for long. These too will soon also become applications running over an IP network. As mobile moves to 5G and deploys small cells running at higher frequencies, that small cell will become a Radio Frequency (RF) gateway that converts between wireless and a wireline IP network with traffic tunneled to a 5G core (5GC).

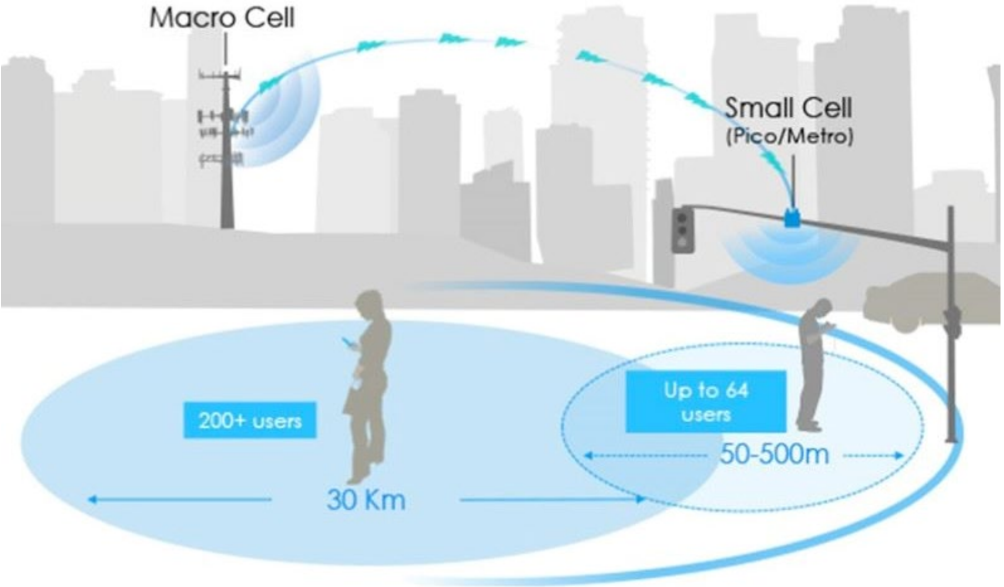


Figure 1 – Small Cell Deployment Model

The same is true with cable. DAA (Distributed Access Architecture) [1][2] nodes are simple RF gateways that convert between digital fiber and RF over coax. This results in fiber to the neighborhood and DOCSIS to the door. With DAA, there is IP over Ethernet over fiber, followed by IP over Ethernet over DOCSIS over coax, followed by IP over Wi-Fi or Ethernet.

This leads us to another important premise.

Behind every great wireless network is a great wireline network

Every radio that creates its part of the mobile wireless network must be connected to a wireline network. In Figure 1, we see the deployment model published by the city of Danville, CA [1]. Notice that the small cell coverage is a fraction (0.2% to 2%) of the macrocell coverage. That is a big difference.

How many small cells will it take to provide the equivalent coverage of a macrocell? How will those get connected? What is the impact to cost? Those are the questions we will tackle in this white paper.

2. Small Cells per MacroCell

2.1. CBRS Quick Primer

Going forward, a very important frequency band of interest to the cable and mobile industry is the Citizens Broadband Radio Service (CBRS) which is a 150 MHz band located between 3550 MHz and 3700 MHz. This RF region is also known as band 48.

The CBRS spectrum is allocated amongst three tiers. The first tier and highest priority are the incumbents like the US Navy and they get first use. The second tier is a licensed spectrum known Priority Access License (PAL) and is composed of operators who have bought local spectrum in the lower 100 MHz through a system known as the Spectrum Access System (SAS). The third and lowest priority tier is unlicensed (which means it is free) known as General Authorized Access (GAA). GAA is composed of 80 to 100 MHz of spectrum that is dynamically allocated out of the 150 MHz CBRS band. This is where “Private LTE” will exist.

CBRS spectrum tends to get allocated out in sub-bands of 10 MHz. Sub-bands can be combined together. As an example of performance, an example outdoor small cell radio would have 40 MHz max RF bandwidth, 200 Mbps max throughput with one-watt Effective Isotropic Radiated Power (EIRP). That works out to 5 bits/Hz. Note how well 100 Mbps to 200 Mbps throughput matches to a DOCSIS CM.

2.2. Small Cell and Macrocell Coverage

Macrocell on a Tower **Small cell on a Lamp Post**

Figure 2 – Macrocell versus Small Cell Sites

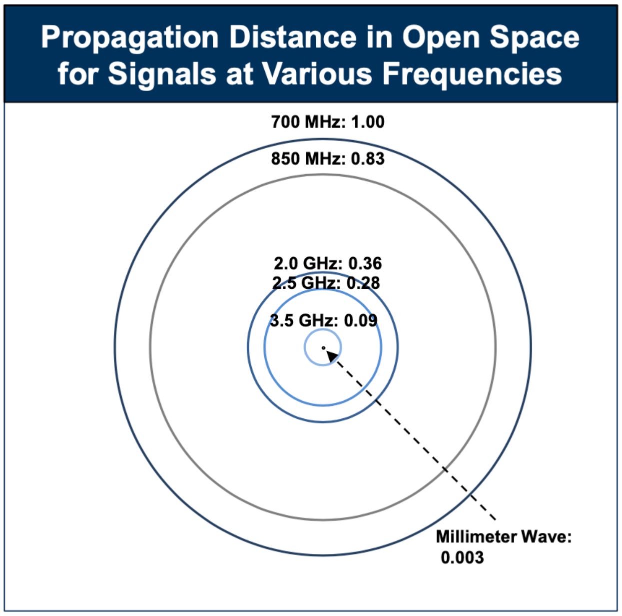
Radio coverage depends on three fundamental factors:

- Frequency
- Power
- Height and physical interference

The higher the frequency, the higher the propagation loss and hence the smaller the coverage area. Higher frequencies generally tend to experience higher loss from objects in the path of propagation. The higher the power, the longer the propagation. And the higher the antenna, the less likely it will have physical interference from tree, hills, and walls.

Macrocells tend to be lower in frequency, higher in power, and mounted at higher heights. Small cells tend to be higher in frequency, lower in power, and mounted at lower heights. These combined factors drastically lessen the coverage ratio of a small cell compared to a macrocell. Some typical installations are shown in Figure 2.

There are other factors to be sure such as modulation and error-correction that impact channel capacity and toleration to distance, but they are more secondary factors.



Source: Samsung, Verizon investor presentation, MoffettNathanson estimates and analysis

Figure 3 – RF Cell Radius Comparison

Figure 3 shows the ratio of a macrocell radius to a small cell radius [4]. The cell radius at 700 MHz is normalized to one. The frequencies at or adjacent to 700 MHz are used for Long Term Evolution (LTE) mobile systems. The values from Figure 3 are also shown in Table 1.

Table 1 – RF Cell Radius Comparison

Band	Service	Cell Type	Relative Radius
700 MHz	LTE	macrocell	1.0
3.5 GHz	CBRS	small cell	0.09
28 GHz	mmWave	small cell	0.003

MoffetNathanson states that the numbers are just illustrative; they assumed the same power level and antenna height for each spectrum band. When compared to Figure 1, where the ratio was 0.2% to 2%, the numbers in Table 1 which are based on free air may actually be optimistic. This means in practice, with lower heights and lower powers, the relative radius may be lower and the calculated small cell count will be higher.

Conversely, small cells can take advantage of the latest technologies including beam forming and MIMO to extend their reach. It also makes a big difference whether the small cells are deployed on a strand-mount in a crowded downtown area or in a rural area or a rooftop or hilltop. Still, it is important to start somewhere to establish a baseline, and then that baseline can be adjusted up or down.

With these data points and some high school algebra, we can calculate how many small cells it would take for an equivalent macrocell footprint.

2.3. Mathematical Model I

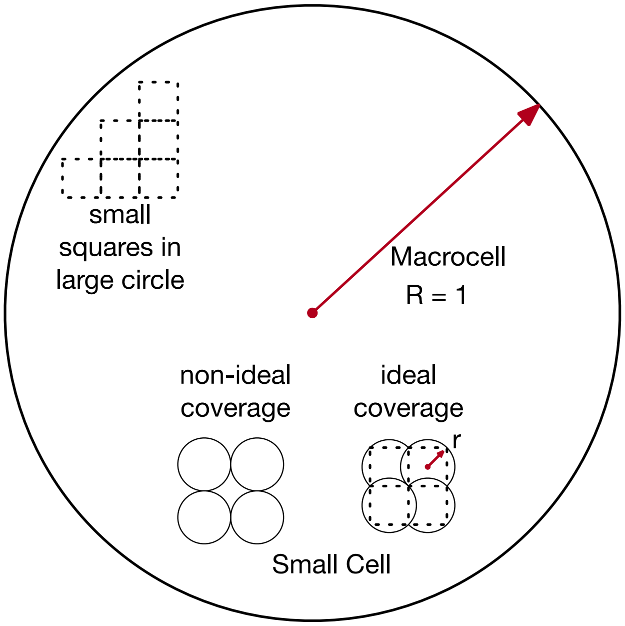


Figure 4 – Model of Small Cell per Macrocell (Max)

The following is a mathematical model of how many small cells it would take to achieve 100% coverage equivalence to a macrocell. The analysis assumes free air, so real-world results will vary.

The models in this white paper are derived here and do not reply on previous literature.

Let's first assume that a cellular radio cell RF coverage is a perfect circle. It is not enough to divide the area of the small circle of the small cell into the large circle of a macrocell since this would assume no overlap. Circles that have no overlap also have gaps in coverage as shown in Figure 4. Instead, if we assumed a maximized square inside the small circle, then the squares can then be tiled to create 100% coverage.

In practice, there is almost always either too much overlap of cell radius, resulting in some loss of coverage efficiency, or not enough overlap, resulting in gaps of coverage. Also, the macrocell itself is overlapping or gapping with other neighboring macrocells. None the less, this model provides a starting point where the optimized configuration which can then be adjusted up or down, based on deployment considerations.

The following should bring back pleasant memories of high school algebra. If those memories are more of a nightmare, then just skip this section. I won't be offended.

Let's define:

R = Radius of the macrocell

r = radius of the small cell

The coverage of the macrocell area, based on a large circle, is:

$$macrocell\ coverage = \pi R^2 \qquad \textit{formula (1)}$$

That was easy. Now the next part. The coverage of the small cell area is based on a maximum sided square inside the small circle. The radius of the small circle is equal to the distance from the center of the square to the corner of the square. That radius is part of a small triangle in the corner of the square. This is shown in Figure 5.

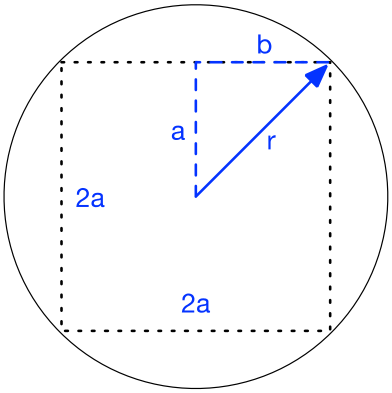


Figure 5 – Coverage of a Small Cell with Ideal Overlap

The Pythagorean Theorem provides the length of the triangle side.

$$a^2 + b^2 = r^2$$

If b = a, then

$$a^2 + a^2 = r^2$$

$$2a^2 = r^2$$

$$a^2 = {r^2}/{2}$$

$$a = {r}/{\sqrt{2}}$$

The length of the side of the square is twice this value.

$$box\ side = 2a = {2r}/{\sqrt{2}} = \sqrt{2}r$$

The area of the square, and hence the small cell coverage we are looking for, is the square of the box side.

$$small\ cell\ coverage = (2a)^2 = \left(\sqrt{2}r\right)^2$$

$$small\ cell\ coverage = 2r^2 \qquad \textit{formula (2)}$$

We can now compute the ratio of macrocell coverage, formula (1), to small cell coverage, formula (2).

$$\#SC\ per\ MC = {}^{macrocell\ coverage}/_{small\ cell\ coverage}$$

$$\#SC\ per\ MC = {}^{\pi R^2}/_{2r^2}$$

$$\#SC\ per\ MC = {}^{\pi}/_{2}\left({}^{R}/_{r}\right)^2 \qquad formula\ (3)$$

If R is normalized to 1, then we get a simplified version that looks like

$$\#SC\ per\ MC = {}^{\pi}/_{2r^2} \qquad formula\ (4)$$

2.4. Mathematical Model II

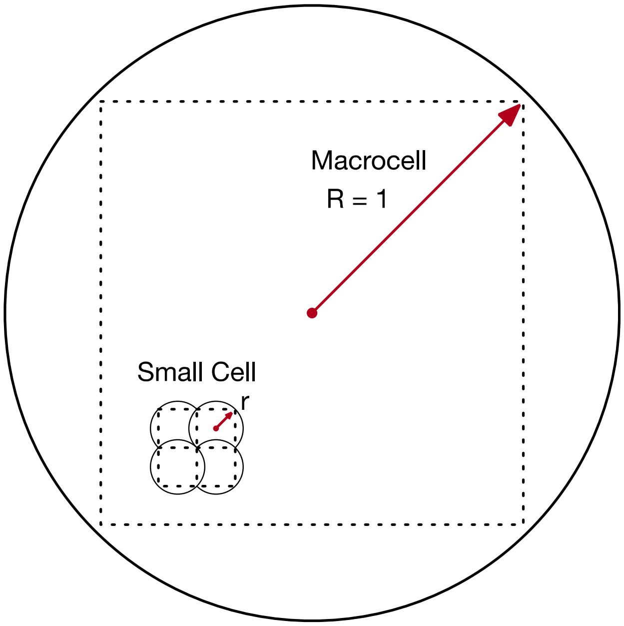


Figure 6 – Model of Small Cell per Macrocell (Min)

In the previous section, we placed overlapping small cells into a macrocell radius. To be a bit more optimistic, what if that macrocell was also was just perfectly overlapping with other macrocells. Then, the calculation would simplify to small squares filling a big square. This approach provides a range between two extreme cases – one with no overlap and one with perfect overlap.

Formula (2) provided the area of a square based on its radius. This can be applied to

$$\#\ SC\ per\ MC\ min\ = {}^{\pi R^2}/_{\pi r^2}$$

$$\#SC\ per\ MC\ min = \left({}^{R}/_{r}\right)^2 \qquad formula\ (5)$$

Normalizing the larger radius R to R = 1:

$$\#SC\ per\ MC\ min = {}^{1}/_{r^2} \qquad formula\ (6)$$

There, that was not so bad. Now let's plug in some numbers and see what happens.

2.5. Small Cell Radios per Macrocell Example

Now let's take the values from Table 1 and insert them into formula (4) and formula (6) to get Table 2.

Table 2 – RF Cell Radius Comparison

Band	Service	Cell Type	Relative Radius	# Radios
700 MHz	LTE	MC	1.0	1
3.5 GHz	CBRS	SC	0.09	125 to 200
28 GHz	mmWave	SC	0.003	110,000 to 175,000

The results in Table 2 state that for the CBRS band which located at 3.5 MHz, it would take about 125 to 200 small cell radios to match the coverage of one LTE macrocell at 700 MHz. Note that the results in Table 2 have been rounded off in alignment with rules for significant figures.

28 GHz is the band of interest that Verizon is currently using for 5G mmWave [5]. It would take 110,000 to 175,000 small cell radios to replace one LTE macrocell. That's a lot of radios. Even at only 1% coverage, that would be 1750 radios.

Now, if the strategy is to not achieve 100% coverage and to also rely on the LTE network as a background network, then these numbers can be scaled down. Conversely, small cells that operate at a both a higher frequency and a lower installation height than LTE towers are also more likely to get blocked by trees or walls. Under those circumstance, the number of radios in Table 2 may actually need to be increased.

2.6. Cost Implicatons

Depending upon business needs, operators may not need a 100% replacement of the macrocell. For example, when AT&T used LTE femtocells to supplement LTE, those femtocells were only needed in areas of weak or no coverage. Conversely, as US cable operators enter into mobile virtual network operator (MVNO) arrangements, they will be financially motivated to put CBRS small cells in areas where there is any significant amount of traffic so that they do not have to pay back carriage charges to their MVNO partner that manages the LTE network. The flow of money from roaming fees for an MSO acting as an MVNO and its host network partner is shown in Figure 7 which is from the discussion in [6].

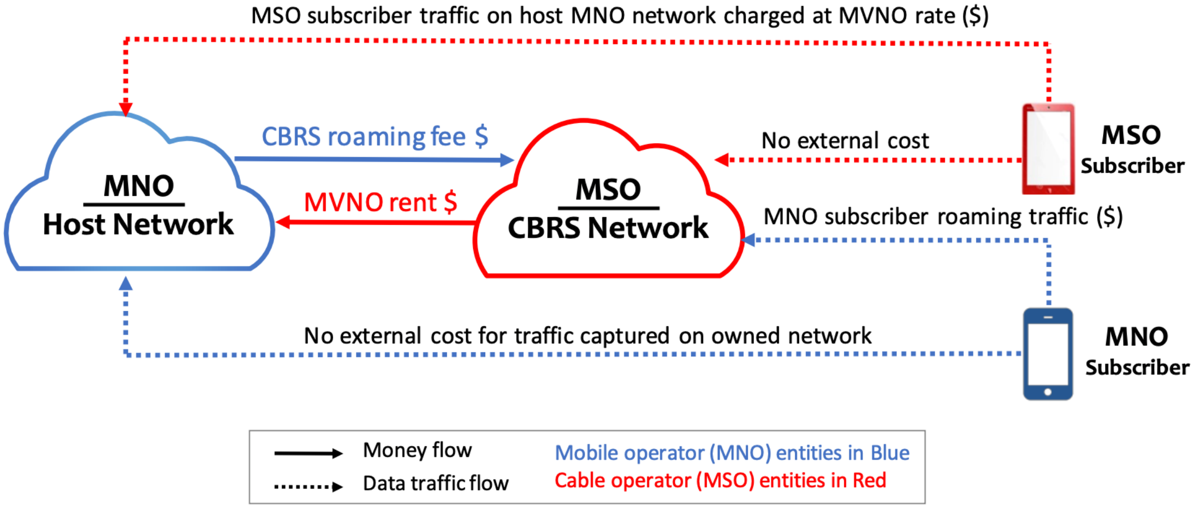


Figure 7 – MVNO Roaming Costs

This paper has shown that it can take 200 CBRS small cells to cover an area equivalent to the area covered by one LTE macrocell. Even if the goal was only 50% coverage, that is still 100 small cells. And if the goal was to build a new radio network that cost equal to or less than the LTE network, then the install cost of each small cell would have to be 1% of what it took to install an LTE macrocell.

So, it has to be almost free.

A typical macrocell installation cost is $20,000 to $50,000 to rent a tower, get permits, trench and run power and fiber, and mount a radio. If economics need to drop to 1% with 50% coverage, then the small cell deployment installation would have to be $200 to $500 per small cell. Is that possible? Well, that is about the cost it takes to deploy a residential CM if there is a truck roll. So, if a small cell was as cheap and easy to deploy as a CM, then yes. As a case in point, Wi-Fi is almost free to install because it is included in the CM install. So, if a small cell cost were also included in the CM cost, it could see similar cost structures.

So, it can be almost free.

There is another important consideration, and that is xhaul. Xhaul refers to backhaul, midhaul, or fronthaul. For LTE, the eNB generates GTP (GPRS Tunneling Protocol) encapsulated packets ready for backhaul. In 5G, the equivalent gNB is divided into an RU (Radio Unit), DU (Distributed Unit) and a CU (Centralized Unit). DOCSIS can support either the backhaul from a gNB (RU+DU+CU) or midhaul from a RU+DU. DOCSIS does not have the bandwidth or latency to support fronthaul from an RU.

Today’s macrocells often have a fiber backhaul. If you had to deploy 100x more radios at 100 new locations, is it cost effective to run 100 more fibers? If the broadband cable team could not justify the cost of the additional fiber for residential broadband, how is it that the company business case changes such that it works for small cells?

These economics are now driving cable operators such as Charter and Telecom Argentina [7], Cogeco [8], Shaw [9], Cox [10], and Altice [11] amongst others, to deploy mobile backhaul over DOCSIS. I have also previously discussed this business case in my blog post [11].

In the next section, we will look at some real-world results between using coax direct connect versus running fiber a few blocks.

3. Small Cells per HFC Fiber Node

3.1. DOCSIS-Attached Small Cells

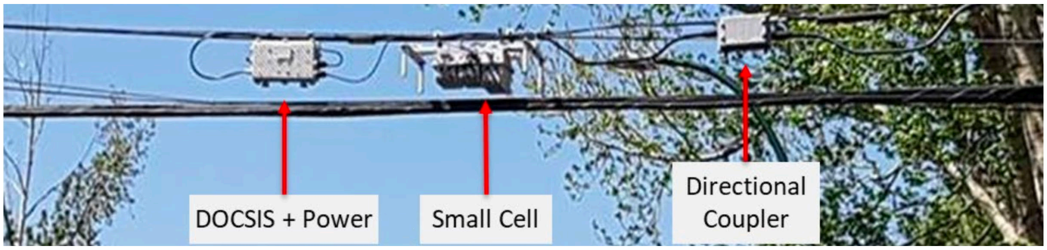


Figure 8 – Strand-Mount Small Cell Deployment

Macrocells have traditionally been on towers and backhauled by fiber, but there are not enough towers or fiber for the new 5G small cells.

Cellular radios require the following basic requirements:

1. Site/Location
2. Power
3. Backhaul

The following requirements are also useful based upon the installation

4. Timing support
5. Low latency

DOCSIS over HFC (Hybrid Fiber Coax) supports all these requirements. HFC passes 93% of USA HHP and provides strand mount or in-home. Altice, Cox and Shaw have already deployed strand-mount small cell Xhaul over DOCSIS (>20,000).

Figure 8 from [13] shows a typical strand mount small cell. There is a directional coupler that couples power and RF from the coax plant. This goes to a strand mount CM which then connects to a strand mount small cell.

It should be noted that the HFC plant has to be designed to allow for the power drop across the directional coupler and for the additional power draw of the small cell as well as the additional power dissipation of the cable modems and small cells.

An alternative mounting configuration is to locate the small cell in the subscriber residence. This again provides location, power, and backhaul.

So, what does this cable plant look like, and how many small cells would a fiber node in an HFC plant be expected to support?

3.2. Real World Case Study

A study was done by Shaw Communications in 2019 [9] that compared a fiber backhaul solution to a coax/DOCSIS backhaul solution for a set of 15 small cells deployed across 13 node locations. In this study, only time and construction costs were considered. The deployment diagram is shown in Figure 9.

For fiber backhaul case, fiber was run (yellow lines) from the small cell location (red stars) to the node location and connected to available dark fiber. Only the cost of this short fiber run was included. The cost of the fiber from the node to the hub was not included. If it was, the difference would even be more dramatic.

For the coax backhaul case, the small cells were powered from the HFC plant with a 10’ coax drop and a connected with a bidirectional coupler. The strand mount small cells did not require any permitting or have any access issues and no civil build was required.

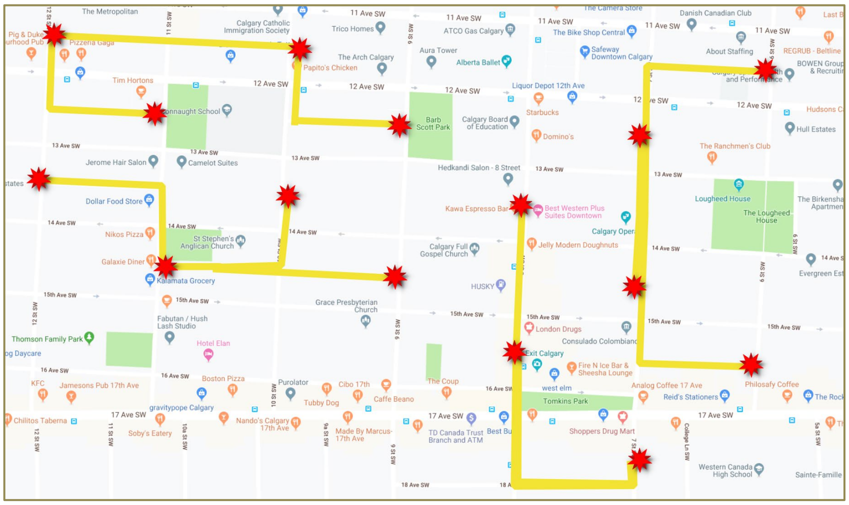


Figure 9 – Real World Analysis of xHaul

The results are in Table 3 and are astonishing. <u>The cost of installation dropped to 1% and the time-to-deploy became 20x faster</u>. Using an available HFC plant instead of new fiber was a clear winner.

Table 3 – Real World Case Study of xHaul over DOCSIS

Backhaul Option	Broadband Fibers	Construction Cost	Time to Build
Fiber	1	$182,500	4-6 months
Coax	0	$1,500	1 week
Savings		**1% of the cost** ***99% reduction***	**20x Faster** ***95% reduction***

Now that we have established a deployment and business case baseline, let’s figure out how many small cells might fit into an HFC plant.

3.3. Mathematical Model

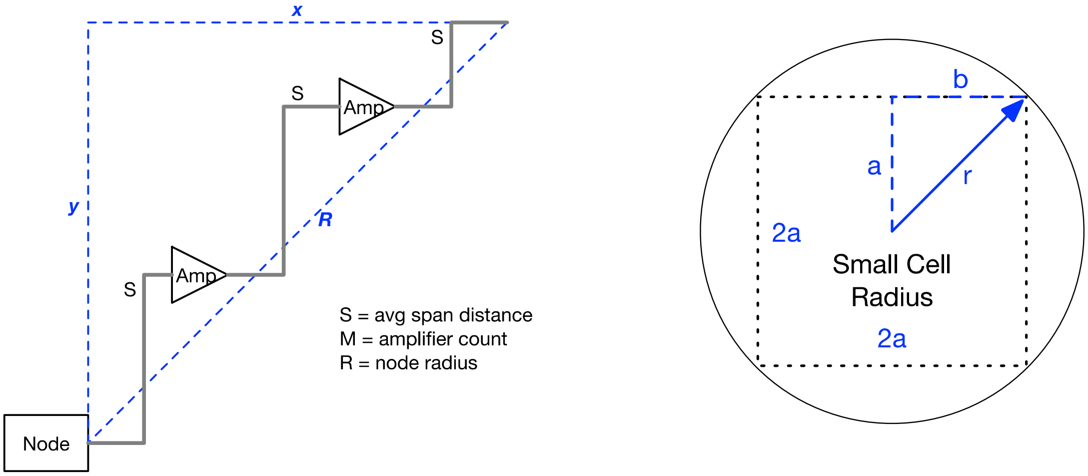


Figure 10 – Model of Small Cell per HFC Optical Node

So how many small cells would it take to cover an area that is currently covered by a DOCSIS service group that is associated with one fiber node?

That depends on the size of the plant. HFC plants are described by their amplifier depth. An N+0 plant is a node plus zero amplifiers. An N+5 plant is a plant with a node followed by five consecutive amplifiers. Note that the signal path in an N+5 plant is constantly being split, which creates the area coverage. Thus a single node could have as many as 25 to 40 total amplifiers across all paths.

Let's define the following variables:

S = the average span distance between node-to-amp and amp-to-amp

M = the number of amplifiers in the longest cascade, as in "N + M"

R = The resulting node radius

A diagram of an N+2 plant is shown in Figure 10. A radius line "R" is drawn from the node to the end of the last cable segment. Note that a two-amplifier system has three cable segments. Coax is usually run down streets which leads to rectangular shapes. It can be seen that the horizontal segments fully line up with the "x" axis and the vertical segments fully line up with the "y" axis. These observation leads to the following formula:

$$x + y = (M + 1)S$$

So, the total horizontal "x" and vertical distance "y" is equal to the average segment length "S", times the number of segments which is one more than the number of amplifiers "M". If we assume that the triangle is an isosceles triangle where x = y, then:

$$x + x = (M + 1)S$$

$$2x = (M + 1)S$$

$$x = {}^{(M+1)S}/_{2} \qquad \textit{formula } (7)$$

Checking back in with Pythagoras, we also know from Figure 10 that

$$x^2 + y^2 = R^2$$

Since y = x

$$x^2 + x^2 = R^2$$

$$2x^2 = R^2$$

$$x^2 = {}^{R^2}/_{2}$$

$$x = {}^{R}/_{\sqrt{2}} \qquad \textit{formula } (8)$$

Equating formula (7) and formula (8) yields

$$ {}^{R}/_{\sqrt{2}} = {}^{(M+1)S}/_{2}$$

$$R = {}^{(M+1)S}/_{\sqrt{2}} \qquad \textit{formula } (9)$$

Formula (9) calculates the radius of a fiber node serving area. An alternate form of formula (9) is

$$R = 0.707(M+1)S \qquad \textit{formula } (10)$$

As a rule of thumb, that means the radius of an HFC plant is approximately equal to 70% of the total span length.

Formula (9) can be put into formula (3) to calculate the number of small cells that are needed to cover the fiber node serving area.

$$\#SC\ per\ FN = {}^{\pi}/_{2} \left({}^{R}/_{r}\right)^2$$

$$\#SC\ per\ FN = {}^{\pi}/_{2} \left({}^{(M+1)S}/_{\sqrt{2}r}\right)^2$$

$$\#SC\ per\ FN = {}^{\pi}/_{4} \left({}^{S}/_{r}\right)^2 (M+1)^2 \qquad \textit{formula } (11)$$

Formula (11) calculates the number of radios in a fiber node serving area for an average amplifier span distance of S, and amplifier count of M, and a small cell serving radius of r.

What we can observe from this formula, is that when the small cell radius is equal to the node segment distance (S = r) on a deep fiber plant (M = 0), only one small cell radio is needed per node. This makes sense.

As HFC plant grows beyond N + 0, the number of radios required is proportional to the square of the number of amplifiers plus 1. If the small cell radius is larger or smaller than the span distance, then there is also an additional relationship to the square of the ratio of the span distance, S, to the small cell radius, r, as well.

3.4. Small Cells per Fiber Node Example

Formula (9) and formula (11) use the average span length of an HFC plant. The average span length depends on how many spans there are. So, to construct a table of results, we need to modify the average span length for each N+M plant design. Here is the methodology used to construct Table 4.

- An N+0 HFC plant can actually run the fiber node output amplifier closer to saturation and achieve longer distances. This example will add 10% length for N+0.
- An N+M HFC plant will have an initial span length. A typical value is 1000' (300m).
- Each amplifier adds to the noise floor which reduces MER, so the span length is shortened slightly for each subsequent span. This is a minor consideration as each plant is unique. The number of tap groups per span also may change. The table uses a manual entry for total plant length for each case and calculates an average.

Note that in deployment, the fiber nodes that drive an N+M plant are often called BAU (Business as Usual) nodes and the nodes that drive an N+0 plant are often called SHO (Super High Output) nodes.

To make comparisons easy, the small radius has been chosen to be 50%, 100% and 200% of the initial span length. This will illustrate the squared relationship of the span length to cell radius ratio and the number of small cells needed.

The results of this study are in Table 4. There are some interesting takeaways. First, there is not one rule for all deployments. It is not that one small cell per fiber node always works. Instead, it depends upon the size of the HFC plant. There could be anywhere from one to 20 or even 80 small cells required to cover a plant area.

Does that make sense? Well, if you had a 500 HHP (households passed) N+5 node with 50% of those households being cable-mobile customers, and the small cell was located inside the house, then that would be 250 small cells per node. So, by that argument, the results in Table 4 are conservative or should be looked at as strand-mount numbers.

Note that these calculations are for free air, which implies line-of-site with no hills, trees, or walls, so more small cells are likely to be needed in a real-world deployment.

Table 4 – Small Cells per Fiber Node

		Small cell radius r:		*500*	*1000*	*2000*
M Amps	Total Span	Node Radius	Avg Span	# radios	# radios	# radios
0	*1100*	778	1100	4	1	1
1	*2000*	1414	1000	13	3	1
2	*2850*	2015	950	26	6	2
3	*3700*	2616	925	43	11	3
4	*4600*	3253	920	66	17	4
5	*5460*	3861	910	94	23	6
6	*6300*	4455	900	125	31	8

The caveats are all around height of the small cell, trees, hills, and walls, as well as HFC plant design. Individual results will vary. However, the basic principle remains.

Reach out to me on LinkedIn or email if you would like a copy of these calculations in a spreadsheet.

3.5. Kindred Spirits

Here is a philosophical-techno thought.

The mobile small cell RF downlink and the HFC node RF downstream both try and do the same thing, and that is to propagate RF through a media. One does so through the air and the other through coax. The one through the air runs into trees, hills, and walls, while the one on coax goes past trees, over hills, and through walls.

Both cover a serving radius. The one that propagates through air goes wherever air goes, which is everywhere. The one that propagates through coax goes only where coax goes, which is strand, underground coax and customer premises wiring.

Both have the same propagation limitations based on frequency and power, although that for a given frequency, the loss per unit distance is much higher through coax than that through air. They both use similar electronics and modulations, and sometimes similar frequencies. Where the coax distribution loses power to taps, the air distribution loses power to trees and walls.

Each has similar goals but has its own struggles and accomplishments.

So, it makes some sense, that the radius of a small cell might be on the order of a span of coax.

Note that coax express runs are one dimensional with no taps and go longer distances. They do not apply to this study or analogy.

4. Is DOCSIS Up to the Job?

4.1. CBRS Use Case for HFC

A common misconception is that if you deploy many small cell radios, the network bandwidth required is an aggregate the sum of all that bandwidth. CBRS radios can support 50 Mbps per 10 MHz of spectrum (advanced configurations may get to 100 and 200 Mbps by combining spectrum). If you take a serving area that is supported by one large radio at 100 Mbps and replace it with 50 small radios, each at 100 Mbps, would you need 50 radios x 100 Mbps = 5 Gbps of data capacity? No, you would not.

This is about capacity versus connectivity. Small cells, like CMs, need to be at a certain location like a home to provide coverage, regardless if the network is idle or active. When replacing one macrocell with say 50 small cells, it is about coverage and connectivity first and capacity second. Those 50 small cells will connect to the same end points – that would be you and your family, with your smart phones, laptops, and IP set-top boxes.

For these reasons, not all small cells will operate at peak capacity at the same time. We see that with cable modems deployments where there is a large over-subscription of offered data bandwidth with respect to the actual data bandwidth used. This also occurs in fiber installations where the backhaul interface from a fiber OLT has a typical concentration of 20:1. This is traffic engineering at work. Small cells can take care of this over-subscription as well. The inverse of over-subscription is concurrency. A 20:1 over-subscription would support 5% concurrency.

We also know that the radios peak throughput decreases with distance. That means that different users will get different peak throughputs. In traffic engineering, that is managed with an average throughput per user. A more reasonable way to calculated network loading of small cells (SC), taking into account 75% average throughput per user and a generous 20% concurrency (5:1 over-subscription), would be:

$$SC\ Network\ Loading = \#\ SC * 100\ Mbps\ peak * \ avg\ capacity * \ concurrency \qquad formula\ (12)$$

$$SC\ Network\ Loading = 50\ SC * 100\ Mbps\ peak * 75\%\ avg\ capacity * 20\%\ concurrency$$

$$SC\ Network\ Loading = 750\ Mbps$$

Now, if those small cells are added to the home network with existing subscribers and existing devices, this bandwidth may already be accounted for and very little increase may be seen. If those small cells are located outdoors and pick up new subscribers and new devices, then 750 Mbps is about one-half of an OFDM channel backhaul.

As a gut check, the CMs in deployment typically provide 100 Mbps to 1 Gbps of service. If in a deployment of 200 devices (CMs), you added 50 more devices (small cells) at 100 Mbps, the difference would be incremental, not monumental.

4.2. The Future Potential of DOCSIS Capacity

A common question often comes up. Does DOCSIS have enough bandwidth to support a small cell infrastructure? DOCSIS has two growths paths. These are spectrum and segmentation. Let's look at both.

Figure 11 (original by author) shows select downstream and upstream spectrum usage for DOCSIS 3.1 and the upcoming DOCSIS 4.0 [14]. Today the downstream spectrum is shared with legacy MPEG-TS video, so the entire downstream is not available for DOCSIS. Actually, a good way to increase DOCSIS spectrum is through legacy video reclamation.

Today's deployed DOCSIS downstream paths are 1 to 2 Gbps in capacity. Many downstream paths are still 750 MHz or 862 MHz. With an increase to full DOCSSI 3.1 1218 MHz spectrum and with video reclamation, this could provide a 200% to 400% increase in data capacity. With DOCSIS 4.0, there can be an additional 40% to 60% increase. With these numbers multiplied, the downstream has a 10x growth potential in data capacity.

The upstream spectrum is defined by a 42 MHz return path with about 100 Mbps. An upgrade to 204 MHz would be a 1400% increase and DOCSIS 4.0 could more than double that again. So, the return path has considerably more than 10x growth to go.

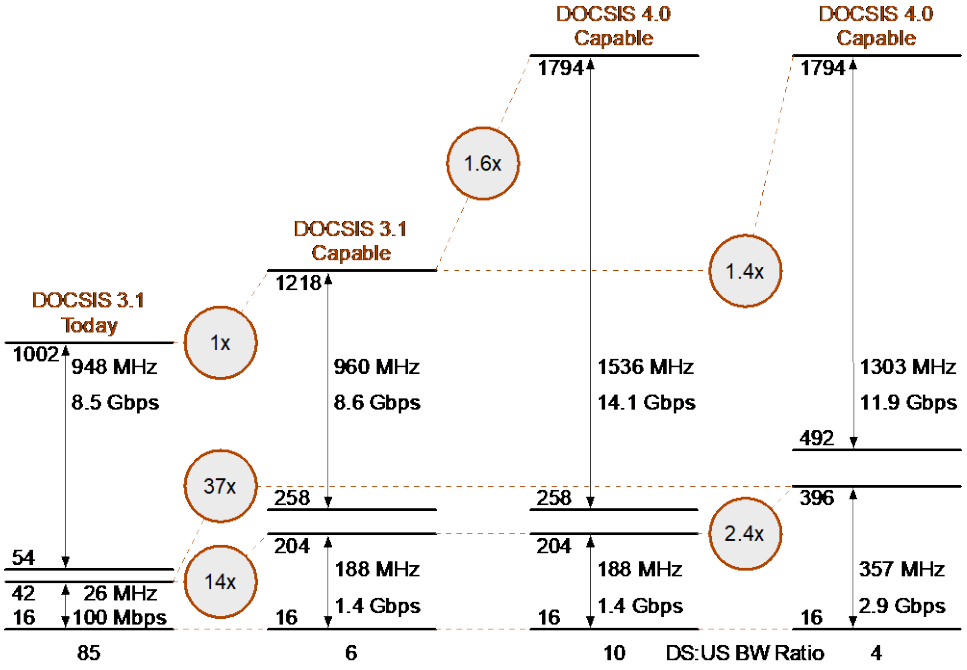


Figure 11 – DOCSIS Plans for Spectrum Increases

Then there is segmentation. A 500 HHP N+5 plant could be segmented down to 50 HHP N+0. These are approximate numbers as each plant is unique. However, this represents another 10x increase in capacity.

Combining the 10x growth available through spectrum and the 10x growth available through segmentation, there is 100x growth potential available in the DOCSIS HFC network.

CBRS small cells are on the order of 100 to 200 Mbps, depending upon spectrum usage and distance. Cable Modems today are 100 Mbps to 1 Gbps in the downstream. So, roughly, another small cell load is like another CM load, or less, on the network.

DOCSIS could even be extended to 3 GHz one day in the downstream using distributed gain amplifiers (DGA). This was first discussed in [15]. As an alternative to extending the downstream frequency range, DOCSIS 4.0 permits the use of full-duplex technology which would allow up to a 5 Gbps in the 5 to 684 MHz return spectrum to co-exist with the 10 Gbps in the 108 to 1218 MHz forward spectrum downstream spectrum. This technology was laid out in the following papers [16][17][18][19][20][21][22].

So, yes, DOCSIS does have enough bandwidth to handle small cell distribution.

4.3. SYNC – 1588 and SyncE Support

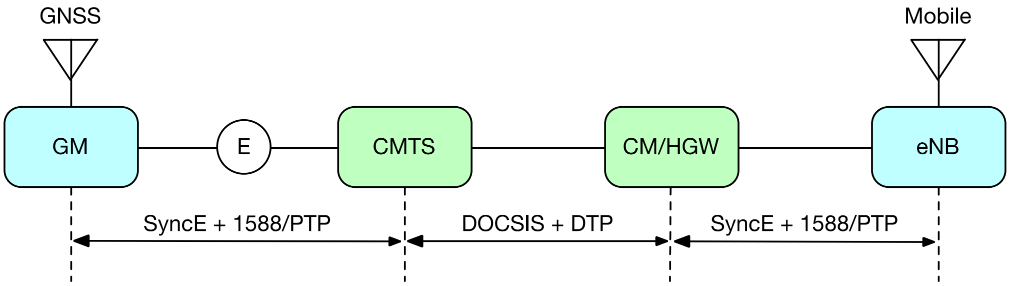


Figure 12 – SYNC Operating Model

In addition to the three basics of location, power, and backhaul, small cells that are located indoors and do not have access to the GNSS network, will need timing support. This is often done by having a synchronized wireline network using Synchronous Ethernet and IEEE-1588. Support for these two protocols are being designed into the DOCSIS protocol and product. The approach is shown in Figure 12.

DOCSIS is a highly accurate synchronous network. DOCSIS 3.1 defines a method to derive the DOCSIS timestamp from a Precision Time Protocol (PTP) slave port. DTP (DOCSIS Time Protocol) is used to measure the time difference across the DOCSIS network. The CM implements a PTP master clock and uses this time difference and the DOCSIS timestamp to regenerate an accurate PTP clock. This has been standardized at CableLabs [15] [24] and is described further in [25][26][27].

LTE small cells at 700 MHz are frequency division duplex (FDD) based and can use ranging to work around timing. This allows LTE FDD small cells to not have to worry about network timing. CBRS small cells at 3.5 MHz typically uses TDD (Time Division Duplex) which requires tight timing synchronization of +/- 1500 ns from radio to radio in order to prevent the radios from stepping on each other’s transmissions.

4.4. LLX – Low Latency Xhaul

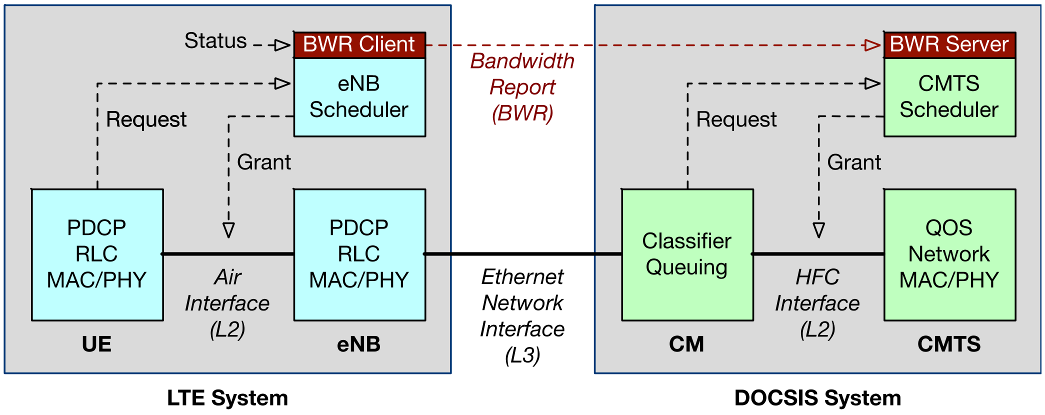


Figure 13 – LLX Operating Model

As mobile networks move to 5G, there is an interest in low latency operation. DOCSIS has a new protocol called LLX that pipelines the requests from the eNB/gNB to the CMTS scheduler so that packets do not have to re-request for bandwidth when entering the DOCSIS system. This will allow the DOCSIS system to have approximately 2 ms of equivalent latency. This is illustrated in Figure 13. This has been standardized at CableLabs [28] and is described further in [29][30][31][32][33].

5. Conclusion

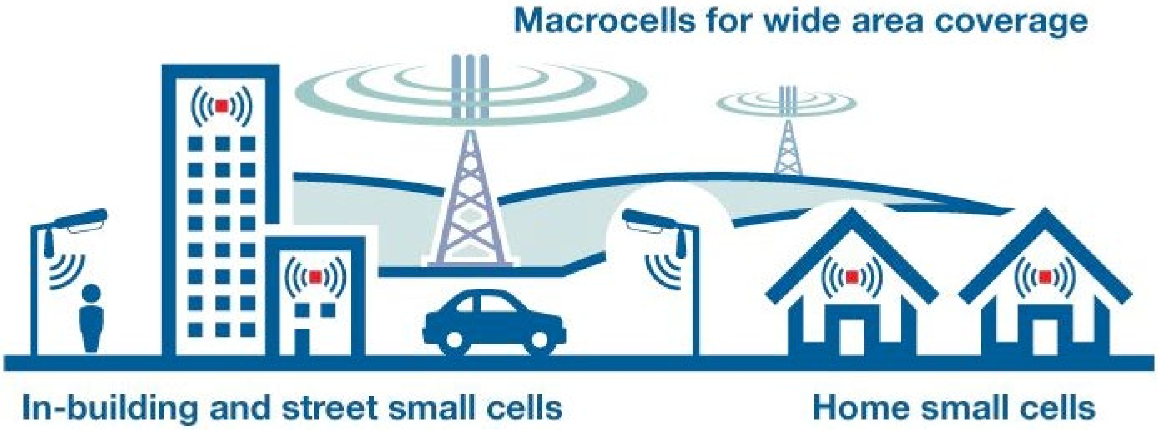


Figure 14 – Macrocells and Small Cells in Deployment

We started this paper with a deployment model from the City of Danville and we are ending with another diagram in Figure 14 also from the city of Danville, CA [1] . This diagram clearly shows that small cells will be located on poles, in buildings and in homes. Today's foreground macrocell based LTE network will become tomorrow's background network to fill in the gaps in the new 5G small cell architecture.

Here is a summary of the important formulas:

$$\#SC\ per\ MC = {}^{\pi}/_{2}\left({}^{R}/_{r}\right)^{2} \qquad per\ formula\ (3)$$

$$\#SC\ per\ FN = {}^{\pi}/_{4}\ \left({}^{S}/_{r}\right)^{2}(M+1)^{2} \qquad per\ formula\ (11)$$

where:

R = *larger radius of macrocell or node*
r = *smaller radius of small cell*
S = *average coax span between actives*
M = *number of amplifiers in an N+M cascade*

Here is a summary of the important points raised in this white paper:

- Today's cable operators are tomorrow's mobile operators
- Behind every great wireless network is a great wireline network
- The number of radios for CBRS can be 100x that of an LTE macrocell, and for mmWave, the number of radios could be 100,000x that of an LTE macrocell.
- This dramatically impacts deployment economics and makes the existing HFC plant and interesting choice for mobile backhaul.
- The number of small cells in an HFC plant is proportional to the square of the span count and the square of the ratio of span length to cell radius.
- DOCSIS has a 100x growth potential in downstream and upstream bandwidth
- The DOCSIS HFC network is a viable backhaul/midhaul network that can meet the location, bandwidth, powering, timing, and latency requirements of a small cell network.

Abbreviations

5G	Fifth Generation Mobile Network
5GC	5G Core
BAU	Business as Usual
CBRS	Citizens Broadband Radio Service
CM	Cable Modem (DOCSIS)
CMTS	Cable Modem Termination System (DOCSIS)
CU	Centralized Unit
DAA	Distributed Access Architecture
DGA	Distributed Gain Amplifier
DOCSIS	Data over Cable System Interface Specification
DTP	DOCSIS Time Protocol
DU	Distributed Unit
EIRP	Effective Isotropic Radiated Power
eNB	Evolved Node B (LTE)
FDD	Frequency Division Duplex
GAA	General Authorized Access
gNB	Next generation NodeB
GPRS	General Packet Radio Service
GTP	GPRS Tunneling Protocol
HFC	hybrid fiber-coax
HHP	households passed
IP	Internet Protocol
LLX	Low Latency Xhaul
MVNO	Mobile Virtual Network Operator
LTE	Long Term Evolution
N+M	Node plus M amplifiers in an HFC network
PAL	Priority Access License
PDCP	Packet Data Convergence Protocol
PTP	Precision Time Protocol
RF	Radio Frequency
RLC	Radio Link Control
RRC	Radio Resource Control
RU	Radio Unit
SAS	Spectrum Access System
SHO	Super High Output
TDD	Time Division Duplex
XHAUL	Backhaul, midhaul, or fronthaul
UE	User Equipment

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