HFC Spectrum Expansion: Design and Component Impacts

A Technical Paper prepared for SCTE•ISBE by

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Introduction

As data demand continues to increase, cable operators are looking at ways to meet that demand by increasing the capacity of their Hybrid Fiber Coax (HFC) networks. Traditionally this has been done by pushing fiber deeper into the network, reducing amplifier cascades, reducing the number of customers in a service group and increasing modulation orders. However, the continuing development of the Converged Cable Access Platform (CCAP) and the introduction of DOCSIS® 3.1 has given operators additional methods to meet customer demands. At the top of this list is ability to support operation at extended frequencies up to 1.2 and even 1.8 GHz. There is also an effort currently underway at CableLabs® which is looking at the viability of increasing the upper frequency band to 3 GHz. Given that many of today's HFC networks have capacities ranging from 750 MHz up to 1002 MHz, how can an operator upgrade their networks without having to do a total rebuild or move to a Fiber to the Home (FTTH) network? This paper will discuss the impact of different network components and design options on the bandwidth expansion of an HFC network and present the results of a network model that applies these options to a 1002 MHz legacy plant design.

1. Options for Increasing Network Capacity

Cable operators have at least three approaches to increase the capacity of an HFC network. These can be implemented separately or together as they are not mutually exclusive but instead build upon each other. The first is probably the most familiar, and at its core, is modifying the network to reduce the number of subscribers associated with a radio frequency (RF) port on a CCAP platform. This can be achieved by implementing smaller node serving areas, splitting or segmenting a node, or just reducing the number of nodes on a CCAP port.

Figure 1 shows an example of node splitting where a 1000 households passed (HHP) node, that is fed by one CCAP port, is split into four 250 HHP nodes each served by a different CCAP port. This increases the data rate per HHP by a factor of four, which for a 1 GHz DOCSIS® 3.1 system operating at 256 QAM, provides ~6 Gb/s capacity to 250 HHP instead of 1000 HHP. Of course, this comes at the cost of additional CCAP ports, optical transmitters/receivers, nodes, and Dense Wavelength Division Multiplexing (DWDM) devices if spare fiber is not available.

Node splitting has limitations, as described in [Ulm/Maricevic, 2016], as service level data rates increase. This has traditionally been the approach to capacity expansion but going forward will not be as effective as the other options for increasing network capacity.

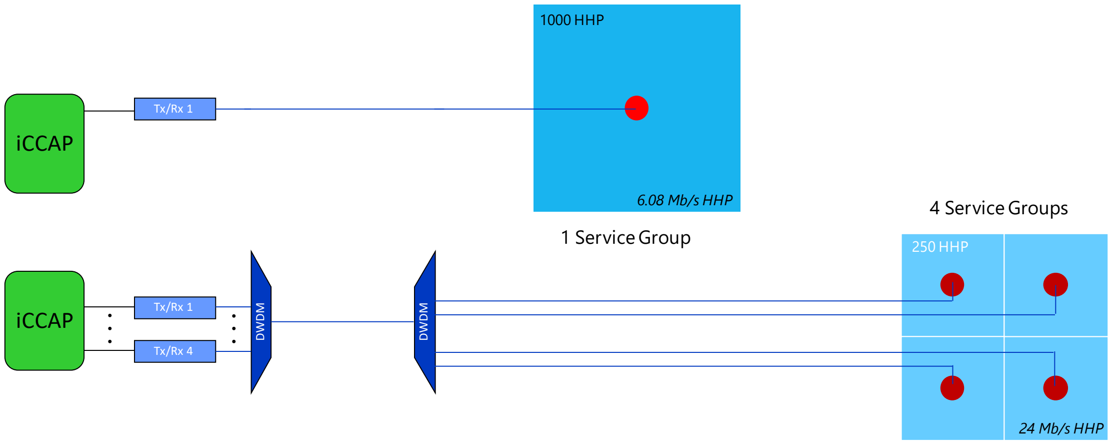


Figure 1 - Node Splitting

Increasing the modulation order is another method to increase capacity. DOCSIS ® 3.1 allows for a modulation order as high a 4096 QAM. Networks generally support 256 QAM which has a spectral efficiency of 8 bits/symbol. 4096 QAM modulation would raise this to 12 bits/symbol or a 50% increase in capacity per channel.

Of course, everything has its price and for modulation it is the received Carrier to Noise Ratio (CNR) at the cable modem as shown in the table in Figure 2 below (data rates are for a 258 to 1026 MHz downstream spectrum, and are the raw data rates which include framing/header overhead). As the modulation order increases so does the required CNR, which makes sense as there is a higher density of symbols in higher order modulations. This issue is somewhat mitigated as networks have evolved, because the number of amplifiers in cascade has been continually reduced which improves the resultant end of line CNR. One of the other benefits of DOCSIS® 3.1 is that it enables the use of multi-carrier Orthoganl Frequency Division Multiplexing (OFDM), where individual sub-carriers (within the channel) can each have a different modulation order. As a result the modulation of each sub-carrier can be tuned to accommodate the level or CNR at its operating frequency.

Modulation	SG Capacity (Gb/s)	CNR (dB)
256	6.1	27
512	6.8	30.5
1024	7.6	34
4096	9.1	41

Figure 2 - Data Capacity and CNR Requirements as a Function of Modulation Order

The third approach operators have for increasing capacity is bandwidth or spectrum expansion. By increasing the network operating spectrum from the current frequencies of 750, 860 or 1002 MHz to 1.2, 1.8 or 3.0, cable operators can add additional DOSCIS® channels and therby increase the network data capacity. DOCSIS® 3.1 adds downstream capacity in blocks of 192 MHz, and so an increase in spectrum from 1 GHz to 1.2 GHz adds one 192 MHz block, to 1.8, adds another three blocks (four total), and to 3 GHz another six blocks (10 total).

The table in Figure 3 below shows the resulting network capacities again as a function of modulation order (assumes all DOCSIS® 3.1 channels). Utilizing modulation order and spectrum, an operator can move their 1 GHz network from a service group capacity of 6.1 GHz to 32 GHz. However, operating at higher frequencies means greater attenuation in passive devices and therefore greater difficulty in meeting end of line signal level requirements. It will also mean that the network needs to be upgraded to accommodate the higher operating frequencies.

	SG DS Capacity (Gb/s)			
Modulation	1 GHz	1.2 GHz	1.8 GHz	3 GHz
256	6.1	7.6	12.2	21.3
512	6.8	8.6	13.7	23.9
1024	7.6	9.5	15.2	26.6
4096	9.1	11.4	18.2	31.9

Figure 3 - Downstream Capacity as a Function of Modulation Order & Network Spectrum

2. Component and Network Design Impacts

Of the three approaches to increasing capacity, expanding spectrum potentially has the greatest impact on the existing HFC networks since every element in the signal path must support the extended spectrum. It also will have the biggest impact on network capacity and support legacy systems while also utilizing the bit loading (i.e. ability to use different modulation on each sub-carrier) capabilities of DOCSIS® 3.1 to maximize capacity. This paper will therefore focus on that particular approach.

Inherently, operating at a higher frequency introduces additional attenuation in the signal path. A signal operating at 3 GHz will experience greater attenuation than one operating at 1 GHz due to the higher losses in the outside plant components. Hardline trunk and drop cable both have higher losses at higher frequencies as shown in the tables in Figure 4 below. The magnitude will be dependent on the cable size, but all will have a higher attenuation at higher frequencies.

For example, PIII 500 cable has a loss of 4.8 dB/100’ of cable at 3GHz compared to a 2.5 dB loss at 1 GHz which is an increase of ~2.3 dB/100’. However, this works both ways. To overcome this additional loss, an operator can move to a larger cable size which will have a lower loss at higher frequencies compared to a smaller cable, and will also introduce a smaller negative tilt. Again, looking at the tables in Figure 4, an F50 cable has the same loss at 3 GHz as an F11 cable does at 1.2 GHz and an F6 cable at 550

MHz. In others words, by moving to an F11 cable (instead of an F6), an operator can gain 3.9 dB for a 100' drop @3 GHz, and ~7 dB by using an F50 drop.

	Loss (dB/100')		
Frequency (MHz)	PIII 500	PIII 625	PIII 875
5	0.16	0.13	0.09
55	0.55	0.46	0.33
211	1.09	0.92	0.66
870	2.35	1.95	1.41
1002	2.54	2.11	1.53
1218	2.84	2.36	1.72
1800	3.55	2.96	2.18
2000	3.77	3.15	2.32
3000	4.79	4.02	3.00
Dia Over Outer Cond (in)	0.500	0.625	0.875

	Loss (dB/100')		
Frequency (MHz)	F6	F11	F50
5	0.58	0.38	0.24
55	1.6	0.96	0.57
211	3.05	1.9	1.13
870	6.1	3.98	2.29
1002	6.55	4.35	2.51
1218	7.21	4.92	2.90
1800	8.97	6.00	3.46
2000	9.50	6.37	4.03
3000	11.86	8.02	4.94
Dia Over 1st Tape (in)	0.187	0.287	0.463

Figure 4 - Trunk (PIII) and Drop Cable Attenuation Tables

RF taps and splitters inside the home will also introduce a higher loss at higher frequencies. This could be 2-3 dB of additional loss at 3 GHz compared to operation at 1 GHz. Like cable, this can be overcome by using lower split levels in the case of a home splitter. Each reduction in split level, 8-way to 4-way, 4-way to 2-way, will reduce the loss by about 4 dB. For taps, the value of the tap can't be reduced since the signal level to the residence must be maintained, however, the number of taps in a tap run can be reduced. Each tap that is eliminated (actually moved from cable leg to another) not only eliminates the through attenuation of that tap, it also eliminates the cable attenuation for the cable that is connected to that tap.

It is not all bad news, however, with frequency extension. There are other changes to the network design that can be made to reduce the impact of additional plant loss. One is to allow a lower signal level at the end device. Typically, operators will set a device input level of 0 dBmV (analog signal level, digital signals -6 or more dBs below that). However, this level could be reduced at higher frequencies to accommodate the higher losses at those frequencies. Today's cable plants are much cleaner from an SNR/CNR perspective due to the reduction in amplifier cascades, so the impact of lowering the level on end of line SNR will not be so significant. Also since DOCSIS® 3.1 enables modulation on a per sub-carrier basis, worse case it means that the modulation order will need to be lowered at higer frequencies to a level that supports the reduced SNR at that frequency.

Another design option is to move to a Gateway architecture as shown in Figure 5. In this approach, the RF network is terminated at a single point somewhere near the entrance to the subscriber location. The device that performs this function is called a Gateway. The Gateway terminates all DOCSIS signals and sends that data throughout the residence via Wi-Fi, wired Ethernet, or over the existing coaxial network via MoCA® or some other in-home protocol. The benefit of the gateway architecture is that the loss associated with the home coaxial network (cable + splitter) is eliminated, which can be 10+ dB of attenuation.

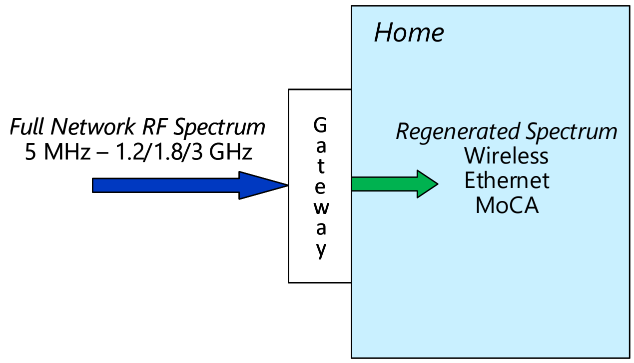


Figure 5 - Gateway Architecture

The final tool available is the improvement made in gain block technology which enables a higher RF output level from the optical node and sub-tending amplifiers. New high output GaN technology increases the Total Composite Power (TCP) of gain blocks relative to existing GaAs/GaN technology. As a result TCP levels can be raised as high as ~74 dBmV in a Node + 0 architecture, and to ~71 dBmV for Node + X architectures. This is reduced by about 3 dB (71./68 dBmV) with the circuit board implementation losses. For this paper, all levels will be referenced to "Virtual" analog signal levels, which will be 6 dB higher than that actual implemented digital levels (77/74 dBmV). Bottom line is that for Node + X architectures assumed here, this means the max TCP will be ~74 dBmV. As shown in Figure 6, this allows the Legacy system signal levels and tilt to be extended to 1.2 GHz. Unfortunately, these Legacy levels cannot be maintained above 1218 MHz as the TCP increases to ~85 dBmV @1.8 GHz, and ~107 dBmV @3 GHz. This is well beyond the capability of even the new GaN technology. To avoid this and to maintain legacy levels, it has been proposed that the gain is dropped a number of decibels and remains flat above a given legacy frequency (800 or 1002 MHz for example), as also shown in Figure 6. This compromise allows continued operation of the legacy systems and amp spacings (up to the selected frequency), while still providing maximum data capacity above that using DOCSIS® 3.1 bit loading capabilities. For 1.8 GHz, the Legacy level can be maintained to 1002 MHz, with a step down to 50 dBmV. At 3 GHz, to enable more power at higher frequencies, the Legacy frequency is reduced to 800 MHz, with a step down to 47 dBmV.

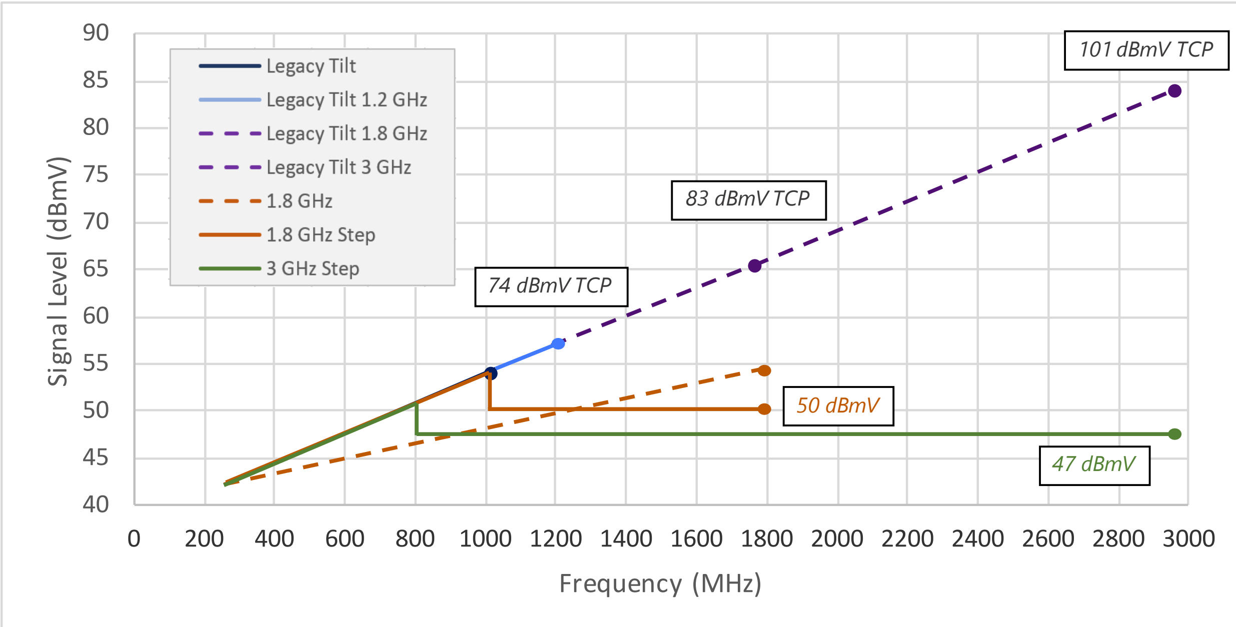


Figure 6 - System Signal Level & Total Composite Power Profiles

Another profile was considered @1.8 GHz that has a linear slope that is less than the Legacy levels, but which maintains the target TCP. Relative to the step profile, this profile places more power in the higher frequencies where loss/attentuation is the greatest. It does not maintain the Legacy levels at the lower frequencies, but better utilizes the excess power that is available when implementing a Gateway architecture (as will be discussed).

3. Upgrading Legacy Plants

So what is the impact to an existing plant when an operator moves to higher operating frequencies and utilizes one or more of these network design options? To determine the answer, a power budget model was built based on a 1002 MHz, legacy HFC plant design. The model does not look at trade offs that could optimize network capacity such as end-of-line signal level vs. supported modulation level. Instead, the model simply looks at the end-of-line signal level and the impact of various network implementations on maintaining that target level. It assumes that tap technology and the technology required to generate higher node/amp signal levels will be available. Also, in the model, all signal level profiles are referenced to virtual analog signal levels (as shown in Figure 6), and actual digital signal levels would be 6 dB lower.

The model looks at a single tap run from the node or last amplifier with the following characteristics:

- Six 4 port taps in cascade w/ equal but maximized spacing
- 5/42 – 54/1002 MHz system
- Target level of 0 dBmV (analog) at subscriber device
- 1x4 split + 50' F6 cable inside the residence
- 100' F6 drop
- PIII 625 (QR 540) hardline cable
- All single carrier QAM channels

Figure 7 show the modelled HFC design and provides the resultant levels, spacing, and tap values. The design is an attempt to represent a "typical" HFC design, however actual designs will differ based on subscriber densities and the design criteria used by each operator. The goal is use a consistent set of criteria to see, in general, what provides the most benefit in reaching the goal of an extended spectrum network.

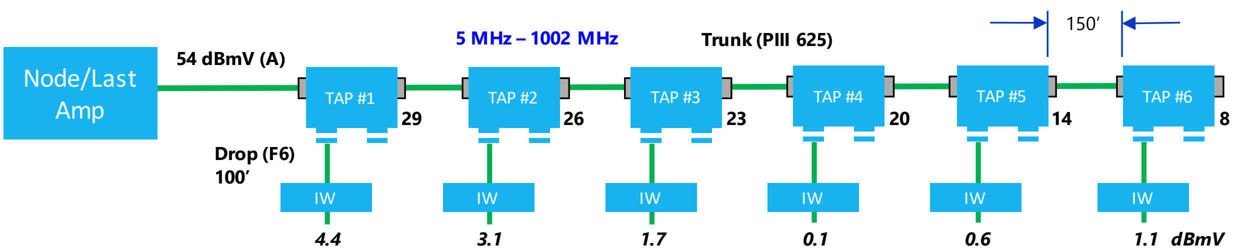


Figure 7 - Model of Legacy 1002 MHz HFC Plant

To do that, 8 scenarios were considered as shown in the bullet list below. All build off of Scenario #1 which upgrades the taps and node/amp modules to one supporting the particular extended frequency (1.2, 1.8 or 3 GHz) and which also implements the signal profiles for the various plant extension frequencies shown in Figure 6 (assumes a 208/258 MHz split). These are followed by several other single or cascaded scenarios that include elimination of the inside wire by utilizing a Gateway architecture, increasing the drop cable size, increasing the trunk cable size of the first section of the tap run, and eliminating a tap in a tap run. These scenarios were run for all three targeted operating bandwidths.

- Scenario #1: Upgrade taps and node/amp modules to support a 1.2, 1.8 or 3 GHz operating bandwidth and the associated signal level profile (Figure 6)
    - Maintain SC QAM levels up to selected frequency
    - DOCSIS 3.1 above that frequency
- Scenario #2: Scenario #1 + eliminate inside wire and implement Gateway architecture
- Scenario #3: #2 + upgrade F6 to F11 drop
- Scenario #4: #2 + upgrade F6 to F50 drop
- Scenario #5: #2 + upgrade 1st hardline section to PIII 875 (QR 860)
- Scenario #6: #5 + upgrade F6 to F11 drop
- Scenario #7: #5 + upgrade F6 to F50 drop
- Scenario #8: #5 + eliminate last tap in tap run

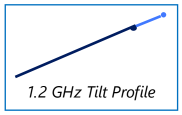
For all scenarios, the end-of-line signal level @800/1002 MHz was also calculated to monitor the impact of network changes to the Legacy levels.

4. Results

The results for a 1.2 GHz extension are shown in Figure 8, a 1.8 GHz extension Figures 9A/B and a 3 GHz plant extension Figure 10. The tables in these figures show the tap values selected and the end of line device input levels for each of the scenarios at both the legacy frequency of 800 MHz (not shown for 1.2 GHz extension), 1002 MHz, and at each of the targeted extension bandwidths. A green highlight means a given tap in a scenario met the targeted end-of-line level, a yellow highlight means the end-of-line level was below the target by up to 0.5 dB, and a red highlight means the signal level was below that.

Baseline: Legacy 53.7 dBmV @1002 MHz (+ ↑OP)

Tap	1002	1218
4 29	4.4	
4 26	3.1	
4 23	1.7	
4 20	0.1	
4 14	0.6	
4 8	1.1	



123	Meets Spec
123	w/in 0.5 dB of Spec
123	Does Not Meet Spec

#1 Node: 57 dBmV @1.2 GHz (TCP[A] 73.7 dBmV) (+ ↑OP)

Tap	1002	1218
4 29	4.4	5.8
4 26	3.1	3.6
4 23	1.7	1.3
4 20	0.1	-1.0
4 14	0.6	-1.4
4 8	1.1	-1.6

#2 Elim IW (+ ↑OP)

Tap	1002	1218
4 29	15.0	17.3
4 26	13.7	15.0
4 23	9.3	9.8
4 20	4.9	4.5
4 14	6.6	5.3
4 8	13.5	11.5

#3* F6 → F11 (+ ↑OP, w/ IW)

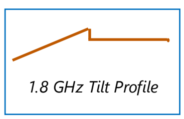
Tap	1002	1218
4 29	6.6	8.1
4 26	5.3	5.9
4 23	3.9	3.6
4 20	2.3	1.3
4 14	2.8	0.9
4 8	3.3	0.7

*Keep IW

Figure 8 - End-of-Line Signal Levels for 1.2 GHz Plant Extension

Baseline: Legacy 53.7 dBmV @1002 MHz

Tap	800	1002	1218	1794
4 29	2.3	4.4		
4 26	1.5	3.1		
4 23	0.8	1.7		
4 20	-0.2	0.1		
4 14	0.8	0.6		
4 8	2.0	1.1		



123	Meets Spec
123	w/in 0.5 dB of Spec
123	Does Not Meet Spec

#1 Node: Legacy to 1002 MHz, 50 dBmV to 1.8 GHz (TCP[A] 73.7 dBmV)

Tap	800	1002	1218	1794
4 29	2.3	4.4	-1.2	-5.7
4 26	1.5	3.1	-3.4	-9.8
4 23	0.8	1.7	-5.7	-13.9
4 20	-0.2	0.1	-8.0	-18.1
4 14	0.8	0.6	-8.4	-20.2
4 8	2.0	1.1	-8.6	-22.3

#2 Elim IW (+ ↑OP)

Tap	800	1002	1218	1794
4 29	12.9	15.0	10.3	7.6
4 26	12.1	13.7	8.0	3.5
4 23	11.4	12.3	5.8	-0.6
4 17	13.4	13.7	6.4	-1.8
4 11	14.4	14.2	6.0	-4.1
4 8	11.1	10.5	1.2	-10.8

#3 F6 → F11 (+ ↑OP, No IW)

Tap	800	1002	1218	1794
4 29	14.9	17.2	12.5	10.6
4 26	14.2	15.9	10.3	6.5
4 23	13.4	14.5	8.1	2.4
4 17	15.4	15.9	8.7	1.2
4 11	16.4	16.4	8.3	-1.1
4 8	13.1	12.7	3.4	-7.8

#4 F6 → F50 (+ ↑OP, No IW)

Tap	800	1002	1218	1794
4 29	16.6	21.6	14.6	12.9
4 26	15.8	20.2	12.4	8.8
4 26	12.0	15.8	7.1	1.8
4 20	14.3	17.5	7.9	0.7
4 14	15.3	17.9	7.5	-1.5
4 8	16.5	18.5	7.3	-3.6

#5 1 Section 875 (+ ↑OP, No IW)

Tap	800	1002	1218	1794
4 29	13.7	15.9	11.2	8.8
4 26	12.9	14.5	9.0	4.7
4 23	12.1	13.2	6.7	0.6
4 17	14.1	14.6	7.4	-0.6
4 11	15.1	15.0	7.0	-2.9
4 8	11.8	11.4	2.1	-9.6

#6 F6 → F11 (+ ↑OP, No IW, 1 Sect)

Tap	800	1002	1218	1794
4 29	15.7	18.1	13.5	11.7
4 26	15.0	16.7	11.3	7.6
4 23	14.2	15.4	9.0	3.6
4 17	16.2	16.8	9.7	2.4
4 14	14.2	14.2	6.2	-2.9
4 8	15.4	14.8	6.0	-5.0

#7 F6 → F50 (+ ↑OP, No IW, 1 Sect)

Tap	800	1002	1218	1794
4 29	17.3	22.4	15.6	14.1
4 26	16.6	21.1	13.3	10.0
4 26	12.8	16.7	8.1	2.9
4 20	15.1	18.4	8.8	1.8
4 14	16.1	18.8	8.5	-0.4
4 8	17.3	19.3	8.3	-2.4

#8 Elim 1 Tap (+ ↑OP, No IW, 1 Sect)

Tap	800	1002	1218	1794
4 29	13.7	15.9	11.2	8.8
4 26	12.9	14.5	9.0	4.7
4 23	12.1	13.2	6.7	0.6
4 14	16.6	17.1	9.9	1.9
4 8	17.8	17.6	9.7	-0.2

Figure 9 - End-of-Line Signal Levels for 1.8 GHz Plant Extension (1002 MHz Step-Down)

Baseline: Legacy 53.7 dBmV @1002 MHz				
Tap	800	1002	1218	1794
4 29	2.3	4.4		
4 26	1.5	3.1		
4 23	0.8	1.7		
4 17	-0.2	0.1		
4 14	0.8	0.6		
4 8	2.0	1.1		

1.8 GHz Tilt Profile

123	Meets Spec
123	w/in 0.5 dB of Spec
123	Does Not Meet Spec

Node: 54.4 dBmV @1.8 GHz (TCP[A] 73.7 dBmV) #1				
Tap	800	1002	1218	1794
4 29	-1.8	-1.2	-1.4	-1.3
4 26	-2.5	-2.6	-3.7	-5.4
4 23	-3.3	-3.9	-5.9	-9.5
4 17	-4.3	-5.5	-8.3	-13.7
4 14	-3.2	-5.1	-8.6	-15.9
4 8	-2.1	-4.5	-8.8	-18.0

Elim IW (+ ↑OP) #2				
Tap	800	1002	1218	1794
4 29	8.8	9.4	10.0	11.9
4 26	8.1	8.0	7.8	7.9
4 26	4.3	3.6	2.5	0.8
4 20	6.6	5.3	3.3	-0.3
4 14	7.6	5.7	3.0	-2.5
4 8	8.8	6.3	2.7	-4.6

F6 → F11 (+ ↑OP, No IW) #3				
Tap	800	1002	1218	1794
4 29	10.9	11.6	12.3	14.9
4 26	10.1	10.2	10.1	10.8
4 26	6.4	5.8	4.8	3.7
4 20	8.6	7.5	5.6	2.6
4 14	9.7	7.9	5.2	0.5
4 8	10.9	8.5	5.0	-1.6

F6 → F50 (+ ↑OP, No IW) #4				
Tap	800	1002	1218	1794
4 29	12.5	15.9	14.4	17.3
4 26	11.7	14.6	12.1	13.2
4 26	8.0	10.2	6.9	6.1
4 20	10.2	11.8	7.6	5.0
4 14	11.3	12.3	7.3	2.8
4 8	12.5	12.8	7.1	0.7

1 Section 875 (+ ↑OP, No IW) #5				
Tap	800	1002	1218	1794
4 29	9.6	10.2	11.0	13.1
4 26	8.8	8.9	8.7	9.0
4 26	5.1	4.5	3.5	1.9
4 20	7.3	6.2	4.3	0.8
4 14	8.4	6.6	3.9	-1.4
4 8	9.6	7.1	3.7	-3.4

F6 → F11 (+ ↑OP, No IW, 1 Sect) #6				
Tap	800	1002	1218	1794
4 29	11.7	12.4	13.3	16.1
4 26	10.9	11.1	11.0	12.0
4 26	7.1	6.7	5.8	4.9
4 23	6.4	5.4	3.5	0.8
4 14	10.9	9.3	6.7	2.1
4 8	12.1	9.8	6.5	0.0

Elim 1 Tap (+ ↑OP, No IW, 1 Sect) #8				
Tap	800	1002	1218	1794
4 29	9.6	10.2	11.0	13.1
4 26	8.8	8.9	8.7	9.0
4 23	8.1	7.5	6.5	4.9
4 17	10.1	9.0	7.2	3.7
4 8	14.6	12.9	10.2	5.0

Figure 10 - End-of-Line Signal Levels for 1.8 GHz Plant Extension (Linear)

Baseline: Legacy 53.7 dBmV @1002 MHz					
Tap	800	1002	1218	1794	2946
4 29	2.3	4.4			
4 26	1.5	3.1			
4 23	0.8	1.7			
4 20	-0.2	0.1			
4 14	0.8	0.6			
4 8	2.0	1.1			

3 GHz Tilt Profile

123	Meets Spec
123	w/in 0.5 dB of Spec
123	Does Not Meet Spec

Node: Legacy to 800 MHz, 47.2 dBmV to 3 GHz (TCP[A] 73.7 dBmV) #1					
Tap	800	1002	1218	1794	2946
4 29	2.3	-2.1	-4.0	-8.5	-15.7
4 26	1.5	-3.5	-6.2	-12.6	-22.7
4 23	0.8	-4.8	-8.5	-16.7	-29.7
4 20	-0.2	-6.4	-10.8	-20.9	-36.8
4 14	0.8	-6.0	-11.2	-23.0	-41.8
4 8	2.0	-5.4	-11.4	-25.1	-46.8

Elim IW (+ ↑OP) #2					
Tap	800	1002	1218	1794	2946
4 29	12.9	8.5	7.5	4.8	0.3
4 26	12.1	7.1	5.2	0.7	-6.7
4 23	11.4	5.8	3.0	-3.4	-13.7
4 20	10.4	4.2	0.6	-7.6	-20.7
4 14	11.4	4.6	0.3	-9.8	-25.8
4 8	12.6	5.2	0.1	-11.9	-30.8

F6 → F11 (+ ↑OP, No IW) #3					
Tap	800	1002	1218	1794	2946
4 29	14.9	10.7	9.7	7.8	4.2
4 26	14.2	9.3	7.5	3.7	-2.8
4 23	13.4	8.0	5.3	-0.4	-9.8
4 20	12.4	6.4	2.9	-4.6	-16.9
4 14	13.5	6.8	2.6	-6.8	-22.0
4 8	14.7	7.4	2.3	-8.9	-27.0

F6 → F50 (+ ↑OP, No IW)					
Tap	800	1002	1218	1794	2946
4 29	16.6	15.0	11.8	10.1	7.2
4 26	15.8	13.7	9.6	6.0	0.2
4 23	15.0	12.3	7.3	2.0	-6.7
4 17	17.0	13.7	8.0	0.8	-10.8
4 14	15.0	11.2	4.5	-4.5	-19.0
4 8	16.2	11.7	4.3	-6.6	-24.0

1 Section 875 (+ ↑OP, No IW) #5					
Tap	800	1002	1218	1794	2946
4 29	13.7	9.4	8.4	6.0	1.8
4 26	12.9	8.0	6.2	1.9	-5.1
4 23	12.1	6.6	3.9	-2.2	-12.1
4 20	11.1	5.1	1.6	-6.4	-19.2
4 14	12.2	5.5	1.3	-8.6	-24.3
4 8	13.4	6.0	1.0	-10.7	-29.3

F6 → F11 (+ ↑OP, No IW, 1 Sect) #6					
Tap	800	1002	1218	1794	2946
4 29	15.7	11.6	10.7	8.9	5.7
4 26	15.0	10.2	8.5	4.8	-1.3
4 23	14.2	8.8	6.2	0.8	-8.3
4 20	13.2	7.3	3.9	-3.4	-15.4
4 14	14.2	7.7	3.5	-5.6	-20.4
4 8	15.4	8.2	3.3	-7.7	-25.4

F6 → F50 (+ ↑OP, No IW, 1 Sect)					
Tap	800	1002	1218	1794	2946
4 29	17.3	15.9	12.8	11.3	8.8
4 26	16.6	14.5	10.5	7.2	1.8
4 23	15.8	13.2	8.3	3.1	-5.2
4 17	17.8	14.6	8.9	1.9	-9.3
4 14	15.8	12.0	5.5	-3.4	-17.5
4 8	17.0	12.6	5.3	-5.4	-22.5

Elim 1 Tap (+ ↑OP, No IW, 1 Sect)					
Tap	800	1002	1218	1794	2946
4 29	13.7	9.4	8.4	6.0	1.8
4 23	15.9	11.0	9.2	4.9	-2.1
4 20	14.9	9.4	6.8	0.7	-9.2
4 14	15.9	9.9	6.5	-1.5	-14.3
4 8	17.1	10.4	6.3	-3.6	-19.3

Figure 11 - End-of-Line Signal Levels for 3 GHz Plant Extension (800 MHz Step-Down)

As can be seen for the 1.2 GHz extention shown in Figure 8, scenario #1 (which changes taps and node/amp modules and raises the TCP to the target level) is mostly sufficient to achieve the desired levels at 1.2 GHz. The last taps in the cascade are slightly below the target (within ~1.5 dB), but this might be acceptable with the bit loading capabilities of DOCSIS® 3.1. All tap EOL signal levels are met with scenario #2 (Gateway), but that is over kill for this a 1.2 GHz extension, and a more reasonable approach to achieve the target levels is to implement scenario #3 (upgrade F6 drop to Fll). These results show that in general, upgrading to 1.2 GHz is a relatively straight forward drop-in upgrade, as traditionally has been done for previous bandwidth extensions.

As expected, implementing scenario #2 in the 1.8 GHz and 3 GHz plant extensions is not sufficient to overcome the high losses at the higher operating frequency, but with the step down profiles, the Legacy levels are maintained. Moving to a gateway architecture and eliminating the home wiring (#3) enables the 1.8 GHz upgrade to almost meet the EOL criteria (except for a few taps @ 1.8 GHz) and significantly improves the 3 GHz. Based on some of the CableLabs Extended Spectrum Effort initial feedback, many vendors and operators are assuming a Gateway architecture will be required for both a 1.8 and 3 GHz upgrade. One interesting aspect of this scenario is that it shows there will be an excess of power at the Legacy frequencies, particularly with the step down profile. For the 1.8 GHz scenario, @1002 MHz the max EOL Legacy signal level is 15 dBmV, where with the linear profile it is 9 dBmV.

Focusing on the 1.8 GHz plant extension, while scenario #3 doesn't quite meet the EOL target (w/in 11 dB for the step profile and 5 dB for the linear profile), it may be sufficient with the use of DOCSIS® 3.1 bit loading capabilities. Alternatively, upgrading the drop cable to F11 or F50 brings everything within the target EOL level for the linear profile, and within ~4 dB for the step profile. Implementing scenario #5 (upgrading the first section of trunk cable) has a slight impact, but scenarios 6, 7, or 8 are needed to have a significant impact. Again, the linear profile has better EOL performance than the step profile, and meets the EOL targets for scenarios #6-8, while the step down profile improves performance but only meets the EOL criteria with scenario #8. For the step profile, DOCSIS® 3.1 bit loading may enable sufficient performance for these scenarios.

Finally, looking at the 3 GHz extension, all the remaining upgrade scenarios (2-8) meet the EOL signal requirements in the legacy band, and in the 1.2 GHz band. In the 1.8 and 3 GHz band, however, only a couple of the taps meet the criteria. In the 1.8 GHz bands, EOL levels come within 4-12 dB of the target EOL criteria which may be sufficient with DOCSIS® 3.1 bit loading. However, in the 3 GHz band, the levels are only within 19-31 dB of the target EOL criteria which may be too low for DOCSIS® 3.1 cable modem receivers. Overall, the model shows that new technology or alternative architectures still need to be developed to fully utilize a 3 GHz frequency extention in today's HFC networks.

Conclusion

Operators are looking for ways to expand the capacity of their HFC networks. Extended Spectrum DOCSIS or ESD, which is enabled by DOCSIS® 3.1, provides a platform for expanding capacity to 1.2 and 1.8 GHz and in the future 3 GHz. To determine how components and network designs impact the expansion of bandwidth in an HFC network, a power budget model was developed and various upgrade scenarios were run on a Legacy, 1002 MHz network. With the development of new high output GaN gain blocks, an upgrade to 1.2 GHz is achievable in much the same way the other drop-in bandwidth upgrades have been done in the past. A gain block improvement itself is not sufficient for bandwidth extensions to 1.8 or 3 GHz which minimally require an upgrade to a Gateway architecture. Additionally, upgrading drop cables from F6 to F11 or F50 enables the 1.8 GHz plant extension to meet end of line target levels, particularly with a linear tilt profile. Even though this signal profile lowers the signal below Legacy levels as compared to a step down profile, the lower power levels are offset by the lower attenuation of the upgraded network elements and design. Not surprisingly, an upgrade to 3 GHz will be the most difficult and even with a Gateway architecture, and drop, trunk, and tap upgrades, the EOL signal levels at 3 GHz fall short of the target by 20-30 dB. This indicates new technologies or other architectures will be required to fully utilize a 3 GHz network.

Overall, as the model shows, utilizing larger cables (particularly drop cable) will help facilitate the move to extended operating frequencies in an HFC network. Operators can start preparing for a future bandwidth expansion by using an F11 or larger drop cable instead of an F6 cable as they install new or maintain their existing drop plant.

Abbreviations

CCAP	Converged Cable Access Platform
CNR	Carrier to Noise Ratio
CPE	Customer Premises Equipment
dBmV	Decibels with respect to a millivolt
DOCSIS	Data over Coax System Interface Specification
DWDM	Dense Wavelength Division Multiplexing
FTTH	Fiber to the Home
GaAs	Gallium Arsenide
GaN	Gallium Nitride
GHz	Gigahertz
HFC	Hybrid Fiber Coax
HHP	Households Passed
MoCA®	Multimedia over Coax Alliance
MSO	Multiple Systems Operator
OFDM	Orthorgonal Frequency Division Multiplexing
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
SC	Single Carrier
SCTE	Society of Cable Telecommunications Engineers
SG	Service Group
SNR	Signal to Noise Ratio
TCP	Total Composite Power

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