The Path to 100 Gbps DAA Nodes

Analyzing DOCSIS Bandwidth and its Impact on the CIN.

A Technical Paper prepared for SCTE by

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1. Introduction

This white paper will look at DOCSIS bandwidth as it relates to a DAA (Distributed Access Architecture) node. Although similar to an Integrated CMTS (Cable Modem Termination System), there are some additional design considerations to be aware of. The first section looks at various design considerations. The second section then goes right into the bandwidth calculations.

Specifically, the following goals will be addressed with this white paper:

Network Design Considerations

- Review channel and port differences between an integrated CMTS (I-CMTS) and a DAA node
- Discuss a new concept of DS:US bandwidth ratio (DUCR) and peak versus average capacity

Bandwidth Studies of DAA Nodes and its CIN requirements

- What is possible today (with some DOCSIS 3.1 and video)
- What is possible with DOCSIS 3.1
- What is possible with DOCSIS 4.0
- What is possible after DOCSIS 4.0

This white paper will establish a set of metrics and then use them along with an extensive bandwidth analysis of DOCSIS to provide guidelines on what technology direction operators may decide to go.

All calculations are supported by a publicly available spreadsheet as show in Figure 20 by contacting the author. The numbers capture in the while paper are supportive of general conclusions. As time goes on, the spreadsheet may contain more exact bandwidth numbers for a given upstream and downstream channel configuration.

2. Network Design Considerations

2.1. Review of I-CMTS channel/port configurations

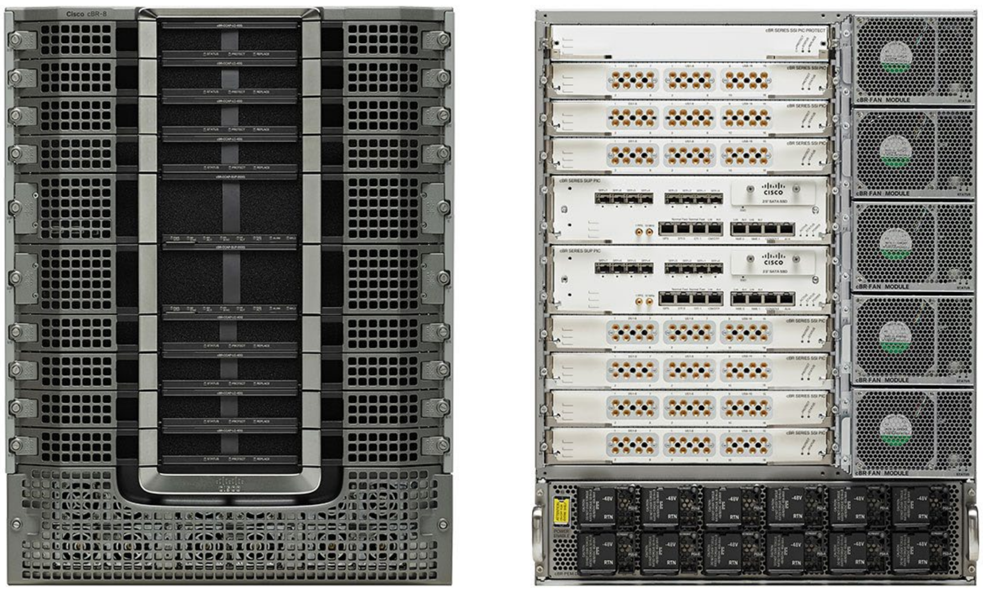


Figure 1 - Example of an I-CMTS

To start the analysis, we first begin with the Integrated CMTS (I-CMTS). A typical I-CMTS is shown in Figure 1. The I-CMTS was designed to connect to separate radio frequency (RF) downstream (DS) combining and upstream (US) combining network. As such, the DS and US RF ports are separate and do not contain a diplexer.

The I-CMTS also contains RF redundancy. In this example, there are eight line cards (8 LCs) but only seven RF physical interface cards (PICs). Internally, there is a 7+1 redundancy scheme that allows one LC to replace any of the other seven line cards without changing the external RF path.

Here are some example I-CMTS capacity values

CMTS Ports

- 7 LC @ 8 DS ports x 16 US ports = 56 DS ports and 112 US ports per I-CMTS chassis

Channels per I-CMTS Port

- DS: 96 SC-QAM and 2 OFDM
- US: 8 A-TDMA and 2 OFDMA

The SC-QAM and A-TDMA channels are for DOCSIS 3.0 and earlier versions. OFDM and OFDMA channels are added for DOCSIS 3.1 and DOCSIS 4.0

Ethernet Capacity

- Dual 100 Gbps

The Ethernet connectivity represents the total aggregate capacity of the chassis. The DOCSIS protocol allows for over subscription on the HFC (Hybrid Fiber-Coax) plant. In addition, the I-CMTS allows for some oversubscription on the CMTS chassis. Thus, the total RF capacity may be greater than the Ethernet capacity. Over-subscription is important as each Ethernet port needs to connect to a router port, so each port has a cost associated with it. Over-subscription both keeps costs down and represents proper traffic patterns.

Internal Constraints

- Bus and backplane bandwidths, various memory sizes, packets-per-second (PPS) limitations of data and control planes, CPU core count and clock speeds, software architecture, etc.

These internal constraints lead to DOCSIS performance constraints such at the number of service groups (SGs), classifiers, and data throughput.

2.2. DAA Node channel/port configurations

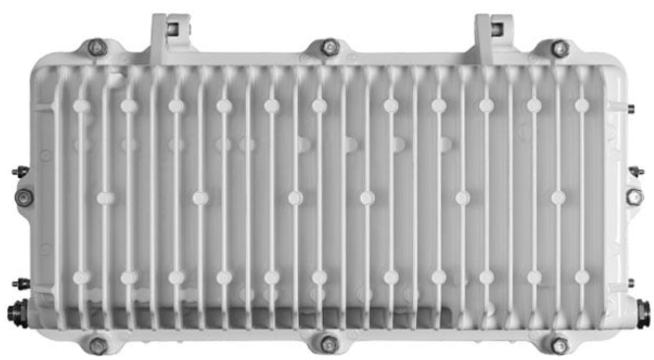


Figure 2 - HFC DAA Node

There are two types of DAA nodes defined at CableLabs.

- The first type is the Remote PHY (RPHY) system. The RPHY design takes the PHY chip out of the I-CMTS and puts it in the RF node. The MAC chip remains in the I-CMTS and is connected to the PHY chip in the node with a 10 Gbps (or higher) link. [1][2][3]
- The second approach is a Remote MAC and PHY (RMACPHY) system where the entire layer 1 and layer 2 CMTS is placed in the node. Layer 3 connectivity is supplied by a leaf router. Aggregation of RMACPHY nodes replies on system software known composed of a MAC Manager and a PacketCable Aggregator.

Both RPHY and RMACPHY are part of the Flexible MAC Architecture (FMA), although FMA commonly refers to RMACPHY as RMACPHY is its first system deliverable. Additional non-DOCSIS features such as MPEG-TS video, narrowband digital forward (NDF), narrowband digital return (NDR), out-of-band (OOB) channels, are all managed using the RPHY protocols and add to the Ethernet bandwidth requirements.

For the analysis in this white paper, which focuses on RF channels, RF ports, and Ethernet ports, both the RPHY and RMACPHY systems are identical. Hence forth, the term DAA node equally applies to an RPHY node or a RMACPHY node. A typical RF node is shown in Figure 2. A breakdown of the connectivity of that node is shown in Figure 3.

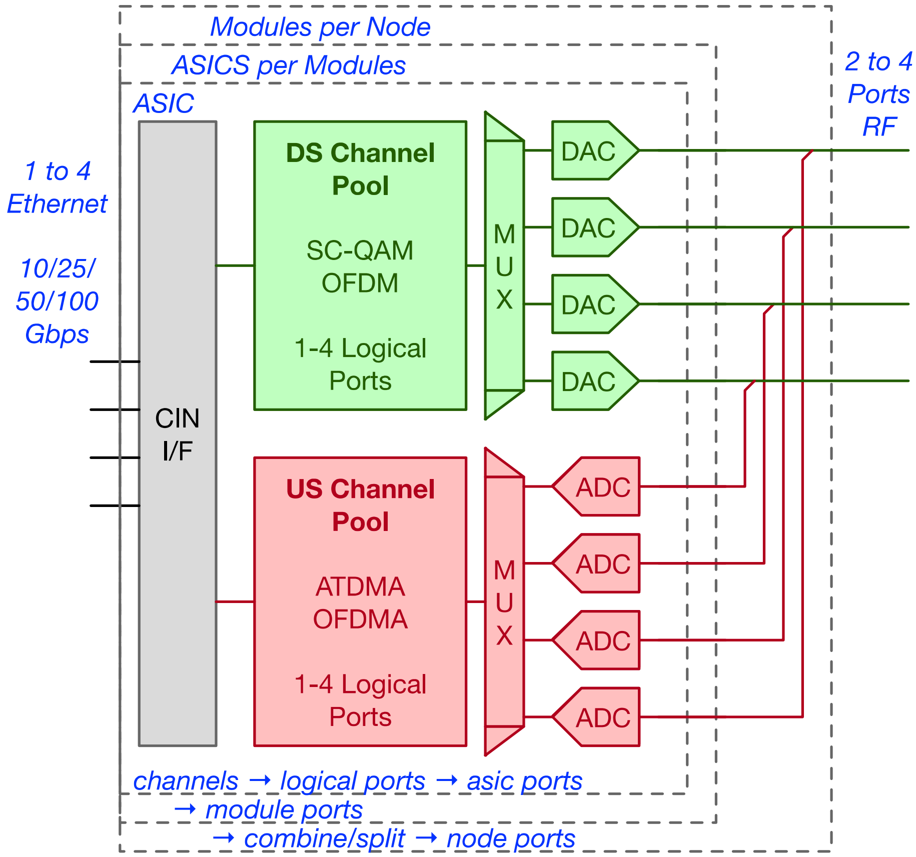


Figure 3 - DAA Node channels and ports

A DAA node has two to four RF ports. These RF ports after a diplexer, so they contain both DS and US spectrum and channels. That is different than an I-CMTS. There is also no RF redundancy which simplifies things.

A DAA node is composed of:

- One or more RF ASICS that fit into a module
- One of more modules that fit into a node

The DAA ASIC contains a pool of RF channel for SC-QAM, OFDM, ATDMA, OFDMA as well as resources for NDR, NDF, OOB 55-1, OOB 55-2, and the upstream spectrum burst receiver. This pool of resources can be organized into one or more port groups which are then mapped into DS digital-to-analog (DAC) and US analog-to-digital (ADC).

Now, here is a tricky part. Say that the chip supports a 1x2 port config (so 1 DS and 2 US). That could map to one DAC and two ADC. Or, it could map to four DAC and four ADC. Now, why would that be interesting? There is an additional function that DAA silicon may provide called digital pre-distortion (DPD).

The downstream power amp is a class A amplifier which means it does not run anywhere near saturation. DPD pre-distorts the DS signal in the opposite manner that the DS power amp may distort it. When combined, the linearity of the power amp is increased. This allows the output power amp in the node to be biased at a lower voltage and thus the power amp runs at a lower power level for a given output level. To make this all work, the ideal DPD circuit has to monitor all four DS power amps. It does with an extra four set of full range ADC converters.

In the upstream direction, a node would normally combine RF inputs from four down to two or one and then connect to an ASIC. This creates noise funneling where the noise floor from multiple inputs is combined. Instead, if each RF upstream input is received on a separate ADC, and then digitally processed, then the impact of noise funneling can be reduced.

The DAA module acts like a small CMTS. There can be one or two modules in DAA node. The modules may be split across downstream ports or directly connected. The upstream ports may be combined or directly connected to the US ports on the modules.

2.3. DAA Node CIN connectivity

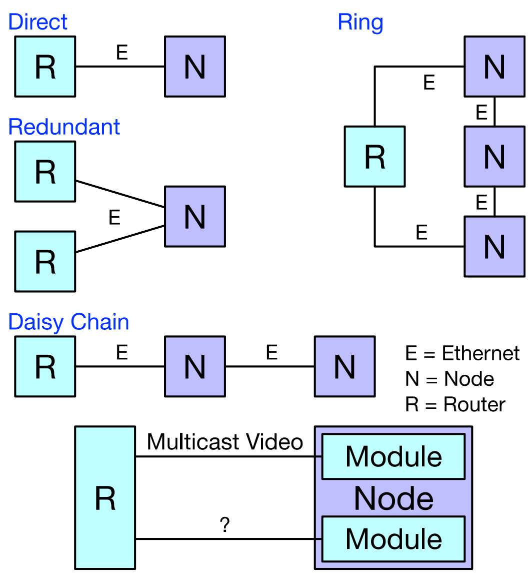


Figure 4 - DAA Node Ethernet Connectivity

The aggregate of all bits from all the DS and US RF channels pass through the Ethernet ports and through the Converged Interconnect Network (CIN). The definition of the CIN is in part defined by the use of the Ethernet ports.

The various Ethernet configurations are shown in Figure 4.

- Direct is most common
- Daisy chain allows multiple nodes to share a common 10 GE link. This may become a less popular option as node bandwidth increases
- Rings are rare but they do provide a redundant path on a common 10 GE link. Rings may become less popular use as the node bandwidth requirements increase. Or, the rings could just move to higher bandwidth
- Redundant connectivity is rare today, but may become useful in the future for a CIN.

Imagine a DAA node that connects to separate hub sites. If one hub site fails, the DAA nodes remain connected to the other hub site. In fact, since the DAA nodes are now IP connected, each DAA node connects to all hub sites, not just the next hop hub site. This is a powerful concept as it allows DAA nodes that might not fit on one hub site to be connected to another hub site.

Backhaul may be one or more Ethernets per Node, in addition to the above configurations. This presents both an opportunity and a dilemma for MPEG-TS video. Linear video which can consume 64 SC-QAM channels is usually sent using IP Multicast.

- Multicast video may be shared across network ports of the same module if designed to do so
- Multicast video cannot be shared across network ports that go to separate modules

So, if you have to 1x2 modules to make a 2x4 node, then the multicast video will have to be sent separately to each. If you have one 2x4 module, and if the ASICs permit sharing of video, then you may only need to send one multicast video stream to the node.

This is a very important consideration for DAA node planning as it could double the number of Ethernets you require. For denser DAA node configurations, like for DOCSIS 4.0, it may be necessary to move to 25 Gbps Ethernet or higher.

Make sure to work out these considerations on the DAA bandwidth spreadsheet.

2.4. DUCR – Downstream to Upstream Capacity Ratio

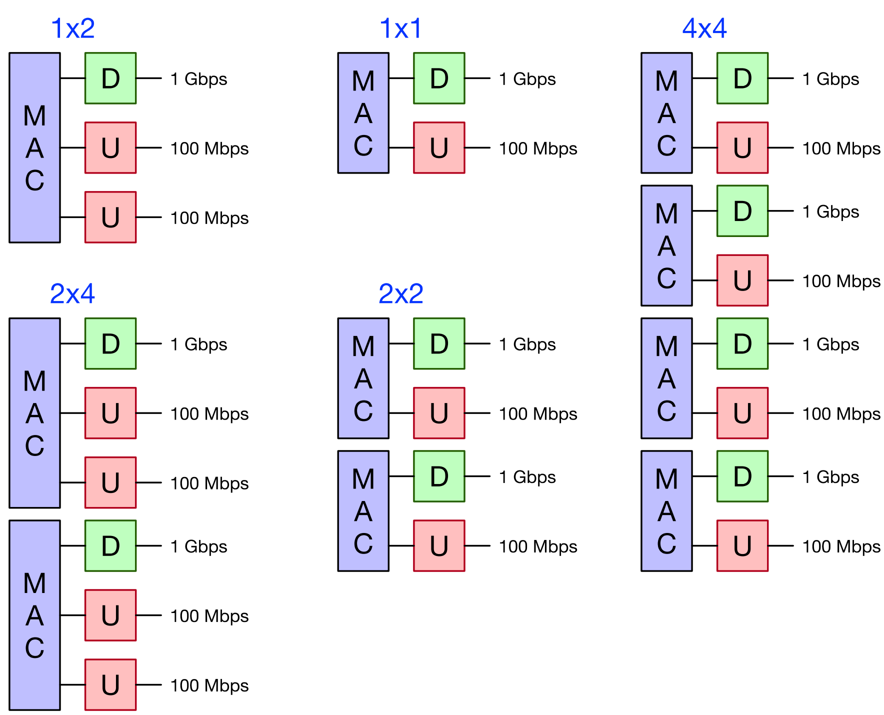


Figure 5 - DAA Node Ethernet Connectivity

As mentioned before, even though a DAA node may have four physical DS and US ports, it has an effective number of ports depending upon the internal configuration of resources. Figure 5 shows these various combinations with example bandwidth numbers. Here are the important points to keep in mind.

1x1 modules

- One module creates a 1x1 node
- Two modules create a 2x2 node
- The 1x1 module may be a 1x2 module with one port disabled.

1x2 module

- One module creates a 1x2 node
- Two modules create a 2x4 node
- This is the current state of the industry in 2021

2x2, 2x4 module

- Next generation chipsets contained in a single module
- Targeted at one module per node.

4x4 module

- Not available or deployed yet, but could be with future ASIC densities. ADC and DAC density is already here.
- Also, two 2x2 modules could form a 4x4 node.

These port configurations can be further sorted into two classes:

- Single-return: 1x1, 2x2, 4x4
- Dual-return: 1x2, 2x4
- Quad-return: 1x4 (not in actual use)

A single-return system has the same number of DS and US ports; a dual-return system has twice the upstream ports as downstream ports. Quad-return is not in use but is included for consistency. (the usage of these terms are defined here)

So, when should you use a single-return system versus a dual-return system?

The first reason may be cost. If you as an operator are paying a license per channel or per port, a dual-return system will cost more money. However, if you are paying a license per customer, then a single-return and dual-return system may be the same price if the hardware is the same.

The second reason is peak capacity versus total capacity.

The peak capacity is set by the port capacity, and any one particular CM is only connected to one physical port of a DAA node and thus one DS port and one US port. Thus, a single-return system and a dual-return system have the same peak capacity.

The total capacity is set by the aggregate bandwidth of all ports and how they fit within the Ethernet port bandwidth. In this scenario, a dual-return system has twice the upstream capacity as a single-return system, although they both have the same amount of downstream bandwidth.

Here is a potential conclusion.

- If a significant number of your customers are running at an upstream rate that is higher than say 50% of the upstream bandwidth (say 1 Gbps service rate on a 1.4 Gbps port), there are a low number of CMs on a node, and sales are based upon good speed-test performance, and then you may want to go with a single-return system.
- If a significant number of your customers are running at an upstream rate that is lower than say 50% of the upstream bandwidth (say 300 Mbps on a 1.4 Gbps upstream), there are a high number of CMs on a node, and sales are based on connectivity and overall throughput, then you may pick the dual-return system.

The third reason is if there are not enough OFMDA channels. For example, the silicon may support two upstream ports at 2 OFDMA each, but only one upstream port at 4 OFDMA each. Both solutions have the same average capacity, but the single upstream port has higher peak capacity.

The fourth reason is to get to a desired DS:US capacity ratio (DUCR) for a DAA node. DUCR (*pronounced "duck-r"*) is a proposed definition originating in this white paper.

- Average DUCR takes into account the total bandwidth from the total number of DS ports and US ports. This is a measure of the capacity of the HFC plant from the CMTS viewpoint.
- Peak DUCR only takes into account the bandwidth of one DS port and one US port. This is a measure of the capacity of the HFC plant from a CM viewpoint.

A single-return system will have the same value for average and peak DUCR. A dual-return system, the average DUCR will be half the peak DUCR.

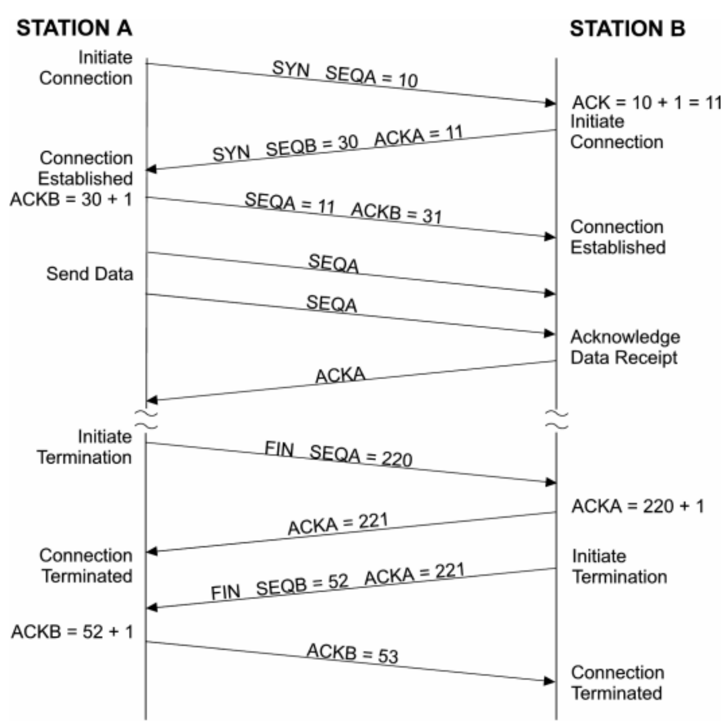


Figure 6 - TCP Handshakes

So, what is a good value DUCR? That depends upon the nature of traffic being run over the DOCSIS interface. About 75% of Internet traffic is TCP (transport control protocol). To understand this, let's do a quick re-hash on how TCP works.

A set of TCP signaling actions are shown in Figure 6. Typical TCP stack implementations try to send one ACK for every two data packets. TCP will fragment files into max MTU (about 1500 bytes) packet sizes with the last packet being a remainder. Note that Ethernet packets on an Ethernet interface have a 12-byte inter-packet gap (IPG). When the Ethernet frames are put on DOCSIS, that IPG is removed by replaced with DOCSIS framing overhead which is 13 bytes or more.

- DS: (1518 + 12 bytes IPG) x 2 = 3060 bytes
- US: 64 bytes + 12 bytes IPG = 72 bytes
- TCP DS:US ratio 3060 / 72 ~= 40 (most extreme case)

Shorter TCP transfers from web pages can dramatically reduce this ratio. The remaining UDP traffic and upstream TCP traffic also reduces this ratio. The DUCR value of the DOCSIS system should be less than the TCP ratio in order to all the downstream to fill with TCP traffic and still allow room in the upstream for non-ACK traffic.

Cable Modems (CM) contain a TCP ACK suppression mechanism that removes redundant TCP ACKs, which in term allow for a higher ratio to work. Ack suppression will remove an older ACK from a TCP flow if a new ACK comes along, if there is upstream queuing in a CM, and if the ACKs are in a burst. A nice side effect is if the upstream queue begins to build up due to upstream compression, the probability of a redundant ACK being present goes up.

5G TDD (time division duplex) systems share the same spectrum for downlink and uplink transmissions. The proportion of bandwidth between downstream and upstream is set by a frame structure configuration. The typical profile used in 5G is the so called "DDDSU" where D = downlink, U = uplink, and S = 10:2:2 (D:G:U) where G is guard time. Thus, there is a time ratio of about 3.25:1 for DL:UL. Ignoring overhead, that would correspond to a DUCR value of 3.25 if the modulation was the same. If the mobile downlink has a higher modulation that the mobile uplink, then the mobile DUCR value could be closer to 4 or 5.

Table 1 - Proposed DUCR Guidelines

DUCR		Usage Notes
Average	Peak	
40	80	• Downstream may not get fully utilized as there is not enough upstream bandwidth to support TCP ACK traffic. • Not recommended • ACK suppression in the CMs allow this extreme condition to work and this does represent some
20	40	• At the edge of working for DS and US. • This is what is often deployed today but really only works because of ACK suppression.
10	20	• Good balance between DS and US bandwidth for asymmetric traffic.
5	10	• Better balance between DS and US bandwidth for asymmetric traffic that also allows for upstream originated TCP transfers • Average DUCR on DOCSIS matches 5G TDD systems
< 2.5	< 5	• Upstream may not get fully utilized in the presence of asymmetrical traffic • Allows high symmetrical SFs to be sold. • Peak DUCR on DOCSIS matches 5G TDD systems

Based on upon these data points, Table 1 provides some guidelines for picking the right DUCR value.

A high DUCR means the downstream may not get full utilized. A low DUCR means the upstream will may get fully used (unless there is a lot of upstream TCP transfers).

Note that the asymmetry of a CM service flow may be different that the asymmetry of the DOCSIS channels. For example, say there is a 1 Gbps downstream and a 100 Mbps upstream with a 1x2 node. Thus, the upstream capacity is really 200 Mbps, the average DUCR is 5 and the peak DUCR is 10. Meanwhile, the CM has been configured to use 200 Mbps downstream and 10 Mbps upstream which is a DUCR of 20. How does that play out?

The CM will follow its individual CM DUCR, and either the downstream or upstream service flow will max out first. The DOCSIS channel, however, is an aggregate of all CMs, and of CMs are different rates. Thus, the aggregate traffic will ultimately shape to the channel DUCR.

3. DOCSIS Bandwidth Basics

3.1. Baseline assumptions

Summary	Explanation
2 x 4 Node Capacity	Number of DS and US ports on Node
Scenario	Reference number
DS End MHz	DS Spectrum upper limit
DS Start MHz	DS Spectrum lower limit
US End MHz	US Spectrum upper limit
VOD/SDV MPEG-TS	VOD used in calculation
Linear Video MPEG-TS	Linear channels used in calculation
DOCSIS DS port Gbps	DOCSIS Downstream Port
DOCSIS US port Gbps	DOCSIS Upstream port
Ethernet DS Gbps	Ethernet Downstream (DOCSIS + Video)
Ethernet US Gbps	Ethernet Upstream (DOCSIS)
DUCR, Avg	Node Ratio for DS:US capacity
DUCR, Peak	Port Ratio for DS:US capacity
ODFM ch per Node	DS OFDM channels needed per node
OFDMA ch per Node	US IFDMA channels needed per node
DOCSIS DS BW MHz	Total DS DOCSIS RF Bandwidth
Cross-over MHz	Cross-over band
DOCSIS US BW MHz	Total DS DOCSIS RF Bandwidth

Figure 7 - Spreadsheet Inputs/Outputs Explained

The study in this paper is contained within a spreadsheet. The outputs of the spreadsheet and what they represent are summarized in Figure 7 and the common set of input assumptions is in Figure 8.

32	VOD/SDV MPEG-TS	1794	DS Stop MHz for D4.0	ESD	ESD or FDX for D4.0	4096	OFDM Mod
64	Linear Video MPEG-TS	16.4	US Start MHz	YES	Video in FDX Trans Band	2048	OFDMA Mod
2	DS ports per Node	32	ch SC-QAM @ 6 MHz	120	MHz FDX Trans Band	256	SC-QAM Mod
4	US ports per Node	4	ch ATDMA @ 6.4 MHz	24	MHz DS unused < 108	64	ATDMA Mod

Figure 8 - Spreadsheet Common Inputs with default values

VOD/SDV MPEG-TS

- Unicast video services that are reserved on each downstream. The analysis is that VOD is carried on IP unicast on Ethernet and delivered to one downstream. SDV may be on IP multicast on the Ethernet, but is also delivered to only one downstream. For 6 MHz video spacing, 32 channels of video will be 192 MHz.

Linear Video MPEG-TS

- Also known as broadcast video. The analysis assumes that linear video is carried on IP multicast so there is one copy on a shared Ethernet for two DOCSIS downstreams.

Ports per node

- The number of unique downstream and upstream ports per DAA node.

DS Stop MHz for D4.0

- This allows the ending frequency for DOCSIS 4.0 to be manually set higher or lower

US Start Frequency

- Common starting point for the upstream. The spreadsheet will subtract out ATDMA channels and then fill the remaining upstream spectrum with OFDMA. To prevent OFDMA being calculated below 42 MHz, specify 4 channels of ATDMA (default is 6.4 MHz each), and a start frequency of 16.4 MHz (42 – 4*6.4).

Channels of SC-QAM

- These are downstream channels. DOCSIS 3.0 CMs have/had configurations of 8x4, 24x8, and 32x8. SC-QAMs are retained for legacy CMs.

Channels of ATDMA

- Typically, four upstream ATDMA channels were used for DOCSIS 3.0 and this occupied all available bandwidth in the upstream.

ESD or FDX for DOCSIS 4.0

- Changes the downstream starting frequency. You can tell FDX is being used when the "cross-over MHz" is negative.

Video in the FDX transition band

- FDX excludes 684 MHz to 804 MHz. That band can be used for MPEG-TS video or for legacy CMs. This is usually a yes.

FDX Transition Band

- This is defined as 120 MHz in the specification and is included here in case operators need to change it.

DS MHz skipped below 108 MHz

- 72 MHz to 76 MHz is used for the legacy OOB channel, and 88 MHz to 108 MHz are used for the FM band. Typically, these bands are not available for DOCSIS downstream or MPEG-TS video. This totals to 24 MHz.

Modulation

- The average QAM modulation level used for DOCSIS 3.0 and DOCSIS 3.1
- ODFM and OFDMA have profiles which can be configured to optimize modulation levels per subcarrier [4][5]

Note that if the upstream was configured for no ATDMA channels, and there would be seven full 96 MHz channels of OFDMA between 12 and 684 MHz, and if the modulation of each data subcarrier was 4K QAM, then the theoretical throughput of the upstream channel would be 6 Gbps. This matches the 10G vision in the Cable industry [6]. The analysis in this whitepaper, however, assumes four ATDMA channels for backwards compatibility below 42 MHz.

3.2. Acceptance criteria

Scenario	1	2	3	4	5	6	7	8	9	10	11
DS End MHz	1002	1002	1002	1218	1218	1794	1794	1794	1794	1794	1794
US Rtn Path MHz	42	42	85	85	204	85	204	300	396	492	684
1) DS Path ≥ 5 Gbps	54%	54%	49%	92%	62%	207%	177%	154%	130%	108%	62%
2) 2 < avg DUCR < 20	148%	148%	131%	246%	52%	181%	149%	91%	56%	36%	14%
3) US SF 1 Gbps, 0.4 K	7%	7%	33%	33%	106%	33%	106%	151%	209%	268%	385%
4) 100% > 85 MHz US	-78%	-78%	0%	0%	217%	0%	217%	350%	526%	701%	1051%
Combined Results:	-78%	-78%	0%	0%	52%	0%	106%	91%	56%	36%	14%

Acceptance	1)	5	Gbps DS path min					Success Critieria	
Criteria	2)	2	DUCR min	20	DUCR max	avg	based	success if >	100%
	3)	1	Gbps US SF with	40%	of additional headroom (K)			borderline	
	4)	100%	more BW than a	85	MHz return path			reject if <	90%

Diplexer ratio %	29%	29%	27%	27%	26%	27%	26%	24%	24%	23%	22%

Figure 9 - Acceptance Criteria

One of the extended features of the spreadsheet is to evaluate each scenario against a set of criteria. These criteria so far are.

How close is:

- the downstream above a desired speed?
- DUCR between two level for peak or avg?
- the headroom of a service flow?
- how much better is the proposed return path compared to another return path solution?

The results can then be ranked within an upper and lower percentage.

There is also a diplexer ratio calculator. Negative values indicated FDX operation.

3.3. QAM/ATDMA calculator

Table 2 - QAM Configuration

Country	USA	USA	Europe	Europe
J.83 Annex	Annex B	Annex B	Annex A	Annex A
bandwidth (MHz)	6	6	8	8
constellation size	64	256	64	256
symbol rate (Msps)	5.056941	5.360537	6.952	6.952
alpha	0.186	0.119	0.151	0.151
bits per symbol	6	8	6	8
PHY Layer Raw BW (Mbps)	**30.34**	**42.88**	**41.71**	**55.62**
FEC Frame Sync	0.08%	0.05%	0.00%	0.00%
FEC Parity bytes	4.69%	4.69%	7.84%	7.84%
Trellis Coding Overhead	6.67%	5.00%	0.00%	0.00%
PHY Overhead	11.11%	9.50%	7.84%	7.84%
PHY Payload BW (Mbps)	**26.97**	**38.81**	**38.44**	**51.25**
MPEG Header	2.13%	2.13%	2.13%	2.13%
MPEG Pointer Byte	0.09%	0.09%	0.09%	0.09%
MPEG Total Overhead	2.22%	2.22%	2.22%	2.22%
PDU Layer BW (Mbps)	**26.37**	**37.95**	**37.59**	**50.12**
PDU after DOCSIS OH	**26.03**	**37.46**	**37.11**	**49.47**
Adjusted b/s/Hz	**4.34**	**6.24**	**4.64**	**6.18**

Ethernet Avg Frame Size	1000	bytes
DOCSIS Overhead	13	bytes

This calculation is the bit rate for an Ethernet frame rate.

3.4. OFDM Configuration

Table 3 - OFDM Configuration

Downstream			
Scenario	**A**	**B**	
Size of channels (MHz) - 24-192 MHz[1]	192	192	MHz
FFT size (4K or 8K FFT)	4096	8192	subcarriers
Subcarrier spacing	50	25	kHz
Cyclic prefix (Ncp)	192	192	samples[2]
Roll-off (Nrp) - must be less than Ncp	128	128	samples[2]
Ncp overhead	4%	2%	
Guard band override (leave blank if not used)[3]	1	1	MHz
Guard band on upper and lower edge (MHz)[4]	1.000	1.000	MHz
Number of active subcarriers	3800	7600	subcarriers
PLC overhead (number of subcarriers)	8	16	subcarriers
Continuous Pilot Scaling (48 - 120 subcarriers)	48	48	subcarriers
Continuous Pilots (include pilots for PLC)	56	56	subcarriers
Scattered Pilots (estimate)	29	59	subcarriers
Num of NCP - must be >0 (estimate)	4	4	
QAM order of NCP (QPSK, 16QAM, 64QAM)	6	6	bits / sym
NCP overhead (including CRC)	40	40	subcarriers
FEC overhead	12%	12%	8/9 code
Data QAM order (bits per symbol)	12	12	bits / sym
Data Rate (Mbps)	**1844**	**1911**	**Mbps**
Overhead % based on active subcarriers	19.1%	16.2%	
Efficiency	80.9%	83.8%	
Adjusted bits/second/Hz	9.61	9.95	

Notes

1. If using exclusion bands, reduce channel size by amount of spectrum excluded for data rate
2. Sampling rate is 204.8 MHz (based on OFDM spectrum - FFT size x subcarrier width)
3. Note that maximum active OFDM spectrum is 190 MHz so must have 1 MHz or higher guard band if channel is 192 MHz
4. Note that guard bands are based on Appendix V of D3.1 PHY spec based on roll-off period samples shown below (rounded to whole number of subcarriers)

OFDMA for DOCSIS was first introduced for DOCSIS in [6]. For a great discussion on OFDM and OFDMA settings, refer to [8].

3.5. OFDMA Configuration

OFDMA Upstream			
FFT size (2K or 4K FFT)	2048	4096	subcarriers
Subcarrier spacing	50	25	kHz
Size of channels (MHz) - 7.4 - 96 MHz[1]	96	96	MHz
Exclusion bands (or unused bands)			MHz
Guard band on upper and lower edge (MHz)[3]	0.5	0.5	MHz
Number of active subcarriers	1900	3800	subcarriers
Cyclic prefix (Ncp)	96	96	samples[2]
Roll-off (Nrp) - must be less than Ncp	64	64	samples[2]
Ncp overhead	4.48%	2.29%	
Maximum K values based on channel size	18	9	
OFDM symbols per OFDMA Frame (K)[4]	18	9	
Minislot size (400 kHz)	8	16	subcarriers
Minislots per OFDMA frame - (minimum 25 or 16 to ASIC)	237	237	
Edge minislots per OFDMA Frame (estimate)[5]	23	23	
Unused subcarriers (assumes continuous exclusion band)	4	8	
OFDMA frame duration	376.88	368.44	µsec
Pilot pattern	1	8	pattern
Pilots per minislot (body)	2	2	pilots
Pilots per minislot (edge)	4	4	pilots
complementary pilots per minislot (body)	2	2	comp pilots
complementary pilots per minislot (edge)	4	4	comp pilots
Total data carriers per OFDMA frame	33088	33088	
Total complementary pilots per OFDMA frame	520	520	
Data QAM order (bits per symbol)	10	10	bits / sym
bits per minislot (body) - no FEC overhead	1412	1412	bits
bits per minislot (edge) - no FEC overhead	1384	1384	bits
FEC overhead (long codeword)	11.11%	11.11%	8/9 code
FEC overhead (medium codeword)	15.15%	15.15%	28/33 code
FEC overhead (short codeword)	25.00%	25.00%	3/4 code
bits per OFDMA frame	296889	296889	bits
Data Rate (Mbps)	**788**	**806**	**Mbps**
Overhead % based on active subcarriers	17.08%	15.18%	

Table 4 - OFDMA Configuration

Notes

1. Valid channel sizes 11 - 96 MHz for 50 kHz; 7.4 - 96 MHz 25 kHz (includes 0.5 MHz guard band per edge)
2. sampling rate is 102.4 MHz (based on OFDM spectrum - FFT size x subcarrier width)
3. Note that guard bands are fixed at 0.5 MHz on cBR-8
4. K values must fall in range from table on right
5. Edge minislots occur at start of OFDMA frame, after excluded or unused spectrum, and at start of modem burst (10% might be a good estimate - has minimal impact on estimate)

4. DAA Bandwidth Studies

4.1. DOCSIS 3.1 with 1002 MHz, low split and 2x4 DAA Node (today)

2 x 4 Node Capacity	(a)		(b)	
Scenario	1	2	1	2
DS End MHz	**1002**	**1002**	**1002**	**1002**
DS Start MHz	**54**	**54**	**54**	**54**
US Rtn Path MHz	**42**	**42**	**42**	**42**
VOD/SDV MPEG-TS	32	10	10	0
Linear Video MPEG-TS	64	48	48	0
DOCSIS DS port Gbps	2.8	5.0	5.0	8.5
DOCSIS US port Gbps	0.10	0.10	0.20	0.20
Ethernet DS Gbps	10.3	12.6	12.6	17.0
Ethernet US Gbps	0.4	0.4	0.8	0.8
DUCR, Avg	14	25	13	21
DUCR, Peak	27	50	25	43
ODFM ch per Node	2	4	4	8
OFDMA ch per Node	0	0	4	4
DOCSIS DS BW MHz	348	576	576	924
Cross-over MHz	12	12	12	12
DOCSIS US BW MHz	26	26	32	32

(a)

2	DS ports per Node	4096	OFDM Modulation
4	US ports per Node	2048	OFDMA Modulation
32	SC-QAM 6 MHz ch	256	SC-QAM Modulation
4	ATDMA 6.4 MHz ch	64	ATDMA Modulation

24	DS MHz skipped below 108 MHz
1794	ESD Stop Frequency (MHz)
16.4	US Start Freq (MHz)

(b)

2	DS ports per Node	4096	OFDM Modulation
4	US ports per Node	1024	OFDMA Modulation
32	SC-QAM 6 MHz ch	256	SC-QAM Modulation
2	ATDMA 6.4 MHz ch	64	ATDMA Modulation

24	DS MHz skipped below 108 MHz
1794	ESD Stop Frequency (MHz)
10	US Start Freq (MHz)

Figure 10 - Bandwidth today with low-split

Deployment scenarios today are generally with a 1x1 or 1x2 DAA node with newer ones using a 2x2 or 2x4 DAA node. This scenario looks at a 2x4 node on an existing 1002 MHz HFC plant, with and without MPEG-TS video, and with a 42 MHz return path.

DOCSIS 3.1 CMs are capable of receiving 32 6 MHz SC-QAM channels (192 MHz total) plus two OFDM channels (192 MHz each), for a total of 576 MHz of DOCSIS spectrum. That is over half of the available spectrum on the HFC plant today. At this time, few deployments are fully utilizing that available DOCSIS capacity on their HFC plant.

In scenario 1 (a) with video and on a 1002 MHz plant, there is 96 SC-QAM carriers (576 MHz) of MPEG-TS video is present, resulting in only 348 MHz of remaining spectrum available for DOCSIS. The resulting DOCIS downstream bandwidth is about 3 Gbps which can be implemented a partial OFDM channel (132 MHz) and 32 SC-QAM channels (or a full 192 MHz OFDM channel and 26 SC-QAM channels).

The total Ethernet DS bandwidth, including video, is about 10 Gbps. If the multicast video cannot be shared across the RF downstream ports, there is an additional about 2.5 Gbps (64 x 38.5 Mbps) load on the Ethernet. This exceeds a single 10 Gbps backhaul, so two 10 Gbps backhauls may be needed or one 25 Gbps backhaul.

The upstream is 100 Mbps and the resulting average DUCR is around 14 and peak DUCR is around 27. These are reasonable ratios.

In Scenario 2 (a), only 58 channels of video are deployed, so DOCSIS can now be allocated a full 576 MHz. That equates to two OFDM channels (2 x 192 MHz) and 32 SC-QAM channels (192 MHz). The DOCSIS downstream increases to about 5 Gbps per DS port. The avg/peak DUCR jumps to about 25/50. This is high but in alignment with today's practices.

In scenario 1 (b), the upstream is changed from the default four ATDMA channels below 42 MHz to only 2 A-TDMA channels, while ODFM fills in the gaps down to 10 MHz (19.2 MHz). The average modulation was dropped to 1024-QAM. The resulting theoretical throughput is 200 Mbps, although in practice it may be slightly less than this due to plant noise. Bear in mind with a 2x4 node, that is the equivalent of 400 Mbps of capacity for each 5 Gbps downstream. This shows up with slightly high but good DUCR values.

In scenario 2 (b), all MPEG-TS video is removed, and 948 MHz (54 MHz to 1002 MHz) is used for DOCSIS. The DOCSIS downstream is about 8.5 Gbps per port. This could be used to drive two banks of CMs that share a common set of 32 SC-QAMs but separate pairs of OFDMA channels. Or, the 32 SC-QAM could be used for legacy CMs and there would be two banks of DOCSIS 3.1 CMs, each connected to two OFDMA channels but not the SC-QAM channels.

The doubling of the US throughput has kept the DUCR values from getting too high which would mean the upstream may saturate and the downstream may not get fully utilized. The DAA silicon should be able to support this scenario. Without the increase in upstream bandwidth, this may not make sense. Instead, it shows that the upstream return path needs to be increased, and that is the subject of the next section.

The observation from these scenarios is that video could be reduced to 58 or so channels on a 1002/42 MHz plant to allow the full potential of a DOCSIS 3.1 CM to be used. Further, if OFDM is placed below 42 MHz, then the upstream can be almost doubled. If video is entirely removed, DOCSIS can be increased three-fold from about 2.8 Gbps to about 8.5 Gbps. There is a lot that can be done for DOCSIS without changing the HFC plant.

4.2. DOCSIS 3.1 with 1218 MHz, mid/high split and 2x4 DAA Node

2 x 4 Node Capacity	DOCSIS 3.1			DOCSIS 3.1		
Scenario	3	4	5	3	4	5
DS End MHz	1002	1218	1218	1002	1218	1218
DS Start MHz	108	108	258	108	108	258
US Rtn Path MHz	85	85	204	85	85	204
VOD/SDV MPEG-TS	32	32	32	0	0	0
Linear Video MPEG-TS	64	64	64	0	0	0
DOCSIS DS port Gbps	2.5	4.6	3.1	8.2	10.3	8.8
DOCSIS US port Gbps	0.47	0.47	1.48	0.47	0.47	1.48
Ethernet DS Gbps	9.7	14.0	11.0	16.4	20.7	17.7
Ethernet US Gbps	1.9	1.9	5.9	1.9	1.9	5.9
DUCR, Avg	2.6	4.9	1.0	8.7	11.0	3.0
DUCR, Peak	5.2	9.8	2.1	17.5	22.1	6.0
ODFM ch per Node	2	4	2	8	10	8
OFDMA ch per Node	4	4	8	4	4	8
DOCSIS DS BW MHz	318	534	384	894	1110	960
Cross-over MHz	23	23	54	23	23	54
DOCSIS US BW MHz	69	69	188	69	69	188

2	DS ports per Node	4096	OFDM Modulation	24	DS MHz skipped below 108 MHz
4	US ports per Node	2048	OFDMA Modulation	YES	Video in FDX Transition Band
32	SC-QAM 6 MHz ch	256	SC-QAM Modulation	1794	D4.0 Stop Frequency (MHz)
4	ATDMA 6.4 MHz ch	64	ATDMA Modulation	16.4	US Start Freq (MHz)

Figure 11 - Bandwidth with DOCSIS 3.1 mid-split and high-split

This section exams the move to an 85 or 204 MHz return path. There are three deployment plans suggested and are shown in Figure 11.

Scenario 3, looks at the impact of moving to an 85 MHz return path but retaining the 1002 MHz downstream. This can be a reality of the downstream RF limit that is imposed by the HFC amps and/or the CMs, rather than the DAA node. The return path now has four times the capacity with over 450 Mbps rather than the previous 100 Mbps.

Scenario 3 with video has a decent 2.5 Gbps downstream with low DUCR values. Low DUCR values in theory allow for symmetrical bandwidth, but in practice may mean that the US is under-utilized. When MPEG-TS video is completely removed from the HFC plant, the DOCSIS downstream bandwidth can go to over 8 Gbps. The DUCR values are almost ideal at 10 and 20. With no video, the Ethernet backhaul barely fits into two 10 Gbps links. With video, it fits.

Scenario 4 increases the downstream to 1218 MHz with an 85 MHz return path. The downstream bandwidth goes up to about 4.5 Gbps and the DUCR values increase to the ideal zone where both downstream and upstream can be fully utilized. With no video, the downstream goes to about 10 Gbps and the DUCR values are still excellent. Note that the OFDM channel count is getting high. The Ethernet bandwidth crosses 20 Gbps which is not good as it does not allow headroom for signaling and there could be the multicast video hit. This is a good place for a 25 Gbps Ethernet serving both downstream ports.

Scenario 5 increases the upstream return path to 204 MHz. This allows a 1 Gbps upstream service tier to be sold. But it also ends up decreasing the DS spectrum and throughput somewhat. The downstream is about 3 Gbps with video and 9 Gbps without video, which is quite decent. The DUCR values are on the low side so the upstream may not be fully utilized, and the Ethernet bandwidth falls back into a dual 10 Gbps target.

The observation here is that DOCSIS 3.1 provide a huge amount of bandwidth growth in both the downstream and upstream, especially if video is removed.

4.3. DOCSIS 4.0 with ESD 1794 MHz and 2x4 DAA Node

2 x 4 Node Capacity	D4.0 ESD with video						D4.0 ESD with no video					
Scenario	6	7	8	9	10	11	6	7	8	9	10	11
DS End MHz	1794	1794	1794	1794	1794	1794	1794	1794	1794	1794	1794	1794
DS Start MHz	108	258	372	492	606	834	108	258	372	492	606	834
US Rtn Path MHz	85	204	300	396	492	684	85	204	300	396	492	684
VOD/SDV MPEG-TS	32	32	32	32	32	32	0	0	0	0	0	0
Linear Video MPEG-TS	64	64	64	64	64	64	0	0	0	0	0	0
DOCSIS DS port Gbps	10.3	8.8	7.7	6.5	5.4	3.1	16.1	14.6	13.4	12.2	11.1	8.8
DOCSIS US port Gbps	0.47	1.48	2.11	2.93	3.75	5.39	0.47	1.48	2.11	2.93	3.75	5.39
Ethernet DS Gbps	25.5	22.5	20.2	17.8	15.6	11.0	32.1	29.2	26.9	24.5	22.2	17.7
Ethernet US Gbps	1.9	5.9	8.4	11.7	15	22	1.9	5.9	8.4	11.7	15	22
DUCR, Avg	11.0	3.0	1.8	1.1	0.7	0.3	17.2	4.9	3.2	2.1	1.5	0.8
DUCR, Peak	22.1	6.0	3.7	2.2	1.4	0.6	34.3	9.8	6.4	4.2	3.0	1.6
ODFM ch per Node	10	8	8	6	6	2	16	14	14	12	12	8
OFDMA ch per Node	4	8	12	16	20	28	4	8	12	16	20	28
DOCSIS DS BW MHz	1110	960	846	726	612	384	1686	1536	1422	1302	1188	960
Cross-over MHz	23	54	72	96	114	150	23	54	72	96	114	150
DOCSIS US BW MHz	69	188	261	357	453	645	69	188	261	357	453	645

2	DS ports per Node	4096	OFDM Modulation	27	DS MHz skipped below 108 MHz
4	US ports per Node	2048	OFDMA Modulation	YES	Video in FDX Transition Band
32	SC-QAM 6 MHz ch	256	SC-QAM Modulation	1794	D4.0 Stop Frequency (MHz)
4	ATDMA 6.4 MHz ch	64	ATDMA Modulation	16.4	US Start Freq (MHz)

Figure 12 - Bandwidth with DOCSIS 4.0 ESD at 1794 MHz

Six scenarios, each with a different upstream split (85, 204, 300, 396, 492, 684 MHz) but a common downstream cap of 1794 MHz are shown in Figure 12, with and without MPEG-TS video. This version of DOCSIS 4.0 is referred to as extended spectrum DOCSIS (ESD). [6] The 85 MHz return path is not an actual DOCSIS 4.0 use case, but is included for comparative purposes.

The DUCR values are very telling here. For almost all the higher splits, the ratios are so low that it is likely that the upstream will get fully utilized, unless all the traffic was symmetrical, which it is not. In fact, for a 684 MHz 1x2 or 2x4 node, DUCR drops below one which means there is more upstream capacity than downstream capacity. For 1x1, it is still low. So, 684 MHz may not be a good choice. The 492 MHz upstream also has low ratios.

Note the impact on the Ethernet backhaul per node. In general, two 10 Gbps backhauls for a 2x4 node are no longer enough. 25 Gbps is likely needed or even 40 Gbps. At 25 Gbps and a 2x4 node, both downstream paths could not be saturated at the same time, although that is probably acceptable. Not that this analysis is not included downstream bandwidth for OOB and NDF, so some headroom is required.

The 396 MHz upstream is right in the middle. It has twice the upstream bandwidth of 204 MHz. But remember 204 MHz already did a 15x increase over 42 MHz, so is another 2x worth it? The driving goal would have to be the ability to offer a 2 Gbps upstream service. Note that the OFDM channel count without video is high and may not fit some silicon implementations.

With no video, and at lower return paths, the DOCSIS downstream goes past the 10 Gbps mark. With a 204 MHz upstream, and no video, the DOCSIS downstream is about 15 Gbps, which could allow a 10 Gbps x 1 Gbps service to be sold to the home. That’s interesting for competitive purposes.

The observation here is that 204 MHz looks like a great choice for asymmetrical traffic and for a potential 10 Gbps x 1 Gbps service offering. 396 MHz is a second choice for more symmetrical traffic and a 2 Gbps upstream service offering.

4.4. DOCSIS 4.0 with ESD 1602 MHz and 2x4 DAA Node

2 x 4 Node Capacity	D4.0 ESD with video						D4.0 ESD with no video					
Scenario	6	7	8	9	10	11	6	7	8	9	10	11
DS End MHz	1602	1602	1602	1602	1602	1602	1602	1602	1602	1602	1602	1602
DS Start MHz	108	258	372	492	606	834	108	258	372	492	606	834
US Rtn Path MHz	85	204	300	396	492	684	85	204	300	396	492	684
VOD/SDV MPEG-TS	32	32	32	32	32	32	0	0	0	0	0	0
Linear Video MPEG-TS	64	64	64	64	64	64	0	0	0	0	0	0
DOCSIS DS port Gbps	8.4	6.9	5.8	4.6	3.5	1.2	14.2	12.7	11.5	10.3	9.2	6.9
DOCSIS US port Gbps	0.47	1.48	2.11	2.93	3.75	5.39	0.47	1.48	2.11	2.93	3.75	5.39
Ethernet DS Gbps	21.6	18.7	16.4	14.0	11.7	7.2	28.3	25.3	23.1	20.7	18.4	13.9
Ethernet US Gbps	1.9	5.9	8.4	11.7	15	22	1.9	5.9	8.4	11.7	15	22
DUCR, Avg	9.0	2.3	1.4	0.8	0.5	0.1	15.1	4.3	2.7	1.8	1.2	0.6
DUCR, Peak	18.0	4.7	2.7	1.6	0.9	0.2	30.2	8.5	5.5	3.5	2.5	1.3
ODFM ch per Node	8	6	6	4	4	0	14	12	12	10	10	6
OFDMA ch per Node	4	8	12	16	20	28	4	8	12	16	20	28
DOCSIS DS BW MHz	918	768	654	534	420	192	1494	1344	1230	1110	996	768
Cross-over MHz	23	54	72	96	114	150	23	54	72	96	114	150
DOCSIS US BW MHz	69	188	261	357	453	645	69	188	261	357	453	645

2	DS ports per Node	4096	OFDM Modulation	27	DS MHz skipped below 108 MHz
4	US ports per Node	2048	OFDMA Modulation	YES	Video in FDX Transition Band
32	SC-QAM 6 MHz ch	256	SC-QAM Modulation	1602	D4.0 Stop Frequency (MHz)
4	ATDMA 6.4 MHz ch	64	ATDMA Modulation	16.4	US Start Freq (MHz)

Figure 13 - Bandwidth with DOCSIS 4.0 ESD at 1602 MHz

What if the HFC plant can't make it to 1794 MHz and only gets to say 1602 MHz? or even 1506 MHz or 1554 MHz? All is not lost. The results are shown in Figure 13 for 1602 MHz. Both the 85 MHz and 204 MHz cases have good DUCR values. Above that, the DUCR values are too low.

The observation here is that the DUCR values suggest that the 204 MHz upstream in this scenario is the way to go. DOCSIS 4.0 CMs would still be required.

4.5. DOCSIS 4.0 with FDX and 2x4 DAA Node

2 x 4 Node Capacity	D4.0 FDX with video						D4.0 FDX with no video					
Scenario	6	7	8	9	10	11	6	7	8	9	10	11
DS End MHz	1218	1218	1218	1218	1218	1218	1218	1218	1218	1218	1218	1218
DS Start MHz	108	108	108	108	108	108	108	108	108	108	108	108
US Rtn Path MHz	85	204	300	396	492	684	85	204	300	396	492	684
VOD/SDV MPEG-TS	32	32	32	32	32	32	0	0	0	0	0	0
Linear Video MPEG-TS	64	64	64	64	64	64	0	0	0	0	0	0
DOCSIS DS port Gbps	4.6	4.6	4.6	4.6	4.6	4.6	10.3	9.1	9.1	9.1	9.1	9.1
DOCSIS US port Gbps	0.47	1.29	2.11	2.93	3.75	5.39	0.47	1.29	2.11	2.93	3.75	5.39
Ethernet DS Gbps	14.0	14.0	14.0	14.0	14.0	14.0	20.7	18.3	18.3	18.3	18.3	18.3
Ethernet US Gbps	1.9	5.2	8.4	11.7	15	22	1.9	5.2	8.4	11.7	15	22
DUCR, Avg	4.9	1.8	1.1	0.8	0.6	0.4	11.0	3.5	2.2	1.6	1.2	0.8
DUCR, Peak	9.8	3.6	2.2	1.6	1.2	0.9	22.1	7.1	4.3	3.1	2.4	1.7
ODFM ch per Node	4	4	4	4	4	4	10	10	10	10	10	10
OFDMA ch per Node	4	8	12	16	20	28	4	8	12	16	20	28
DOCSIS DS BW MHz	534	534	534	534	534	534	1110	990	990	990	990	990
Cross-over MHz	23	-96	-192	-288	-384	-576	23	-96	-192	-288	-384	-576
DOCSIS US BW MHz	69	165	261	357	453	645	69	165	261	357	453	645

2	DS ports per Node	4096	OFDM Modulation	27	DS MHz skipped below 108 MHz
4	US ports per Node	2048	OFDMA Modulation	YES	Video in FDX Transition Band
32	SC-QAM 6 MHz ch	256	SC-QAM Modulation	1218	D4.0 Stop Frequency (MHz)
4	ATDMA 6.4 MHz ch	64	ATDMA Modulation	16.4	US Start Freq (MHz)

Figure 14 - Bandwidth with DOCSIS 4.0 FDX

DOCSIS 4.0 full-duplex (FDX) with a downstream limit of 1218 MHz, a maximum upstream return path of 204 to 684 MHz, and with and without video is shown in Figure 14. [9][10][11][12][13]. The 85 MHz return is not an FDX use case an dis included here for comparative purposes.

The DUCR values are low and suggest that a 684 MHz return will not fill the upstream with asymmetrical traffic. A 1218 MHz downstream with two 85 MHz upstream has very nice DUCR values, although it is not FDX. The FDX choices would be a 204 MHz return path for 1 Gbps subscriber service or 396 MHz return path for a 2 Gbps subscriber service.

The downstream bandwidth is about 4.5 Gbps with video present and about 9 Gbps with all video removed.

The OFDM channel requirements are high and care should be taken on silicon choices. Alternatively, using more than 32 channels of SC-QAM for DOCSIS is an alternative.

The Ethernet bandwidth should be doable with two 10 Gbps interfaces or one 25 Gbps. Again, be careful of how multicast MPEG video is shared as this could make two 10 Gbps Ethernet saturate and the DOCSIS downstream would not be fully utilized.

4.6. Post DOCSIS 4.0 with ESD + FDX and 2x4 DAA Node

2 x 4 Node Capacity	D4.0 FDX with video						D4.0 FDX with no video					
Scenario	6	7	8	9	10	11	6	7	8	9	10	11
DS End MHz	1794	1794	1794	1794	1794	1794	1794	1794	1794	1794	1794	1794
DS Start MHz	108	108	108	108	108	108	108	108	108	108	108	108
US Rtn Path MHz	85	204	300	396	492	684	85	204	300	396	492	684
VOD/SDV MPEG-TS	32	32	32	32	32	32	0	0	0	0	0	0
Linear Video MPEG-TS	64	64	64	64	64	64	0	0	0	0	0	0
DOCSIS DS port Gbps	10.3	10.3	10.3	10.3	10.3	10.3	16.1	14.9	14.9	14.9	14.9	14.9
DOCSIS US port Gbps	0.47	1.29	2.11	2.93	3.75	5.39	0.47	1.29	2.11	2.93	3.75	5.39
Ethernet DS Gbps	25.5	25.5	25.5	25.5	25.5	25.5	32.1	29.7	29.7	29.7	29.7	29.7
Ethernet US Gbps	1.9	5.2	8.4	11.7	15	22	1.9	5.2	8.4	11.7	15	22
DUCR, Avg	11.0	4.0	2.5	1.8	1.4	1.0	17.2	5.8	3.5	2.5	2.0	1.4
DUCR, Peak	22.1	8.0	4.9	3.5	2.8	1.9	34.3	11.5	7.1	5.1	4.0	2.8
ODFM ch per Node	10	10	10	10	10	10	16	16	16	16	16	16
OFDMA ch per Node	4	8	12	16	20	28	4	8	12	16	20	28
DOCSIS DS BW MHz	1110	1110	1110	1110	1110	1110	1686	1566	1566	1566	1566	1566
Cross-over MHz	23	-96	-192	-288	-384	-576	23	-96	-192	-288	-384	-576
DOCSIS US BW MHz	69	165	261	357	453	645	69	165	261	357	453	645

2	DS ports per Node	4096	OFDM Modulation	27	DS MHz skipped below 108 MHz
4	US ports per Node	2048	OFDMA Modulation	YES	Video in FDX Transition Band
32	SC-QAM 6 MHz ch	256	SC-QAM Modulation	1794	D4.0 Stop Frequency (MHz)
4	ATDMA 6.4 MHz ch	64	ATDMA Modulation	16.4	US Start Freq (MHz)

Figure 15 - Bandwidth with ESD + FDX, 2x4 DAA Node

The following post DOCSIS 4.0 scenarios are not official CableLabs projects, and are thus theoretical and for discussion and planning purposes.

The scenarios in Figure 15 combines FDX and ESD from DOCSIS 4.0. The upstream return path would be 204 to 684 MHz and the downstream path would extend to from 108 MHz to 1794 MHz. This could be an achievable design goal by combining the best of ESD and FDX. With video, there is enough downstream spectrum for a shared 10 Gbps and without video, there is about 15 Gbps of bandwidth. The upstream is about 5 Gbps. This could allow service offerings of 10 Gbps x 4 Gbps.

The DUCR values are low suggesting that all the upstream bandwidth may not get used. The OFDM channel count is high and could be a challenge for ASICs. The Ethernet bandwidth also exceeds the 25 Gbps limit, so either a 25 or 40 Gbps Ethernet would be needed.

4.7. Post DOCSIS 4.0 with 3 GHz ESD and 2x4 DAA Node

2 x 4 Node Capacity	Post D4.0 ESD with video						Post D4.0 ESD with no video					
Scenario	6	7	8	9	10	11	6	7	8	9	10	11
DS End MHz	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946
DS Start MHz	108	258	372	492	606	834	108	258	372	492	606	834
US Rtn Path MHz	85	204	300	396	492	684	85	204	300	396	492	684
VOD/SDV MPEG-TS	32	32	32	32	32	32	0	0	0	0	0	0
Linear Video MPEG-TS	64	64	64	64	64	64	0	0	0	0	0	0
DOCSIS DS port Gbps	21.8	20.3	19.2	18.0	16.8	14.6	27.5	26.0	24.9	23.7	22.6	20.3
DOCSIS US port Gbps	0.47	1.48	2.11	2.93	3.75	5.39	0.47	1.48	2.11	2.93	3.75	5.39
Ethernet DS Gbps	48.4	45.4	43.1	40.8	38.5	33.9	55.1	52.1	49.8	47.4	45.2	40.6
Ethernet US Gbps	1.9	5.9	8.4	11.7	15	22	1.9	5.9	8.4	11.7	15	22
DUCR, Avg	23.3	6.8	4.5	3.1	2.2	1.4	29.4	8.8	5.9	4.0	3.0	1.9
DUCR, Peak	46.6	13.7	9.1	6.1	4.5	2.7	58.8	17.5	11.8	8.1	6.0	3.8
ODFM ch per Node	22	20	20	18	18	14	28	26	26	24	24	20
OFDMA ch per Node	4	8	12	16	20	28	4	8	12	16	20	28
DOCSIS DS BW MHz	2262	2112	1998	1878	1764	1536	2838	2688	2574	2454	2340	2112
Cross-over MHz	23	54	72	96	114	150	23	54	72	96	114	150
DOCSIS US BW MHz	69	188	261	357	453	645	69	188	261	357	453	645

2	DS ports per Node	4096	OFDM Modulation	27	DS MHz skipped below 108 MHz
4	US ports per Node	2048	OFDMA Modulation	YES	Video in FDX Transition Band
32	SC-QAM 6 MHz ch	256	SC-QAM Modulation	2946	D4.0 Stop Frequency (MHz)
4	ATDMA 6.4 MHz ch	64	ATDMA Modulation	16.4	US Start Freq (MHz)

Figure 16 - Bandwidth with 3 GHz ESD, 2x4 DAA Node

The scenarios in Figure 16 is a 3 GHz version of ESD [14]. The value of 2946 MHz is derived from taking 1794 MHz from DOCSIS 4.0 ESD and adding six more 192 MHz OFDM channels.

The downstream bandwidth is nice and high and is around 25 Gbps with no video. What is interesting with the DUCR values is that 204 MHz is a good choice, especially if it is a dual-return upstream. However, this would limit service offerings to 1 Gbps. Alternatively, a single 396 MHz would work which could allow a 20 Gbps x 2 Gbps service to be sold.

The OFDM channel count is very high indicating yet another generation of silicon, which would be needed anyway to hit 3 GHz. The Ethernet bandwidth is hitting the 50 Gbps level now.

4.8. Post DOCSIS 4.0 with 3 GHz FDX and 2x4 DAA Node

2 x 4 Node Capacity	Post D4.0 FDX with video						Post D4.0 FDX with no video					
Scenario	6	7	8	9	10	11	6	7	8	9	10	11
DS End MHz	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946
DS Start MHz	108	108	108	108	108	108	108	108	108	108	108	108
US Rtn Path MHz	85	204	300	396	492	684	85	204	300	396	492	684
VOD/SDV MPEG-TS	32	32	32	32	32	32	0	0	0	0	0	0
Linear Video MPEG-TS	64	64	64	64	64	64	0	0	0	0	0	0
DOCSIS DS port Gbps	21.8	21.8	21.8	21.8	21.8	21.8	27.5	26.3	26.3	26.3	26.3	26.3
DOCSIS US port Gbps	0.47	1.29	2.11	2.93	3.75	5.39	0.47	1.29	2.11	2.93	3.75	5.39
Ethernet DS Gbps	48.4	48.4	48.4	48.4	48.4	48.4	55.1	52.7	52.7	52.7	52.7	52.7
Ethernet US Gbps	1.9	5.2	8.4	11.7	15	22	1.9	5.2	8.4	11.7	15	22
DUCR, Avg	23.3	8.5	5.2	3.7	2.9	2.0	29.4	10.2	6.2	4.5	3.5	2.4
DUCR, Peak	46.6	16.9	10.3	7.4	5.8	4.0	58.8	20.4	12.5	9.0	7.0	4.9
ODFM ch per Node	22	22	22	22	22	22	28	28	28	28	28	28
OFDMA ch per Node	4	8	12	16	20	28	4	8	12	16	20	28
DOCSIS DS BW MHz	2262	2262	2262	2262	2262	2262	2838	2718	2718	2718	2718	2718
Cross-over MHz	23	-96	-192	-288	-384	-576	23	-96	-192	-288	-384	-576
DOCSIS US BW MHz	69	165	261	357	453	645	69	165	261	357	453	645

2	DS ports per Node	4096	OFDM Modulation	27	DS MHz skipped below 108 MHz
4	US ports per Node	2048	OFDMA Modulation	YES	Video in FDX Transition Band
32	SC-QAM 6 MHz ch	256	SC-QAM Modulation	2946	D4.0 Stop Frequency (MHz)
4	ATDMA 6.4 MHz ch	64	ATDMA Modulation	16.4	US Start Freq (MHz)

Figure 17 - Bandwidth with 3 GHz FDX, 2x4 DAA Node

The scenarios in Figure 17 are a 3 GHz version of FDX, with and without video, on a 2x4 DAA node.

The bandwidths are higher than the 3 GHz ESD case since there is more downstream spectrum on each of the downstream ports (606 MHz per port). However, the downstream is slightly above 25 Gbps and will likely be held at 25 Gbps due to the Ethernet backhaul which will be dual 25 Gbps or 50 Gbps.

4.9. Post DOCSIS 4.0 with 3 GHz ESD and 4x4 DAA Node

4 x 4 Node Capacity	Post D4.0 ESD with video						Post D4.0 ESD with no video					
Scenario	6	7	8	9	10	11	6	7	8	9	10	11
DS End MHz	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946
DS Start MHz	108	258	372	492	606	834	108	258	372	492	606	834
US Rtn Path MHz	85	204	300	396	492	684	85	204	300	396	492	684
VOD/SDV MPEG-TS	32	32	32	32	32	32	0	0	0	0	0	0
Linear Video MPEG-TS	64	64	64	64	64	64	0	0	0	0	0	0
DOCSIS DS port Gbps	21.8	20.3	19.2	18.0	16.8	14.6	27.5	26.0	24.9	23.7	22.6	20.3
DOCSIS US port Gbps	0.47	1.48	2.11	2.93	3.75	5.39	0.47	1.48	2.11	2.93	3.75	5.39
Ethernet DS Gbps	94.4	88.4	83.9	79.1	74.6	65.5	110.1	104.2	99.6	94.8	90.3	81.2
Ethernet US Gbps	1.9	5.9	8.4	11.7	15	22	1.9	5.9	8.4	11.7	15	22
DUCR, Avg	46.6	13.7	9.1	6.1	4.5	2.7	58.8	17.5	11.8	8.1	6.0	3.8
DUCR, Peak	46.6	13.7	9.1	6.1	4.5	2.7	58.8	17.5	11.8	8.1	6.0	3.8
ODFM ch per Node	44	40	40	36	36	28	56	52	52	48	48	40
OFDMA ch per Node	4	8	12	16	20	28	4	8	12	16	20	28
DOCSIS DS BW MHz	2262	2112	1998	1878	1764	1536	2838	2688	2574	2454	2340	2112
Cross-over MHz	23	54	72	96	114	150	23	54	72	96	114	150
DOCSIS US BW MHz	69	188	261	357	453	645	69	188	261	357	453	645

4	DS ports per Node	4096	OFDM Modulation	27	DS MHz skipped below 108 MHz
4	US ports per Node	2048	OFDMA Modulation	YES	Video in FDX Transition Band
32	SC-QAM 6 MHz ch	256	SC-QAM Modulation	2946	D4.0 Stop Frequency (MHz)
4	ATDMA 6.4 MHz ch	64	ATDMA Modulation	16.4	US Start Freq (MHz)

Figure 18 - Bandwidth with 3 GHz ESD, 4x4 DAA Node

The scenarios in Figure 18 take the 3 GHz ESD scenarios and expand them to a 4x4 node.

We now see the capacity of the DAA node hit 100 Gbps. The DUCR values are the same for average and peak as the DAA node is single-return. This implementation packs around 50 OFDM channels into a node housing.

4.10. Post DOCSIS 4.0 with 3 GHz FDX and 4x4 DAA Node

4 x 4 Node Capacity	Post D4.0 FDX with video						Post D4.0 FDX with no video					
Scenario	6	7	8	9	10	11	6	7	8	9	10	11
DS End MHz	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946
DS Start MHz	108	108	108	108	108	108	108	108	108	108	108	108
US Rtn Path MHz	85	204	300	396	492	684	85	204	300	396	492	684
VOD/SDV MPEG-TS	32	32	32	32	32	32	0	0	0	0	0	0
Linear Video MPEG-TS	64	64	64	64	64	64	0	0	0	0	0	0
DOCSIS DS port Gbps	21.8	21.8	21.8	21.8	21.8	21.8	27.5	26.3	26.3	26.3	26.3	26.3
DOCSIS US port Gbps	0.47	1.29	2.11	2.93	3.75	5.39	0.47	1.29	2.11	2.93	3.75	5.39
Ethernet DS Gbps	94.4	94.4	94.4	94.4	94.4	94.4	110.1	105.4	105.4	105.4	105.4	105.4
Ethernet US Gbps	1.9	5.2	8.4	11.7	15	22	1.9	5.2	8.4	11.7	15	22
DUCR, Avg	46.6	16.9	10.3	7.4	5.8	4.0	58.8	20.4	12.5	9.0	7.0	4.9
DUCR, Peak	46.6	16.9	10.3	7.4	5.8	4.0	58.8	20.4	12.5	9.0	7.0	4.9
ODFM ch per Node	44	44	44	44	44	44	56	56	56	56	56	56
OFDMA ch per Node	4	8	12	16	20	28	4	8	12	16	20	28
DOCSIS DS BW MHz	2262	2262	2262	2262	2262	2262	2838	2718	2718	2718	2718	2718
Cross-over MHz	23	-96	-192	-288	-384	-576	23	-96	-192	-288	-384	-576
DOCSIS US BW MHz	69	165	261	357	453	645	69	165	261	357	453	645

4	DS ports per Node	4096	OFDM Modulation	27	DS MHz skipped below 108 MHz
4	US ports per Node	2048	OFDMA Modulation	YES	Video in FDX Transition Band
32	SC-QAM 6 MHz ch	256	SC-QAM Modulation	2946	D4.0 Stop Frequency (MHz)
4	ATDMA 6.4 MHz ch	64	ATDMA Modulation	16.4	US Start Freq (MHz)

Figure 19 - Bandwidth with 3 GHz ESD, 4x4 DAA Node

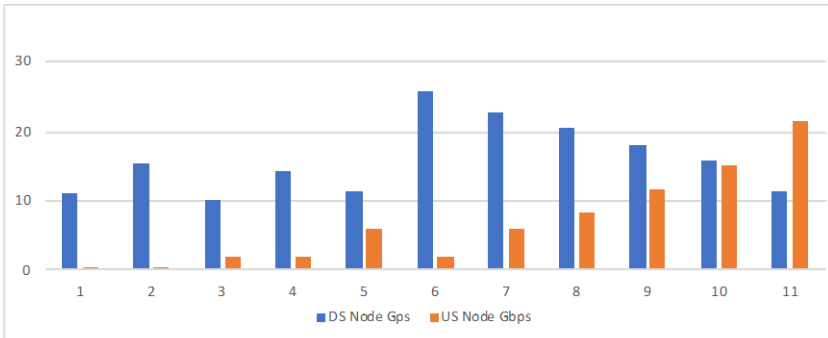
The scenarios in Figure 18 is a 3 GHz version of FDX with a 4x4 DAA node.

The downstream DOCSIS speeds are a healthy 25 Gbps per port which adds up to 100 Gbps downstream for the node. FDX has an extra 606 MHz per port which adds up across four ports. The DUCR levels are the same for average and peak since the number of downstream and upstream ports are the same.

100 Gbps per DAA node is impressive and an indication of where the CIN network may need to scale to in the future.

4.11. Summary of Calculations

HFC 2 x 4 Node Capacity



Summary

2 x 4 Node Capacity	User	DOCSIS 3.1 with MPEG video					DOCSIS 4.0 with MPEG video					
Scenario	Calc	1	2	3	4	5	6	7	8	9	10	11
DS End MHz	1002	1002	1218	1002	1218	1218	1794	1794	1794	1794	1794	1794
DS Start MHz	714	54	54	108	108	258	108	258	372	492	606	834
US End MHz	42	42	42	85	85	204	85	204	300	396	492	684
VOD/SDV MPEG-TS	0	32	32	32	32	32	32	32	32	32	32	32
Linear Video MPEG-TS	0	64	64	64	64	64	64	64	64	64	64	64
DOCSIS DS port Gbps	2.3	3.2	5.3	2.6	4.8	3.3	10.5	9.0	7.9	6.7	5.6	3.3
DOCSIS US port Gbps	0.10	0.10	0.10	0.47	0.47	1.48	0.47	1.48	2.11	2.93	3.75	5.39
Ethernet DS Gbps	4.7	11.1	15.4	10.1	14.4	11.4	25.8	22.8	20.6	18.2	15.9	11.4
Ethernet US Gbps	0.4	0.4	0.4	1.9	1.9	5.9	1.9	5.9	8.4	11.7	15	22
DUCR, Avg	11.6	16	26	2.8	5.1	1.1	11.2	3.0	1.9	1.1	0.7	0.3
DUCR, Peak	23.1	31	53	5.6	10.2	2.2	22.5	6.1	3.7	2.3	1.5	0.6
ODFM ch per Node	2	4	6	2	6	4	12	10	8	8	6	4
OFDMA ch per Node	0	0	0	4	4	8	4	8	12	16	20	28
DOCSIS DS BW MHz	288	372	588	318	534	384	1110	960	846	726	612	384
Cross-over MHz	-	12	12	23	23	54	23	54	72	96	114	150
DOCSIS US BW MHz	26	26	26	69	69	188	69	188	261	357	453	645

32	VOD/SDV MPEG-TS	1794	DS Stop MHz for D4.0	ESD	ESD or FDX for D4.0	4096	OFDM Mod
64	Linear Video MPEG-TS	16.4	US Start MHz	YES	Video in FDX Trans Band	2048	OFDMA Mod
2	DS ports per Node	24	ch SC-QAM @ 6 MHz	120	MHz FDX Trans Band	256	SC-QAM Mod
4	US ports per Node	4	ch ATDMA @ 6.4 MHz	24	MHz DS unused < 108	64	ATDMA Mod

<u>**Acceptance Criteria**</u>

Scenario	Calc	1	2	3	4	5	6	7	8	9	10	11
DS End MHz	1002	1002	1218	1002	1218	1218	1794	1794	1794	1794	1794	1794
US End MHz	42	42	42	85	85	204	85	204	300	396	492	684
1) DS Path ≥ 5 Gbps	47%	63%	106%	53%	96%	66%	210%	180%	158%	134%	111%	66%
2) 2 < avg DUCR < 20	173%	127%	76%	141%	255%	55%	178%	152%	94%	57%	37%	15%
3) US SF 1 Gbps, 0.4 K	7%	7%	7%	33%	33%	106%	33%	106%	151%	209%	268%	385%
4) 100% > 85 MHz US	-78%	-78%	-78%	0%	0%	217%	0%	217%	350%	526%	701%	1051%
Combined Results:	-78%	-78%	-78%	0%	0%	55%	0%	106%	94%	57%	37%	15%

Acceptance	1)	5	Gbps DS path min					Success Critieria	
Criteria	2)	2	DUCR min	20	DUCR max	avg	based	success if >	100%
	3)	1	Gbps US SF with	40%	of additional headroom (K)			borderline	
	4)	100%	more BW than a	85	MHz return path			reject if <	90%

Diplexer ratio %	1600%	29%	29%	27%	27%	26%	27%	26%	24%	24%	23%	22%

Figure 20 - DAA and DOCSIS Bandwidth Calculator

5. Conclusions

The future of DOCSIS is inter-twined with the DAA Node. The bandwidth and port density calculations that used to be done for a I-CMTS are now done for the DAA Node.

For any frequency plan, DAA has benefits over a conventional CMTS.

1. By placing the modulation in the node where there is a lower noise floor, high modulations can be run.
2. The number of nodes that a single physical CMTS can support increases, sometimes 4x or more
3. The fiber network is converted to a Ethernet based CIN which can now support PON, business services, and mobile backhaul.

Care must be taken that the DAA node has enough OFDM channels to support a particular configuration. The CIN network has to be designed to support the Ethernet capacity of the Node. DOCSIS 4.0 breaks through the 10 Gbps Ethernet capacity boundary. In the future, DAA nodes could approach 100 Gbps in downstream capacity.

DUCR was defined in this white paper as the ratio of downstream to upstream capacity of a node. The average DUCR took into account the number of ports and looks at the HFC plant from the CMTS perspective. The peak DUCR only looked at one downstream port and one upstream port and looks at the HFC plant from the CM perspective. High DUCR values indicate the downstream may not get fully utilized while low DUCR values indicate the upstream may not get fully utilized.

DUCR is a good tool for evaluating the usefulness of a deployment plan and is a measure of asymmetry. 5G uses a DUCR value of 5. A good target for cable would be 5 to 10 for average capacity. Too low a value indicates the upstream may not be fully used. Too high a value indicates that the downstream may not get fully used. CM ACK suppression allows this value to be artificially high.

Removing MPEG-TS video from the downstream spectrum works well to increase DOCSIS bandwidth. The example used in this white paper showed an increase of 3x in bandwidth, from 3 Gbps to 9 Gbps, on a 1002 MHz plant by just removing video. The 1218 MHz plant for DOCSIS 3.1 was useful for retaining the same downstream spectrum size as 42 to 1002, but with a 204 MHz lower limit. DOCSIS 4.0 ESD added even more bandwidth, but went over the 10 Gbps Ethernet backhaul ceiling.

The 42 MHz return path can be increased by 50% to 100%, from 100 Mbps to 200 Mbps, by removing two of the A-TDMA channels, adding OFDMA, moving the modulation to 2048-QAM, and starting at a lower frequency. An 85 MHz return path provided excellent return path bandwidth with great DUCR values. The 204 MHz return path added more bandwidth than needed on DOCSIS 3.1 and worked well for DOCSIS 4.0. DOCSIS 4.0 would benefit from two 204 MHz return path ports.

For 204 MHz to be deployed, all OOB signaling for video has to be removed from the plant, and OUDP updates have to be done to accommodate signal leakage detection. Return paths greater than 204 MHz have diminishing returns in a 1x2 node configuration, but are more attractive in a 1x1 configuration. Note that two 204 MHz return paths are roughly equivalent to one 396 MHz return path from an average capacity viewpoint.

It was also demonstrated that future silicon solutions could sub-split a node to 4x4 and if the plant went to 3 GHz, then nodes could approach 100 Gbps of capacity.

Abbreviations

ADC	analog-to-digital converter
ATDMA	advanced time division multiple access
CIN	converged interconnect network
CMTS	cable modem termination system
DAA	distributed access architecture
DAC	digital-to-analog converter
DPD	digital predistortion
DS	downstream
DUCR	downstream-to-upstream capacity ratio
ESD	extended spectrum DOCSIS
FDX	full duplex
FMA	flexible MAC architecture
HFC	hybrid fiber coax
I-CMTS	integrated CMTS
LC	line card
MUX	multiplexer
NDF	narrowband digital forward
NDR	narrowband digital reverse
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OOB	out of band
PPS	packets per second
QAM	quadrature amplitude modulation
RF	radio frequency
RMACPHY	remote MAC PHY
RPHY	remote PHY
SC-QAM	single carrier QAM
TCP	transport control protocol
TDD	time division duplex
US	upstream

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