# TAKING THE DOCSIS UPSTREAM TO A GIGABIT PER SECOND

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*Abstract*

*Fiber is here. The competition is deploying it. The cable operators are field trialing it. Is this the end for the HFC Plant? Is this the end for DOCSIS?*

*The on-going challenge for the HFC plant has always been its upstream bandwidth. This white paper focuses on the upstream and how technology can drive the upstream direction to a data capacity of 1 Gbps and beyond.*

*Included is an optimized upstream solution for existing plants consisting of six carriers for North American 5 – 42 MHz HFC plants and a ten carrier solution for European 5 to 65 MHz HFC plants.*

## INTRODUCTION

Imagine the access plant of the future 50 or even 20 years from now. What would it look like? Did the following thoughts come to mind?

- all fiber
- all IP
- 1 to 10 Gbps per subscriber
- symmetrical or close to symmetrical bandwidth
- multiple 100 GE connections to the backbone

Much of this technology exists today or will very soon. So why not skip all the intermediate steps and just build the network of the future today?

Here is where the technology vision must intersect with the business vision. Ultimately, what does it cost? And if it costs too much, is there an interim strategy that gets close to the performance needed but at a much lower price point?

This white paper addresses this issue with the specific focus on the upstream. The downstream direction is important as well, but that will be the subject of another white paper.

The first section of this white paper defines four upstream spectrum options for increasing upstream bandwidth. They are:

- Low-split
- Mid-split
- High-split
- Top-split

The next section of this white paper looks at the operational and technical challenges with these options. Topics include:

- Deep fiber
- Spectrum allocation
- Transition Plans
- Analog TV
- Legacy OOB
- Legacy tuners
- CM upstream power amp
- Aeronautical interference
- Optical node technology
- Amplifier technology
- In-line equalizers
- RF transmission path
- Plant power
- Professional installation

The final section then covers the cost of each of the four techniques and compares it to a fiber build.

## UPSTREAM SPECTRUM OPTIONS

There are at least four general approaches for providing upstream bandwidth with respect to the RF spectrum. These are shown in Table 1 and explained below. Note that these are variations on the classic mid- and high-split frequency plans long used by cable operators. The data capacity is calculated in this white paper based upon assumptions stated in this white paper.

This section focuses on the definition of these options. The pros and cons of each approach are covered in later sections.

| Name | Upstream Frequency Range | RF BW | Data Capacity |
|---|---|---|---|
| Low-Split | 5-42 MHz<br>5–65 MHz | 37 MHz<br>60 MHz | 120 Mbps<br>210 Mbps |
| Mid-Split | 5–85 MHz | 80 MHz | 300 Mbps |
| High-Split | 5–200 MHz | 195 MHz | 770 Mbps<br>1 Gbps |
| Top-Split | > 1 GHz | 1 GHz | 2.2 Gbps<br>3.6 Gbps |

**Table 1** – Upstream Spectrum Options

Low-Split

A low-split system is what is in use today. In the USA, low-split refers to 5 MHz to 42 MHz with downstream spectrum beginning at 54 MHz. In most of Europe, low-split refers to 5 MHz to 65 MHz with downstream spectrum beginning at 85 MHz.

Table 2 below shows the upper bound of the upstream spectrum and the lower bound of the downstream spectrum for various countries.

The spectrum below 20 MHz is quite noisy and is generally not used by DOCSIS. 26-28 MHz is the CB (Citizen's Band radio) and is usually avoided.

| Region or Country | Band Split |
|---|---|
| North, Central and South America | 42/54<br>40/54<br>30/52 |
| China, Korea, Philippines, Thailand, Singapore, Australia | 65/85 |
| Japan, New Zealand | 55/70 |
| India, Malta, Eastern Europe | 30/48 |
| Western Europe, Ireland, United Kingdom | 65/86 |

**Table 2** – HFC Band Splits

There are many ways that this spectrum is used. The upstream spectrum may be shared between:

- DOCSIS 1.0, 1.1, 2.0, and 3.0 CMs,
- legacy set-top box (STB) out-of-band (OOB) return path signaling channel,
- legacy TDM voice
- Telemetry (power supplies, nodes, amps, sweeps).

It is reasonable to assume that the legacy TDM voice either no longer exists or will not exist in a full DOCSIS scenario. The legacy OOB channel and telemetry usually can be hidden in spectrum below 20 MHz that is not used normally by DOCSIS.

So how much data capacity can DOCSIS extract out of the current upstream path? To answer that, it is useful to look at a max-fit six carrier (for North America) scenario that is emerging. The European scenario could contain up to 10 carriers. This is shown in Table 3.

| # | From (MHz) | To (MHz) | BW (MHz) | Modulation | Style | Primary Usage |
|---|---|---|---|---|---|---|
| 10 | 61.4 | 64.6 | 3.2 | 64-QAM | ATDMA | D3.0 (Europe only) |
| 9 | 54.8 | 61.2 | 6.4 | 64-QAM | ATDMA | D3.0 (Europe only) |
| 8 | 48.2 | 54.6 | 6.4 | 64-QAM | ATDMA | D3.0 (Europe only) |
| 7 | 41.6 | 48.0 | 6.4 | 64-QAM | ATDMA | D3.0 (Europe only) |
| 6 | 35.0 | 41.4 | 6.4 | 64-QAM | ATDMA | D3.0, D2.0 |
| 5 | 28.4 | 34.8 | 6.4 | 64-QAM | ATDMA | D3.0, D2.0 |
| 4 | 23.6 | 26.8 | 3.2 | 16-QAM | TDMA | D1.1, D1.0 |
| 3 | 20.2 | 23.4 | 3.2 | QPSK | TDMA | D1.0, DSG |
| 2 | 13.6 | 20.0 | 6.4 | 64-QAM | SCDMA | D3.0 |
| 1 | 7.0 | 13.4 | 6.4 | 64-QAM | SCDMA | D3.0 |

**Table 3** – Maximum Upstream Spectrum Usage

DOCSIS 3.0 CMs that are being deployed are capable to transmitting four return path carriers. Those carriers are being pushed to their maximum modulation of 64-QAM with a 6.4 MHz RF bandwidth. The data capacity of each carrier, assuming 10% overhead, is approximately 27 Mbps. So, in theory, four carriers will allow slightly more than 100 Mbps upstream performance.

DOCSIS 2.0 CMs do not understand bonding, but they do understand the higher order modulation that DOCSIS 3.0 CMs use. Thus, DOCSIS 2.0 CMs can share the same carriers that DOCSIS 3.0 uses.

Table 3 suggests that two ATDMA carriers are enough for DOCSIS 2.0. This is based upon a limited deployment of DOCSIS 2.0 CMs. This also limits load balancing algorithms and allows the SCDMA channels to focus on optimizing performance with only DOCSIS 3.0 CMs.

DOCSIS 1.1 CMs only support carriers up to 16-QAM modulation and 3.2 MHz bandwidth. In order to allow DOCSIS 2.0 and 3.0 CMS to run at optimum speeds, a completely separate carrier is required for legacy DOCSIS 1.1 CMs. Assuming about a 10% overhead, the maximum data capacity of a DOCSIS 1.1 carrier is 9 Mbps. This would be a 5th carrier.

Then there are STBs with embedded cable modems (eCM) in them. It turns out that these STBs do not get the same preferred home wiring treatment. The STBs are often located behind several layers of splitters. The result is that the attenuation of the reverse path in the home is too much for the eCM in the STB to transmit on.

Thus, when DSG is enabled, it does not always work. DSG (DOCSIS Set-top Gateway) is a protocol that places the STB downstream OOB signaling protocol into an IP tunnel that is managed by DOCSIS, and uses the upstream for signaling advanced services such as video on demand (VOD) and pay per view (PPV).

The practical solution has been to use a dedicated carrier that runs at 1.6 MHz bandwidth and with a modulation of QPSK. The result is an upstream carrier that is more tolerant of noise and can work when the CM is operating a maximum power. The throughput of this carrier is about 2 Mbps. This would be a 6th carrier.

DOCSIS 1.0 CMs support the same modulation as DOCSIS 1.1 so they can share the same carrier. (5th carrier) However, since DOCSIS 1.0 was the first version of DOCSIS available, there are DOCSIS 1.0 CMs out there that do not behave well on a plant. Many of them are from manufacturers who are no longer in business and the software is out of date.

In general, cable operators have tried to eliminate the DOCSIS 1.0 CMs from their network. When they still exist, and they cause problems, the easiest solution is to put them on a dedicated upstream so they do not interfere with the other CMs. This would be a 6th carrier.

Summing these values together, the upstream capacity of a 5-42 MHz spectrum is (4 * 27 Mbps) + 9 Mbps + 2 Mbps ~= 120 Mbps.

The European upstream has an extra 22 MHz of bandwidth. The most aggress use of upstream spectrum would be to assume three 6.4 MHz carriers and one 3.2 MHz carrier. That would allow two sets of bonding groups at 4 channels per bonding group. The total data capacity would be 119 + 94.5 ~= 210 Mbps

Mid-Split

There have been various definitions of mid-split. Some earlier mid-split networks had an upstream frequency range of 5 MHz to 108~116 MHz. This white paper is going to use the newer definition of mid-split with a frequency range defined by DOCSIS 3.0.

DOCSIS 3.0 has an upstream frequency range of 5 MHz to 85 MHz and comes up just below the FM band of 88 MHz to 108 MHz. Downstream spectrum starts at 108 MHz.

To compare data capacity, lets assume the 5 MHz to 42 MHz spectrums remains the same. 44 MHz +/- 3 MHz should be avoided as explained later (section ref TBD) to avoid adjacent tuner issues. That would define the additional spectrum as 47 MHz to 88 MHz. This is an additional 41 MHz of spectrum. (oddly enough, this is the square of 6.4).

41 MHz could handle an additional six 6.4 MHz carriers (6 * 6.4 MHz = 38.4 MHz). If one pushed it, a 3.2 MHz carrier might also fit, although it could not be used by legacy 1.1 CMs because the operating frequency would be too high. The resulting additional data capacity would be 175 Mbps ( 6.5 * 27 Mbps). The total upstream data capacity, when including the baseline of 120 Mbps, would then be approximately 300 Mbps.

High-Split

There have been various definitions of high-split. Some earlier high-split networks had an upstream frequency range of 5 MHz to 162~174 MHz [FSN]. This white paper is going to use a different definition of high-split that is motivated by picking a frequency range that can support 1 Gbps of data payload.

High-split is not currently defined in DOCSIS. The proposed frequency range for high-split in this white paper is 5 MHz to 200 MHz. Downstream spectrum would start at 258 MHz. The split of 258/200 gives the same diplex filter shape factor as a 54/42 split (54 divided by 42 = 258 divided by 200 = 1.29). This means the filters in the CPE will have the same complexity as existing designs.

An alternate definition would be to define 5 MHz to 20 MHz as a legacy band for non-DOCSIS use (OOB, telemetry), and 20 MHz to 200 MHz for DOCSIS use.

Since there are no CMs that can drive this new frequency range, new one will have to be built. That means that different modulations could be used.

To estimate the upstream data capacity, two scenarios are suggested.

- ATDMA, 6.4 MHz carriers, 64-QAM, 47 MHz to 200 MHz

- OFDM, 50 MHz FFT blocks, 256-QAM, more advanced FEC, 33% overhead for cycle prefix, pilot tones, and FEC.

For ATDMA, the spectrum would support 24 carriers (( 200 – 47 ) / 6.4 ) for an additional data capacity of approximately 650 Mbps (24 carriers * 27 Mbps/carrier). When added to the 120 Mbps baseline, the result is 770 Mbps.

For OFDM, the presumption is that with more work and with an improved FEC, that the modulation could be improved enough to support a level of 256-QAM. The data capacity of three OFDM FFT (Fast Fourier Transform) blocks would be approximately (3 * 50 MHz * 8 bits/hertz * 66%) is 750 Mbps.

The total upstream data capacity, when including the baseline of 120 Mbps, would then be approximately 870 Mbps. If the OFDM was applied to the 5 to 50 MHz range, the bit rate would be 1 Gbps.

Top-Split

Top-split refers to placing the upstream spectrum above 1 GHz. There are no real standards or proposals here. One concept is to carve out 1 GHz to 1.2 GHz for MoCA (MoCA D channels start at a center frequency of 1150 MHz and go to 1500 MHz), use 1.3 GHz to 1.8 GHz for upstream spectrum, and reserve 2 GHz to 3 GHz for downstream spectrum.

If a HGW strategy is used where MoCA is only on the home network and top-split is only on the access network, then there is no need to set aside bandwidth for MoCA as the two will never exist on the same media.

Table 4 shows the potential data capacity of a top split system. A 500 MHz RF bandwidth is presumed with an OFDM modulation and 75% bandwidth efficiency.

| Modulation | Bits Per Hz | Data Capacity |
|---|---|---|
| 64-QAM | 6 | 2.2 Gbps |
| 256-QAM | 8 | 3 Gbps |
| 1024-QAM | 10 | 3.75 Gbps |

**Table 4** – Top-Split Data Capacity

The upstream transmitter is generally more expensive than a classic DOCSIS upstream transmitter. Because DOCSIS uses lower frequencies, the upstream spectrum can be directly generated with a DAC (digital to analog converter).

Top-split requires the classic approach of generating an I.F. (intermediate frequency) and then using an upconverter and power amp to get to the target spectrum with the correct power level.

This usually involves adding tripexors to the network. If there is additional downstream spectrum placed up above the new upstream, it could even require quadplexors.

The top-split could be built as a separate overlay network with the existing HFC plant, or as a last mile extension on a node plus zero (N+0) architecture.

For long distances, the modulation technique might be a lower order spread across frequency. For a short distance, a high order modulation could be used.

If the last mile was passive, perhaps even a TDD (time division duplex) could be used to achieve bi-directional bandwidth expansion instead of FDD (frequency domain duplex).

## OPERATIONAL CHALLENGES

This section deals with the challenges and potential solutions involved with implementing a new return path. It should come as no surprise that none of the four techniques are without controversy, complexity, compromise, or cost.

### Deep Fiber

In order to expand the bandwidth of a low-split solution, service groups (SGs) have to be split. This could occur within existing fiber nodes but often requires that fiber has to be pushed deeper. By splitting service groups, more physically separated upstreams exist.

For example, to increase the overall upstream capacity of a single 500 HHP SG from 100 Mbps to 1 Gbps would require the node to be split into ten 50 HP SGs. Usually splits are done in powers of two, so this might really be 8 SG of 62 HHP per SG (on average).

Splitting SGs creates more SGs with less subscribers per SG. While this mathematically provides the same data capacity as a faster upstream, in practice it is not as good. The peak rate will always be limited to the media speed. With a max shared DOCSIS capacity of 100 Mbps, the offered rate per user may only be 50 Mbps which will eventually not meet the needs of the market.

Also, when SGs get smaller, statistical multiplexing is lost. In practice, SG sizes will still vary based upon geography, and subscriber density will be uneven.

Splitting SGs translates to cost. Upgrading the fiber node, adding deeper fiber, adding additional fiber or wavelengths on the existing fiber runs to get 10x the backhaul capacity to the hub costs money. And with 10x the number of returns paths, 10x the number of upstream ports on the CMTS will also be needed. That is also a cost issue.

However, the methodology and technology for doing service group segmentation is simple, well-known, and somewhat optimized. Technologies such as RFOG (RF over Glass) provide a method of achieving a deeper fiber architectures while maintaining the existing data and video infrastructure.

The other three solutions gain more data capacity through spectrum expansion. So, in theory, mid-split and high-split require less or no changes to SG sizes or deeper penetration of fiber, unless the data capacity of the new spectrum is insufficient.

### Impact to Spectrum Allocations

Low-split maintains the existing spectrum plan. No change to the upstream spectrum also means no change to the downstream spectrum and no change to the customer CPE.

Mid-split requires the removal of channels 2 through 6 and channels 95 though 97 (and channel 1 if present). This is 9 channels or 54 MHz of spectrum removed out of the downstream path. The channel count for a 750 MHz system would be reduced from 116 to 107 which is a 7.7% reduction in capacity. If that 750 MHz system was upgraded to a 1002 MHz system with 148 channels (due to mid-split), then that system will see a net gain of 28% in downstream capacity. This is shown in Table 5. [CT-1] [CATV-NA] [CEA-1]

| DS spectrum | Current Channel Count | New Channel Count | Relative Impact | Net Impact |
|---|---|---|---|---|
| 750 MHz | 116 | 106 | - 7.7% | +28% |
| 862 MHz | 135 | 125 | - 7.4% | +10% |
| 1002 MHz | 158 | 148 | -6.3% | -6.3% |

**Table 5** - Impact of a 88/108 MHz Mid-Split and 1002 MHz upgrade on DS Spectrum

High-split requires the removal of channels 2 through 29 (and channel 1 if used) as well as channels 95 though 99. This is 34 channels or 204 MHz of spectrum removed out of the downstream path. The loss of DS channels from high-split and the improvement from upgrading the downstream to 1002 MHz is shown in Table 6.

The removal of downstream spectrum generally will make it imperative for the downstream spectrum to upgrade to 1 GHz if it has not already. The good news is that the upstream and downstream spectrum upgrades share a lot of components and labor costs. Thus, it would be a waste of capital to not include a downstream upgrade at the same time as the upstream upgrade.

| DS spectrum | Current Channel Count | New Channel Count | Relative Impact | Net Impact |
|---|---|---|---|---|
| 750 MHz | 116 | 82 | - 29% | + 7% |
| 862 MHz | 135 | 101 | - 25% | - 8% |
| 1002 MHz | 158 | 124 | - 22% | - 22% |

**Table 6 -** Impact of a 200/258 High-Split and 1002 MHz upgrade on DS Spectrum

Top-split also maintains the existing spectrum. However, it caps the downstream spectrum to a particular frequency (say 1 GHz) that could limit future downstream growth. It builds new spectrum above 1 GHz. This means additional cost in plant operations, maintenance, and customer CPE.

Transition Planning

Mid-split and high-split require the removal of downstream spectrum. This has to happen prior to the start of the plant upgrade. The new downstream spectrum from a 1002 MHz upgrade may not be available until after the upgrade.

That may leave a window during the upgrade cycle where there is a spectrum shortage. That might not be acceptable. Clever planning with duplication of channels in the low spectrum and high spectrum will be needed along with pre-positioning of CPE equipment to ensure a smooth cut-over.

Analog TV

Low-split and top-split do not impact analog TV deployment. While mid-split delivers a severe blow to analog TV services with the removal of channels 2 through 6, high-split effectively backs up the truck and runs analog TV over.

The loss of the lower analog channels 2 through 6 are politically the hardest to get rid of. Getting rid of analog TV also may commit the operator to deploying millions of low-end DTAs (Digital Terminal Adaptors) that would be need to support all the remaining analog TVs.

To seriously deploy a mid-split or high-split system, it is probably time to get rid of all analog TV. While this may be inevitable for some cable operators, for others it would be a tough trade-off

Legacy OOB

Legacy STBs that do not use DSG (DOCSIS Set-top Gateway) instead use a discrete downstream and upstream carrier for communications with the headend. The downstream carrier is 1 MHz wide for SCTE 55-2 (Cisco) and approx 1.7 MHz wide for SCTE 55-1 (Motorola). Typical placement of center frequency is between 73.25 and 75.25 MHz as there is a gap between channels 4 and 5. The older "Jerrold" pilot (prior to Motorola/GI) was at 114 MHz. By spec, the STB must be able to tune up to 130 MHz.

There are no compatibility issues with the STB OOB channel and low-split or top-split.

For mid-split, the OOB channel can be placed above 108 MHz in the downstream spectrum. This should work unless there are some old STB that either can't find the new frequency or don't really support it.

For high-split, this is probably the biggest issue. The 200 MHz cutoff for high-split is well above the 130 MHz upper end of the OOB tuner range. So what to do?

This is primarily a North American issue. In the rest of the world where legacy STB penetration is much lower or non-existent, it may not be a significant issue.

The first approach would be to completely replace legacy STB with DSG capable STB or with STB that can tune the OOB channel above 258 MHz. The challenge with this approach is that 100% of the legacy STB have to be removed before high-split can be enabled.

The second approach would be to send an adaptor to any household that has a STB and has not upgraded to a high-split system. That adaptor might receive DSG and put out a legacy OOB signal. This issue with this approach is that that OOB adaptor design has to be agreed to, manufactured, tested, paid for, shipped, and installed. And once again, 100% of the STB population needs this adaptor before any high-split can be deployed.

The third solution is to provide some sort of OOB source or path deep in the HFC network that can inject the OOB signal into the upstream path. The installation of this solution would be done at the time of the plant upgrade. This is an area for ingenuity.

Legacy Tuners

Tuners in STBs and TVs in North American receive above 54 MHz with an expected maximum input power of +17 dBmV. Low-split and top-split co-exist with legacy tuners. Mid-split and high-split systems output RF energy in the upstream that is within the downstream operating range of the legacy STB and TVs.

If those devices are located near a CM that is blasting out energy above 54 MHz at levels approaching +57 dBmV (DOCSIS 3.0 max power for single 64-QAM), the power levels could saturate the input amplifiers of the legacy tuners, thus preventing the device from receiving a signal at any frequency.

So, what to do? There are several options.

First, it is worth noting that the typical tuner has an output intermediate frequency centered at 44 MHz. If 44 MHz was applied to the input of the tuner, it might pass directly through to the tuner output. Thus, it would be prudent to avoid transmitting any upstream frequencies from 41 to 47 MHz. That is easily done as the DOCSIS 3.0 North American spectrum stops at 42 MHz, so new carriers can be placed above this band.

The general problem is best split up into two smaller scenarios:

- Impact within the same home
- Impact to adjacent homes

The signal levels will be much higher when the CM and legacy tuners are within the same home.

One solution is to put a bandstop filter that would prevent frequencies above 42 MHz and below 85 MHz (for mid-split) or 200 MHz (for high-split) from reaching the legacy device. These bandstop filters need to leave the legacy upstream operating.

Bandstop filters would work for legacy TVs, but may not work for legacy STBs as the bandstop filter would block the downstream OOB signal (typically at 75 MHz). To let the

75 MHz carrier from the headend through but to block the local 75 MHz would require a directional coupler and very specific wiring. This is possible but very error prone.

Should a filtering solution be pursued, having the new upstream spectrum avoid using the downstream OOB frequency range might help the situation. (for example, 74-76 MHz).

Another solution is to avoid the problem altogether. The premise would be that the home gateway (HGW) would be deployed along with a video over IP strategy. The new CM is deployed as a HGW at the edge of the home.

The HGW becomes a demarcation point between DOCSIS and the cable plant on one side, and MoCA and the home network on the other side. This does imply a professional installation (to be discussed in a subsequent section).

DOCSIS could be terminated at the HGW and the HGW would drive the coax in the house with MoCA. Video and data would be deployed with IP STBs that interfaced to the MoCA network.

This is an interesting proposal in several ways. First, it solves the in home legacy tuner interference problem. Second, it isolates all the noise generated by the home network and prevents it from the HFC plant. Third, the HGW can get by with a lower transmit output power level.

It should be noted that there are other HGW upgrade scenarios that pass the downstream spectrum through to legacy STB rather than replacing the STBs.

The other half of the problem was the impact to adjacent homes. The interfering signal would have to travel up the drop from the home, travel between the output ports on the splitter, back down the drop to the next house, and then into the home network of the next house.

The easiest solution would be to set the new upstream power budget such that the signal would be sufficiently attenuated by the path described above so that it would not be a problem. This solution become harder when the customers are in a mutli-dwelling unit (MDU) where the coax drops are short.

There is an additional problem in MDU's where the outlets are cascaded or daisy-chained, where one drop is run to the next, then the next, and so on. This means you cannot easily use MoCA to provide the video and data channels to an individual customer without all customers on that run using the same MoCA channels. MoCA can address this problem through the use of provisioned VLANs.

Worst case, bandstop filters would have to be applied to the drop lines as they leave the in-line tap.

<u>CM Upstream Power AMP</u>

A DOCSIS CM must be capable of transmitting four 64-QAM carriers at +51 dBmV per carrier. [PHY] It should be noted that this is the output transmit power of the upstream amplifier.

The amplifier itself dissipates much more power than this because it tend to be a class A amp which have strong bias currents, and it must operate off of voltage rails large enough to support the dynamic range of the output signal.

An example is the ADA4320-1 from Analog Devices. It has drive current levels that can be programmed to match the number of carriers. For four carriers, it uses about 1.2 W; for one carrier, it uses about 1.0 W. Note it uses a supply voltage of 5 V, D2.0 amps used 3.3 V supplies.

If the new CM was expected to maintain the same Power Spectral Density (PSD) or received power per DOCSIS upstream channel, it the additional output required can be calculated from follows the equation: 10*log10(BW_ratio). [CT-2]

For DOCSIS 3.0, the bandwidth of the four carriers is 4 * 6.4 MHz = 25.6 MHz.

For mid-split, the new spectrum from 46 MHz to 85 MHz which is 39 MHz. The additional power required for mid-split would be

$$10*\log10( 39/25.6 ) = 1.8 \text{ dB}$$

For high-split, the new spectrum from 46 MHz to 200 MHz which is 154 MHz. The additional power required for mid-split would be

$$10*\log10( 154/25.6 ) = 6 \text{ dB}$$

Note that doubling the bandwidth is double the power or +3 dB.

This additional power may create cooling problems in the CM upstream power amplifier. There are several solutions.

The first is to use the HGW architecture and to lower the required power level by at least the additional power calculated above.

A second solution is to turn the power amp off in between transmission bursts. This would allow the CM to burst a full rate for a while, but ultimately the rate would have to be lowered so accommodate the on/off duty cycle required for the amp. (note that this is done today on DOCSIS 3.0 CMs).

Aeronautical Interference

The frequencies from 108 MHz to 138 MHz are used for Maritime Mobile and Radio Navigation. This is shown in Figure 1 [SPECTRUM].

The new CM may be transmitting the frequencies from 108 to 138 MHz at a higher power level than the frequencies where transmitted when they were part of the downstream spectrum. The inherent leakage in the plant might be sufficient enough to cause interference.

Research would have to be done to validate this concern. If it is a problem, then the plant will have to be cleaned up to reduce this leakage.

This concern also existed 15 years ago prior to the deployment of DOCSIS. The plant did require cleaning up in many cases. It was done and the result was an HFC plant a more reliable plant. So, it is doable, but must be planned and budgeted for.

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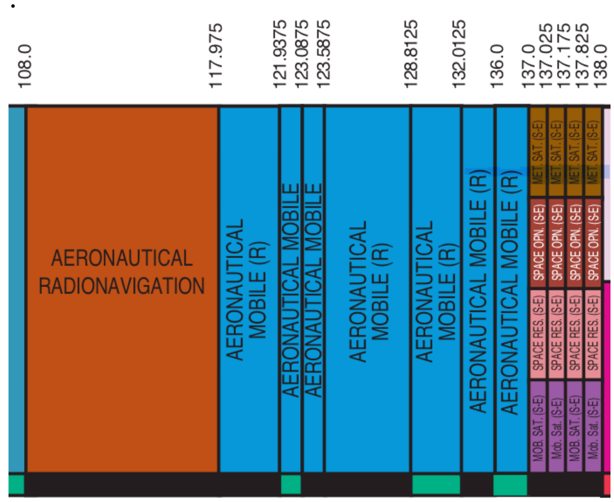


**Figure 1** – Government Spectrum Allocation from 20 MHz to 200 MHz [CATV-NA]

Optical Node Technology

Optical nodes have two common choices for return path lasers. They are Fabry-Perot

(FP) lasers and distributed feedback (DFB) lasers. The optical return path can either be analog or digital (such as Cisco's Baseband Digital Reverse [BDR])

The FP lasers are lower performance and less expensive, but will work for one to two DOCSIS carriers. In order to carry a full four or six carriers, or to handle either mid-split or high-split, the optical node has to be upgraded to a DFB return path laser.

An alternative approach is to put the upstream demodulation electronics in the optical node instead of the hub site. This could be done at the existing optical node location, thus preserving the N+5 (or whatever) cable plant.

This shortens the DOCSIS return path by eliminating the optical segment. Now, instead of having a return path extending from inside the home all the way to the hub, it can be from the edge of the home up to the optical node. Rather than a 100 mile radius, it might be more like a one to two mile radius.

With the upstream QAM demodulators in the optical node and a shorter return path, the transmission impairments normally introduced by the electrical to optical and back to electrical are gone. This allows the transmission path to operate at higher rates.

Also, the optical path leaving the optical node can now be digital. This allows for a less expensive laser to be used. In fact, QAM demods could be placed on each of the up to four physical ports of the optical node. This would segment the optical node without the need of running fiber to the next active. Yet, there would be enough digital bandwidth on upstream fiber that only one wavelength and laser would be required.

The one big caveat on this approach is the handling of non-DOCSIS upstream carriers such as legacy OOB and plant telemetry (monitoring of power supplies, amps, nodes). That might require separate demods or just a digitization of a limited amount of spectrum that can be packetized and sent up to the hub.

For mid-split, the return path amplifier in the optical mode may have the required bandwidth depending upon the age of the optical node. For high-split, there is a higher likelihood the return path amplifier will need to be upgraded.

For top-split, an entirely new optical node is often used that is in parallel with the current optical node or deeper in the fiber network. It manages the top-split as an overlay network. This new optical node would either use separate fibers or separate wavelengths to connect to the hub site.

Mid-split and high-split would require that the diplexers in the optical node be changed. In some optical nodes these are pluggable while in other optical nodes they are soldered in. This depends upon the manufacturer of the optical node and the customer requirements.

For all of these reasons, worst case, a mid-split or high-split upgrade will require a swap of the optical node.

Amplifier Technology

For mid-split, the return path amp may work and if the downstream is not upgraded, the downstream amp may be sufficient. The diplexors will need upgrading.

For high-split, there is a small probability that the return path amp may not work at 200 MHz and will need upgrading. If the downstream is to be upgraded to 1002 MHz, the downstream amp will need upgrading. The diplexors will need upgrading.

For top-split, there has typically been a bypass amp that is placed in parallel with the current amps. It has its own triplexors and two-way amps. A more practical solution would be swap out the amplifier with a new triplex amp.

Since the attenuation of the coax is higher above 1 GHz than below 1 GHz, top-split needs closer amplifier spacing. An HFC plant that is built using maximum distance between conventional amplifiers may need additional amplifiers added to the network.

For all of these reasons, worst case, a mid-split, high-split, or top-split upgrade will require a swap of the amplifier.

In-Line Equalizers

Some HFC plants have passive in-line equalizers. These equalizers use diplexors to isolate the downstream from the upstream so that the passive equalizer can be inserted.

For mid-split and high-split, the in-line equalizers would have to have their diplexors upgraded.

For top-split, the equalizer has to be overlaid with a new device that supports the top-split upstream.

Upstream RF Transmission Path

Low-split extends from 5-42 MHz. The spectrum from 5 MHz to 22 MHz is often special cased due to the presence of noise. If 5-20 is ignored, 20 to 42 MHz is one octave (a doubling of frequency).

Mid-split would contain approximately 2 octaves and high-split would contain approximately 3.3 octaves.

What type of transmission parameters could shift over the span of 3.3 octaves that would become noticeable? Tilt? Group delay? Ideally, the plant would spec its worst case transmission performance, and it would be the job of the new electronics in the new mid-split and high-split devices to compensate.

Plant Power

Mid-split and high split may add new electronics such as QAM modulators or demodulators to the optical node that may increase its power dissipation.

High-split adds an overlay network of optical nodes and amplifiers that will increase overall power requirements for the HFC plant. The HFC plant is powered. That powering typically comes from a mains power at the hub site with backup generators in case of a mains failure. Upgrading these facilities is a cost that should be factored in. Even an increase the power draw on existing facilities is an increase in cost.

Professional Installation

Installation practices vary across cable operators. Some cable operators have separate truck rolls for data, voice, video, cable card, and then a final truck roll to fix everything that did not work.

Other Cable Operators are able to sell DOCSIS service through web signup and mailing a CM. A truck roll is only done when things do not work out.

This latter scenario might not be possible if a CM upgrade is combined with an IP STB and HGW upgrade, along with a check of signal levels, emission levels, and impact on adjacent dwellings.

Table 7 summarizes these operational issues with respect to the 4 solutions under consideration.

| Approach | Pros | Cons |
|---|---|---|
| Low-Split | • All equipment already exists<br>• No disturbance to spectrum<br>• Simple | • Cost: Requires deeper fiber.<br>• Cost: Requires more CMTS ports<br>• Cannot hit peak rates over 100 Mbps of return path throughput |
| Mid-Split | • Supported by DOCSIS 3.0 equipment<br>• Works with DS OOB | • All actives in HFC plant need to be upgraded<br>• Cost about the same as high-split and only doubles the US throughput |
| High-Split | • Supports 1 Gbps throughput<br>• Can co-exist with earlier versions of DOCSIS. | • All actives in HFC plant need to be upgraded<br>• Does not work with DS OOB<br>• New CM and CMTS components |
| Top-Split | • Leaves existing plant in place.<br>• No Impact to existing legacy customer CPE<br>• Only customer taking new tiers would require new HGW CPE | • Requires triplexors<br>• New active return path has to be build on top<br>• Inefficient use of spectrum<br>• High attenuation requires high power. Existing amplifier spacings may not be sufficient<br>• Blocks expansion of downtream bandwidth directly above 1 GHz |

**Table 7** – Summary of Operational Issues

## COST

For all these solutions, the bottom line is:

- Does it work?
- What does it cost?

There are 6 baseline cost scenarios to be considered.

1) The cost of doing nothing
2) The cost of all fiber
3) The cost of low-split
4) The cost of mid-split
5) The cost of high-split
6) The cost of top-split

There are more variations, but this is a good baseline. Now, some caveats.

- Any analysis has lots of assumptions. This one does as well. Therefore, your mileage will vary.
- This is not a price quote. I'm winging it here. Don't take this to the bank.
- My main interest is comparisons. Thus absolute accuracy level could be off by 50% to 100%.
- Costs change with time, technology, and vendor.

There seems to be multiple way of quoting costs for plant upgrades. Be careful when comparing numbers. The ways are:

- $ per mile
- $ per subscriber
- $ per home passed

I am going to use per home passed as that metric is the most common usage in the DOCSIS world.

HFC Plants are often described a N+5 or N+0, etc. The N means node and represents the optical node. The number following this is the number of max number of amplifiers in a row to get to the last mile. The common design point for current HFC networks is N+5. A deep fiber network with no actives in the coax plant is considered an N+0 architecture.

### The Cost of Doing Nothing

Doing nothing can be a viable alternative. It is the lowest cost option, but may not be the best revenue option. If there is competition, inaction can lead to a loss of customers and a loss of revenue.

The other risk is not spending enough when there is an upgrade. For example, if there is an upgrade to IP video which leads to large equipment swaps, performing additional upgrades at the same time may lower cost of both upgrades.

### The Cost of All Fiber

This is the opposite of doing nothing. It is doing everything.

With the advent of new RFOG PON and upcoming DOCSIS EPON technologies, building a fiber to the home network is technically possible. It is also the most expensive solution.

One place to get a reference is the published costs by other of FTTH solutions. Bear in mind, these are usually second hand information, so accuracy may vary.

Bell Canada [FASTNET]

- $650/HP to pass a home

France [FASTNET]

- $650/HP to pass a home

Google: [FASTNET]

- $700/HP to pass a home

Verizon [VERIZON]

- $750/HP to pass a home
- $600/HP additional to connect a home

These prices tend to be for aerial plants. If the fiber is underground, cost could be typically 75% higher.

Telcos have some fiber in the local loop, but not as much as the cable operators. Thus, the cable operator should be able to leverage the fiber already run out to the optical node. It will probably require WDM equipment. Also, the cost of the fiber runs increases as you get closer to the home as there are more runs. All in all, this could translate to a 25% discount, give or take.

Passing a home refers to getting the fiber to the curb. Connecting a home refers to the drop cable plus in-home CPE. The cable scenarios already have a drop cable. So to arrive at a comparable estimate, I will take $700 as the average from above for passing a home and assign $200 in cost for installing a drop cable to the edge of the home (labor, fiber, termination box). I am ignoring the CPE cost. That results in an estimate of $900/HP. This is considered an aggressive number.

This new fiber network would require a new OLT (Optical Line Termination) Edge device at the hub. For comparison to the other cable scenarios that follow, this is a 2x equipment increase at the hub (one CMTS, one OLT vs. just one CMTS)

<u>The Cost of Low-Split</u>

For comparison, to get a 100 Mbps upstream up to 1 Gbps, the plant would have to be split by 10x. That means that optical nodes of 500 HP would have to be split down to 50 HP. This is really a smaller node size than practical. It implies a N+0 architecture.

This would also require 10x the number of CMTS ports.

Throughput would be limited to 100 Mbps aggregate.

<u>The Cost of Mid-Split</u>

For comparison, to increase to 1 Gbps throughput would require a 4x optical node split. This is presuming 300 Mbps per upstream as calculated in Table 1.

In theory, a 4x node split could be accomplished within the existing optical node housing. In practice, new fiber is likely to get added to push four new optical nodes deeper. For analysis, we will assume this is a N+3 or N+4 architecture.

If upstream QAM demodulators are pushed down into the optical node, that circuitry will likely have four ports which will effectively provide the 4x sub-split needed all within the existing node housing.

This would require 4x the number of CMTS ports.

All optical nodes, amplifiers, and in-line equalizers need to be upgraded or swapped out.

This upgrade is very similar (or slightly higher), if not identical to a high-split upgrade. Thus, the cost of the mid-split plant upgrade will be presumed to be the same.

<u>The Cost of High-Split</u>

Since high-split has a Gbps return path, by definition, no node split is required. For this analysis, we will assume that this stays at the N+5 reference.

As with mid-split, all optical nodes, amplifiers, and in-line equalizers need to be upgraded or swapped out.

This would require a new CMTS line card and is the equivalent of 2x the number of CMTS ports.

It turns out that this is roughly the same scenario for a 1002 MHz downstream upgrade. When upgrading the downstream path, all amplifiers and optical nodes need replacing. Often the downstream lasers at the hub are replaced as well. This is why it makes so much economical and technical sense to upgrade both directions at the same time.

In talking with industry experts, a 1 GHz upgrade can range from $55/HP to $85/HP. This partly is influenced if the plant is aerial or underground. Adding an upstream upgrade may add a 30% premium to this, driving it to $70/HP to $110/HP. I am going to take the average of these numbers as $90/HP.

The Cost of Top-Split

Early top-split networks were built as an overlay network that involves additional optical nodes, amplifiers, equalizers, taps, etc. The current thinking for a top-split network is to drive to a deep fiber architecture, potentially as an overlay to the existing coax, and connect into the coax after the last amp as a N+0 (or before as a N+1).

The drop in point would have a circuit that terminated the top-split return path and coupled it to the fiber.

The backbone coax is generally capable of supporting up to 3 GHz and maybe more. The network splitters/taps also may need replacement, depending on where the top-split network is connected into the HFC plant.

The RG6 drop cable may need replacement if the length exceeds 200 feet. If the length is less than 100 feet, it should be fine. If it is between 100 feet and 200 feet, it is a maybe.

The cost estimate would be more than a low-split as the fiber cost would be the same but there are added electronics.

Cost Summary

Table 8 shows the relative pricing for plant upgrades normalized to homes passed. This does not include any CAPEX for CPE equipment of any OPEX.

The right hand column indicates the relative hit to the density of the access edge device (CMTS or OLT). The cost impact is actually a fraction of the plant upgrade cost. However, as the multiple increases, the cost of the edge equipment becomes noticeable. As a base measure, this table suggests that a high-split system for a typical 40K homes passed hub is:

40K HP/CMTS * $90/HP = $3.6M

40K HHP with 1000 HP/SG (Service Group) is 40 SGs which is approximately one CMTS.

A useful metric that occurred in this analysis is truck rolls per active. Every active in the plant needs swapping out in many of these scenarios. Then there are follow-up checks. The average truck roll per active is 1.3 to 2.

This analysis left out all the cost associated with the home including professional install costs, CPE costs, etc. These are valid cost that would play into the final choice

It should be no surprise that an all fiber network is the most expensive solution. A

| Approach | SG Size | Cost/HP | Relative | Edge Impact |
|---|---|---|---|---|
| FTTH | n/a | $900 | 100% | 2x |
| Top-Split | N + 1 | $225 | 25% | 2x |
| Low-split | N + 1 | $180 | 20% | 10x |
| Mid-split | N + 3 | $135 | 15% | 4x |
| High-split | N + 5 | $90 | 10% | 2x |

**Table 8** – Relative Costs for Plant Upgrade

complete new build should always cost more than a retrofit. As such, fiber may be interesting for new builds.

Low-split ended up being the most expensive way to get 1 Gbps of total upstream throughput, and yet each end-point is really limited to 100 Mbps. The counter argument is that it is the simplest solution, the entire solution is available today, there are no compatibility problems, and you can pay as you go.

Mid-split is equal to or maybe even more expensive than high-split. The main disadvantage of mid-split is that for the same plant investment, you can get 4x the bandwidth with high-split and the ability to burst to 1 Gbps. The main advantage is that all the equipment is available today (DOCSIS 3.0) and it allows legacy STB to stay on the plant because is compatible with the downstream OOB.

High-split offers fiber like performance, yet at one-tenth the price of fiber. What a deal! The disadvantage is that it will take 3-5 years to bring the technology to market and the upgrade plan is the most challenging of all the options. Further, the cost of eliminating all STBs and the need for DTAs may reduce the cost benefit of this option.

Top-split offers potentially additional performance compared to high-split but at a higher cost. The upgrade plan is simpler than high-split. Top-split does leave existing customer premise equipment in place and only impacts those taking the newer tiers requiring the higher speeds.

## CONCLUSIONS

The HFC plant has plenty of life left in it. There are several ways to drive the upstream data capacity to 1 Gbps. The downstream can be driven to 5 to 10 Gbps (a topic for another paper).

These approaches offer fiber-like performance but on an HFC plant as low as one-tenth the price of a fiber installation.

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