DOCSIS® 3.1 – An Overview

Adapted from an SCTE webcast by
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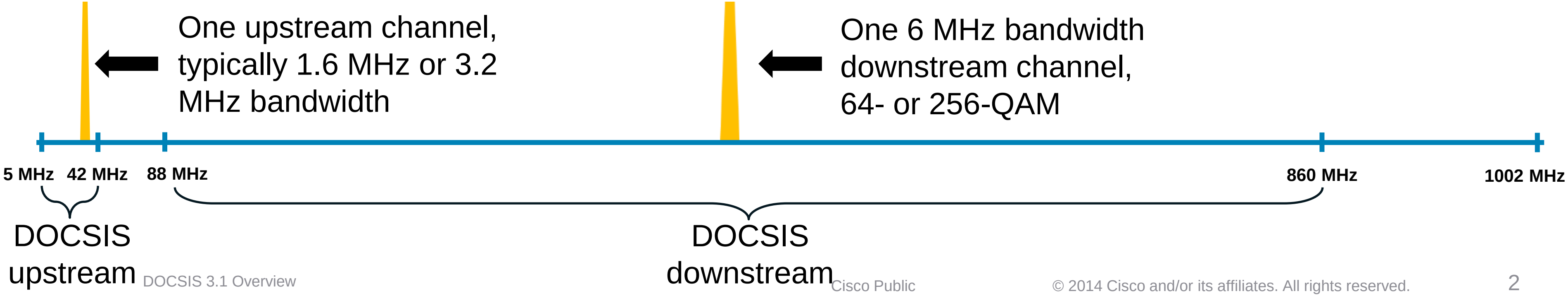
DOCSIS Background

Data-Over-Cable Service Interface Specifications

- **DOCSIS 1.0** gave us standards-based interoperability, which means "certified" cable modems from multiple vendors work with "qualified" cable modem termination systems (CMTSs) from multiple vendors.
- **DOCSIS 1.1** added a number of features, including quality of service (QoS), more robust scheduling, packet classification and other enhancements that facilitate voice and non-best effort data services.



One upstream channel, typically 1.6 MHz or 3.2 MHz bandwidth

One 6 MHz bandwidth downstream channel, 64- or 256-QAM

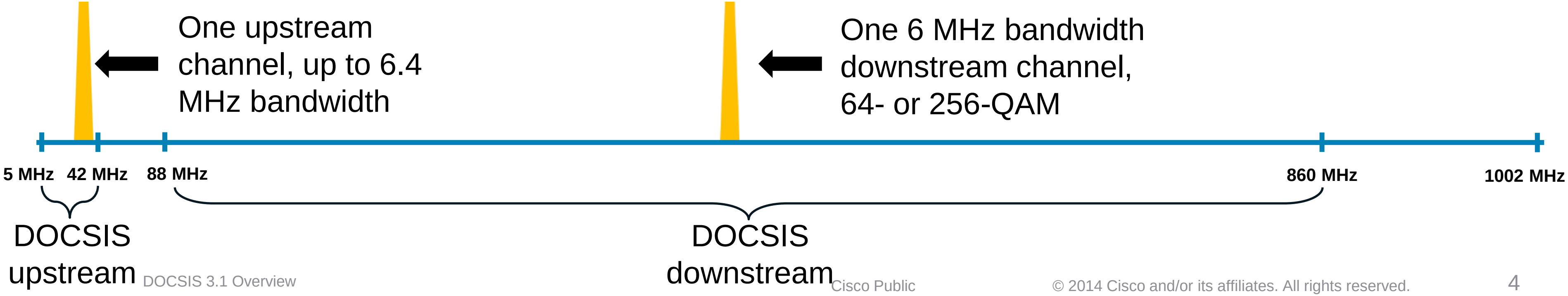
DOCSIS Background

- DOCSIS 1.x supported per-channel downstream data rates of 30.34 Mbps (64-QAM) and 42.88 Mbps (256-QAM) in a 6 MHz channel bandwidth, and several upstream data rates, ranging from a low of 320 kbps to a high of 10.24 Mbps. It also supported two upstream modulation formats – quadrature phase shift keying (QPSK) and 16-QAM – as well as five upstream RF channel bandwidths.
- DOCSIS 1.1 added some enhancement to upstream transmission robustness, using 8-tap adaptive pre-equalization.

Channel bandwidth, MHz	Symbol rate, ksym/sec	QPSK raw data rate, Mbps	QPSK nominal data rate, Mbps	16-QAM raw data rate, Mbps	16-QAM nominal data rate, Mbps
0.200	160	0.32	~0.3	0.64	~0.6
0.400	320	0.64	~0.6	1.28	~1.2
0.800	640	1.28	~1.2	2.56	~2.4
1.60	1,280	2.56	~2.3	5.12	~4.8
3.20	2,560	5.12	~4.6	10.24	~9.0

DOCSIS Background

- **DOCSIS 2.0**: Downstream channel bandwidth and data rates unchanged from DOCSIS 1.x, but higher upstream data throughput per RF channel, up to 30.72 Mbps
- DOCSIS 2.0 supported 64-QAM in the upstream, plus 8-QAM and 32-QAM – and optionally supported 128-QAM trellis coded modulation (TCM) encoded modulations for S-CDMA channels – and up to 6.4 MHz channel bandwidth.
    - To facilitate more robust upstream data transmission, DOCSIS 2.0 introduced advanced PHY (24-tap pre-equalizer, improved FEC, ingress cancellation, direct sampled RF in burst receiver, etc.)

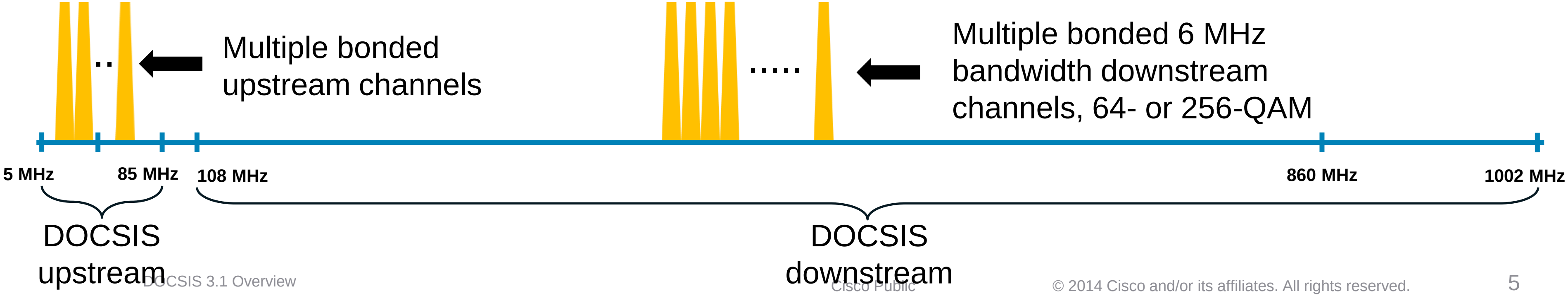


One upstream channel, up to 6.4 MHz bandwidth

One 6 MHz bandwidth downstream channel, 64- or 256-QAM

DOCSIS Background

- **DOCSIS 3.0** retained a downstream channel bandwidth of 6 MHz and upstream channel bandwidths up to 6.4 MHz, and introduced channel bonding
    - Logically bond multiple channels to increase data throughput
    - e.g., 4 bonded downstream channels: 100+ Mbps
- RF spectrum changes – Downstream increased to **1 GHz** and upstream increased from 5 MHz to as high as **85 MHz** (optional)
- DOCSIS 1.x / 2.0 cable modems can reside on same system



Multiple bonded upstream channels

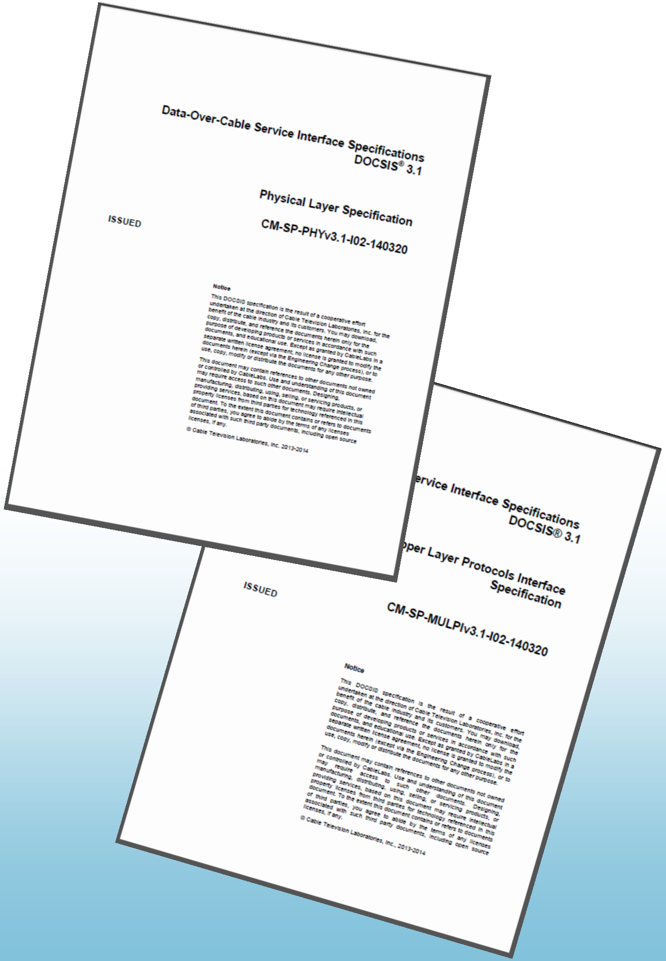
Multiple bonded 6 MHz bandwidth downstream channels, 64- or 256-QAM

DOCSIS upstream

DOCSIS downstream

What is DOCSIS 3.1?

- Answer: The latest *Data Over Cable Service Interface Specifications*
- **DOCSIS 3.1** is the latest Data Over Cable Service Interface Specifications. CableLabs® released version I01 of the new spec in late October, 2013. The latest version is I09, published June, 2016.
- All DOCSIS 3.1 specifications including *MAC and Upper Layer Protocols Interface Specification* (MULPI), *Cable Modem Operations Support System Interface Specification* (OSSI), *Physical Layer Specification* (PHY), *CCAP™ Operations Support System Interface Specification*, and *Security Specification* have been publicly released.
    - (available for download at CableLabs' web site: http://www.cablelabs.com)
- DOCSIS 3.1 specifications became an international standard in early December 2014: ETSI TS 103 311



Data-Over-Cable Service Interface Specifications
DOCSIS® 3.1

Physical Layer Specification

CM-SP-PHYv3.1-I02-140320

ISSUED

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ervice Interface Specifications
DOCSIS® 3.1

pper Layer Protocols Interface Specification

CM-SP-MULPIv3.1-I02-140320

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Why DOCSIS 3.1?

- Why not just continue with DOCSIS 3.0?

    DOCSIS 3.0 could scale to gigabit-class speeds

    DOCSIS 3.1 will scale better, and is more spectrally efficient than today's single carrier quadrature amplitude modulation (SC-QAM) technology

- According to CableLabs:

    "DOCSIS 3.1 technology will enable a new generation of cable services and help operators continue to meet consumer demand for high speed connections and sophisticated applications, positioning them to be the providers of choice in their markets."

Why DOCSIS 3.1?

- Goals
  - Achieve 10+ Gbps in the downstream
  - Achieve 1+ Gbps in the upstream
  - Backwards compatibility with DOCSIS 3.0, 2.0, & 1.1
  - Better spectral efficiency (more bps/Hz)
- Technology
  - OFDM, OFDMA, LDPC
  - Expanded downstream and upstream spectrum
  - Improved energy efficiency
- This will allow DOCSIS 3.1 to support services competitive with FTTH.

Deployable in today’s HFC networks!

Improved performance

- New physical layer (PHY) technology: OFDM (orthogonal frequency division multiplex) and OFDMA (orthogonal frequency division multiple access)
  - Better spectral efficiency than SC-QAM
- Better forward error correction (FEC): low density parity check (LDPC)
  - LDPC is more powerful than the Viterbi/Reed-Solomon FEC used in earlier versions of DOCSIS
  - Time *and* frequency interleaving for improved data transmission robustness
- Higher modulation orders
  - Up to 4096-QAM in the downstream and upstream, optional to 16384-QAM in the downstream
- Expanded downstream and upstream RF spectrum usage
  - Downstream: 258 MHz to 1218 MHz, optional to 1794 MHz (and 108 MHz on lower end)
  - Upstream: 5 MHz to 85 MHz (mandatory), optional to as high as 204 MHz
- Multiple modulation profiles
  - Different modulation orders for different modems

RF transmit power

- Downstream RF transmit power

  CMTS power is configured by power per CTA channel and number of occupied CTA channels for each OFDM channel. For each OFDM channel, the total power is power per CTA channel + $10\log_{10}$(number of occupied CTA channels) for that OFDM channel.

  Required power per channel for N_{eq}' channels combined onto a single RF port:

  Required power in dBmV per channel = 60 – ceil [$3.6*\log_2(N^*)$] dBmV

- Input to the modem

  Total input power < 40 dBmV, 54 MHz to 1.794 GHz (negligible input power outside this frequency range)

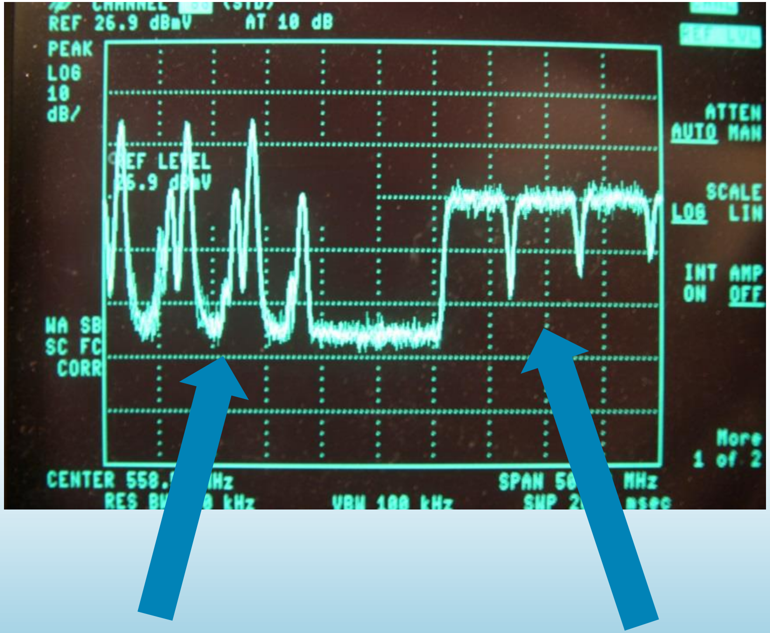
  Level range = -9 dBmV to +21 dBmV (in 24 MHz occupied bandwidth)

  (equivalent PSD to -15 dBmV to +15 dBmV per 6 MHz SC-QAM)

RF transmit power

- Upstream RF transmit power
  - All DOCSIS 3.0 requirements still in place for operating DOCSIS 3.0 mode
  - DOCSIS 3.1 maximum transmit average power (not peak) is required to be at least +65 dBmV
    - As with DOCSIS 3.0, modem vendors may design their products for higher modem transmit power capability, but all spurious emissions requirements (dBc) must still be met even at higher transmit power levels
  - DOCSIS 3.1 has minimum transmit power limits related to transmit grant bandwidth
    - No less than +17 dBmV with 1.6 MHz grant

DOCSIS 3.1 PHY: OFDM



Analog TV signals

Digital signals

- Cable networks (and radio and TV stations in the over-the-air environment) have for decades used frequency division multiplexing (FDM) to allow the transmission of several RF signals through the same length of coaxial cable at the same time

  Each RF signal is on a separate frequency, or more specifically, assigned to its own channel slot

What is OFDM?

- Orthogonal frequency division multiplexing (OFDM) is used in the DOCSIS 3.1 downstream.
- Up to 7600 narrow-bandwidth, active subcarriers make up one OFDM channel.
- Each subcarrier carries a small percentage of the total data payload at a very low data rate.
- The upstream counterpart is called OFDMA, or orthogonal frequency division multiple access.

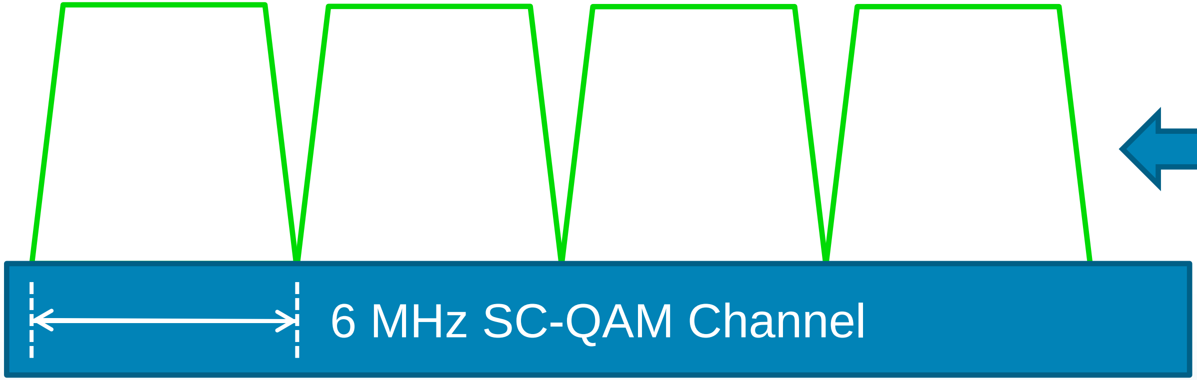
  Don’t forget time division multiple access (TDMA) is also used with OFDMA to share the upstream channel.

OFDM is a proven technology that enjoys widespread use:

Wi Fi™
Lte™
DAB DigitalAudioBroadcasting
MOCA
DVB T2
HiperLAN2
WiMAX

OFDM versus SC-QAM

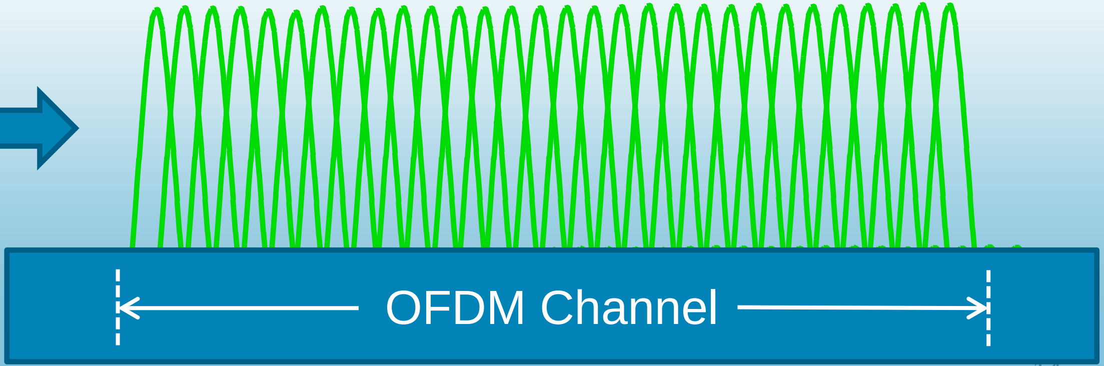
One SC-QAM signal per channel



The 6 MHz-wide downstream channel slots defined by the North American CTA-542-D frequency plan can each accommodate one analog NTSC TV signal or one SC-QAM signal

Multiple subcarriers within one OFDM channel

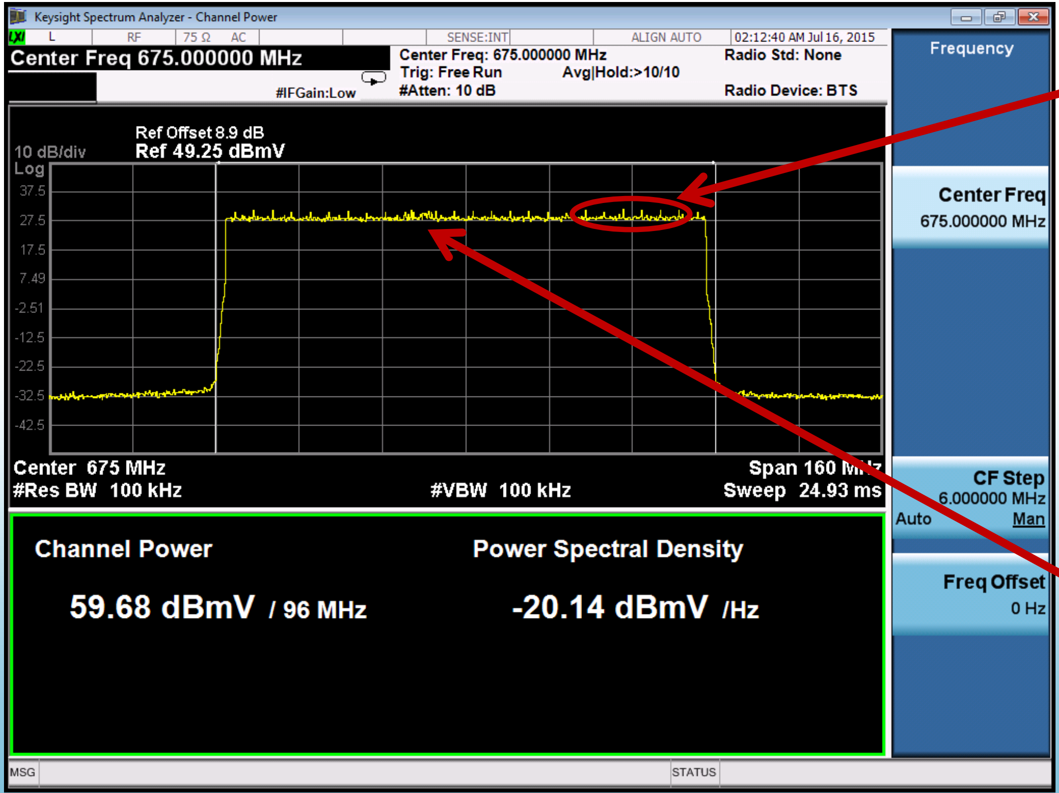
Up to 7600 narrow subcarriers in up to 192 MHz-wide OFDM channel



DOCSIS 3.1 OFDM channel width

- With OFDM, the concept of a 6 MHz or 8 MHz channel is no longer necessary.
- DOCSIS 3.1 OFDM channel bandwidth is flexible
  - DOCSIS 3.1 supports downstream OFDM modulated spectrum from a minimum of 22 MHz to a maximum of 190 MHz, which will occupy at least 24 MHz and 192 MHz, respectively, including a portion of the OFDM band-edge spectral skirts
  - Upstream channel bandwidth: Minimum encompassed spectrum of 6.4 MHz to a maximum encompassed spectrum of 95 MHz

DOCSIS 3.1 downstream OFDM channel (96 MHz occupied bandwidth) on a spectrum analyzer



02:12:40 AM Jul 16, 2015

Center Freq 675.000000 MHz

Center Freq: 675.000000 MHz
Trig: Free Run
Avg|Hold:>10/10
#Atten: 10 dB

Radio Std: None
Radio Device: BTS

Ref Offset 8.9 dB
Ref 49.25 dBmV

Center 675 MHz
#Res BW 100 kHz
#VBW 100 kHz
Span 160 MHz
Sweep 24.93 ms

Channel Power
59.68 dBmV / 96 MHz

Power Spectral Density
-20.14 dBmV /Hz

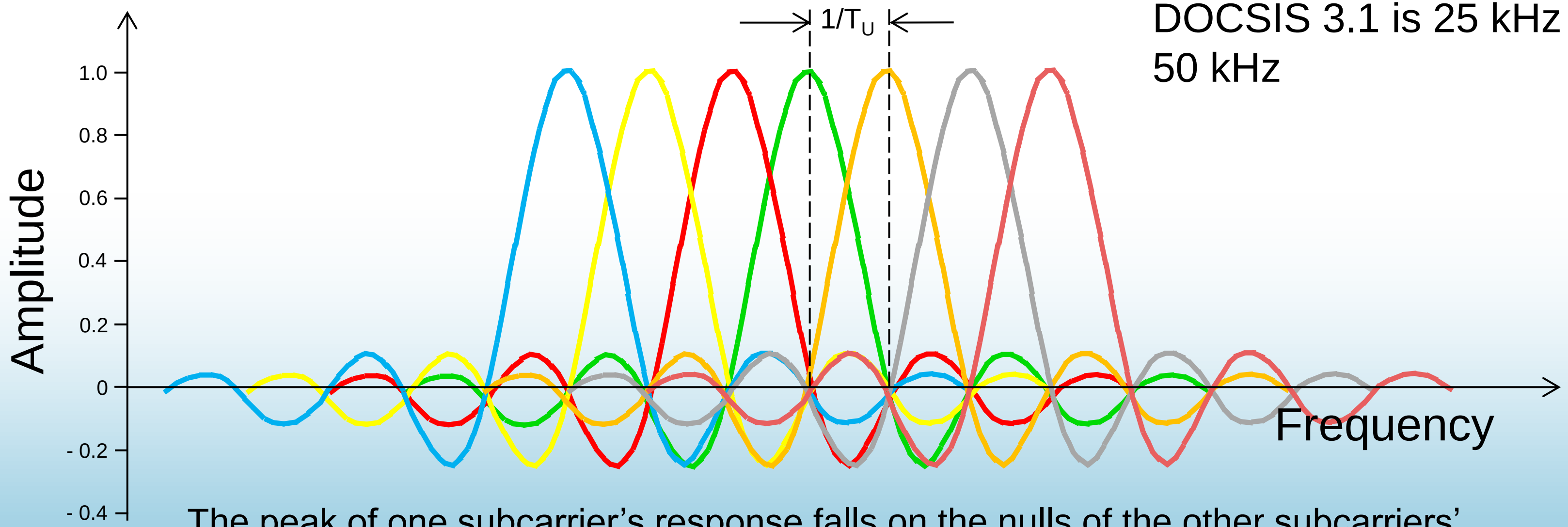
Pilots evenly spaced across channel

PHY link channel (PLC)

OFDM: orthogonal subcarriers

- For improved spectral efficiency, the subcarriers in an OFDM or OFDMA channel overlap one another.
  - Why don’t they interfere with one another?
- The subcarriers are orthogonal.
  - “Orthogonal” in this case means the subcarriers are independent such that there is no interaction between them despite the overlap in frequency.
  - Orthogonal subcarriers have exactly an integer number of cycles in the symbol interval.

OFDM: orthogonal subcarriers

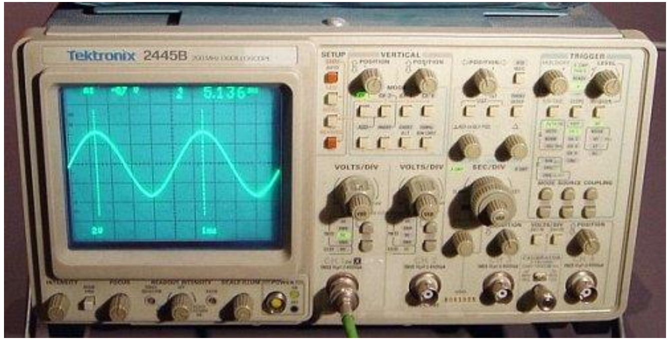


The subcarrier spacing in DOCSIS 3.1 is 25 kHz or 50 kHz

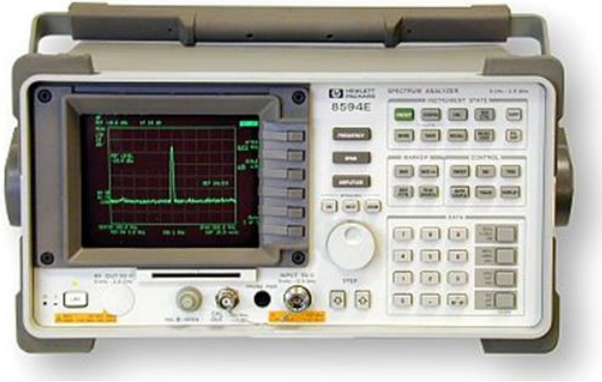
The peak of one subcarrier’s response falls on the nulls of the other subcarriers’ responses, ideally resulting in no interference between the subcarriers. (Note: T_U is the FFT duration or “useful symbol duration” – that is, 20 µs or 40 µs in the case of DOCSIS 3.1.)

OFDM: time and frequency domains

- An oscilloscope shows a signal in the time domain – amplitude versus time.
- A spectrum analyzer displays a signal in the frequency domain – amplitude versus frequency.



Sine wave on oscilloscope



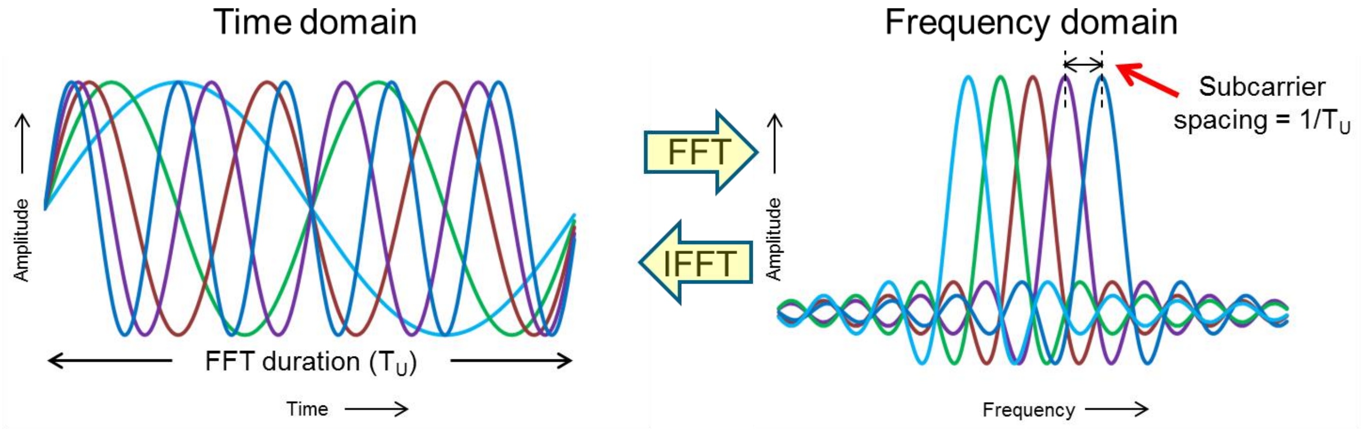
Sine wave on spectrum analyzer

What is the fast Fourier transform?

- The fast Fourier transform (FFT) is a fast way to compute the discrete Fourier transform (DFT).
  - 600/1200x faster than direct computation for length 4096/8192.
- The DFT is a way of expressing any waveform in terms of sine waves.
  - DFT: Break down a complex signal into many sine waves. Used in the OFDM receiver.
  - Inverse DFT (IDFT): Sum many sine waves to construct a complex signal. Used in the OFDM transmitter.
- Some folks are a little lax and use the abbreviations FFT and DFT almost interchangeably. ☺

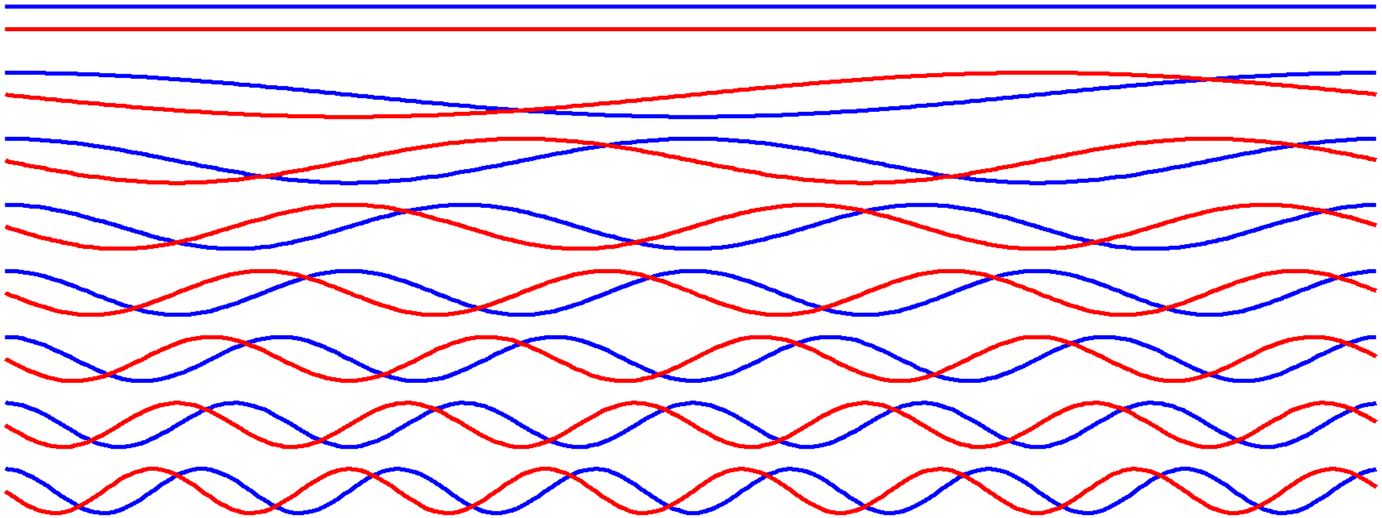
DFT matrix

- To apply the DFT just multiply by a matrix.
- Multiplying by this matrix converts between the time and frequency domains, and performs modulation and demodulation.



DFT matrix

- The DFT matrix contains rows of sine waves.
- Each row has a slightly higher frequency (contains one more full cycle) than the previous row.

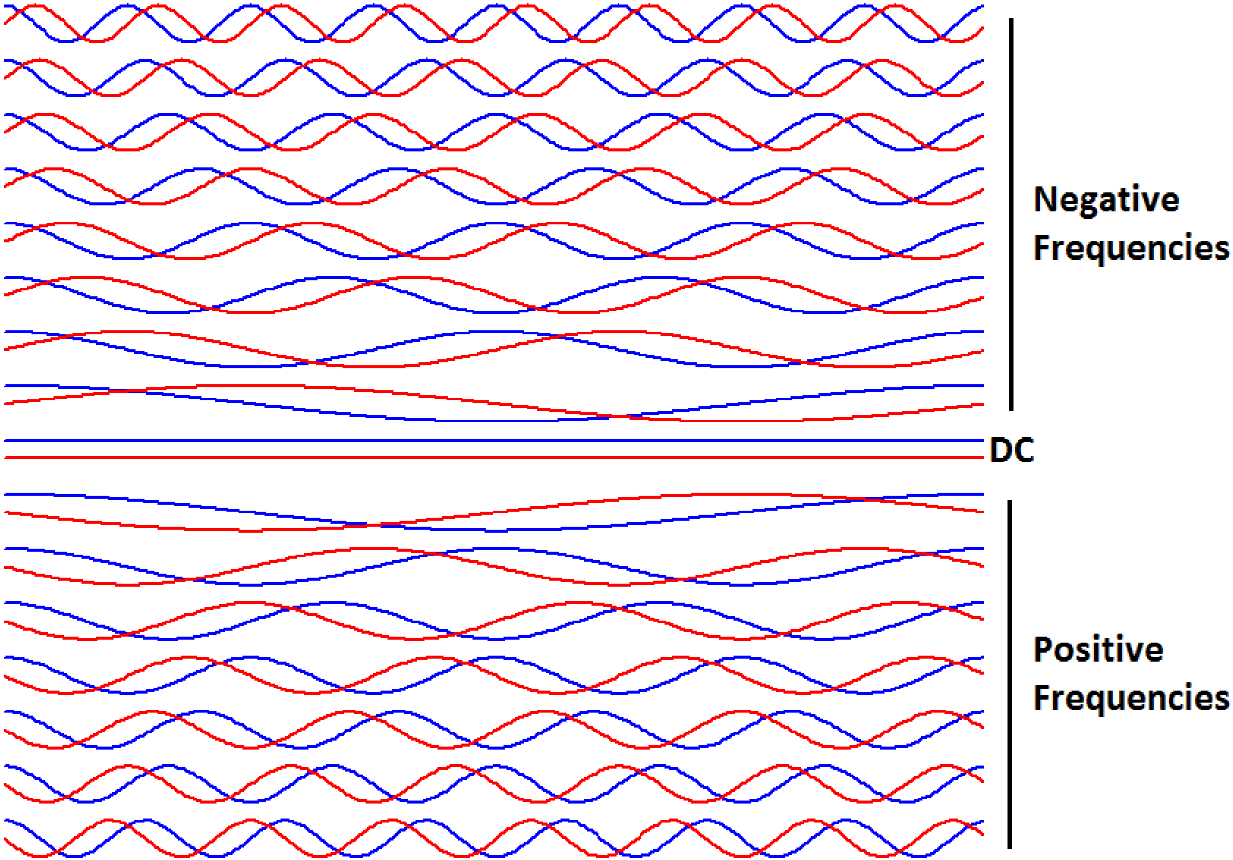


Red = sine
Blue = cosine

N = 16
(half of rows shown)

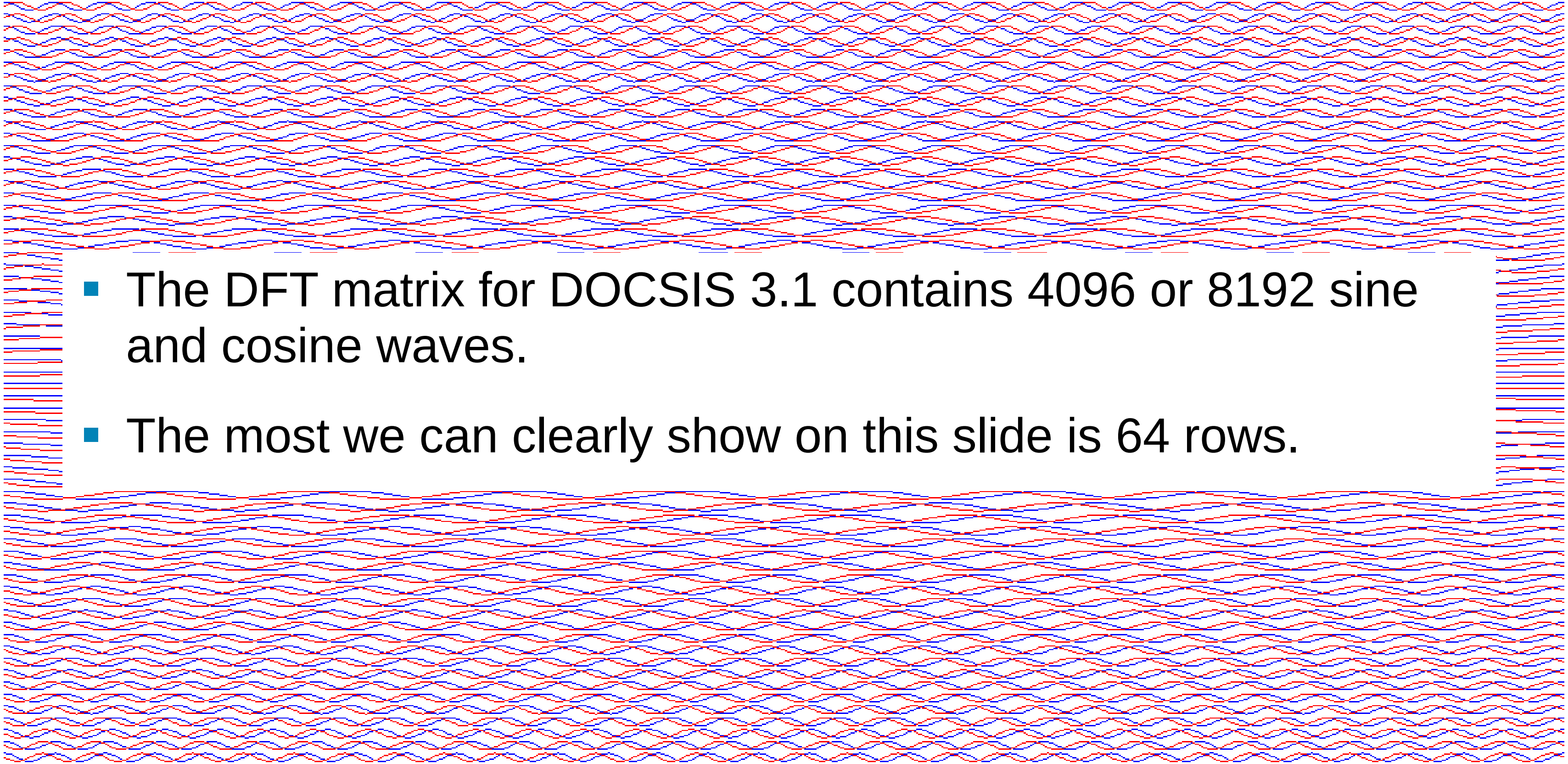
The IDFT matrix is identical except its sines are negated.

Full DFT matrix



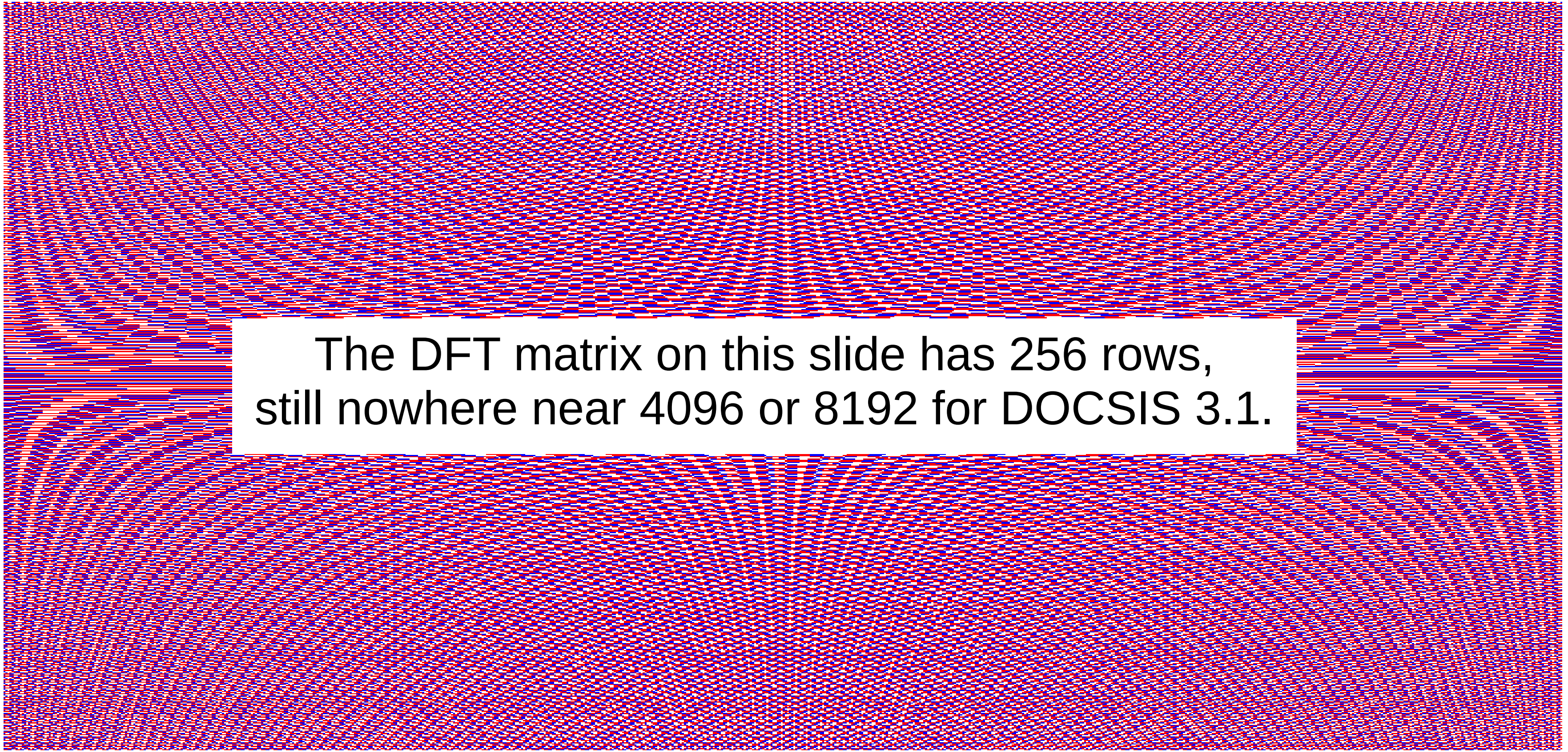
- “Negative” frequencies = below RF center frequency
- DC represents RF center freq
- Positive freqs = above RF center freq
- Sine lags/leads cosine for positive/ negative frequency

How big is the DOCSIS 3.1 DFT matrix?



- The DFT matrix for DOCSIS 3.1 contains 4096 or 8192 sine and cosine waves.
- The most we can clearly show on this slide is 64 rows.

How big is the DOCSIS 3.1 DFT matrix?



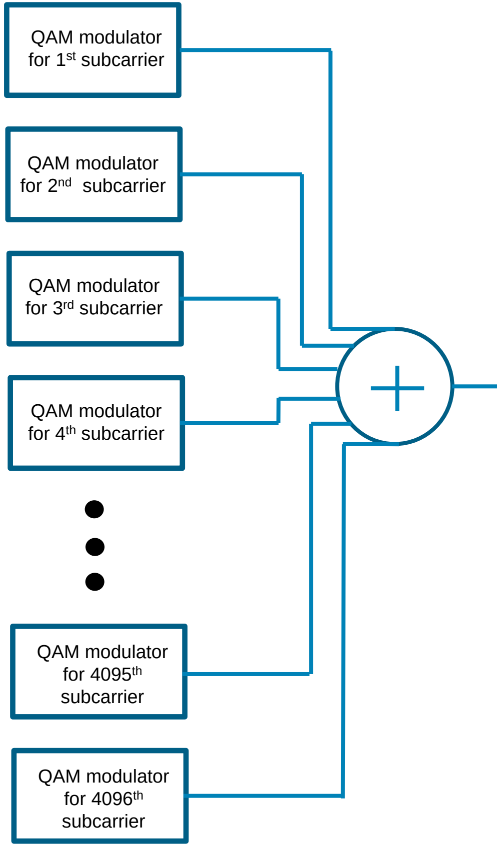
The DFT matrix on this slide has 256 rows,
still nowhere near 4096 or 8192 for DOCSIS 3.1.

Transmitter: Inverse DFT

- Start with 4096 QAM symbols.
- Multiply by the IDFT matrix.

  Actually use IFFT which is 600 times faster to give same answer!
- This gives the *equivalent* of 4096 individual QAM modulators summed together – very powerful!
- Send this summed signal over the cable channel.

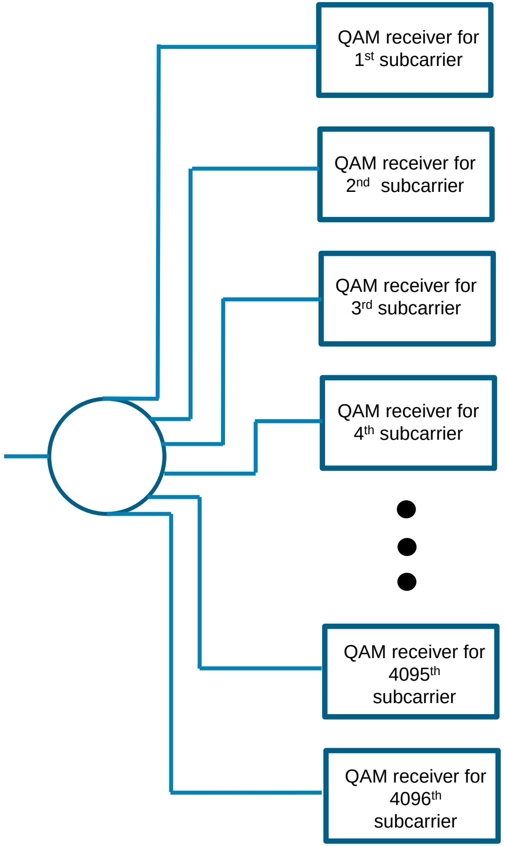
IDFT is the equivalent of this:



Receiver: DFT

- We receive a signal from the cable channel and multiply by the DFT matrix (using FFT algorithm for speed).
- The result tells how the signal correlates with each of the sine waves in the DFT matrix.
- This gives us back the original QAM data.
- The single matrix multiply is *equivalent* to 4096 individual QAM receivers!

DFT is the equivalent of this:



QAM receiver for 1st subcarrier

QAM receiver for 2nd subcarrier

QAM receiver for 3rd subcarrier

QAM receiver for 4th subcarrier

QAM receiver for 4095th subcarrier

QAM receiver for 4096th subcarrier

Don’t forget receiver synchronization

- To get the transmitter IFFT and receiver FFT to line up, we need to synchronize the receiver to the transmitter.
- Timing: Adjust symbol timing so the FFT starts at the right time.

  Cyclic prefix: To make timing easier, the transmitter repeats part of the signal. This also allows time for channel echoes to die out.

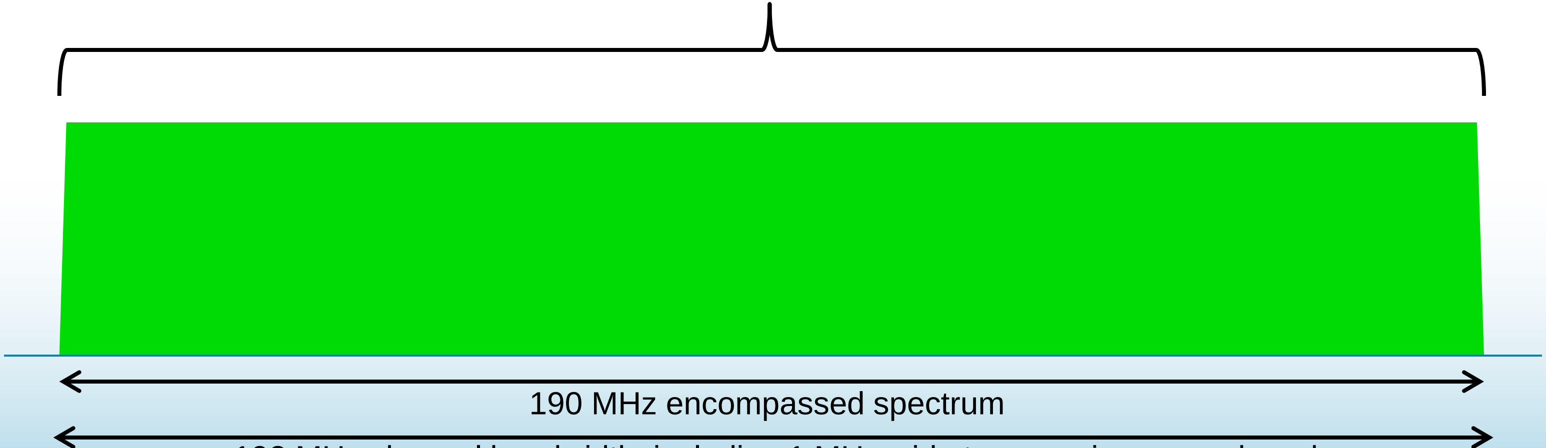
- Frequency: Adjust receiver to the correct center frequency.

  Continuous pilots: Some subcarriers carry no data, and are used to measure frequency offset.

- Equalization: Adjust amplitude and phase of each subcarrier to remove channel effects.

  Scattered pilots: Carry no data, visit each subcarrier location once every 128 symbols, used to measure channel response.

Anatomy of a downstream OFDM channel



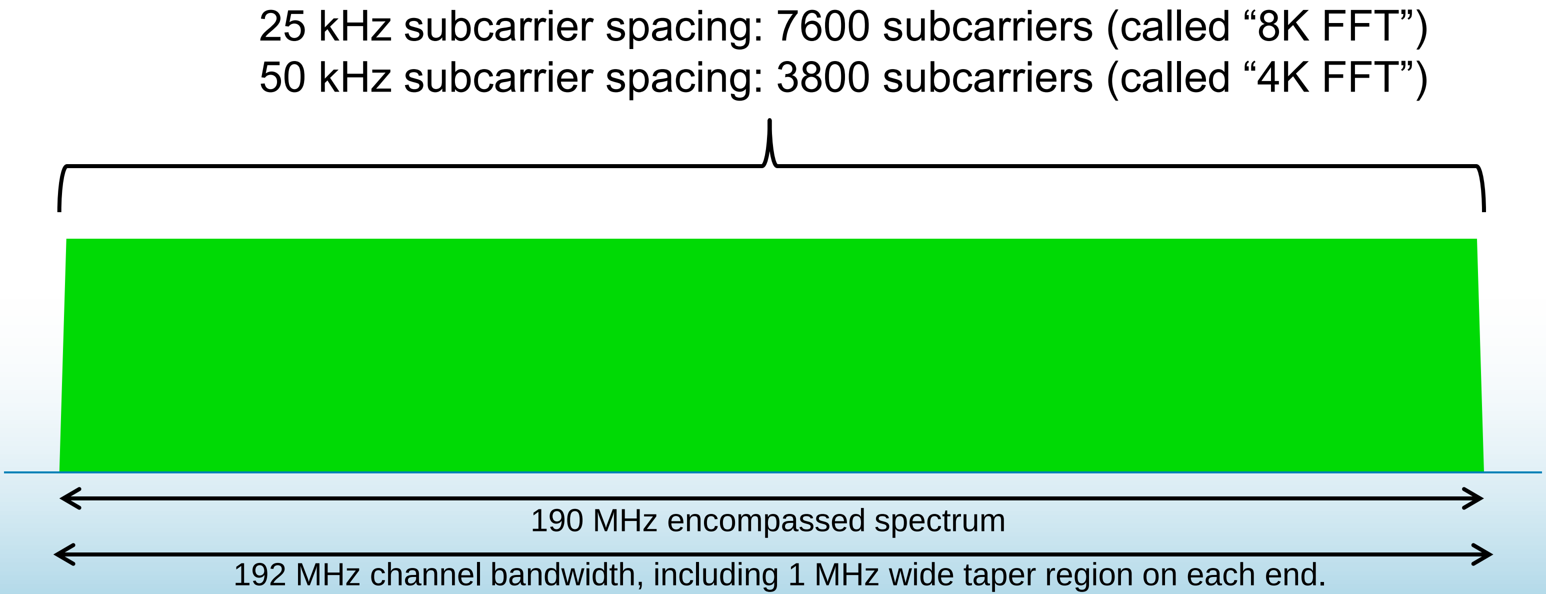
25 kHz subcarrier spacing: 7600 subcarriers (called “8K FFT”)
50 kHz subcarrier spacing: 3800 subcarriers (called “4K FFT”)

190 MHz encompassed spectrum

192 MHz channel bandwidth, including 1 MHz wide taper region on each end.

Since the taper regions in this example total 2 MHz out of 192 MHz, the equivalent excess bandwidth or “alpha” is (2/192) x 100 ≈ 1%, compared to 12% for DOCSIS 3.0 and earlier 256-QAM SC-QAM.

Anatomy of a downstream OFDM channel



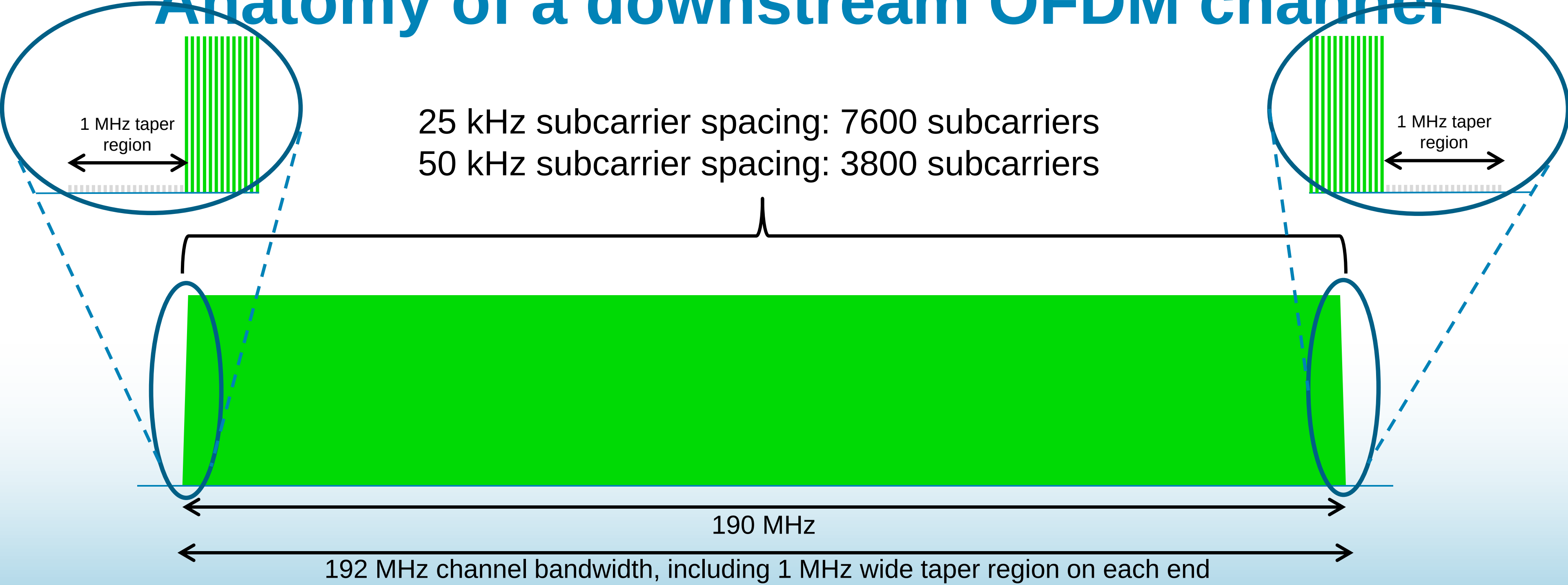
25 kHz subcarrier spacing: 7600 subcarriers (called “8K FFT”)
50 kHz subcarrier spacing: 3800 subcarriers (called “4K FFT”)

190 MHz encompassed spectrum

192 MHz channel bandwidth, including 1 MHz wide taper region on each end.

Although the excess bandwidth shown here is only about 1%, indicating very high raw spectral efficiency, OFDM does require other overhead to aid the receiver in acquiring the signal. This overhead includes the PHY link channel and pilots, which are discussed in the following slides, and next codeword pointer.

Anatomy of a downstream OFDM channel



25 kHz subcarrier spacing: 7600 subcarriers
50 kHz subcarrier spacing: 3800 subcarriers

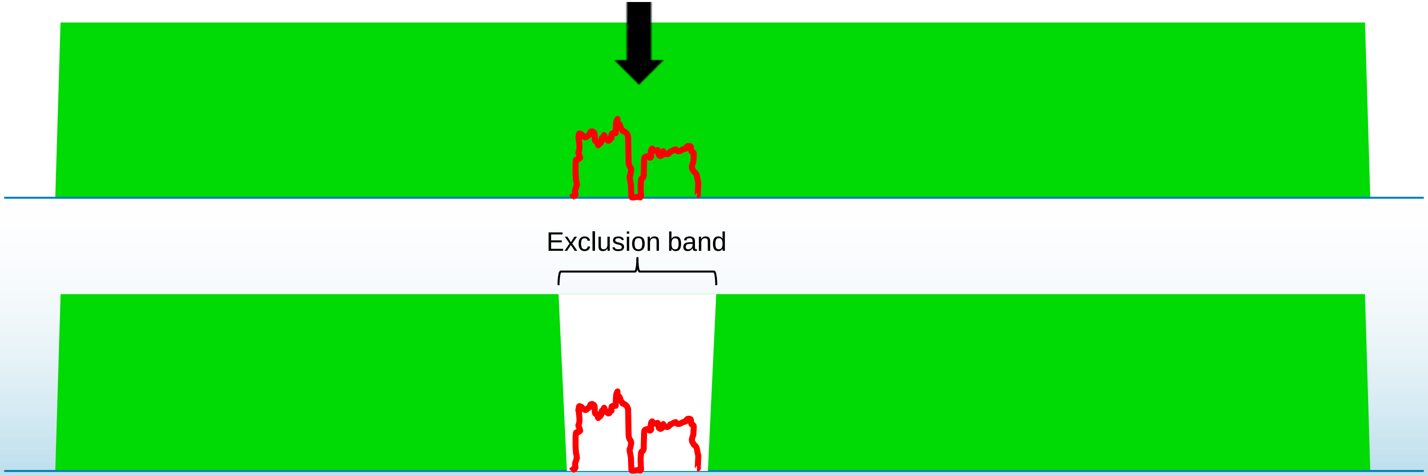
190 MHz

192 MHz channel bandwidth, including 1 MHz wide taper region on each end

Note: The taper regions shown in these examples use the *minimum* bandwidth supported. Actual taper region bandwidth may be greater than 1 MHz.

Anatomy of a downstream OFDM channel

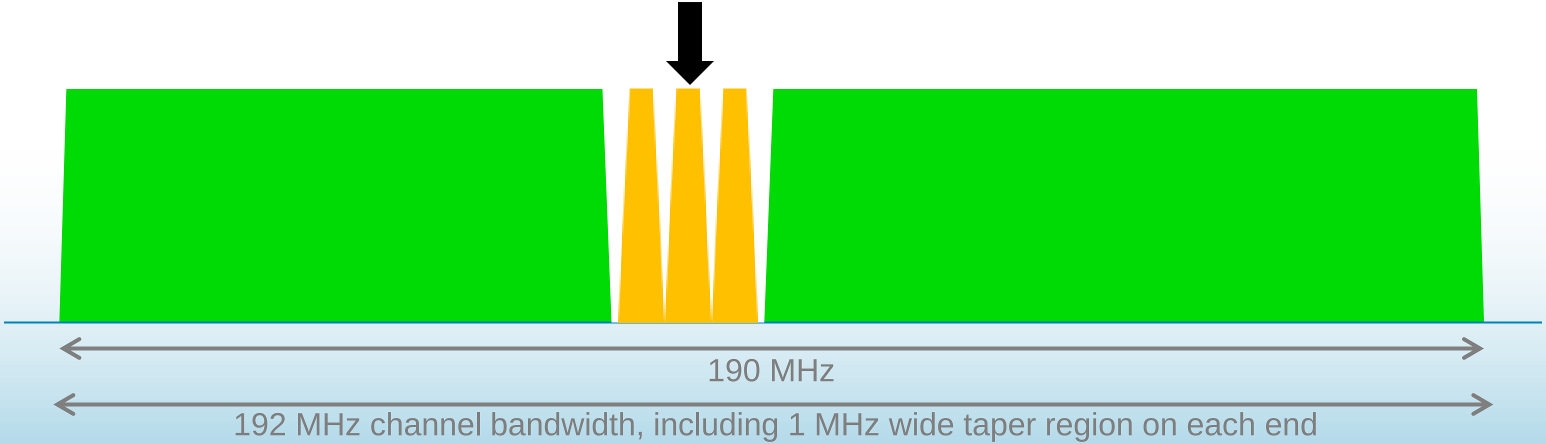
Exclusion bands may be created within an OFDM channel for problems such as strong in-channel ingress (e.g., LTE interference).



An exclusion band is a set of contiguous subcarriers within the OFDM channel bandwidth that are set to zero-value by the transmitter to avoid interference or to accommodate co-existing transmissions such as legacy SC-QAM signals.

Anatomy of a downstream OFDM channel

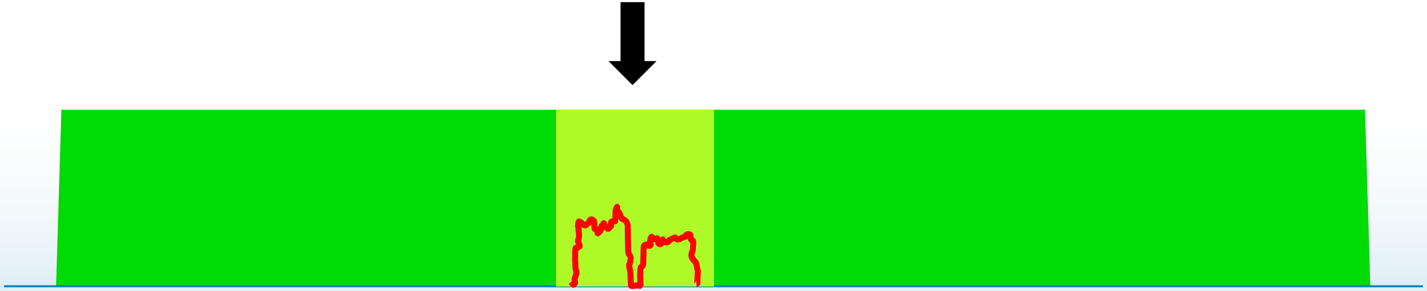
Exclusion bands also may be created within an OFDM channel for the carriage of legacy SC-QAM signals.



An exclusion band is a set of contiguous subcarriers within the OFDM channel bandwidth that are set to zero-value by the transmitter to avoid interference or to accommodate co-existing transmissions such as legacy SC-QAM signals.

Anatomy of a downstream OFDM channel

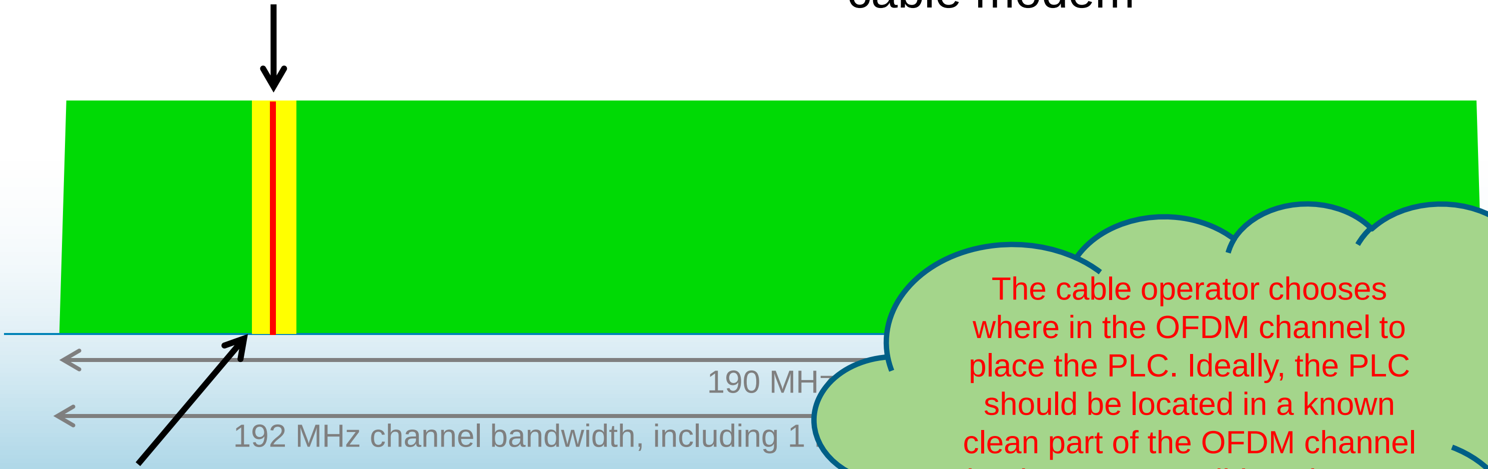
As an alternative to an exclusion band in that part of an OFDM channel experiencing interference, the bit loading may be changed to allow continued carriage of data, but using a more robust lower modulation order.



Anatomy of a downstream OFDM channel

400 kHz bandwidth PHY link channel (PLC), shown here in red, is centered within a 6 MHz contiguous portion of the OFDM channel (yellow) that has no exclusions.

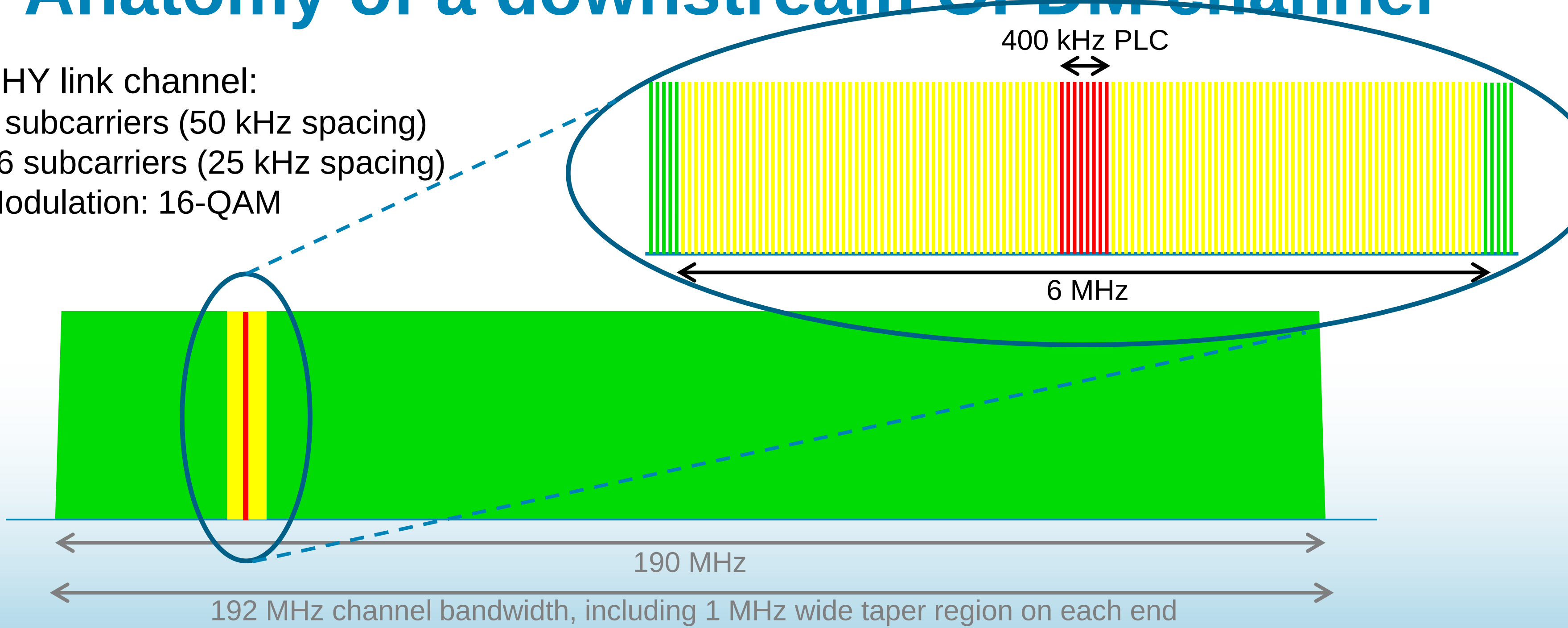
The PLC conveys physical layer parameters from the CMTS to the cable modem



The lowest frequency subcarrier that bounds the 6 MHz portion of the OFDM channel in which the PLC is located is centered on a 1 MHz grid.

The cable operator chooses where in the OFDM channel to place the PLC. Ideally, the PLC should be located in a known clean part of the OFDM channel that is not susceptible to ingress, direct pickup, and other types of interference.

Anatomy of a downstream OFDM channel



PHY link channel:
8 subcarriers (50 kHz spacing)
16 subcarriers (25 kHz spacing)
Modulation: 16-QAM

400 kHz PLC

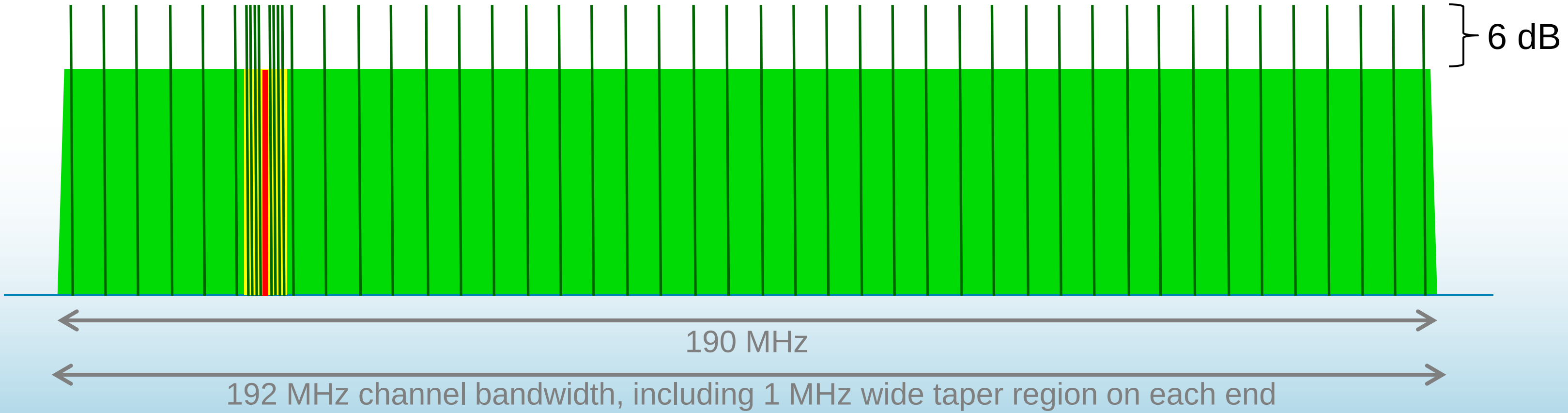
6 MHz

190 MHz

192 MHz channel bandwidth, including 1 MHz wide taper region on each end

Anatomy of a downstream OFDM channel

Subcarriers called continuous pilots are more or less evenly distributed throughout the OFDM channel, and are boosted 6 dB relative to other subcarriers. There can be anywhere from 16 to 128 continuous pilots in an OFDM channel, including 8 in the PLC band (next slide).

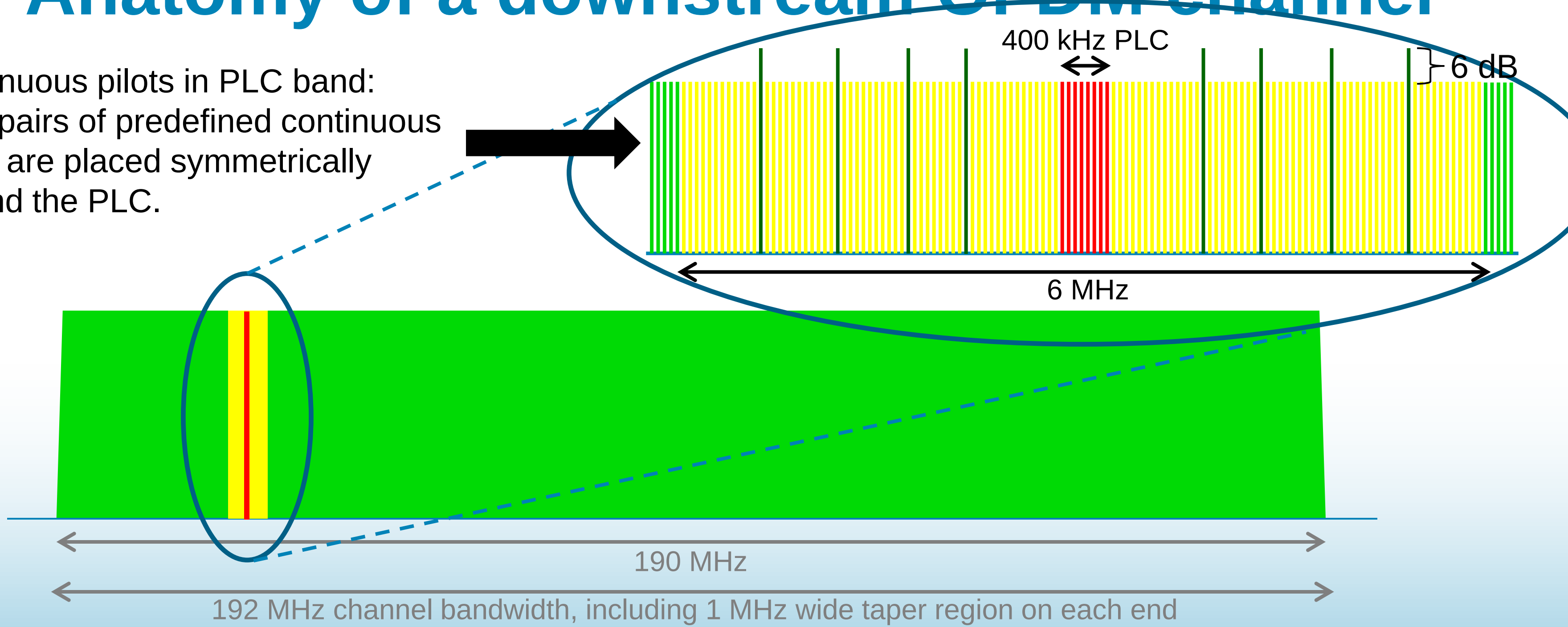


192 MHz channel bandwidth, including 1 MHz wide taper region on each end

Continuous pilots occur at the same frequency in every OFDM symbol, and are used for frequency and phase tracking. Continuous pilots do not carry data (they are BPSK modulated with a pseudo-random sequence, though).

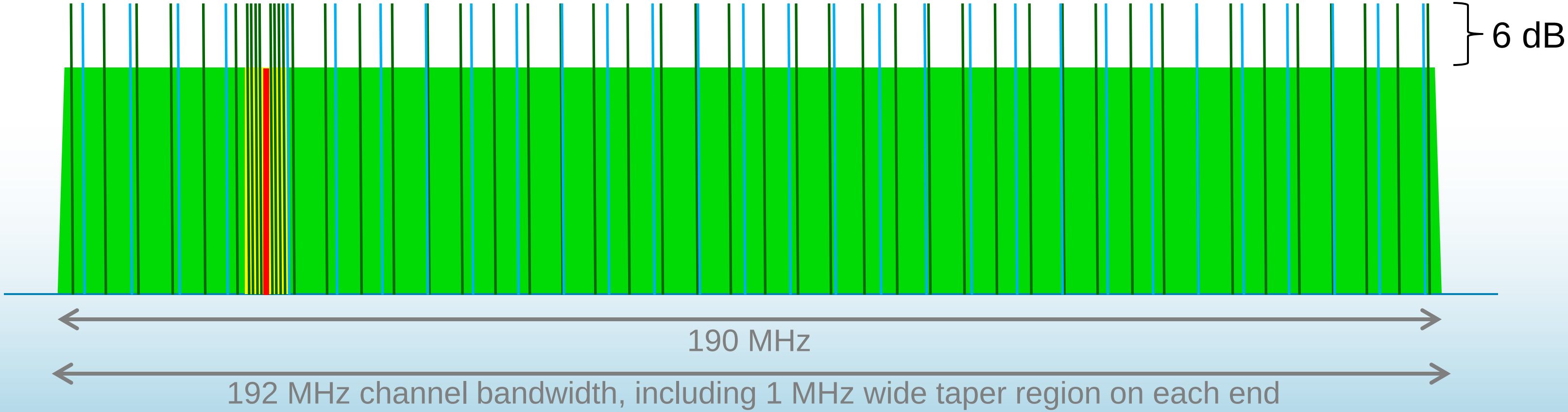
Anatomy of a downstream OFDM channel

Continuous pilots in PLC band:
Four pairs of predefined continuous pilots are placed symmetrically around the PLC.



Anatomy of a downstream OFDM channel

Other subcarriers called scattered pilots (shown here in light blue) occur at different frequency locations in different symbols. From symbol to symbol, scattered pilots are shifted by one subcarrier position in the increasing direction of the frequency axis, so the scattered pilots visit every subcarrier location every 128 symbols. Scattered pilots also are boosted 6 dB.



Scattered pilots occur every 128 subcarriers (but not in the PLC band or in exclusion bands), and are used primarily for estimation of channel frequency response as part of the equalization process. Scattered pilots do <u>not</u> carry data (they are BPSK modulated with a pseudo-random sequence, though).

Anatomy of a downstream OFDM channel

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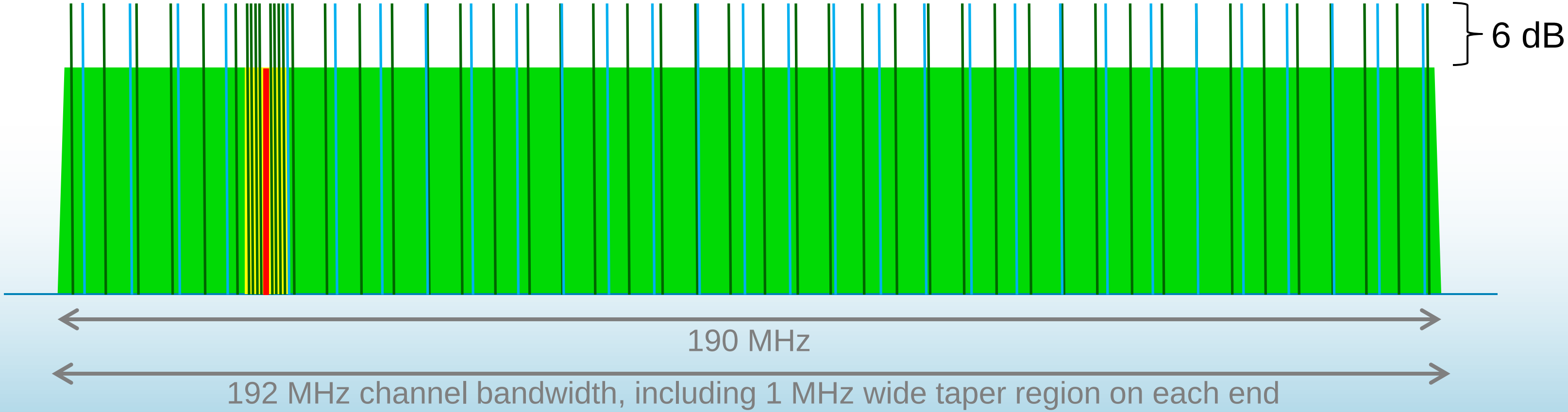
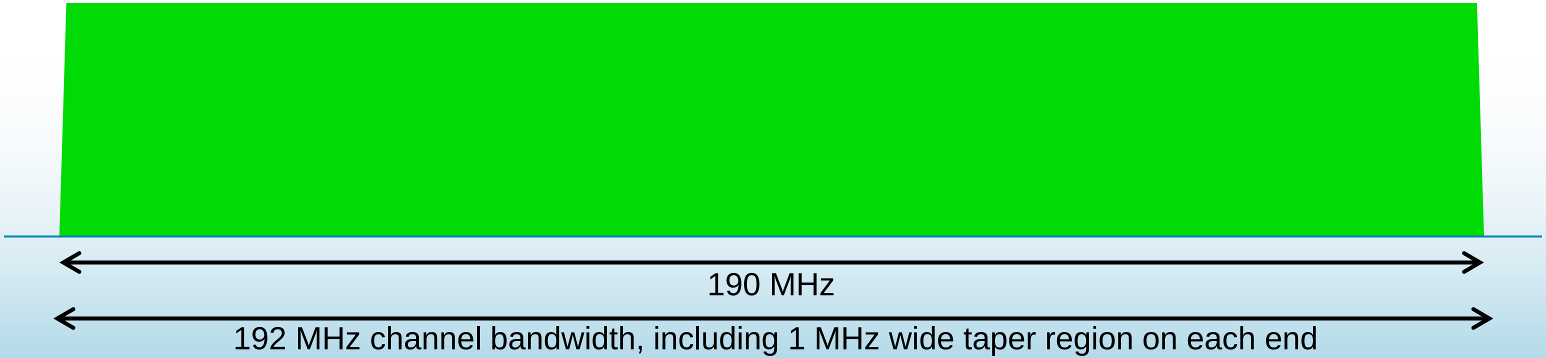


In the PLC band, the PLC preamble acts as a stand-in for the scattered pilots. That is, the scattered pilot sequence is synchronized so that it lands on the PLC preamble locations, so the receiver can use the known values of the PLC preamble to aid it in acquisition at those locations, thereby getting the same benefit as if the scattered pilots had been placed there.

Anatomy of a downstream OFDM channel

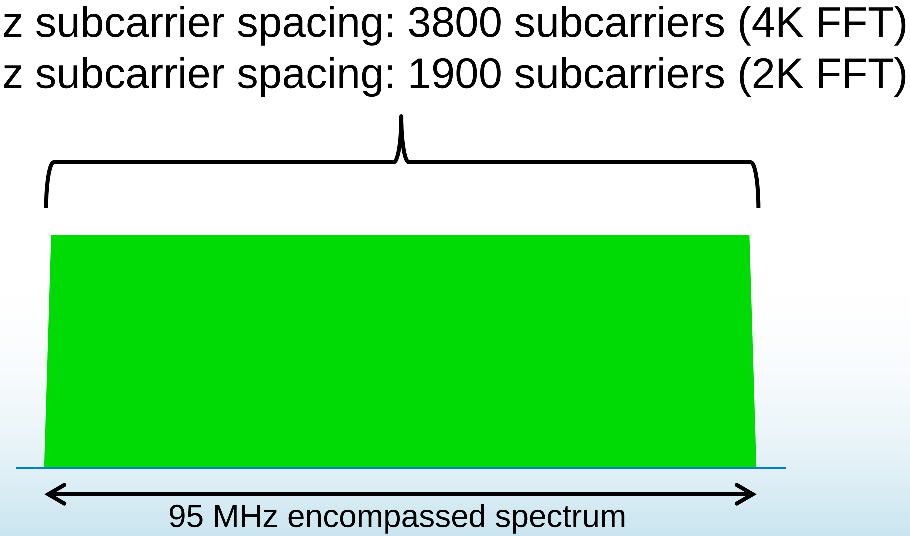
The DOCSIS 3.1 downstream OFDM channel can transmit broadcast, multicast, or unicast traffic on the downstream subcarriers to all modems, multiple modems, or a single modem, respectively. When multiple downstream profiles are used, different modems may receive different sets of subcarriers within an OFDM symbol, because a single OFDM symbol can contain multiple profiles with multiple codewords. If a given modem does not have sufficient SNR for 4096-QAM, for example, it is not required to receive the profile using 4096-QAM.



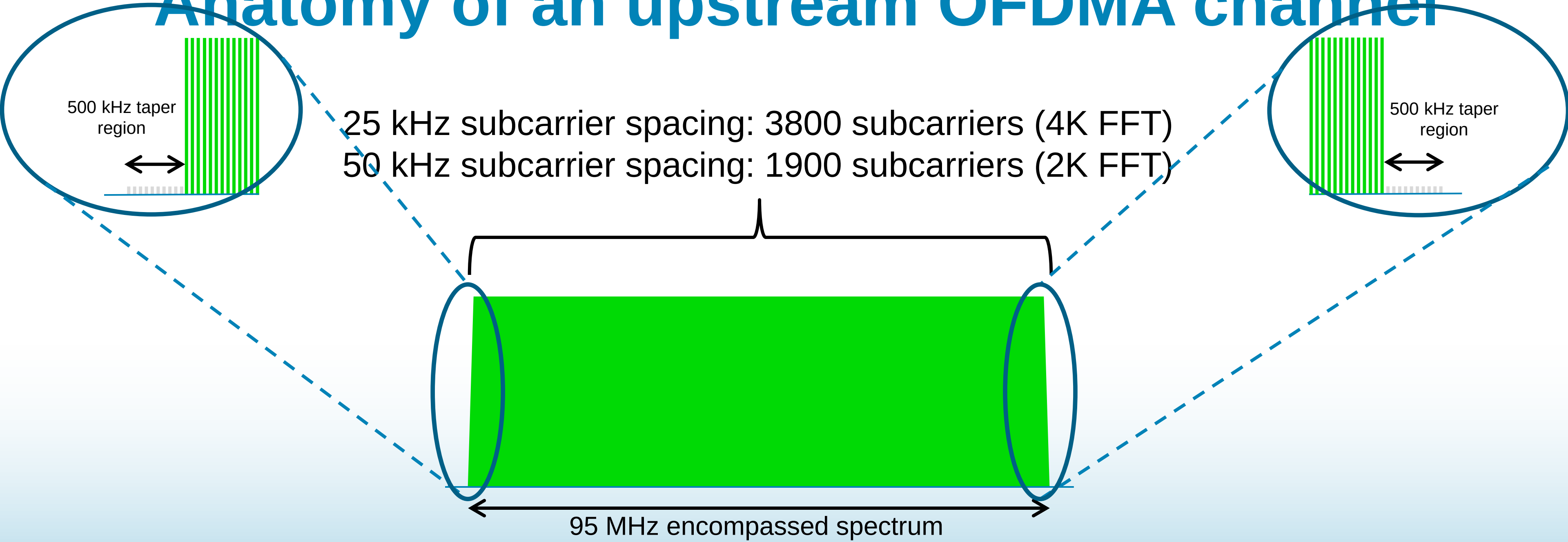
190 MHz

192 MHz channel bandwidth, including 1 MHz wide taper region on each end

Anatomy of an upstream OFDMA channel



Anatomy of an upstream OFDMA channel

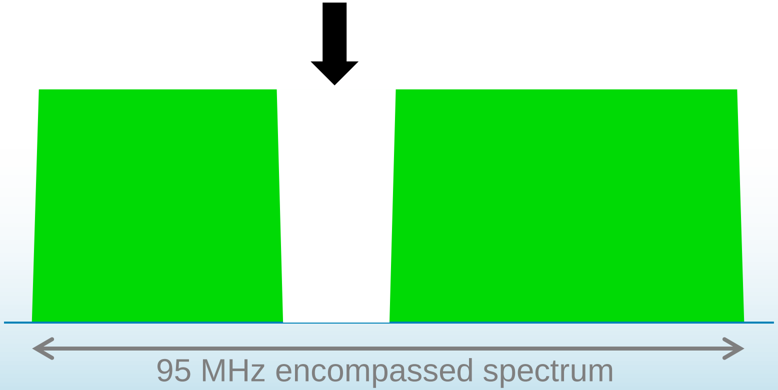


25 kHz subcarrier spacing: 3800 subcarriers (4K FFT)

50 kHz subcarrier spacing: 1900 subcarriers (2K FFT)

Anatomy of an upstream OFDMA channel

Exclusion bands may be created within an OFDMA channel for problems such as strong ingress (e.g., shortwave, CB radio), or for the carriage of legacy SC-QAM signals.



An exclusion band is a set of contiguous subcarriers within the OFDMA channel bandwidth that are set to zero-value by the transmitter to avoid interference or to accommodate co-existing transmissions such as legacy SC-QAM signals.

Anatomy of an upstream OFDMA channel

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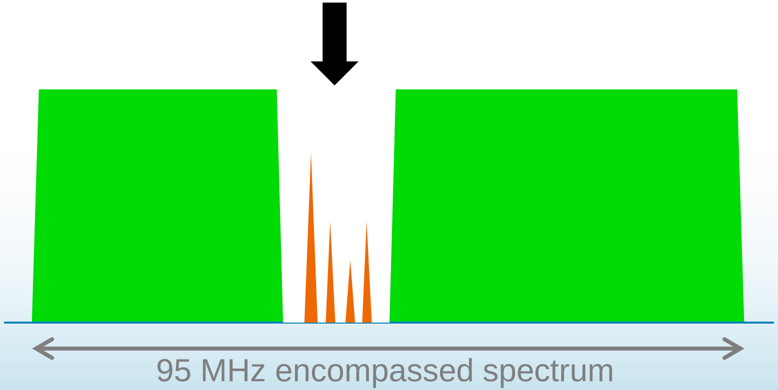

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Anatomy of an upstream OFDMA channel

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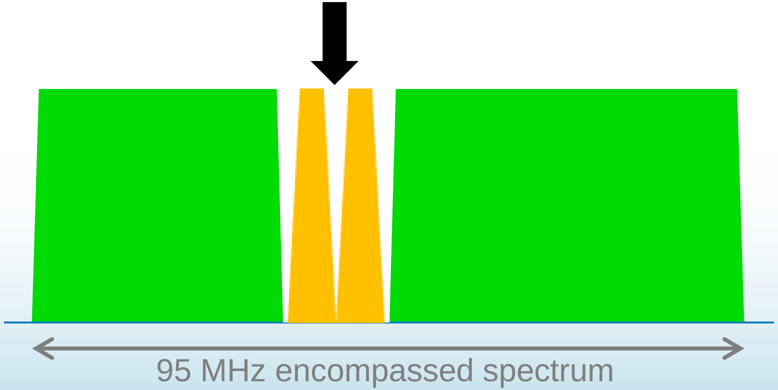

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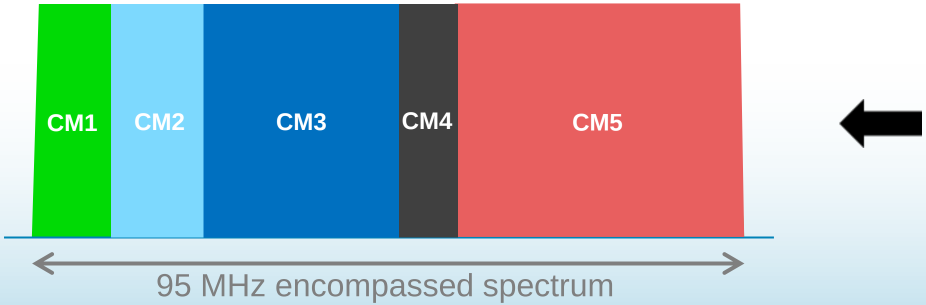
Anatomy of an upstream OFDMA channel

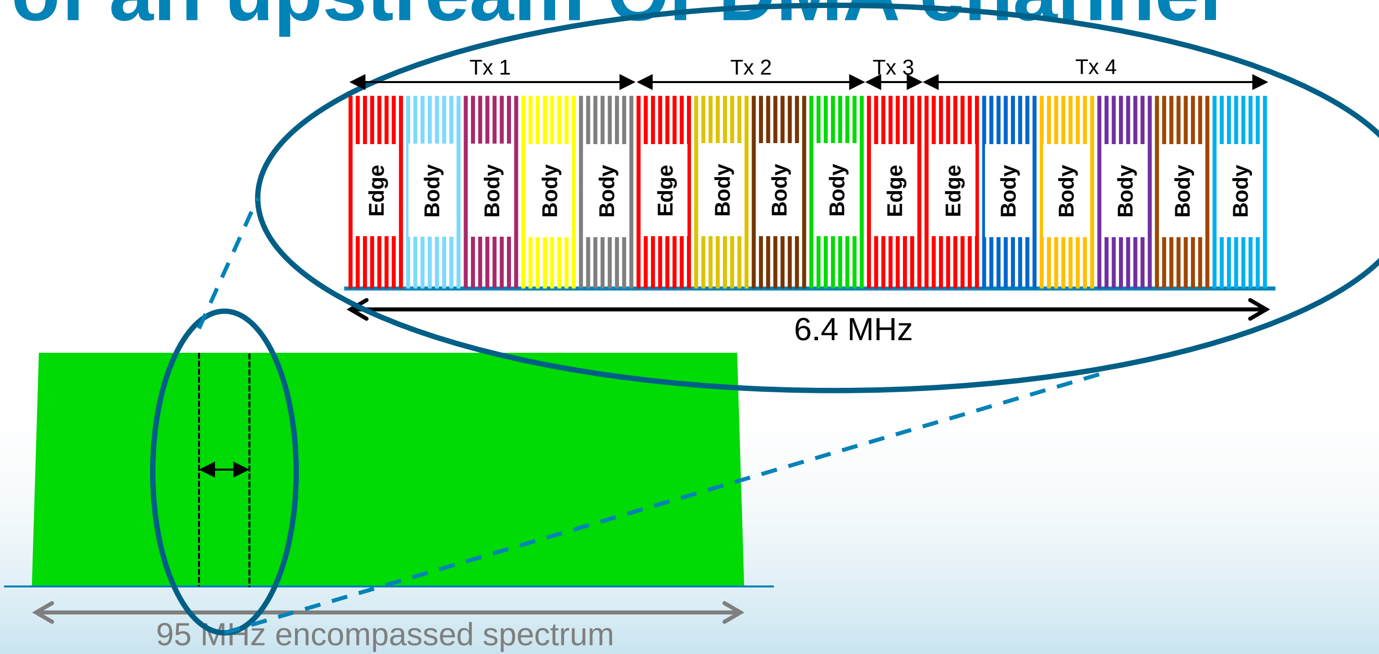
OFDMA is a multi-user version of OFDM, and assigns subsets of subcarriers to individual CMs.



Here, five modems are transmitting simultaneously within the same 95 MHz encompassed spectrum of a hypothetical upstream OFDMA channel. The different colors represent subsets of the channel’s subcarriers assigned to each modem.

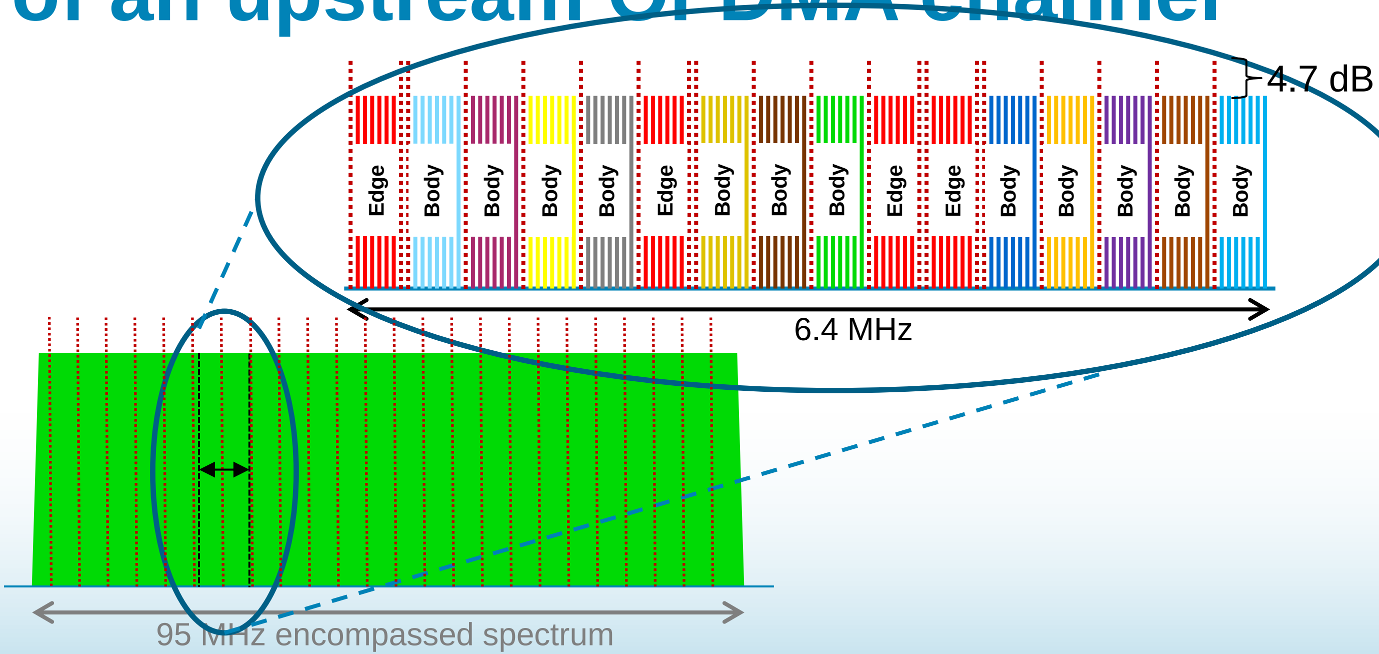
Anatomy of an upstream OFDMA channel

- Minislots comprise groups of 8 or 16 subcarriers (8 subcarriers per minislot shown). A modem may transmit one or more minislots per burst.
- There are two types of minislots for each minislot size: edge and body.
- An edge minislot is the first minislot in an upstream burst; the first minislot after an exclusion band, or after one or more contiguous skipped subcarriers, or after a zero valued minislot; and the first minislot of an OFDMA frame that is not a zero valued minislot.
- All others are body minislots.



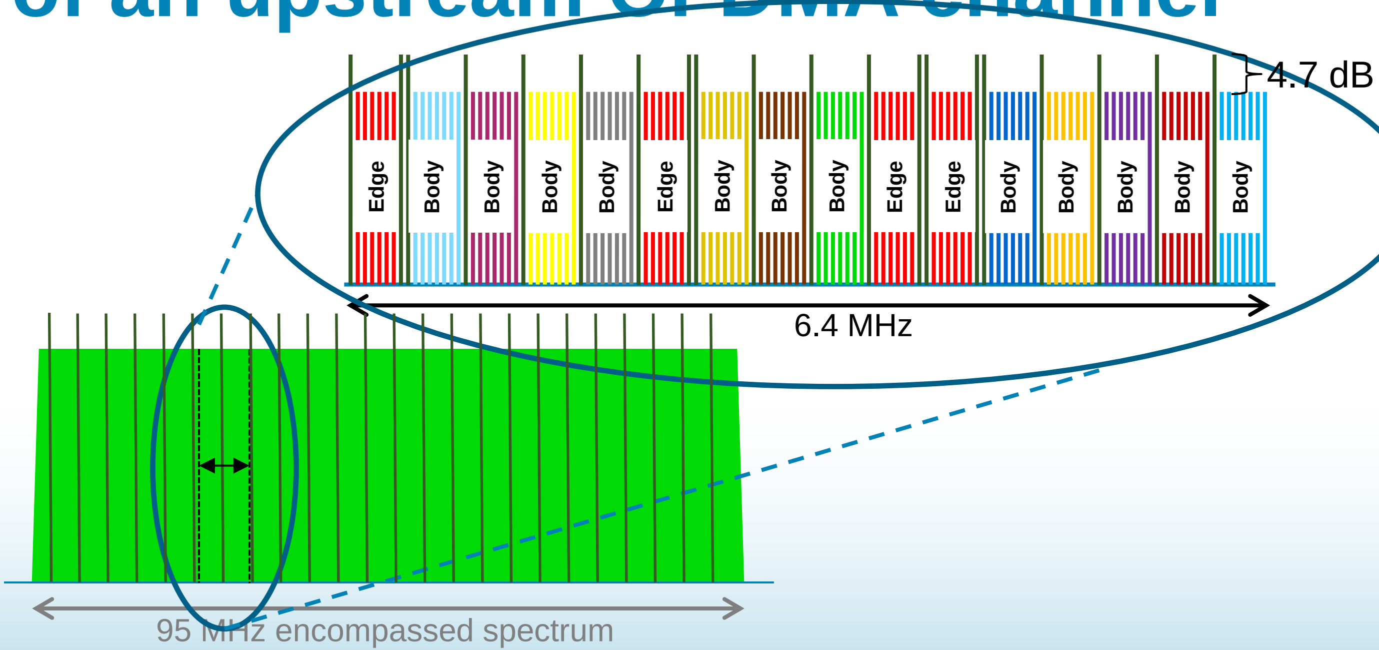
Anatomy of an upstream OFDMA channel

- Subcarriers called pilots do not carry data. They are BPSK modulated with a pseudo-random binary sequence known to the receiver, and are used to adapt to channel conditions and frequency offset.
- Upstream pilots are boosted by approximately 4.7 dB relative to other subcarriers.
- There are seven pilot patterns defined for each minislot size (Pattern #1 for 8-subcarrier minislots shown).



Anatomy of an upstream OFDMA channel

- Subcarriers called complementary pilots (used in the upstream only) do carry data, but at a lower modulation order than other subcarriers (e.g., if data subcarriers are 256-QAM, the complementary pilots are 16-QAM).
- The CMTS receiver MAY use complementary pilots to enhance its signal processing, such improving the accuracy of center frequency offset acquisition.
- Complementary pilots are also boosted by approximately 4.7 dB relative to other upstream subcarriers.
- Pattern #1 for 8-subcarrier minislots shown.



Note: Subslots, not shown in these examples, carry REQ messages (7 bytes or 56 bits long) using QPSK.

Higher modulation orders: downstream

	CMTS downstream transmit	Cable modem downstream receive	Bits per symbol
MUST	16-QAM	16-QAM	4
MUST	64-QAM	64-QAM	6
MUST	128-QAM	128-QAM	7
MUST	256-QAM	256-QAM	8
MUST	512-QAM	512-QAM	9
MUST	1024-QAM	1024-QAM	10
MUST	2048-QAM	2048-QAM	11
MUST	4096-QAM	4096-QAM	12
MAY	8192-QAM	8192-QAM	13
MAY	16384-QAM	16384-QAM	14

Higher orders than DOCSIS 3.0

Higher modulation orders: upstream

	Cable modem upstream transmit	CMTS upstream receive	Bits per symbol
MUST	QPSK	QPSK	2
MUST	8-QAM	8-QAM	3
MUST	16-QAM	16-QAM	4
MUST	32-QAM	32-QAM	5
MUST	64-QAM	64-QAM	6
MUST	128-QAM	128-QAM	7
MUST	256-QAM	256-QAM	8
MUST	512-QAM	512-QAM	9
MUST	1024-QAM	1024-QAM	10
MUST	2048-QAM	—	11
MUST	4096-QAM	—	12
SHOULD	—	2048-QAM	11
SHOULD	—	4096-QAM	12

Higher orders than DOCSIS 3.0 ATDMA

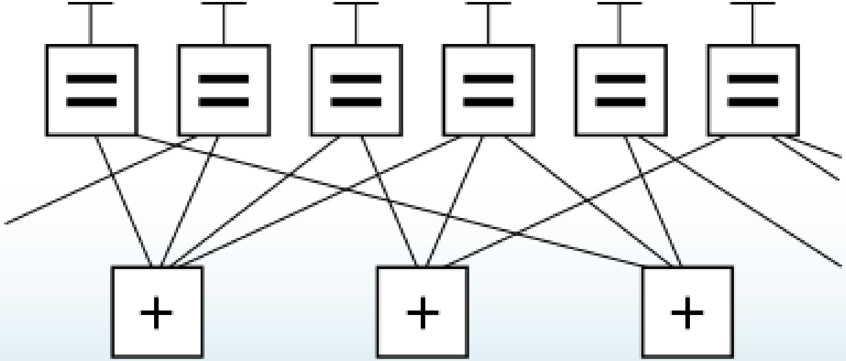
LDPC FEC

- DOCSIS 3.1 uses a form of FEC known as LDPC
- LDPC = low density parity check

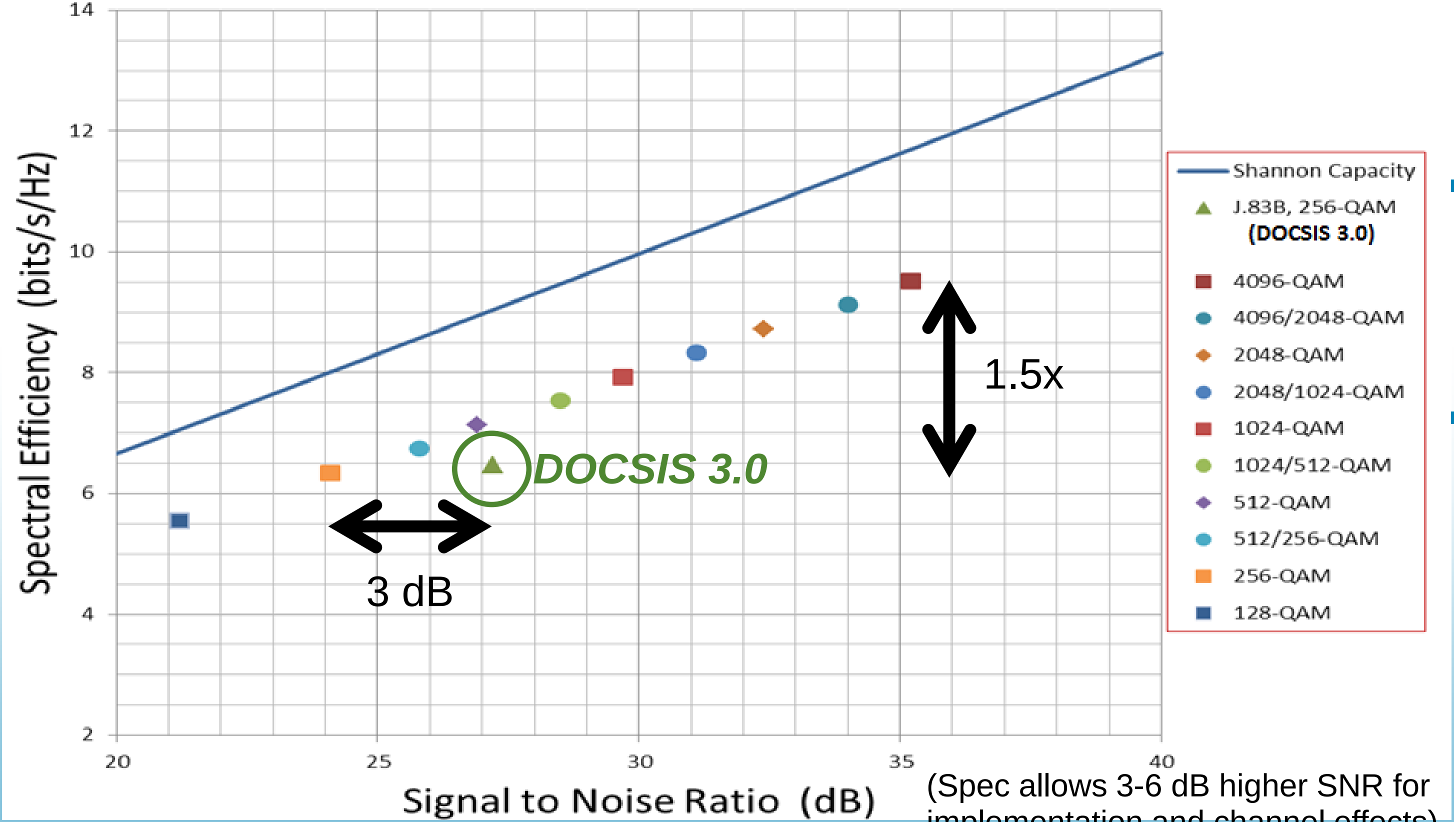
    The concept of LDPC was introduced by Robert G. Gallager in his 1960 Sc.D. thesis at MIT (Gallager’s thesis was published by the MIT Press as a monograph in 1963)

    Because of encoder and decoder complexity, it wasn’t practical to implement LDPC until relatively recently

- BCH (Bose-Chaudhuri-Hocquenghan) outer code corrects residual errors in downstream



FEC: improved SNR and throughput

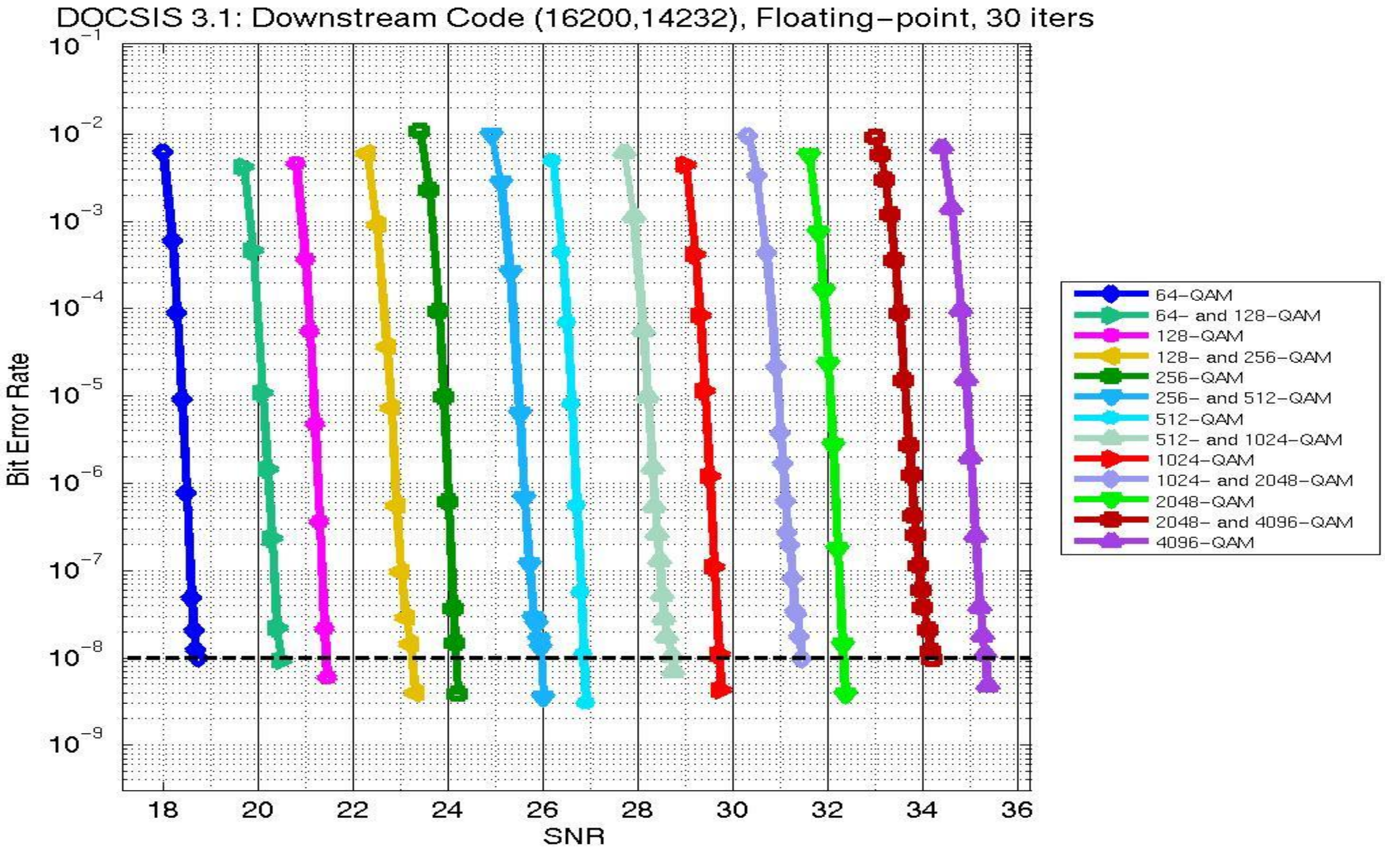


(Spec allows 3-6 dB higher SNR for implementation and channel effects)

- ~3 dB SNR improvement over D3.0 using 256-QAM
- 4096-QAM gives ~50% throughput improvement over 256-QAM

Source: R. Prodan

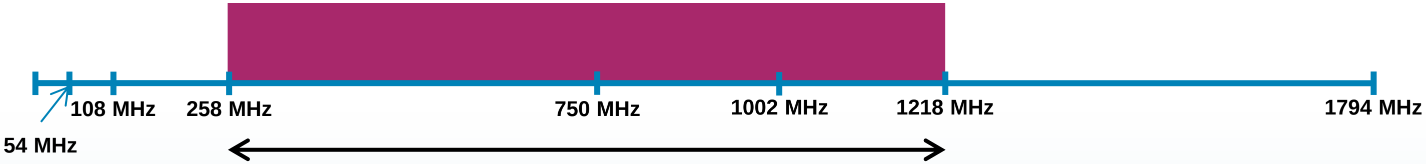
FEC flexibility



- Pick modulation based on SNR

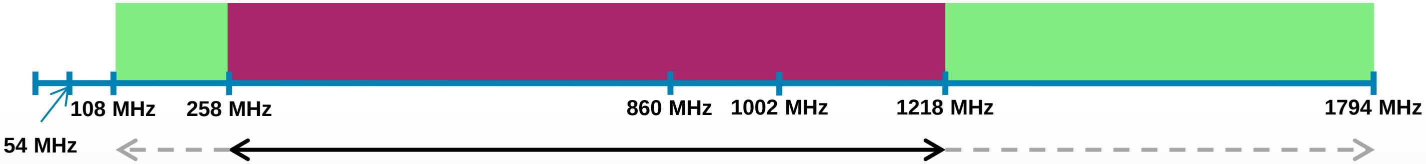
Source: R. Prodan,
SCTE Cable-Tec
Expo 2014

DOCSIS 3.1 downstream frequency usage



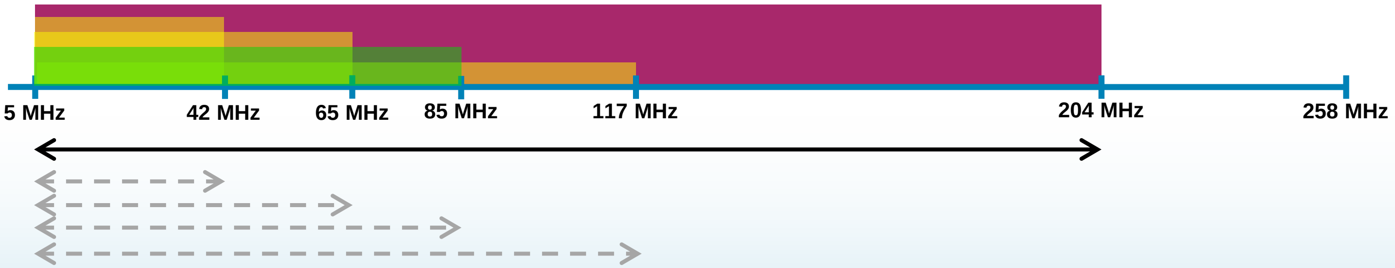
- DOCSIS 3.1 downstream: 258 MHz to 1218 MHz

DOCSIS 3.1 downstream frequency usage



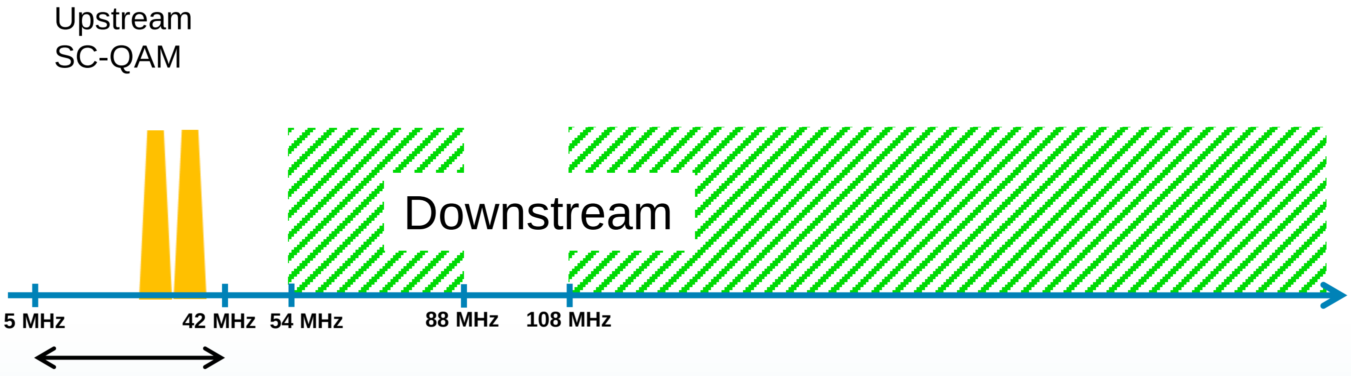
- DOCSIS 3.1 downstream: 258 MHz to 1218 MHz
  - Optional 108 MHz lower end
  - Optional 1794 MHz upper end
- Must support a minimum of two 192 MHz-wide OFDM channels in the downstream

DOCSIS 3.1 upstream frequency usage



- DOCSIS 3.1 upstream: 5 MHz to as high as 204 MHz
  - Also must support 5 MHz to 42 MHz, 5 MHz to 65 MHz, 5 MHz to 85 MHz (mandatory), and 5 MHz to 117 MHz
- Must support a minimum of two full OFDMA channels (95 MHz encompassed spectrum each) in the upstream

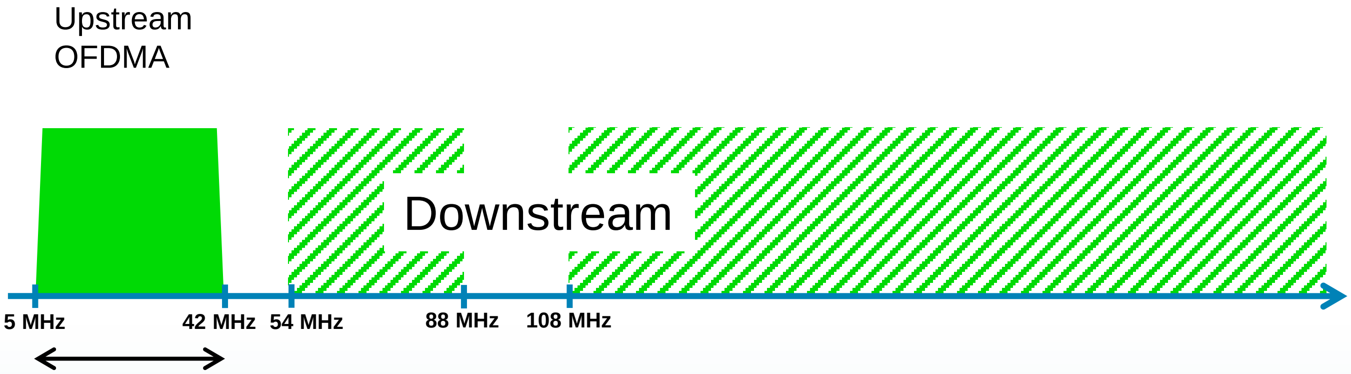
DOCSIS 3.1 upstream frequency usage



- Using time division multiple access, legacy upstream SC-QAM signals can share the return spectrum with full-bandwidth OFDMA.

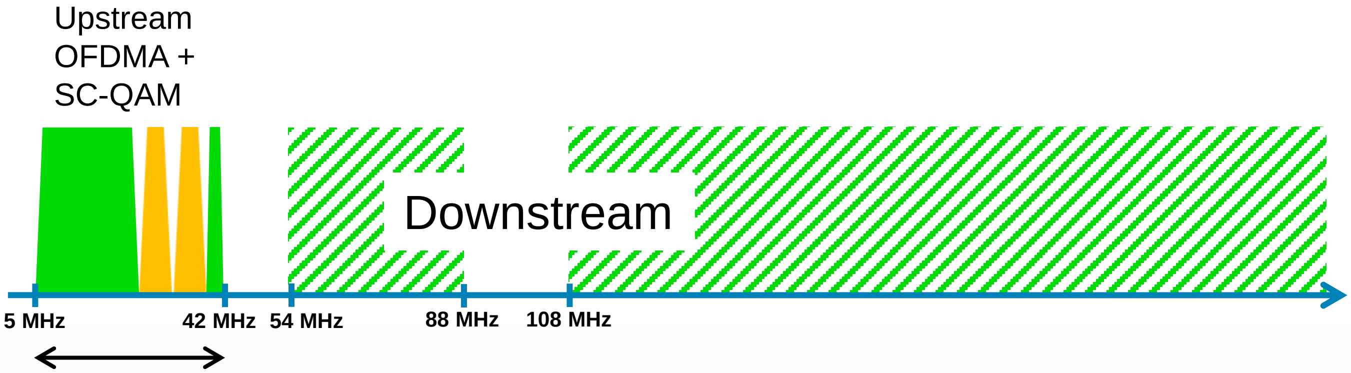
  A DOCSIS 3.0 (or earlier) modem transmits when DOCSIS 3.1 modems are not transmitting

DOCSIS 3.1 upstream frequency usage



- Using time division multiple access, legacy upstream SC-QAM signals can share the return spectrum with full-bandwidth OFDMA.
  - A DOCSIS 3.1 modem transmits when legacy modems are not transmitting

DOCSIS 3.1 upstream frequency usage

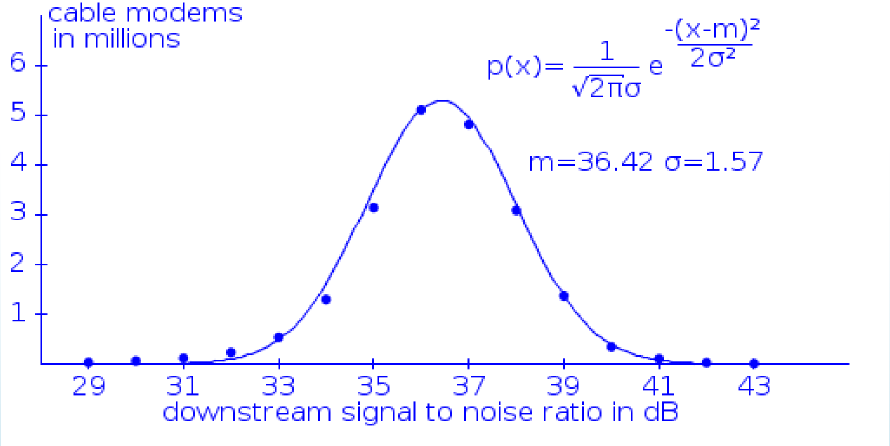


- Alternatively, the OFDMA channel can be configured with an exclusion band to accommodate legacy SC-QAM channels, while the OFDMA signal occupies the rest of the spectrum.

  This would allow legacy and DOCSIS 3.1 modems to use the spectrum simultaneously

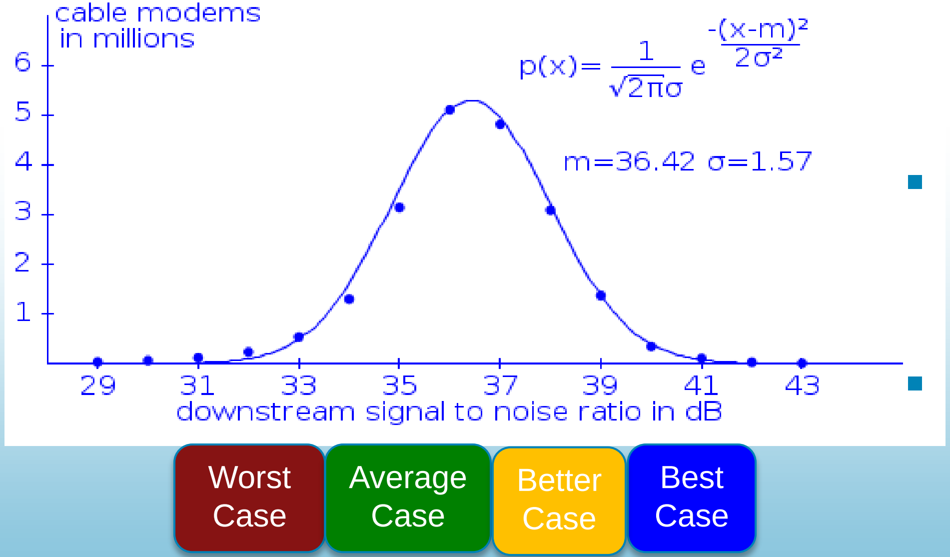
Plant performance?

One cable operator’s analysis showed at least 8 dB variation in downstream SNR (MER) among millions of modems:



Example DOCSIS 3.1 SNR/MER requirements	
Modulation order	MER/SNR
256-QAM	29~30 dB
512-QAM	31~33 dB
1024-QAM	34~36 dB
2048-QAM	37~39 dB
4096-QAM	40~42 dB

Downstream profiles



- Downstream profiles support the transmission of different modulation orders to different modems
- The downstream profiles feature is always used, even if the feature is configured for just one profile
- Multiple downstream profiles could enable operators to leverage SNR/MER variation to improve system capacity
- Example with four profiles:
  A: Worst (say, mostly 256-QAM)
  B: Average (say, mostly 1024-QAM)
  C: Better (say, mostly 2048-QAM)
  D: Best (say, mostly 4096-QAM)

Approximate downstream speeds

Single 192 MHz OFDM channel (full channel, no exclusions)

Modulation order	25 kHz subcarrier spacing	50 kHz subcarrier spacing
256-QAM	1.26 Gbps	1.20 Gbps
512-QAM	1.42 Gbps	1.35 Gbps
1024-QAM	1.58 Gbps	1.50 Gbps
2048-QAM	1.73 Gbps	1.65 Gbps
4096-QAM	1.89 Gbps	1.80 Gbps
8192-QAM	2.05 Gbps	1.96 Gbps
16384-QAM	2.21 Gbps	2.11 Gbps

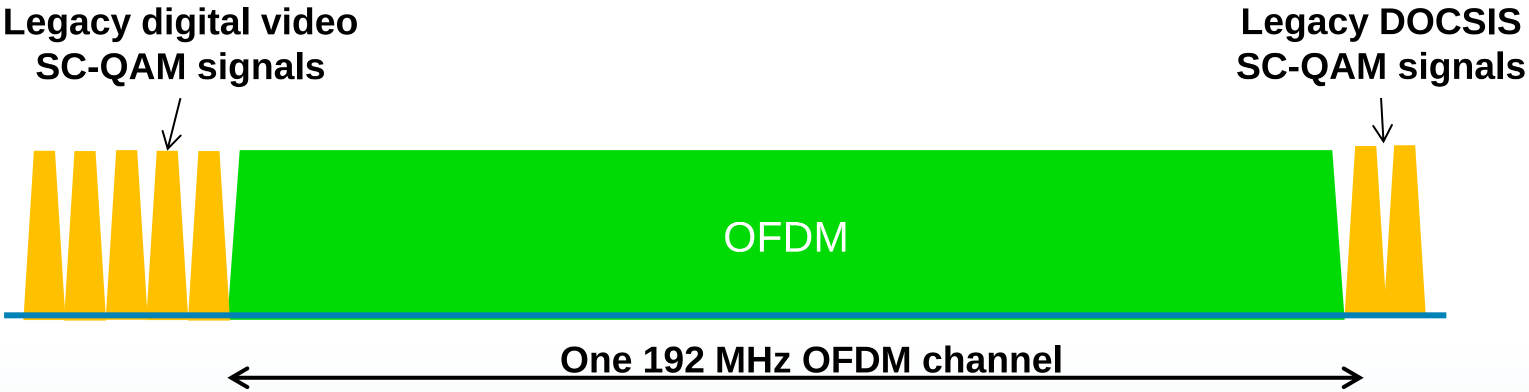
8192-QAM and 16384-QAM are optional, and may not be practical in most of today's plants

Approximate upstream speeds

Single 95 MHz encompassed spectrum OFDMA channel (full channel, no exclusions)

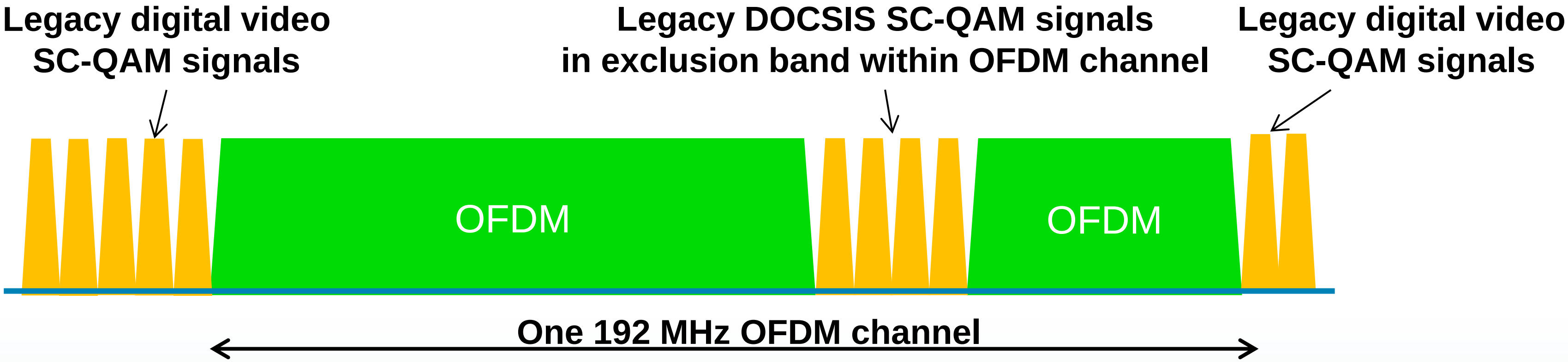
Modulation order	25 kHz subcarrier spacing	50 kHz subcarrier spacing
64-QAM	0.47 Gbps	0.46 Gbps
128-QAM	0.55 Gbps	0.53 Gbps
256-QAM	0.63 Gbps	0.61 Gbps
512-QAM	0.71 Gbps	0.69 Gbps
1024-QAM	0.78 Gbps	0.76 Gbps
2048-QAM	0.86 Gbps	0.84 Gbps
4096-QAM	0.94 Gbps	0.91 Gbps

DOCSIS 3.1 deployment example



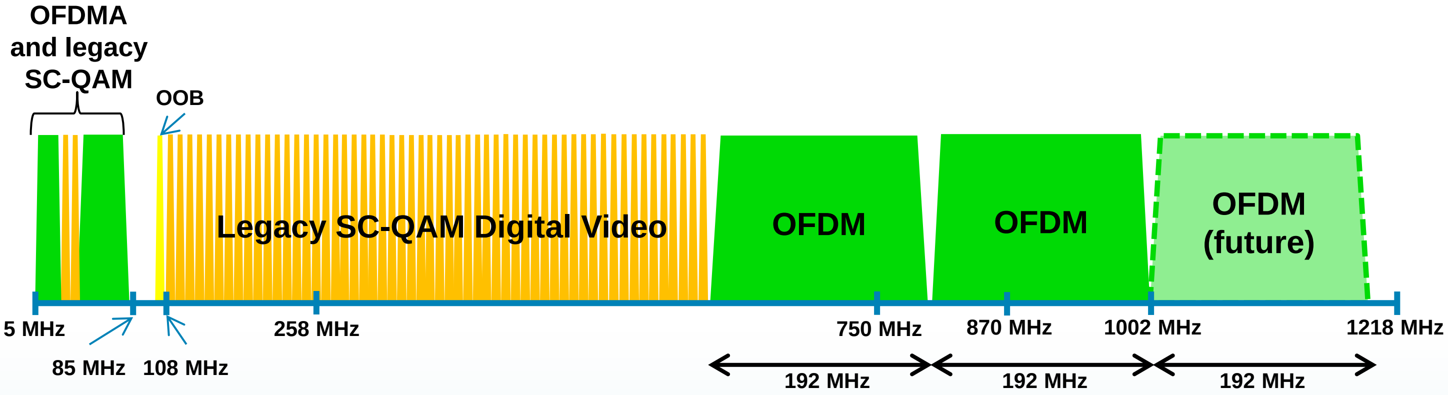
- The OFDM channel can be located in available spectrum
- Windowing can be used to sharpen the spectral edges of the OFDM signal
- Legacy DOCSIS SC-QAM and DOCSIS 3.1 OFDM can be bonded

DOCSIS 3.1 deployment example



- Excluded subcarriers (“nulling”) can be used to facilitate coexistence of an OFDM channel with legacy SC-QAM signals
- The OFDM subcarriers can be located in available spectrum
- As before, legacy DOCSIS SC-QAM and DOCSIS 3.1 OFDM can be bonded

DOCSIS 3.1 deployment example



- Upgrade split to 5-85 MHz upstream, 108 MHz* to 1002 MHz (or 1218 MHz) downstream

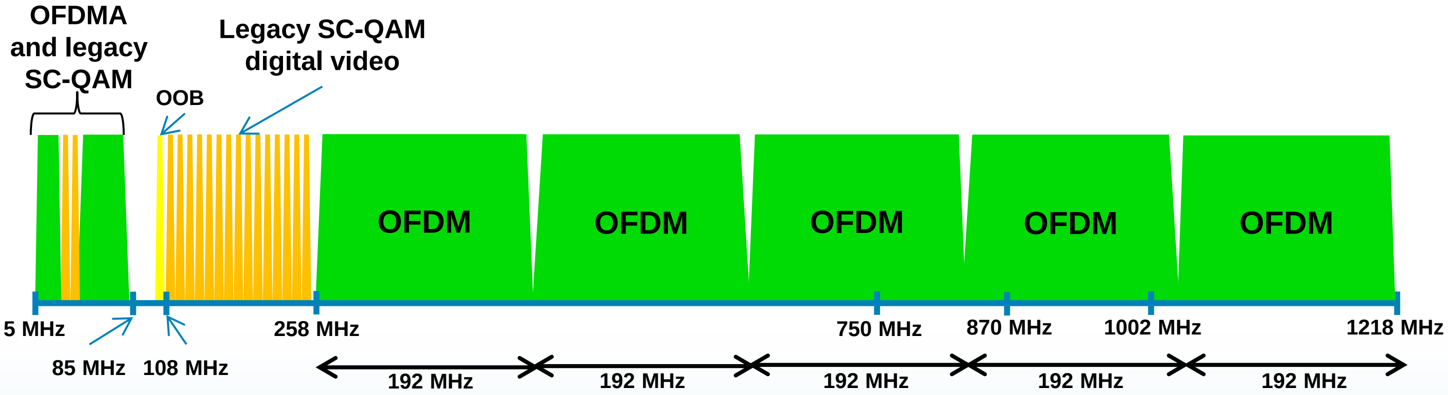
  Legacy SC-QAM digital video in the 108 MHz to ~600 MHz spectrum

  Two 192 MHz wide OFDM signals from 618 MHz to 1002 MHz (optional third OFDM >1 GHz)

  Mix of OFDMA and legacy SC-QAM in upstream

  * Note: Downstream out-of-band for set-tops may be carried in the 102~108 MHz range (avoid local FM), although it could be anywhere in the 102 MHz to 130 MHz range, assuming available spectrum.

DOCSIS 3.1 deployment example



- Upgrade split to 5-85 MHz upstream, 108 MHz* to 1218 MHz downstream

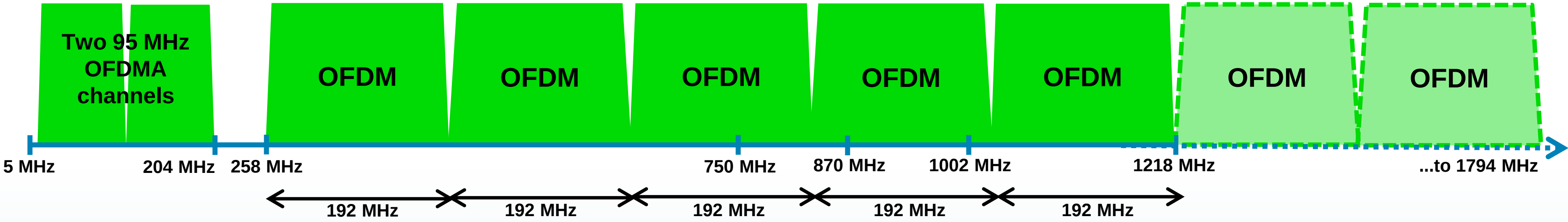
  Legacy SC-QAM digital video in the 108 MHz to 258 MHz spectrum

  Five 192 MHz wide OFDM signals from 258 MHz to 1218 MHz

  Mix of OFDMA and legacy SC-QAM in upstream

  * Note: Downstream out-of-band for set-tops may be carried in the 102~108 MHz range (avoid local FM), although it could be anywhere in the 102 MHz to 130 MHz range, assuming available spectrum.

Full spectrum DOCSIS 3.1 deployment example



- Upgrade split to 5-204 MHz upstream, 258 MHz to 1218 MHz downstream (optionally to 1794 MHz)
  - Five 192 MHz wide OFDM signals from 258 MHz to 1218 MHz
  - Optionally another three 192 MHz wide OFDM signals between 1218 MHz and 1794 MHz
  - Two 95 MHz encompassed spectrum OFDMA signals in the 5 MHz to 204 MHz spectrum

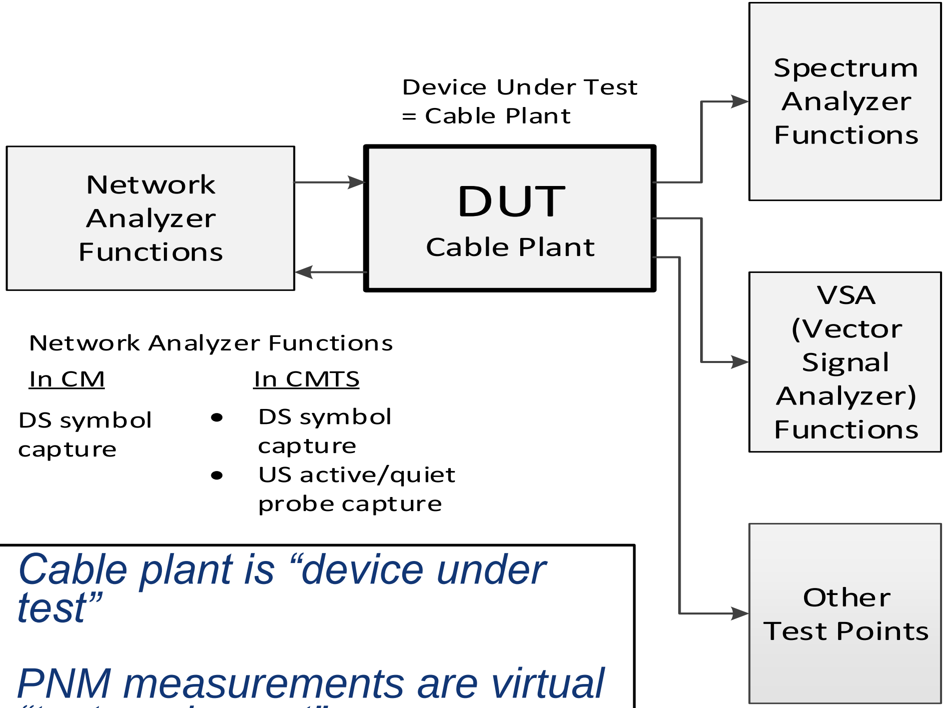
Backwards compatibility

- DOCSIS 3.1 devices will simultaneously support legacy SC-QAM channels and OFDM channels
- Devices will support bonding between OFDM and SC-QAM in order to aggregate that capacity and provide an incremental and orderly migration
- The time division nature of the existing DOCSIS upstream allows for legacy and OFDMA to be time multiplexed
- Allows a gradual and evolutionary introduction of DOCSIS 3.1

DOCSIS 3.1 proactive network maintenance

- PNM designed for DOCSIS 3.1 from the ground up to provide “test points” in the CMTS and cable modem
  - Characterize and troubleshoot HFC plant
  - Support remote proactive troubleshooting of plant faults
  - Improve reliability and maximize throughput from well-maintained plant

DOCSIS 3.1 test points for HFC plant



Spectrum Analyzer Functions

In CM
- Full-band spectrum
- NPR notch

In CMTS
- Triggered spectrum

VSA Functions

In CM
- US pre-equalizer coeffs
- DS channel estimate
- Constellation display
- RxMER vs subcarrier

In CMTS
- US equalizer coefficients

Network Analyzer Functions

In CM
- DS symbol capture

In CMTS
- DS symbol capture
- US active/quiet probe capture

Other Test Points

In CM
- FEC statistics
- Histogram

In CMTS
- Impulse noise statistics
- FEC statistics
- Histogram

- *Cable plant is "device under test"*
- *PNM measurements are virtual "test equipment"*

Downstream PNM “hooks”

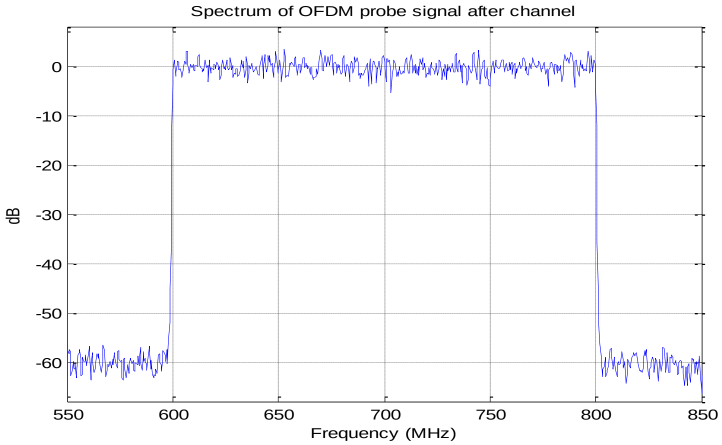
- Downstream symbol capture: Capture OFDM symbol at input and output of plant, solve for plant response
- Wideband spectrum analysis: Spectrum analyzer in cable modem
- Channel estimate coefficients: Downstream equalizer response
- Constellation display: QAM constellation cluster
- Receive modulation error ratio (RxMER) per subcarrier: MER (SNR) vs frequency
- FEC statistics: Correctable and uncorrectable codewords
- Histogram: Signal distribution revealing nonlinearities in plant such as laser clipping
- Received power: RF power received at cable modem

Downstream PNM measurements vs use case

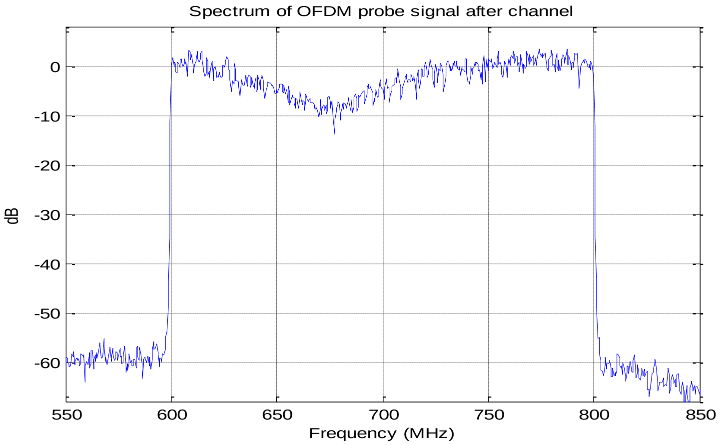
	… ADDRESSES THESE USE CASES											
THIS DOWNSTREAM MEASUREMENT …	Locate microreflections	Spectrum notches, ripple, rolloff, filters, adjacency	Group delay distortion	Non-flat noise under carrier	Laser misalignment, amplifier compression	Malfunctioning/resonant amplifiers	Digital CPD/CSO/CTB	Raised AWGN noise floor	Interferers, spurious, FM, LTE	Burst interference/noise	QAM carrier performance issues	Hi or low total received DS power
DS Symbol Capture	x	x	x	x	x	x	x	x	x		x	
DS Spectrum Analysis in CM		x				x		x	x			x
Noise Power Ratio					x		x	x				
Channel Estimate Coefficients	x		x									
Constellation Display					x			x	x	x	x	
RxMER Per Subcarrier				x			x	x	x	x	x	
Histogram					x			x				
FEC Errored Seconds and Minutes								x		x	x	
CM Received Power												x

Downstream symbol capture

Ordinary OFDM symbol captured by CMTS at input to cable plant

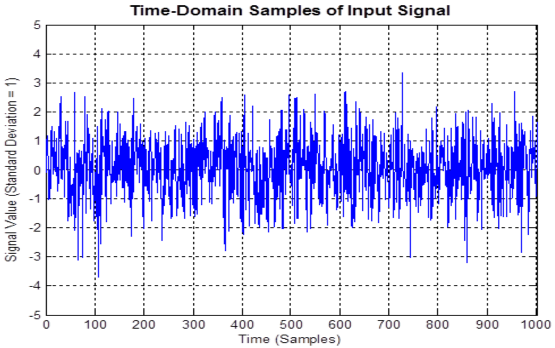


Same received symbol captured by cable modem after cable plant

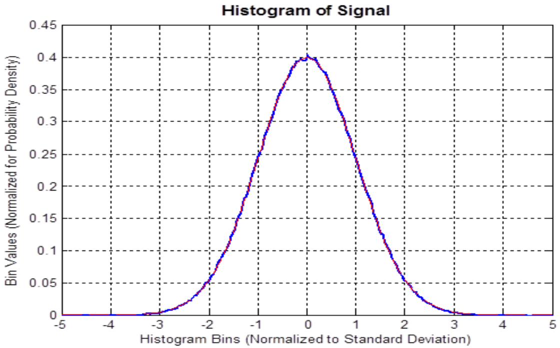


- With known input and output samples, channel can be characterized, including linear and nonlinear effects
- Fast spectrum measurement, magnitude, group delay, compression, laser clipping, CPD, ingress, noise under carrier, plant leakage …
- Trigger message block (MULPI 6.5.5) allows modem and CMTS to capture the same symbol

Histogram of Laser Clipping

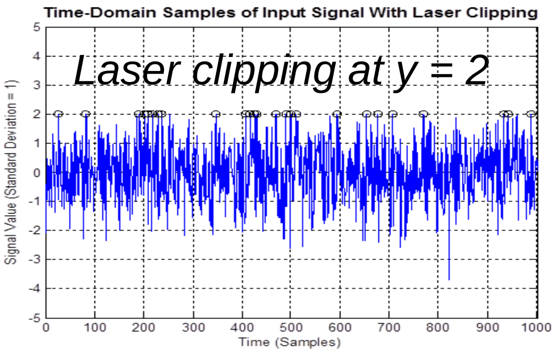


(a)



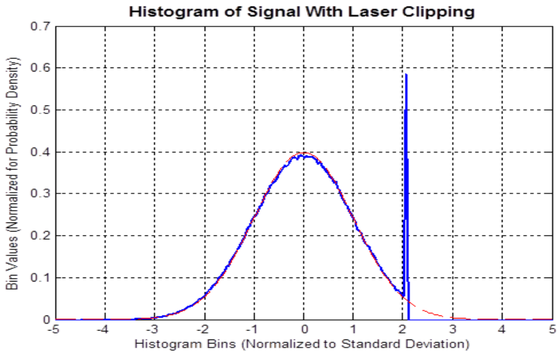
(b)

- Normal OFDM signal has Gaussian-shaped histogram



Laser clipping at y = 2

(a)



(b)

- Laser clipping causes one tail to be chopped off and replaced with spike

Time domain samples

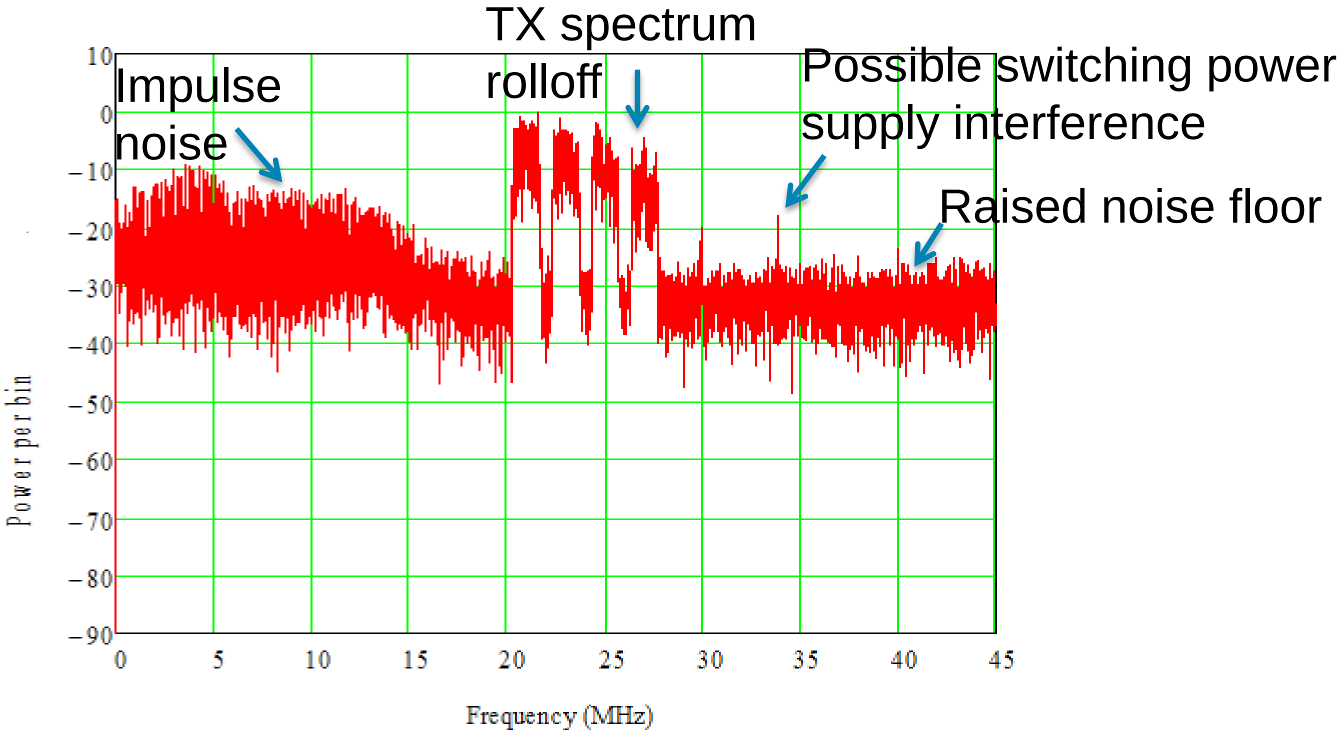
Histogram

Spectrum of upstream band at cable modem

Extension to D3.1 PNM

- **Problem:** Upstream noise funnels to single point at CMTS making it difficult to locate source
- **Solution:** Measure spectrum of upstream band at each cable modem
  - Provides noise source location capability
  - Noise originating in house, drop or plant will have identifiable spectrum signature at cable modems and CMTS

Upstream spectrum at cable modem with damaged cable shielding



Upstream PNM “hooks”

- Capture for active and quiet probe: Capture known probe symbol (or empty slot) at output of plant, solve for plant response (or noise floor)
- Triggered spectrum analysis: Spectrum analyzer synchronized with upstream timeslots
- Impulse noise statistics: Burst/impulse noise level and duration
- Equalizer coefficients: Pre- and post-equalizer responses
- FEC statistics: Error-free, unreliable, and corrected codewords
- Histogram: Signal distribution revealing nonlinearities in plant such as laser clipping
- Channel power: Power received at CMTS (ranging offset)
- RxMER per subcarrier: MER (SNR) vs frequency

Upstream PNM measurements vs use case

	… ADDRESSES THESE USE CASES																	
THIS UPSTREAM MEASUREMENT …	Locate microreflections	Locate source of US noise	Spectrum notches, rolloff, ripple	Group delay distortion	Non-flat noise under carrier	Distortion/noise transmitted by CM	Laser clipping, amplifier compression	Digital CPD/CSO/CTB	Raised AWGN noise floor	Distinguish interference: grow light, motor, switching PS	QAM carrier performance issues	Low or high received power from user						
Capture of Active Probe	x		x	x	x	x	x	x	x		x	x						
Capture of Quiet Probe					x	x		x	x		x							
Triggered Spectrum Analysis at CMTS			x			x	x	x	x	x		x						
Analysis of US Spectrum at CM		x				x												
Impulse Noise Statistics										x								
Equalizer Coefficients (Pre- and Post-)	x		x	x														
RxMER Per Subcarrier					x	x			x		x							
Histogram							x		x									
FEC Errored Seconds										x	x							
CMTS Received Power												x						

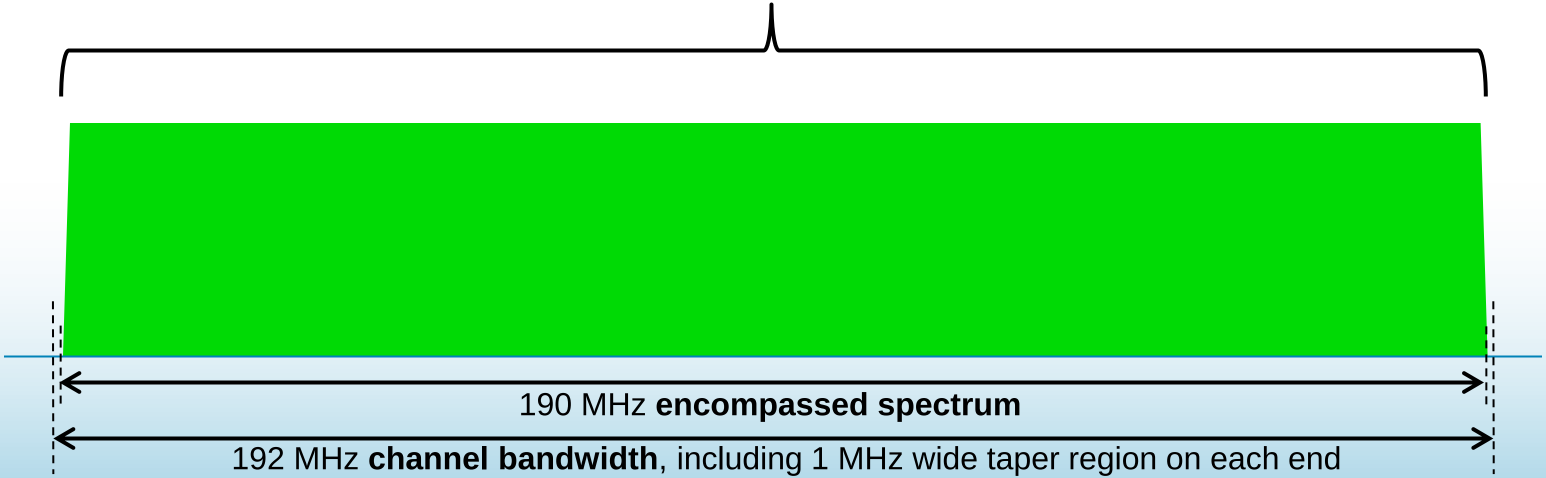
Summary

- New PHY layer: OFDM, OFDMA, and LDPC
- Higher modulation orders
- New spectrum usage options
- Takes DOCSIS to full-spectrum capability
- Cost-effectively scales to 10+ Gbps in the downstream, 1+ Gbps in the upstream
- FTTH equivalent at lower price point on an existing HFC plant
- Deployable in today’s HFC networks

Useful references

- “What is OFDM?” by Ron Hranac; (November 2012 *Communications Technology*)
  - http://www.scte.org/TechnicalColumns/12-11-30%20what%20is%20ofdm.pdf
- SCTE Rocky Mountain Chapter seminar (April 17, 2014): “Introduction to DOCSIS 3.1”
  - http://www.scte-rockymountain.org/information-central/seminar-videos
- DOCSIS 3.1 spec
  - http://www.cablelabs.com/

Downstream **encompassed spectrum** example

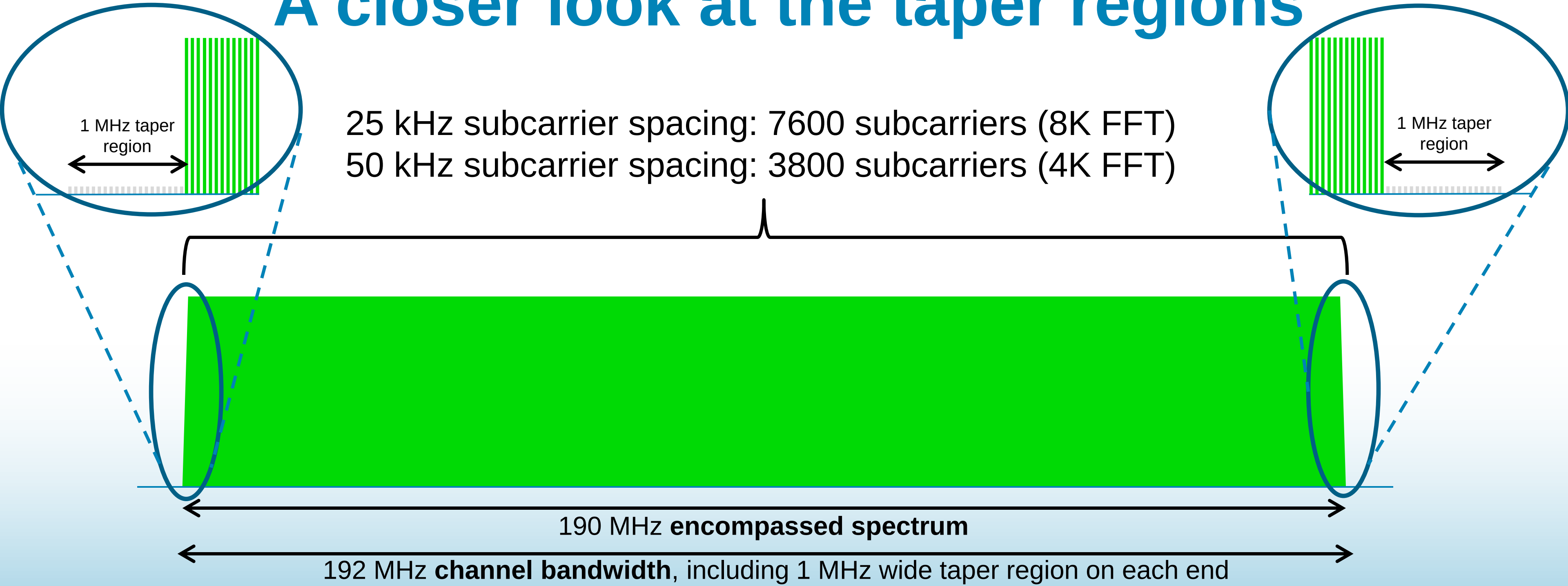


25 kHz subcarrier spacing: 7600 subcarriers (8K FFT)
50 kHz subcarrier spacing: 3800 subcarriers (4K FFT)

190 MHz **encompassed spectrum**

192 MHz **channel bandwidth**, including 1 MHz wide taper region on each end

A closer look at the taper regions



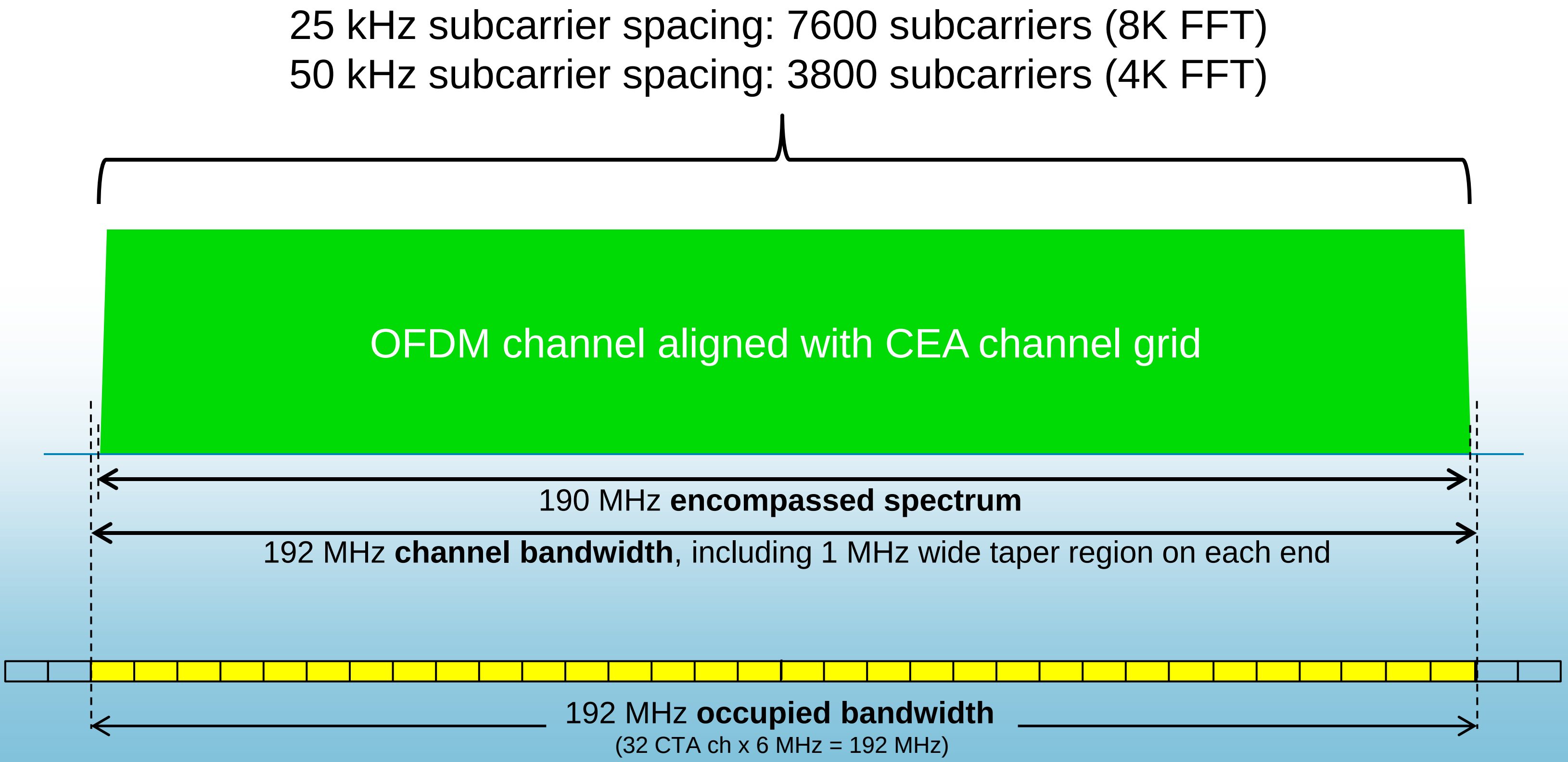
25 kHz subcarrier spacing: 7600 subcarriers (8K FFT)
50 kHz subcarrier spacing: 3800 subcarriers (4K FFT)

190 MHz **encompassed spectrum**

192 MHz **channel bandwidth**, including 1 MHz wide taper region on each end

The 1 MHz taper regions shown are the minimum bandwidth supported. Taper regions may be wider depending on configuration.

Downstream **occupied bandwidth** example (1)



25 kHz subcarrier spacing: 7600 subcarriers (8K FFT)
50 kHz subcarrier spacing: 3800 subcarriers (4K FFT)

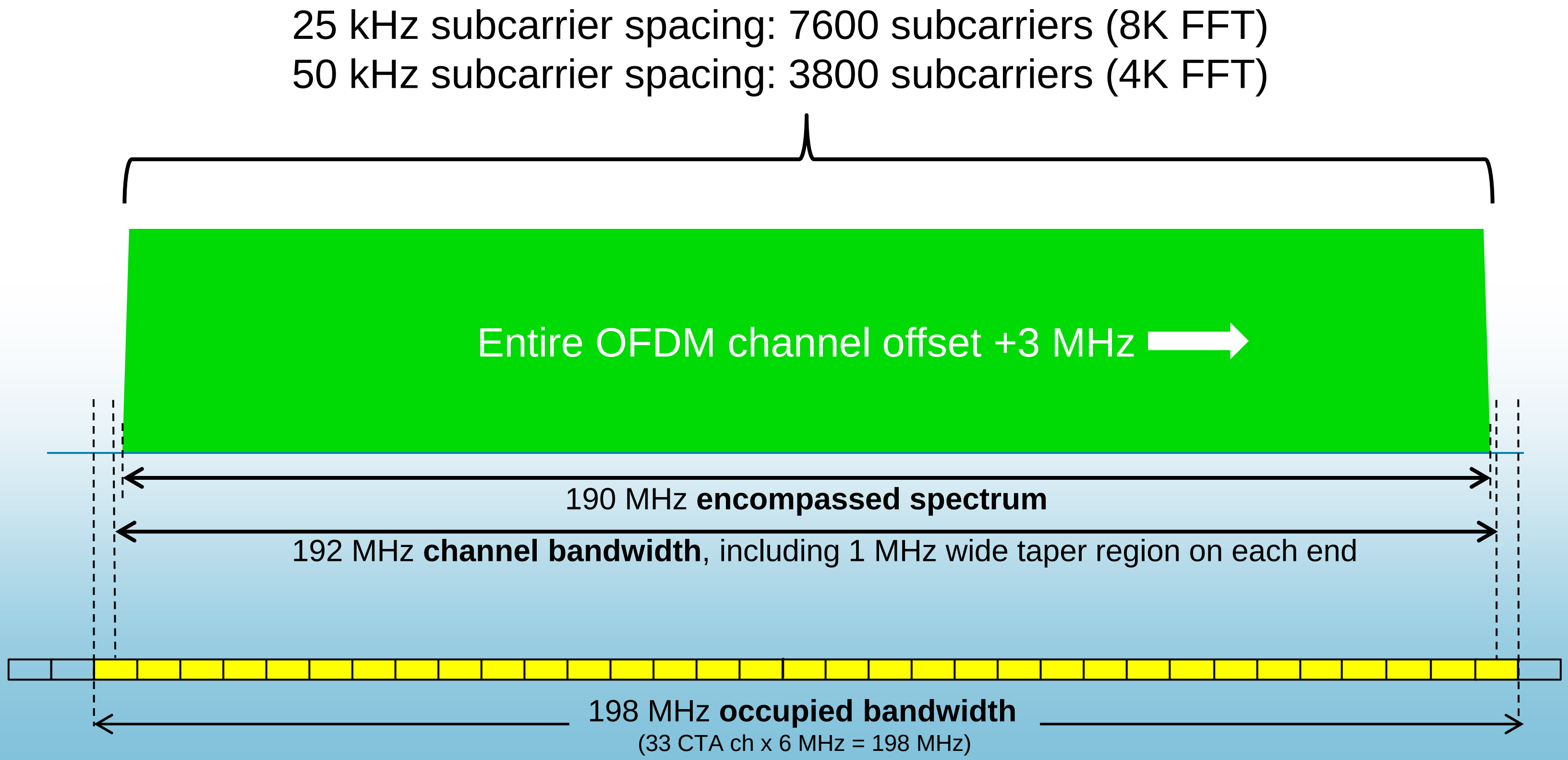
OFDM channel aligned with CEA channel grid

190 MHz **encompassed spectrum**

192 MHz **channel bandwidth**, including 1 MHz wide taper region on each end

192 MHz **occupied bandwidth**
(32 CTA ch x 6 MHz = 192 MHz)

Downstream occupied bandwidth example (2)



25 kHz subcarrier spacing: 7600 subcarriers (8K FFT)
50 kHz subcarrier spacing: 3800 subcarriers (4K FFT)

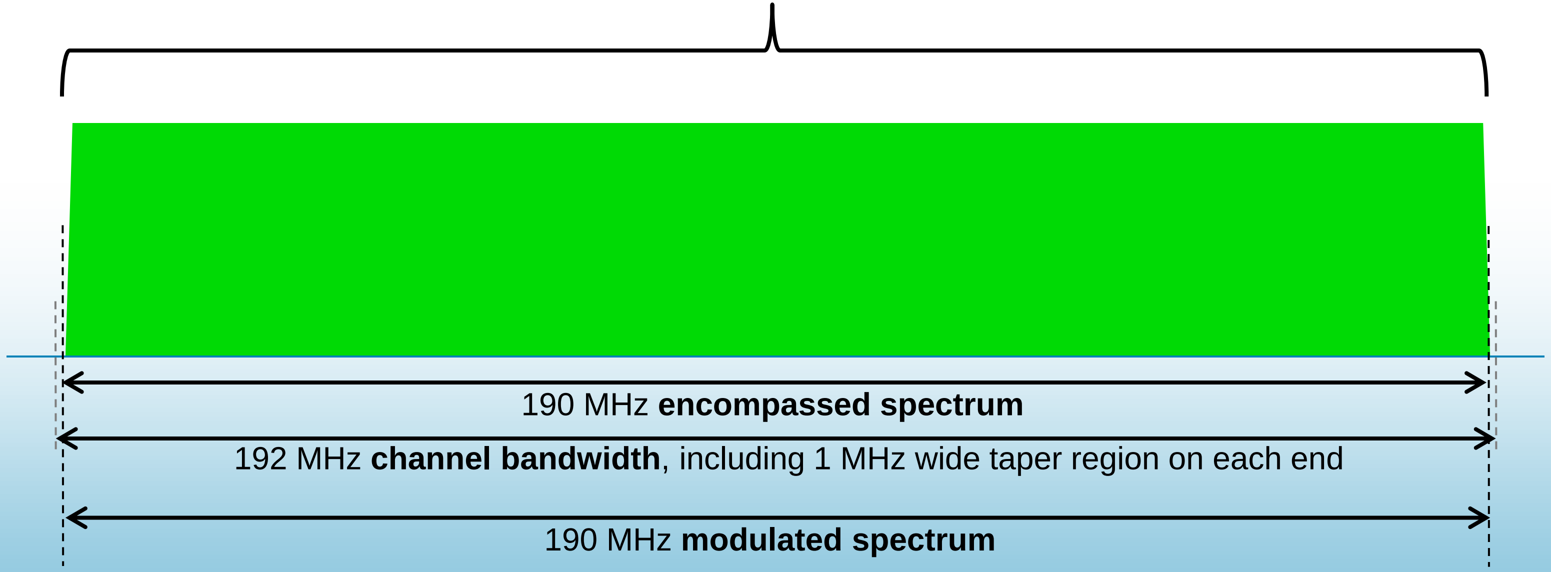
Entire OFDM channel offset +3 MHz

190 MHz **encompassed spectrum**

192 MHz **channel bandwidth**, including 1 MHz wide taper region on each end

198 MHz **occupied bandwidth**
(33 CTA ch x 6 MHz = 198 MHz)

Downstream modulated spectrum example (1)



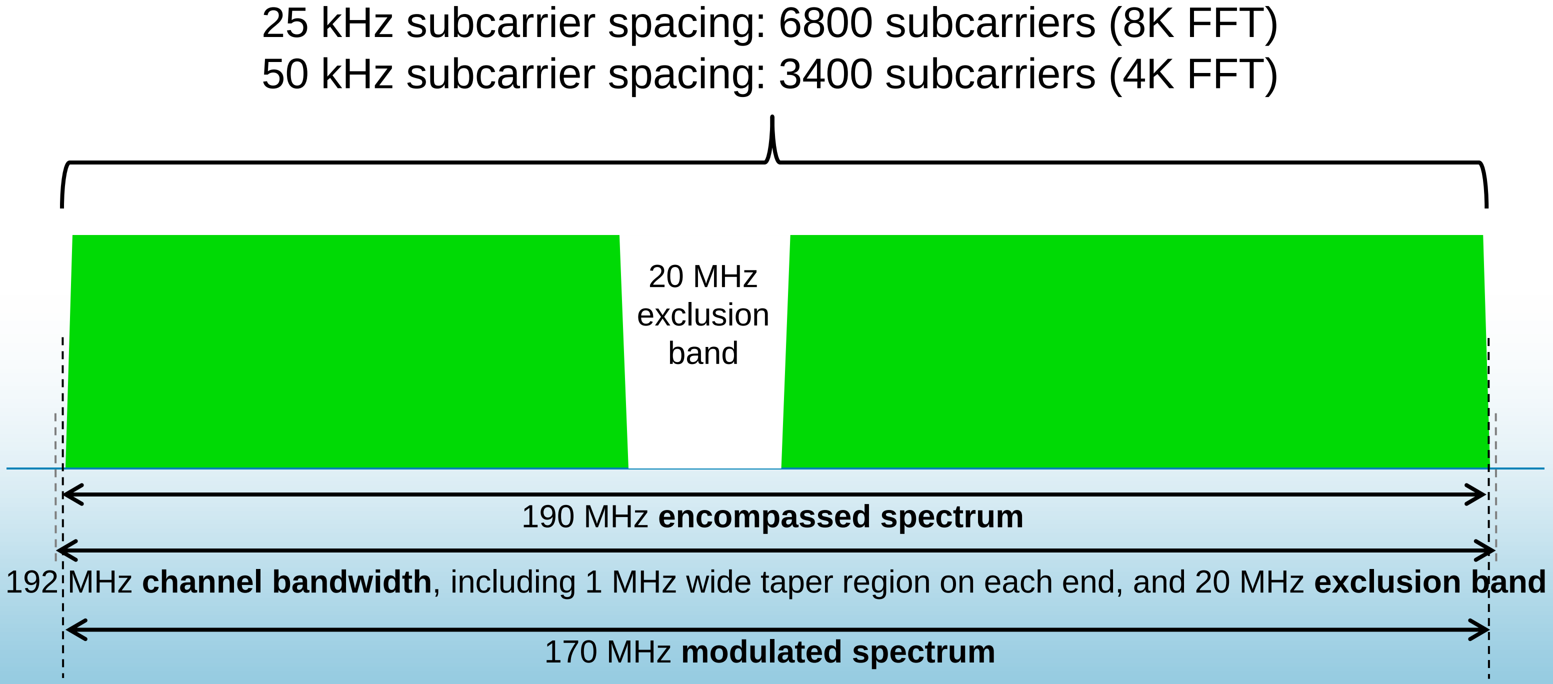
25 kHz subcarrier spacing: 7600 subcarriers (8K FFT)
50 kHz subcarrier spacing: 3800 subcarriers (4K FFT)

190 MHz **encompassed spectrum**

192 MHz **channel bandwidth**, including 1 MHz wide taper region on each end

190 MHz **modulated spectrum**

Downstream modulated spectrum example (2)



25 kHz subcarrier spacing: 6800 subcarriers (8K FFT)
50 kHz subcarrier spacing: 3400 subcarriers (4K FFT)

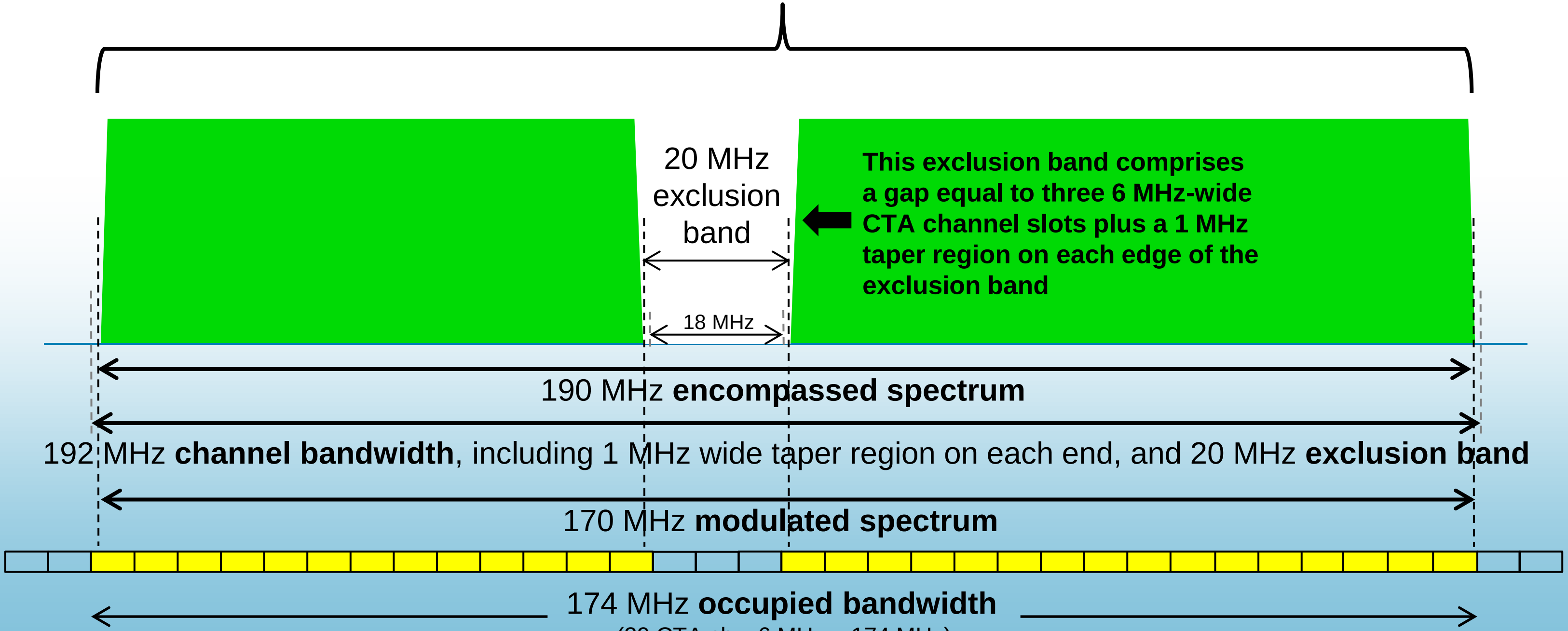
190 MHz **encompassed spectrum**

192 MHz **channel bandwidth**, including 1 MHz wide taper region on each end, and 20 MHz **exclusion band**

170 MHz **modulated spectrum**

Downstream occupied bandwidth example (3)

25 kHz subcarrier spacing: 6800 subcarriers (8K FFT)
50 kHz subcarrier spacing: 3400 subcarriers (4K FFT)



This exclusion band comprises a gap equal to three 6 MHz-wide CTA channel slots plus a 1 MHz taper region on each edge of the exclusion band

190 MHz **encompassed spectrum**

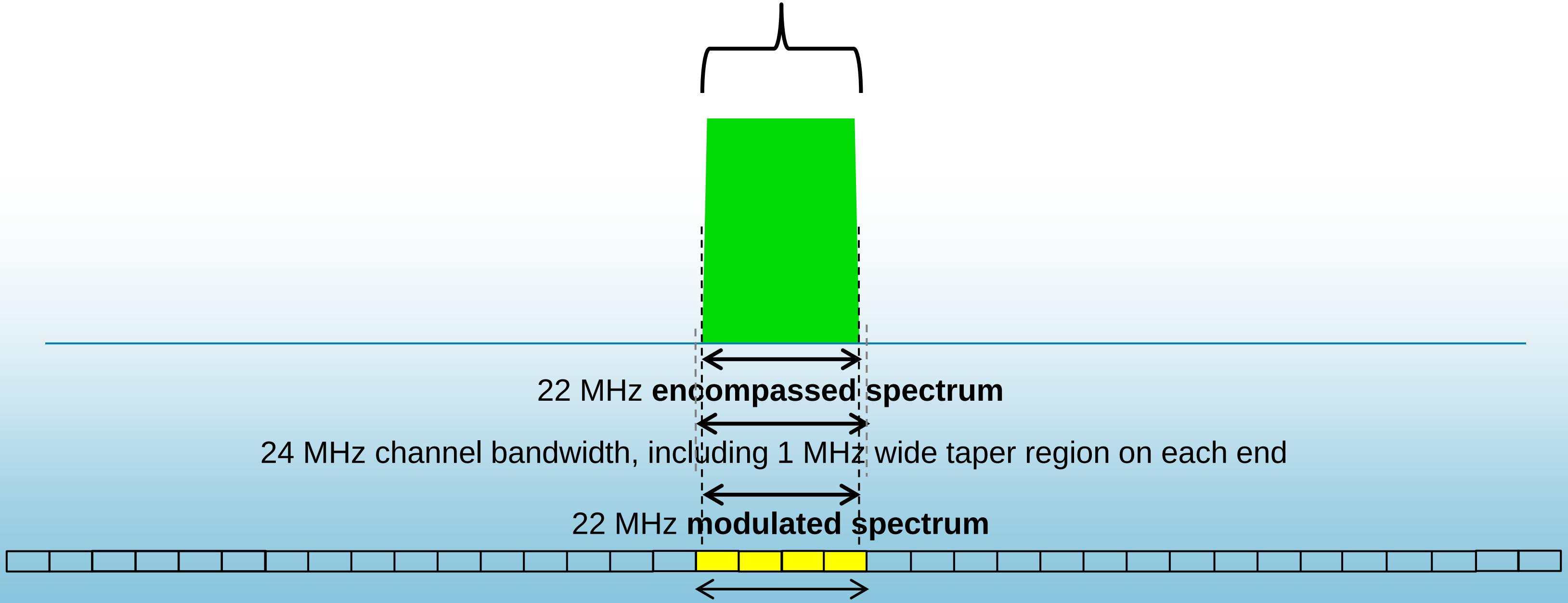
192 MHz **channel bandwidth**, including 1 MHz wide taper region on each end, and 20 MHz **exclusion band**

170 MHz **modulated spectrum**

174 MHz **occupied bandwidth**
(29 CTA ch x 6 MHz = 174 MHz)

24 MHz bandwidth channel example

25 kHz subcarrier spacing: 880 subcarriers (8K FFT)
50 kHz subcarrier spacing: 440 subcarriers (4K FFT)



22 MHz **encompassed spectrum**

24 MHz channel bandwidth, including 1 MHz wide taper region on each end

22 MHz **modulated spectrum**

24 MHz **occupied bandwidth**
(4 CTA ch x 6 MHz = 24 MHz)