Addressing Challenging New RF Test Requirements for DOCSIS 3.1 Upstream Signals

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KEYSIGHT TECHNOLOGIES

Agenda

- DOCSIS 3.1 Upstream Signals
- Test Setup
- Test Challenges
  #1 – Upstream MER
  #2 – Synchronized ACP
  #3 – Symbol Clock Error
  #4 – Burst Triggering
  #5 – Interburst Noise

Webinar Objectives

- Differentiate DOCSIS 3.1 OFDM signals and test methods from earlier DOCSIS.
- Overview available test solutions for DOCSIS 3.1 upstream.
- Detailed examination of five uniquely-difficult test requirements.

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DOCSIS 3.1 Upstream Signals

Important Characteristics

- **Utilizes OFDM modulation**
  Implications:
  - new signal format, with new terminology and characteristics.
  - new test parameters and procedures for measuring them.
  - *more variability at the PHY layer – more configuration items.*

- **CMTS-centric system**
  Implications:
  - similar to earlier DOCSIS, CMTS controls the upstream signal configuration via downstream commands to the CM.
  - *upstream testing requires specific signal configs; this requires visibility (and/or access) to the downstream commands from the CMTS.*

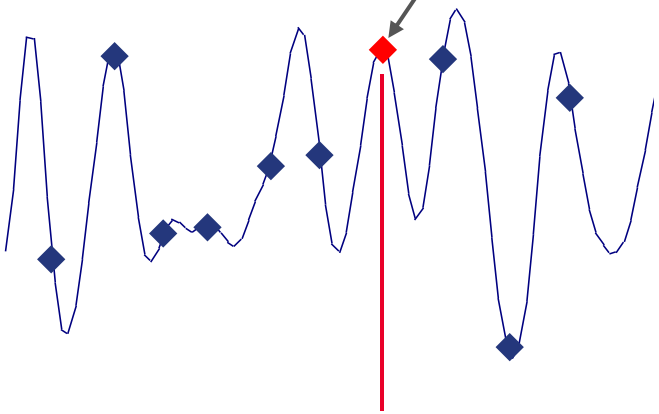
- **Minimal test modes**
  Implications:
  - *significant challenges for test engineers!*

Review: OFDM vs. Single Carrier Modulation

Time Domain View

SC-QAM:

This is a *symbol:*

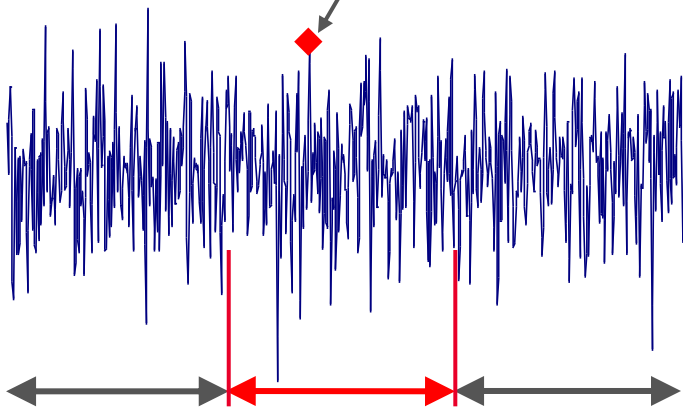


1 symbol
= 8 bits (256QAM)

5.36M sym/sec

OFDM:

This is a *sample:*



1 symbol
= 2^n samples @ F_s
= 2^n subcarriers @ $\Delta F = F_s/2^n$

e.g. for 2K DOCSIS 3.1, F_s = 102.4 MHz
2^n = 2048 subcarriers at ΔF = 50 kHz

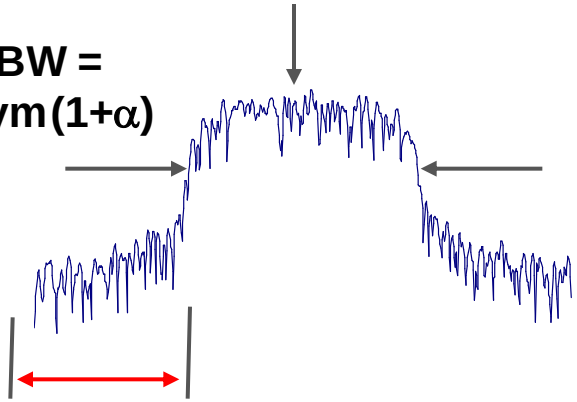
Review: OFDM vs. Single Carrier Modulation

Frequency Domain View

SC-QAM:

1 Carrier

BW = Sym(1+α)

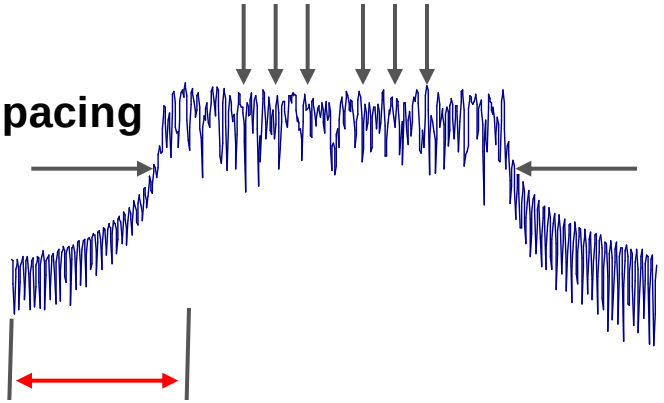


Adj Chan = Distortion

OFDM:

2-8K Carriers*

BW = #carriers x spacing



Adj Chan = Normal Rolloff

*i.e. subcarriers. Subcarriers are spaced so closely that they cannot be observed individually. They can only be separated mathematically, under very specific conditions.

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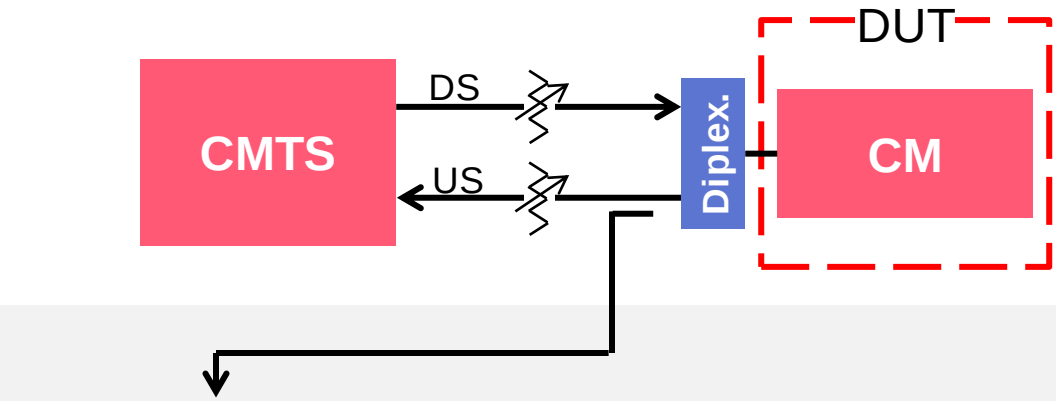
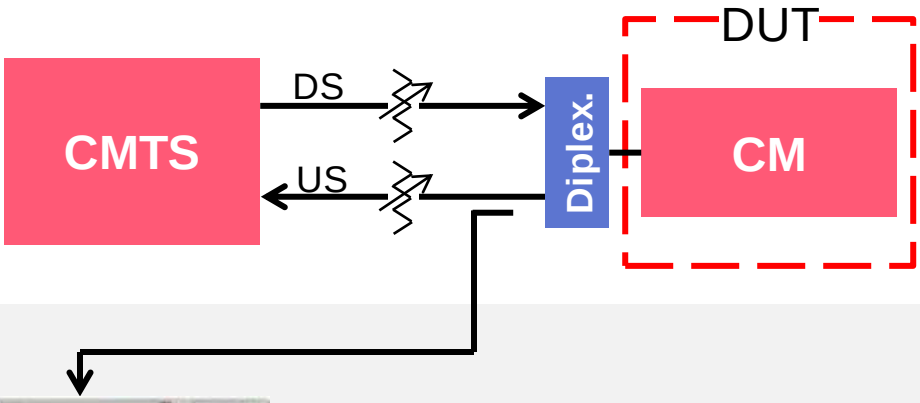
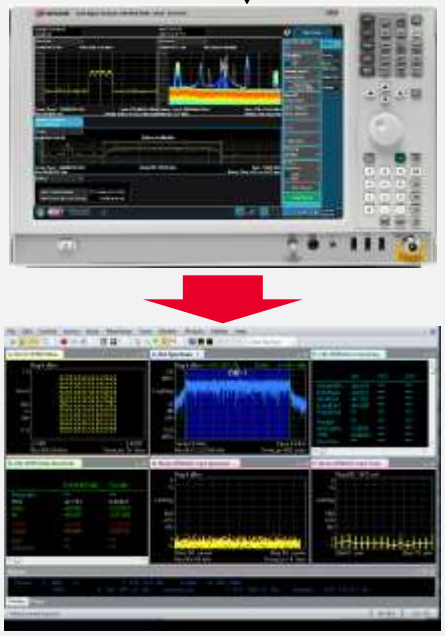
Verification Test Setup



- Key requirements:
  - 5 MHz – 1218 MHz minimum tuning range
  - ≥ 96 MHz analysis bandwidth
  - DOCSIS 3.1 modulation analysis, including MER, ACP
  - Burst-triggered measurements
  - Very low internal noise and distortion

Verification Test Setup



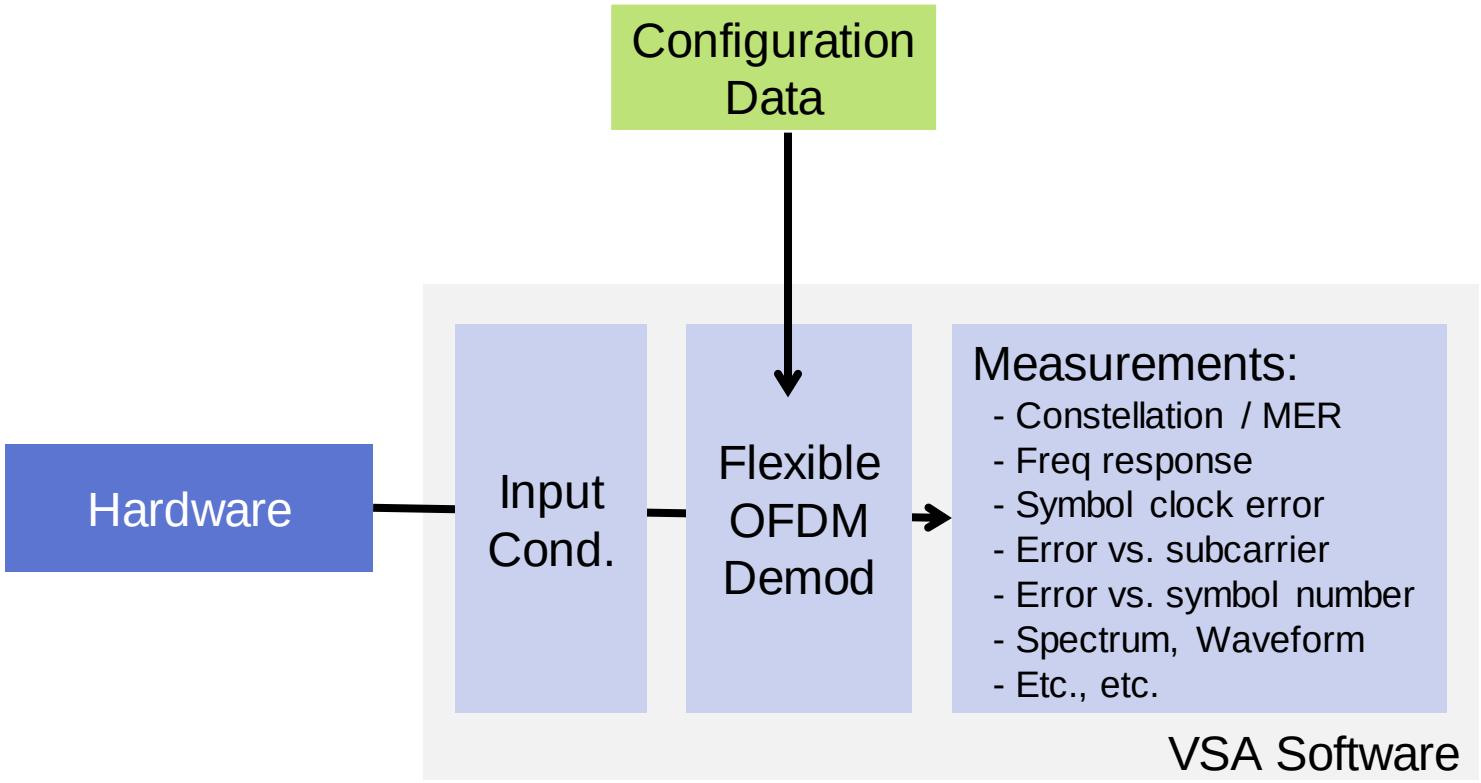


- Standard benchtop or modular analyzer hardware.
- Recommended for DOCSIS 3.1 testing:
  - Keysight UXA Signal Analyzer (3 Hz - 26.5 GHz, 510 MHz BW)
  - Keysight PXA Signal Analyzer (3 Hz - 50 GHz, 160 MHz BW)
  - Keysight U5303A PCIe digitizer (DC -1.4 GHz, 1.25 GHz BW)

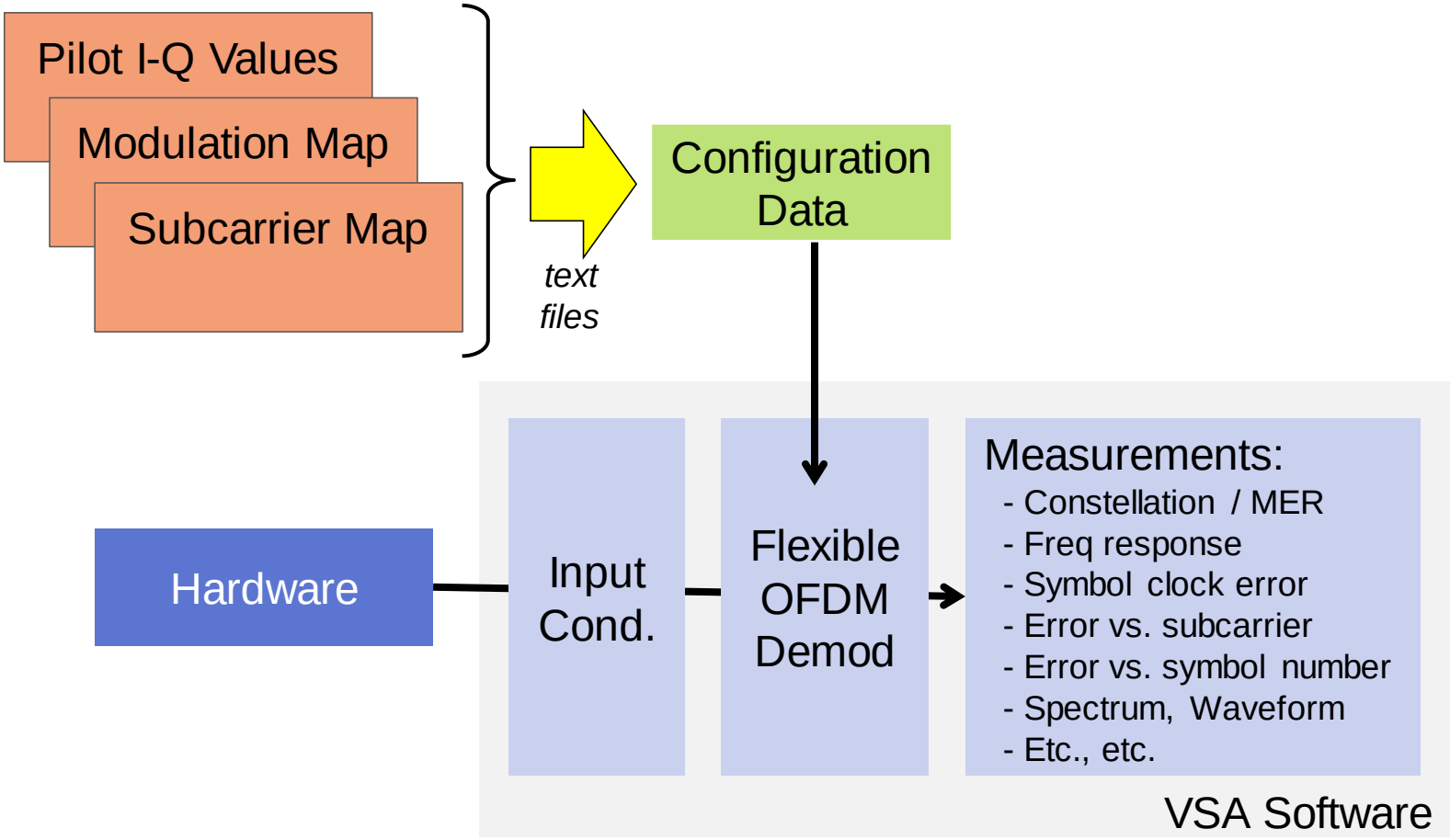
plus…

- Keysight 89600 Vector Signal Analysis software:
  - Industry standard, SW-defined vector signal analysis.
  - Custom OFDM modulation analysis, with DOCSIS 3.1 wizard.
  - Burst triggering and time gating, including Freq Mask Trigger.
  - Record/playback function for transient signals or events.
  - Supports all current-gen Keysight analyzers and digitizers.

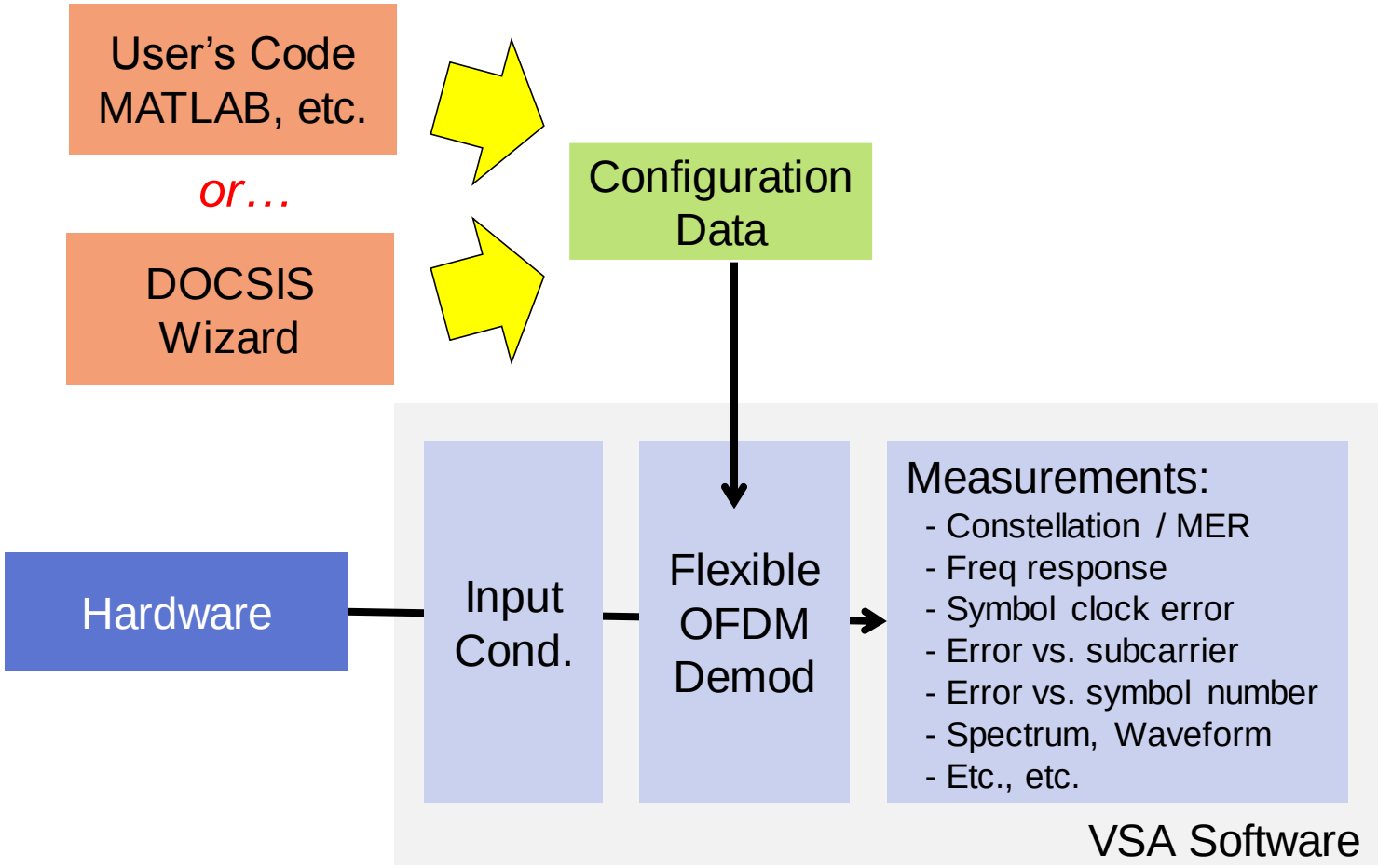
Custom OFDM Analysis with the 89600 VSA



Custom OFDM Analysis with the 89600 VSA



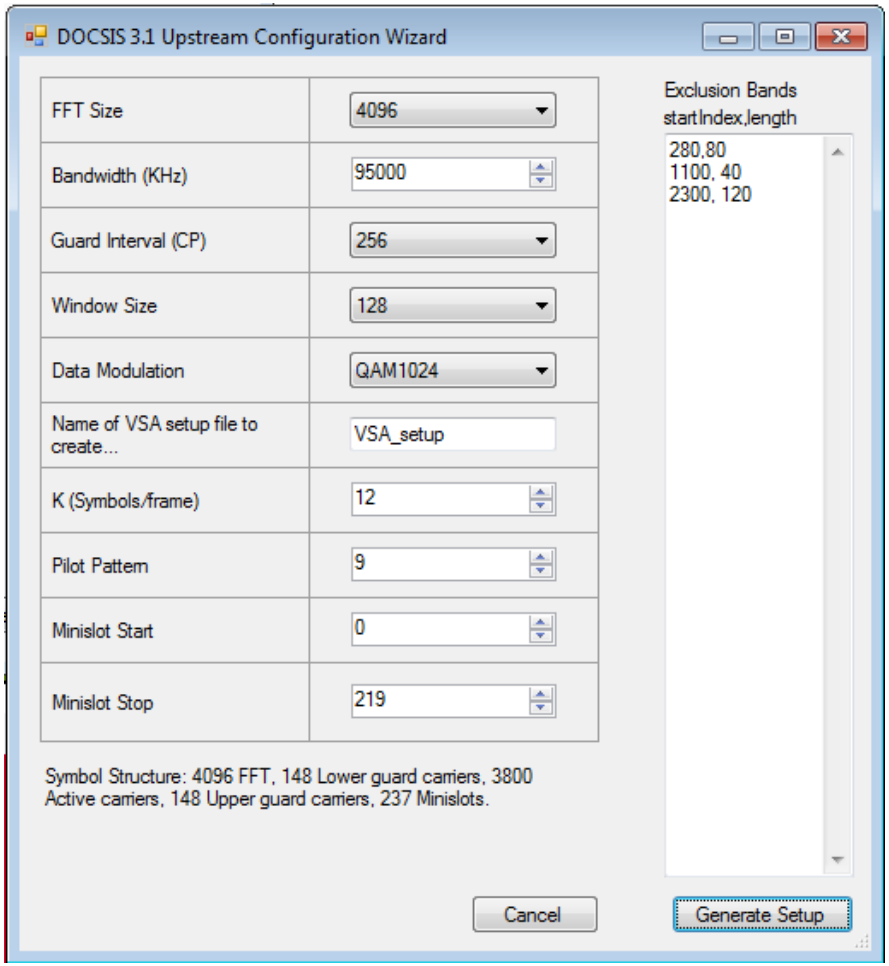
Custom OFDM Analysis with the 89600 VSA



Docsis 3.1 Upstream Configuration Wizard

Free Download from Keysight.com

Upstream Signal Parameters



Configuration Data

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Upstream MER Measurements

– Ref: §7.4.12.5.3 *MER Requirements*

– What's normal:
  - basic definition of MER
  - requirement to verify MER for all FFT sizes, signal bandwidths, modulation formats and pilot patterns.

– What's new: CM's MER is tested with two different analyzer setups:
  - *unequalized* – VSA may not equalize, depends on CM to correct for linear distortion.
  - *partially equalized* – VSA may equalize, but impulse response is limited to 200 ns.

MER = Modulation Error Ratio

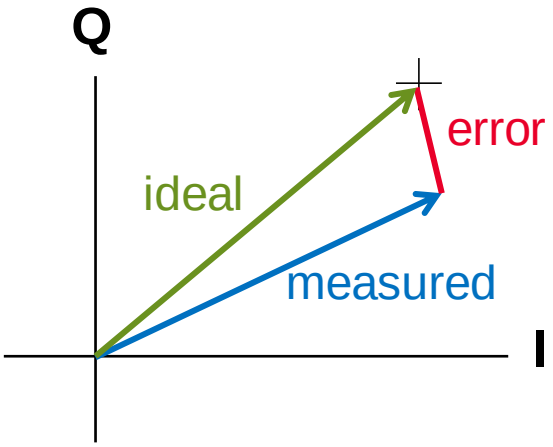
Upstream MER Measurements

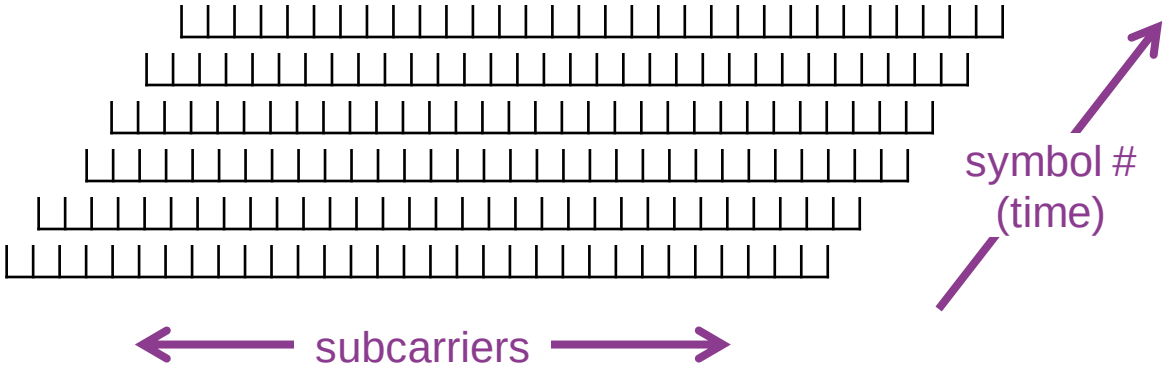
Some Definitions

Modulation Error Ratio (MER):
The magnitude of the error vector, averaged across all subcarriers and symbols, and expressed as ratio to the total signal power.

MER quantifies errors due to:

- *linear distortion (freq response)*
- *non-linear distortion (noise, spurs, IMD)*





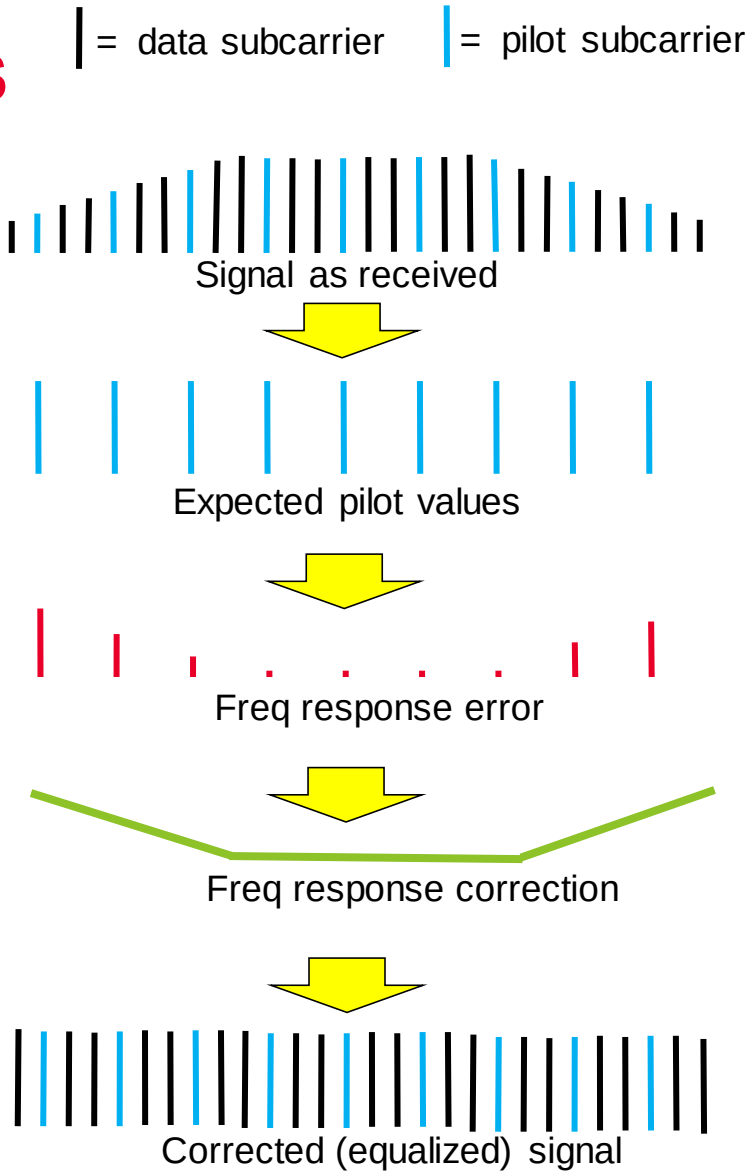
Upstream MER Measurements

Some Definitions

Equalization: the process of measuring and compensating for frequency response variations (linear distortion) in the signal.

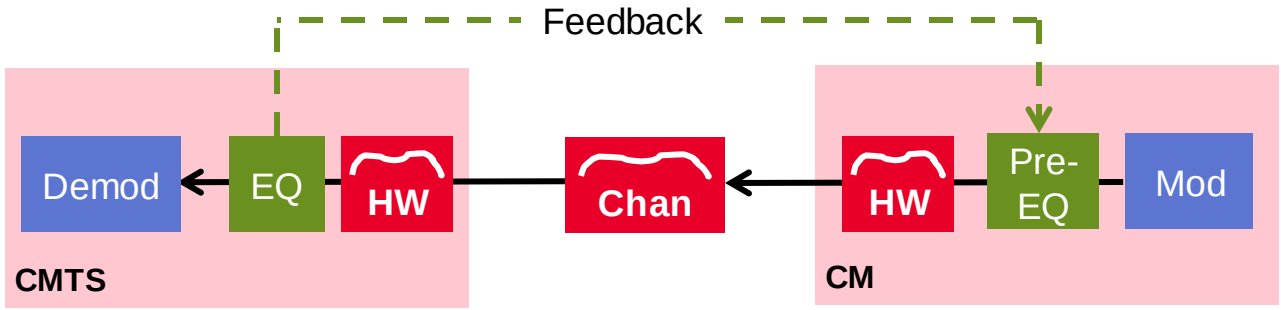
After equalization, the MER result shows only the non-linear distortion.

Note – this is not progressively-converging adaptive equalization as in SC-QAM, but instantaneous, once per symbol equalization.



DOCSIS 3.1 Upstream Equalization

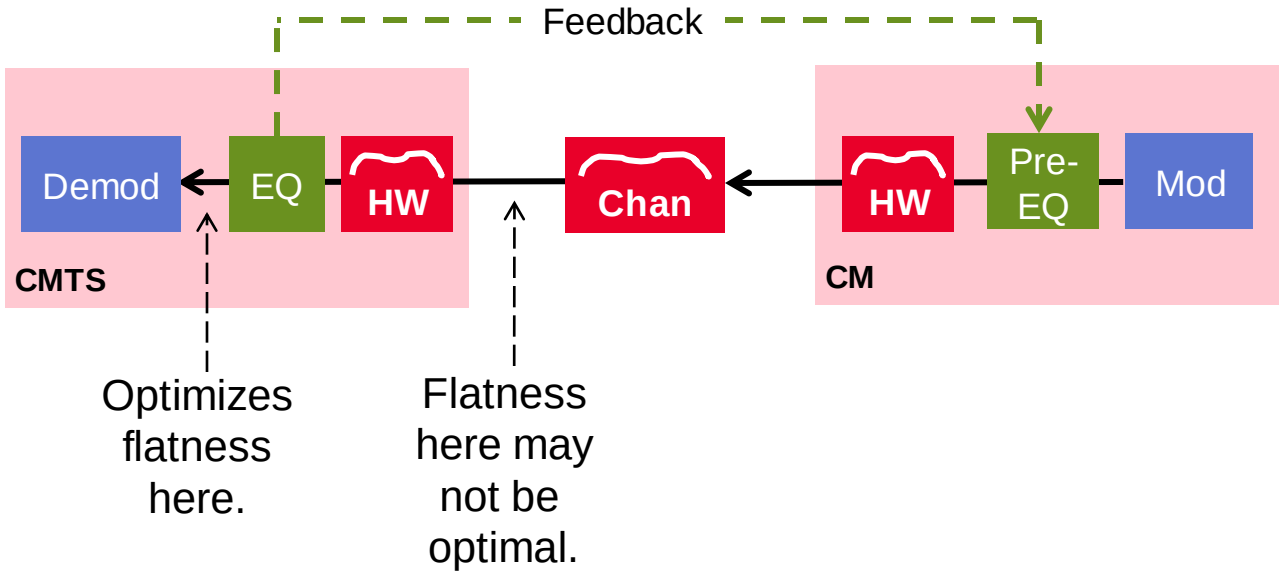
Closed-Loop "Pre-Equalization"



1. CMTS computes freq response of received signal (= combination of CM transmitter HW, cable plant and CMTS receiver HW).
2. Freq response corrections are fed back to the CM as a set of coefficients.
3. CM adjusts gain/phase per subcarrier to offset the frequency response.

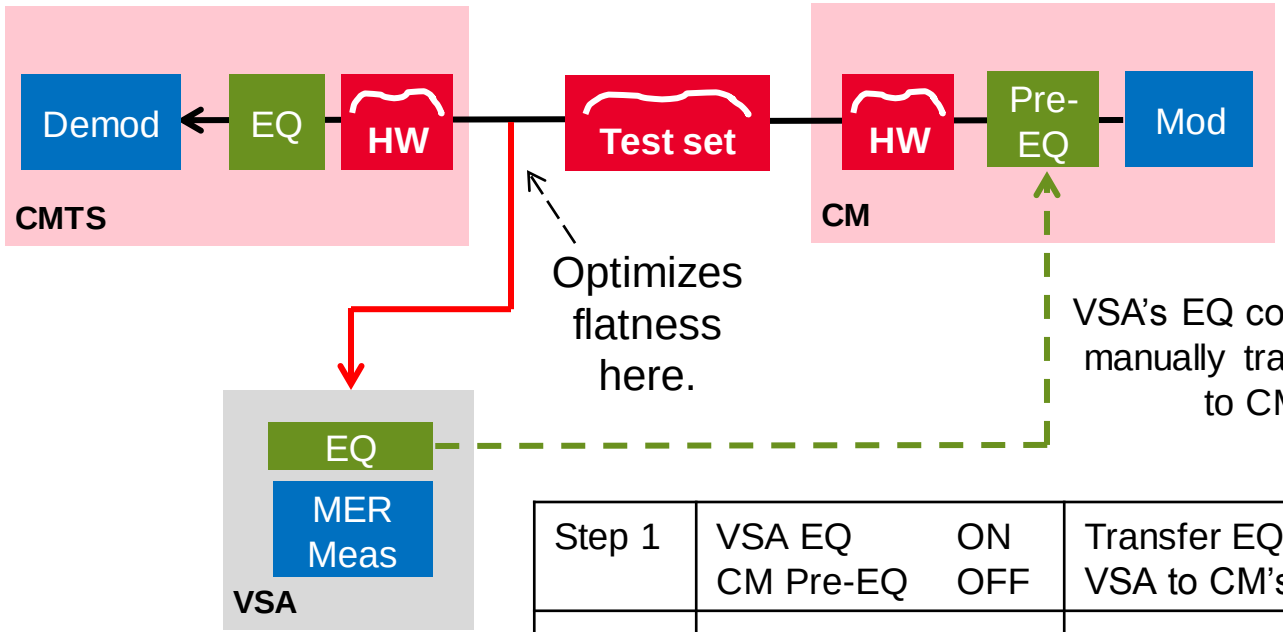
DOCSIS 3.1 Equalization Scheme

Closed-Loop "Pre-Equalization"



DOCSIS 3.1 Upstream MER Test

Part 1 – Unequalized MER (per PHY spec)



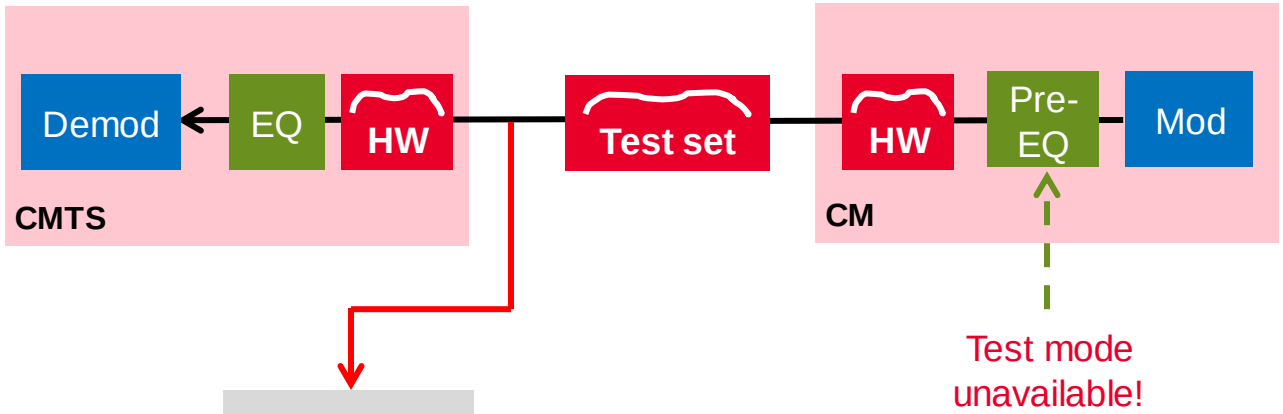
Step 1	VSA EQ CM Pre-EQ	ON OFF	Transfer EQ coeff's from VSA to CM's Pre-EQ
Step 2	VSA EQ CM Pre-EQ	OFF ON	Measure unequalized MER, correct as needed.

Verifies:

- CM's ability to pre-equalize linear distortion
- Residual MER due to CM's non-linear distortion

DOCSIS 3.1 Upstream MER Test

Part 1 – Unequalized MER (interim procedure)



MER Spec:
44-50 dB

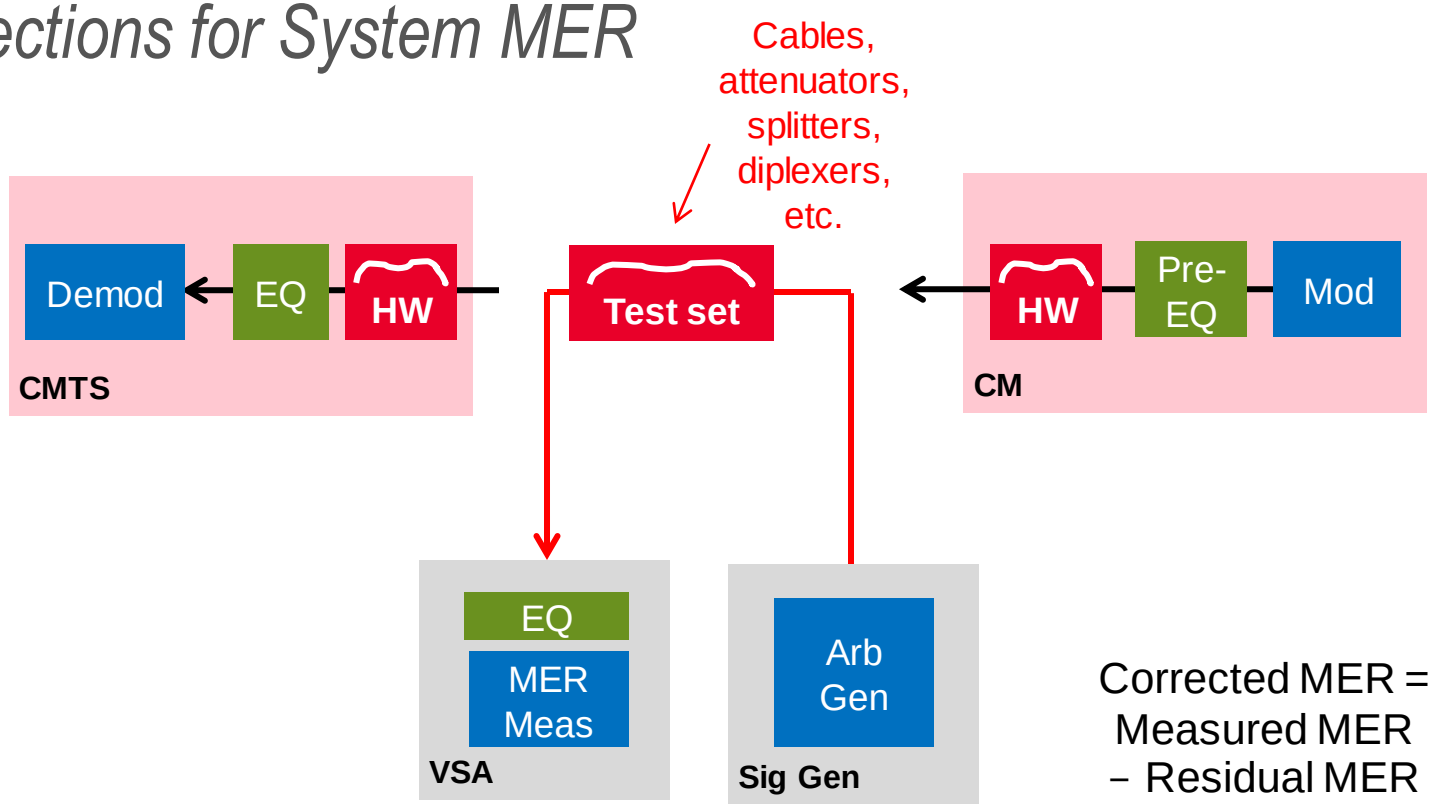
~~Step 1~~	~~VSA EQ~~ ~~CM Pre-EQ~~	~~ON~~ ~~OFF~~	~~Transfer EQ coeff's from VSA to CM's Pre-EQ~~
Step 2	VSA EQ CM Pre-EQ	**ON** **OFF**	Measure equalized MER, correct as needed.

Verifies:

- ~~CM's ability to pre-equalize linear distortion~~ *Tested elsewhere.*
- Residual MER due to CM's non-linear distortion

DOCSIS 3.1 Equalization For MER Measurements

Corrections for System MER



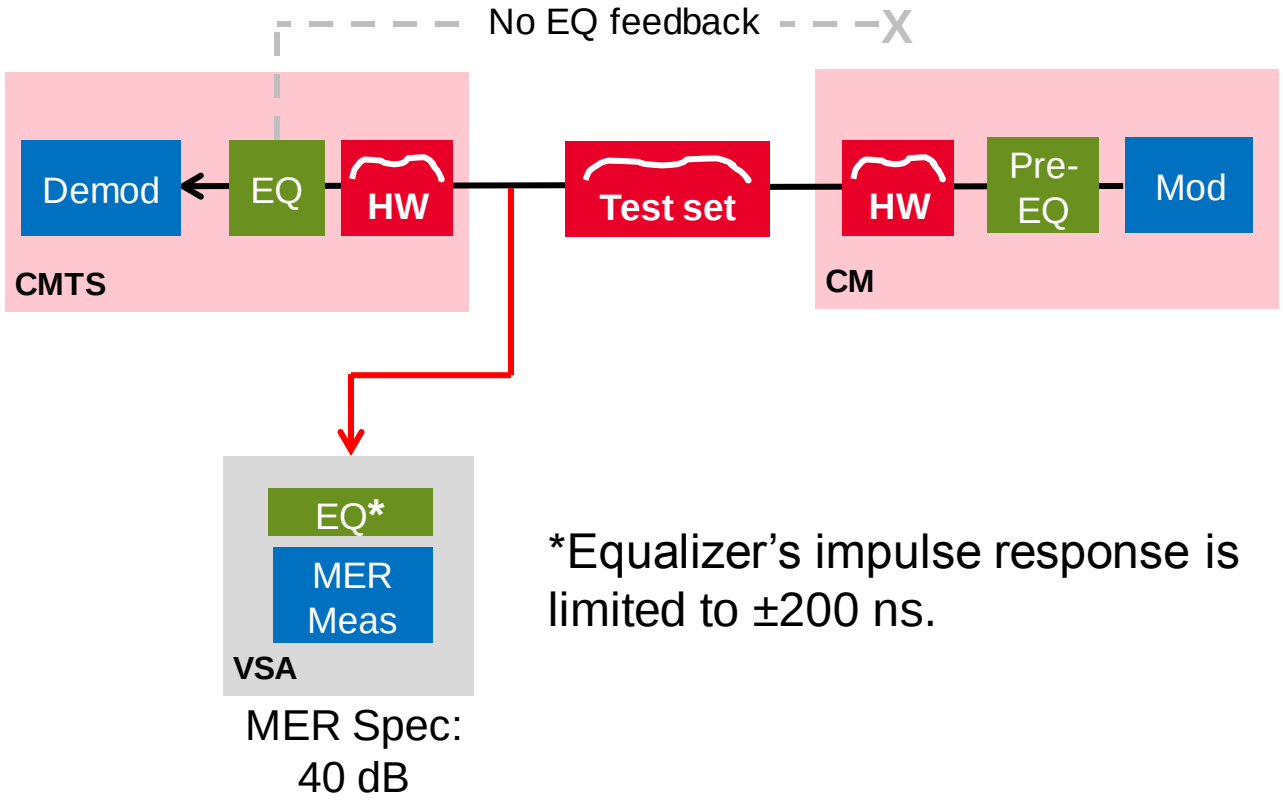
Residual MER = XX dB

Corrected MER = Measured MER – Residual MER

(convert to linear units before subtracting!)

DOCSIS 3.1 Upstream MER Test

Part 2 – Partially-equalized MER

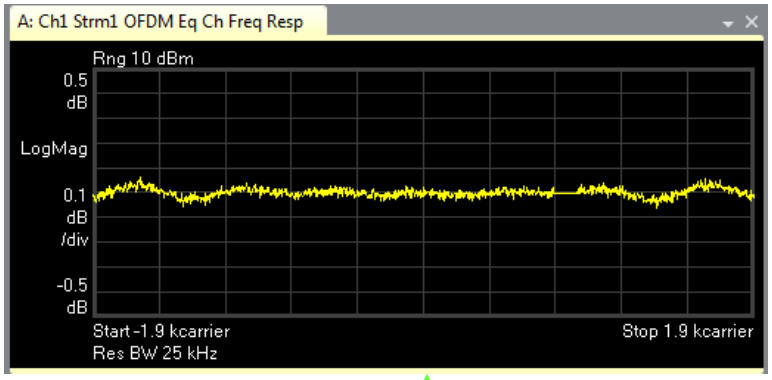


*Equalizer's impulse response is limited to ±200 ns.

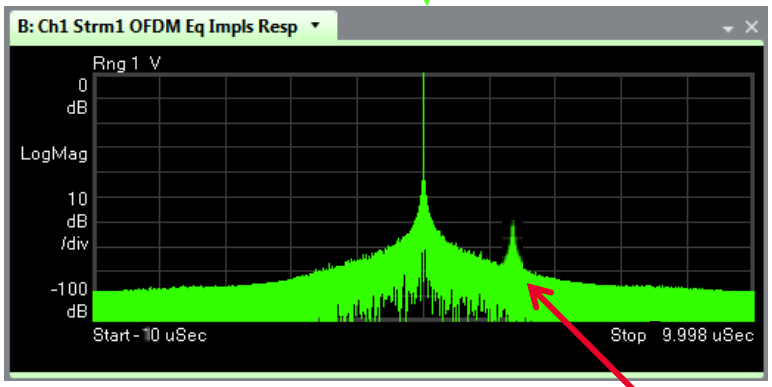
MER Spec: 40 dB

Partial Equalization

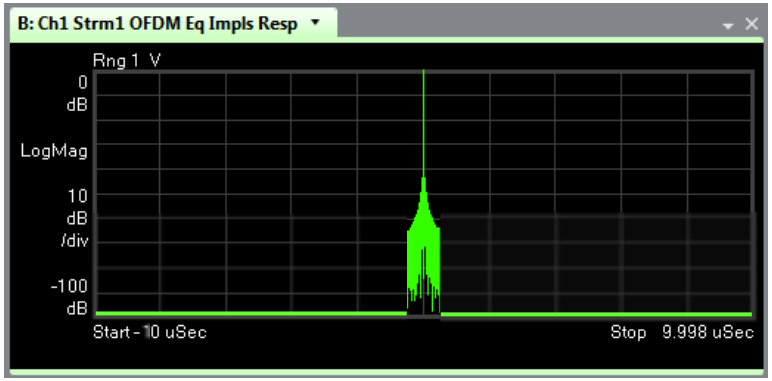
Truncating the Impulse Response (time domain)



Equalizer response may be expressed in either the time or freq domain.



Reflection



The time-truncated response is used the same way as before – except that reflections beyond 200 ns are no longer compensated… they'll degrade MER.

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Synchronized Adjacent Channel Power (ACP)

PHY Spec Requirements

- Ref: §7.4.12.5.1.1 *Spurious Emissions in the Upstream Freq Range*
  §7.4.12.5.1.2 *Adjacent Channel Spurious Emissions*

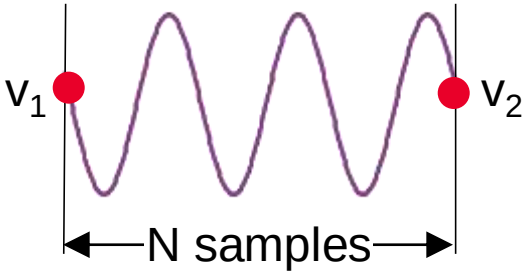
- What's normal: Spurious emissions are measured in defined frequency bands at various offsets from the transmitted signal.

- What's new: The first ACP bands are defined to begin at the *first subcarrier adjacent to the modulation spectrum*. These bands must therefore be measured synchronously with the OFDM modulation.

Why Synchronized ACP?

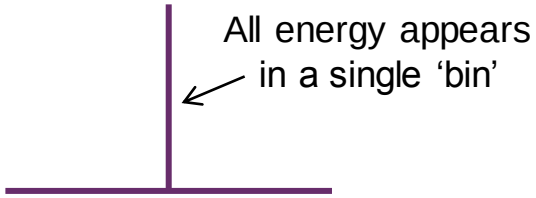
FFT Spectrum vs. Sample Rate: Single Tone Case

Time Domain:

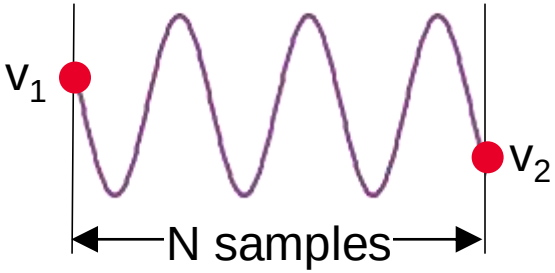


FFT

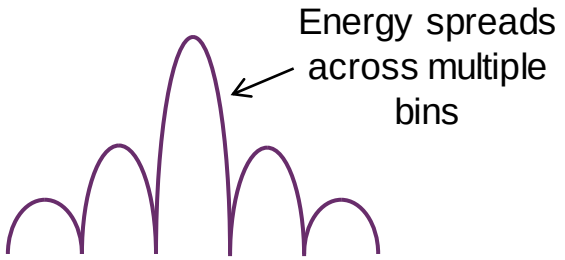
Freq Domain:



Synchronous:
Sample rate is a multiple of signal freq, thus $v_1 = v_2$.



FFT

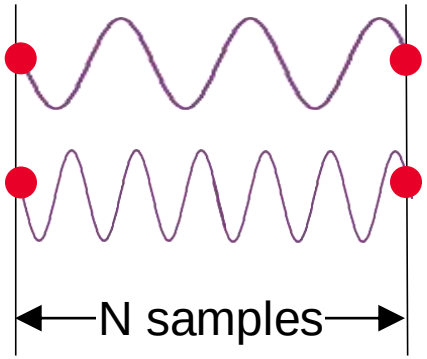


Asynchronous:
Sample rate is unrelated to signal freq, thus $v_1 \neq v_2$.
(causes FFT to see a discontinuity at the wraparound point.)

Why Synchronized ACP?

FFT Spectrum vs. Sample Rate: Multi Tone Case

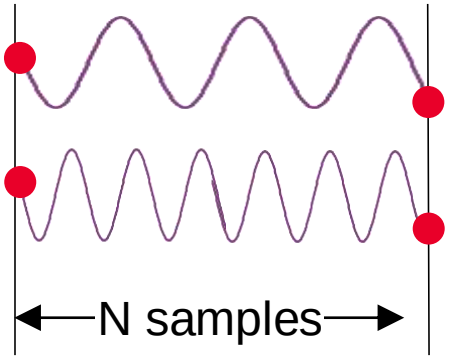
Time Domain:



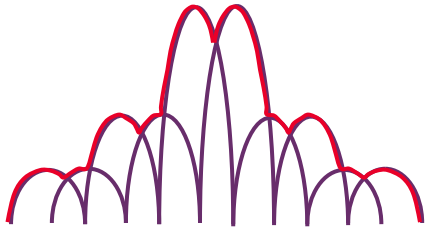
FFT

Freq Domain:

Synchronous:
Sample rate is a multiple of both freq's.



FFT

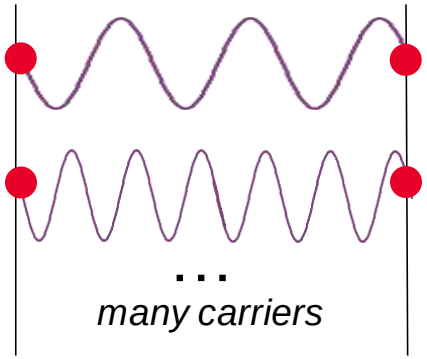


Asynchronous:
Sample rate is unrelated to signal freq's.

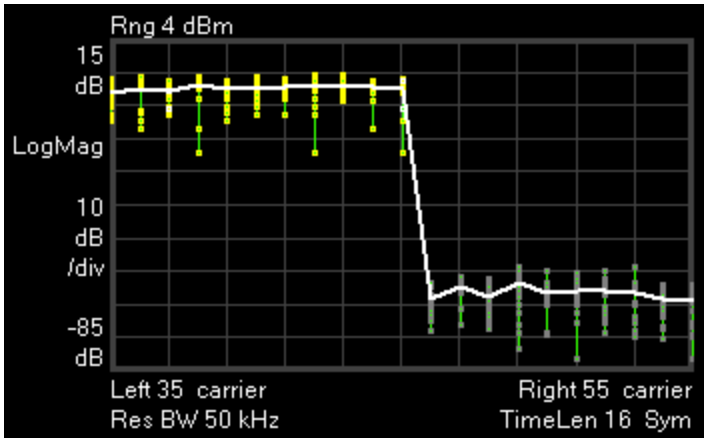
Why Synchronized ACP?

FFT Spectrum vs. Sample Rate: OFDM Case

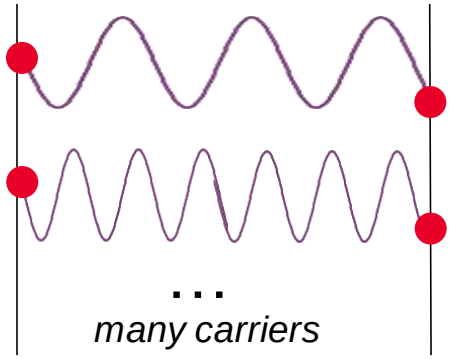
Time Domain:



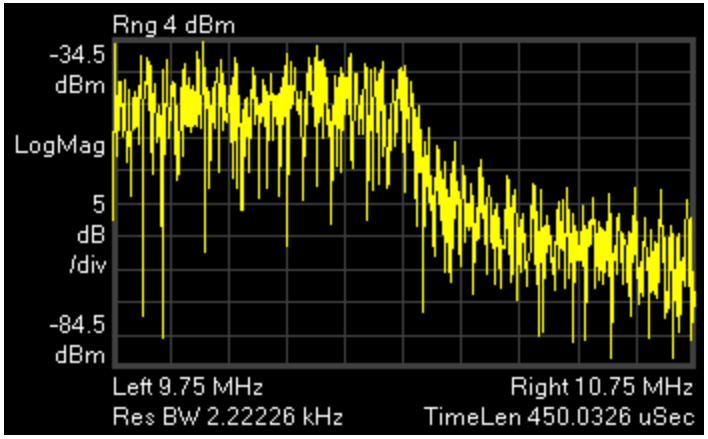
FFT



Synchronous:
Sample rate is a multiple of all freq's
$= \Delta f * N_{FFT}$



FFT

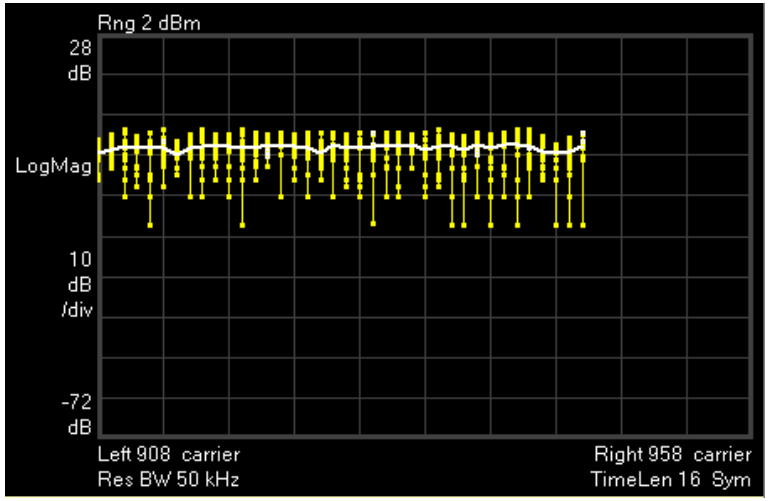


Asynchronous:
Sample rate
$\neq \Delta f * N_{FFT}$

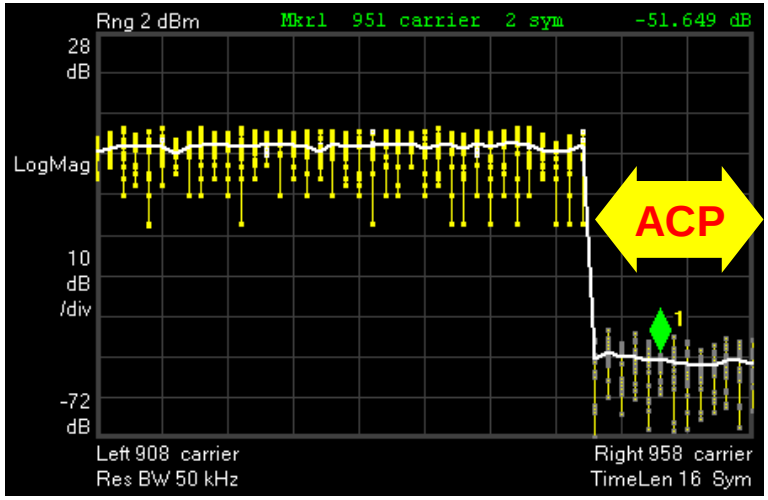
Note: time-aligned, synchronous sampling = OFDM demodulation

Synchronized ACP Measurements

Implementation: Keysight 89600 VSA Software



Default result: subcarrier mag trace ends at last active subcarrier (#950)



Added subcarriers (#951-958) create the required 400 kHz ACP band.

- Reconfigure DOCSIS 3.1 demod to demodulate extra subcarriers in the ACP region; reduce the number of guard subcarriers as needed. (Use Keysight-provided macro).
- Synchronous sampling eliminates modulation sidebands; any residual power is ACP.
- Use markers or band-power cursors to sum power over the specified bandwidth.

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Symbol Clock / Subcarrier Freq Error

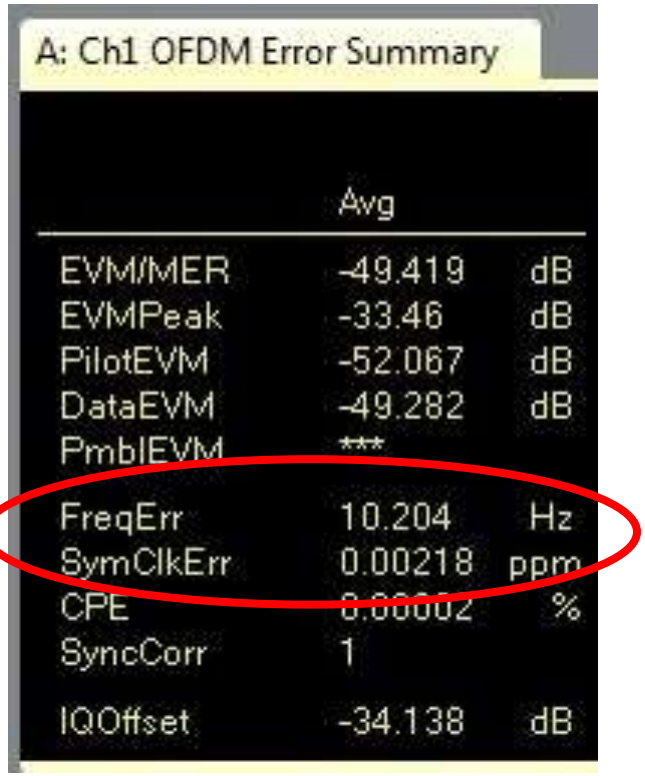
PHY Spec Requirements

– Ref: § 7.4.2.1 *Channel Frequency Accuracy*

– What's normal: subcarrier frequency and symbol clock frequency must be verified to extremely tight specs (30 Hz and 0.4 ppm, respectively)

– What's new:
  - subcarrier frequency error spec applies to every active subcarrier, not just the center (DC) subcarrier.
  - frequency measurements are defined relative to the CMTS master clock reference, not to an absolute standard.

Verifying Subcarrier Frequencies



VSA provides direct readout of:

- Symbol clock error (F_S) in ppm.
  - Verify against subcarrier clock spec (± 0.4 ppm). (Note interchangeable use of terms *sample clock, symbol clock* and *subcarrier clock*.)

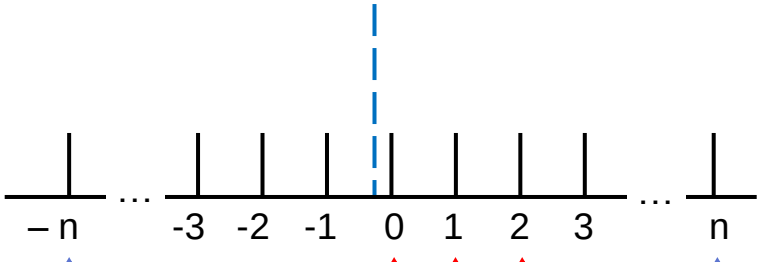
- Frequency error (Fc) in Hz.
  - Applies to center subcarrier only; spec requires checking all subcarriers.

Issue: in OFDM, individual subcarriers cannot be measured directly, due to their ultra-close spacing. However, their frequencies can be mathematically derived as a function of center freq error, symbol clock error and subcarrier number.

Verifying Subcarrier Frequencies

Computing worst-case error

Note: Δf error (Hz) = F_S err * (102.4 MHz / n_{FFT})



$Error_{Hz} = F_C$ error

$Error_{Hz} = F_C$ error + Δf error

$Error_{Hz} = F_C$ error + 2*Δf error

…

Worst case $Error_{Hz} = F_C$ error + n*Δf error

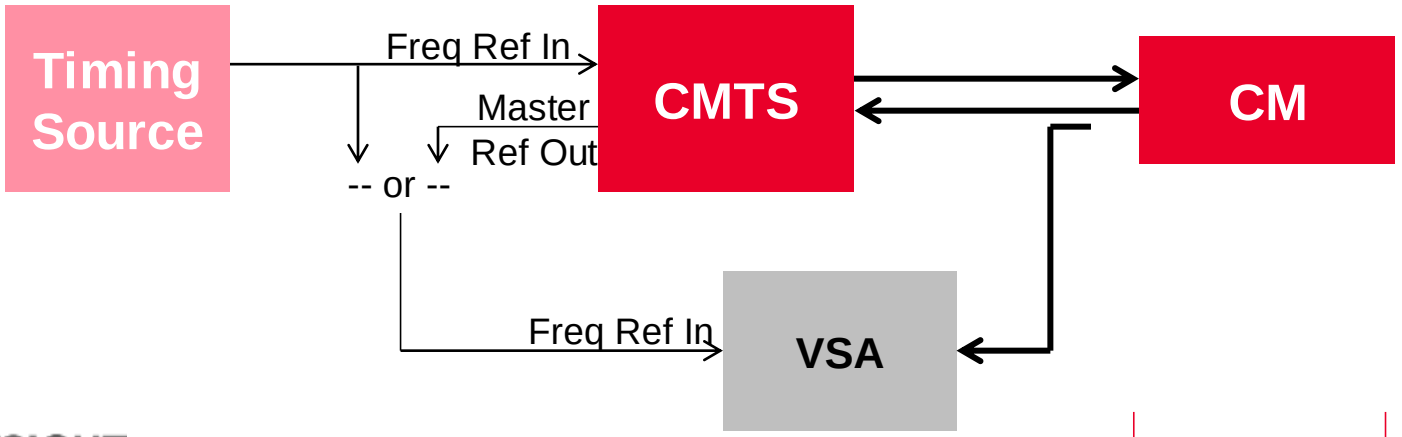
where n is typically ±950 for 2K FFT, ±1900 for 4K FFT

- Mathematically, the worst-case subcarrier frequency error will always occur at one of the outermost subcarriers; thus, only these two need to be computed.
- Implications:
  - larger F_C error means less allowable Δf error, and vice versa.
  - cases exist where the individual errors may each be within spec limits, but the combination of the two is outside the spec limit.

Verifying Subcarrier Frequencies

Absolute vs. Relative Frequency Accuracy

- The PHY Spec requires CM frequencies to be measured relative to the *Master Clock Reference*, a 10.24 MHz signal that exists within the CMTS and serves as a frequency reference for both it and the CM.
- To perform relative frequency measurements, the VSA's frequency reference input must be connected to either:
  - the Master Clock Reference output from the CMTS (if available)
  - the same frequency/timing source used by the CMTS as its reference input (in-house standard, GPS, DOCSIS Data Timing Interface, etc.)



Agenda

- DOCSIS 3.1 Upstream Signals
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  #1 – Upstream MER
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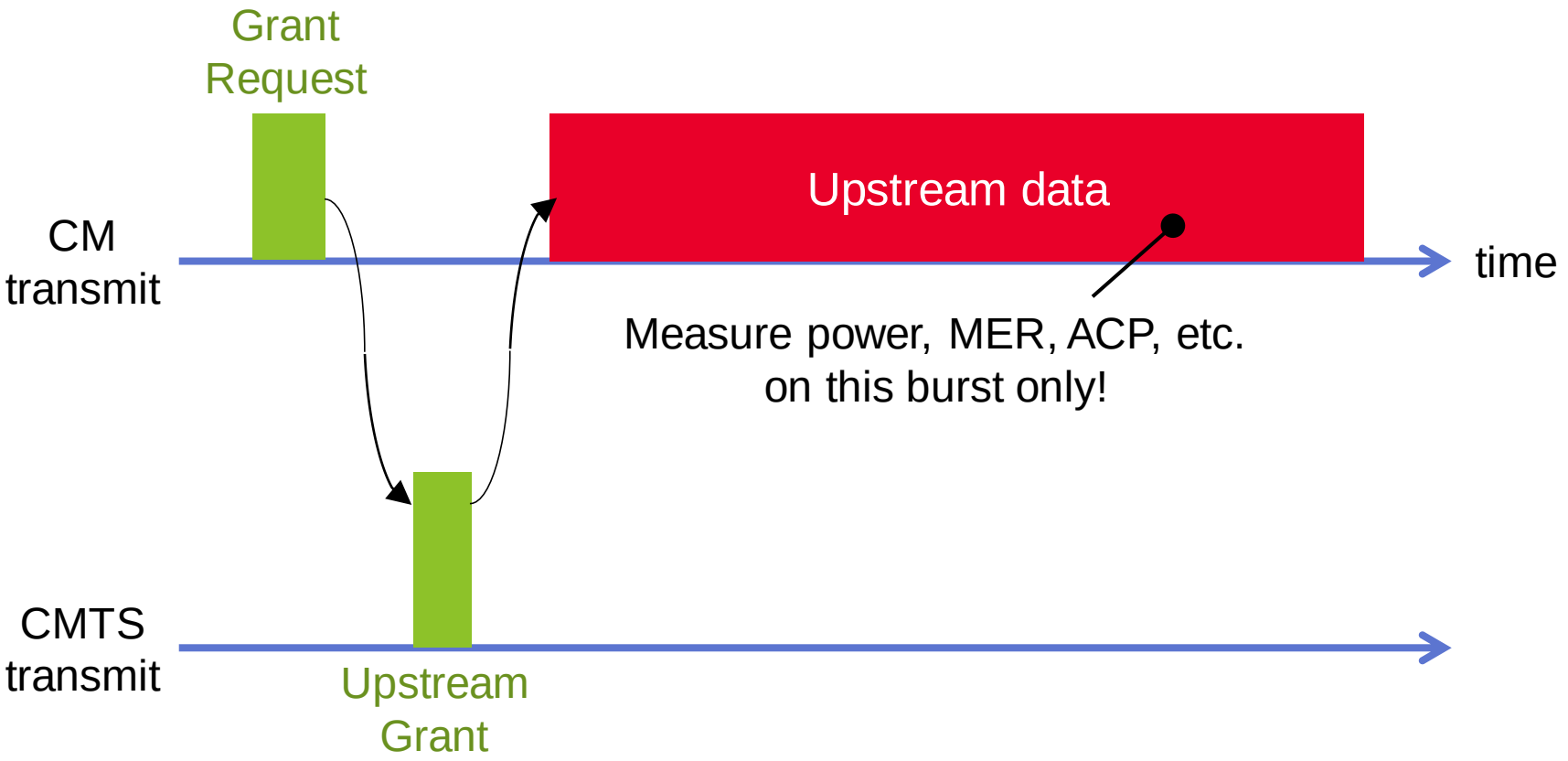
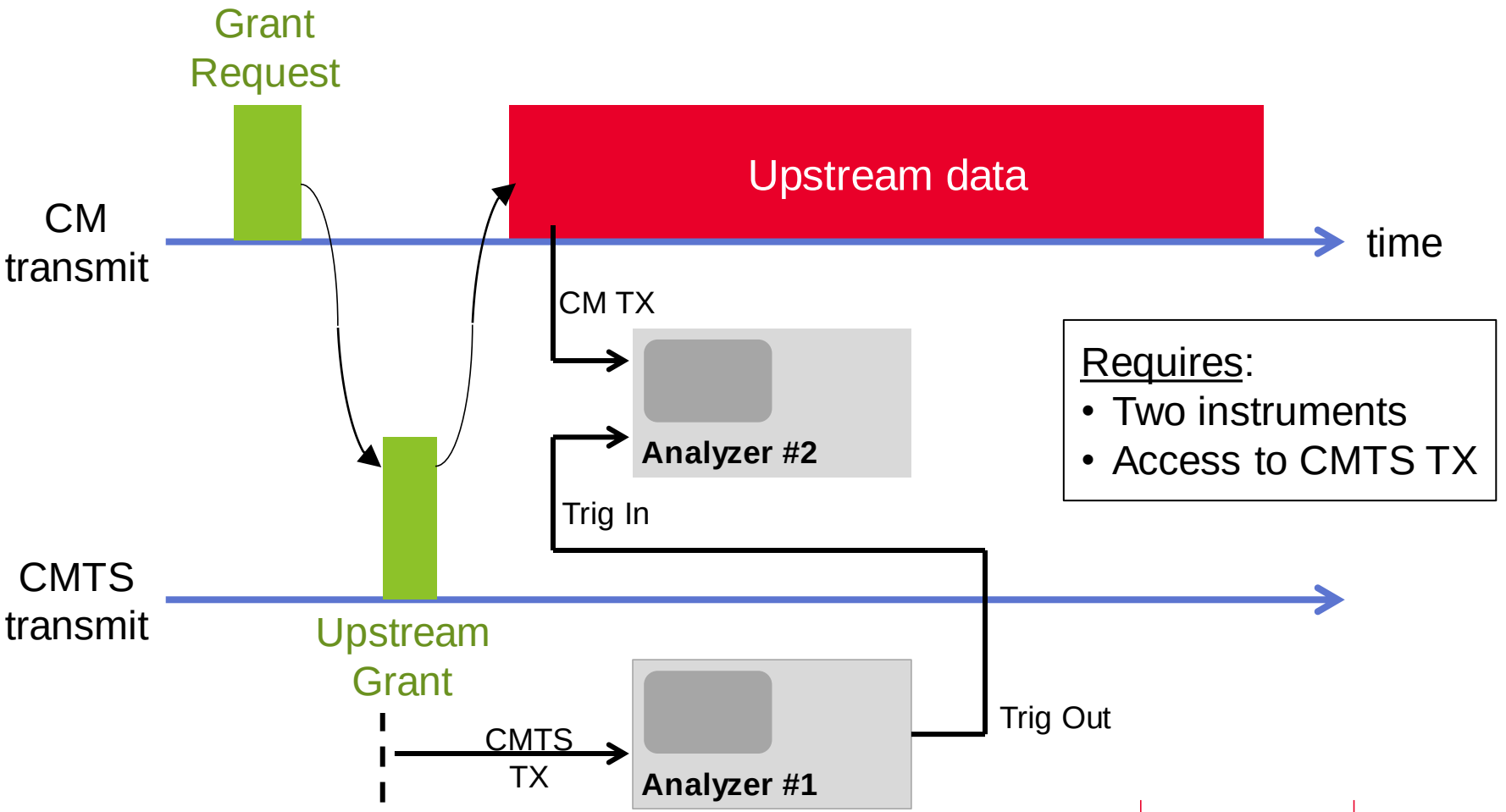
  #5 – Interburst Noise

Burst Triggering for Upstream Measurements



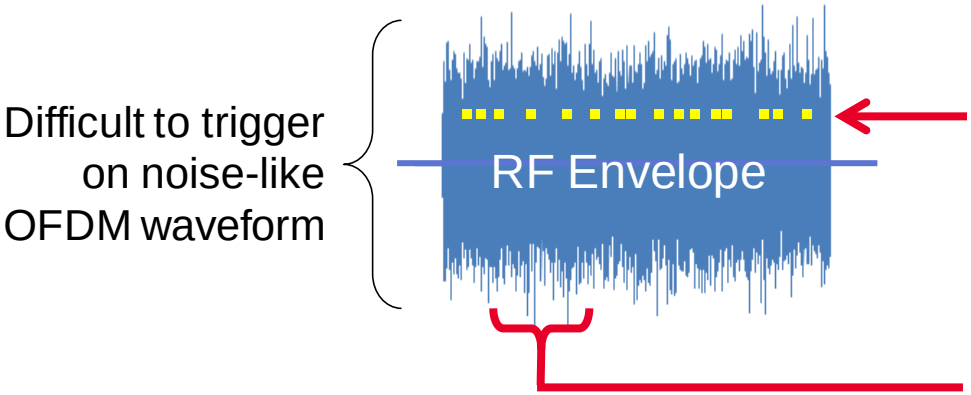
Burst Triggering for Upstream Measurements

Rich / Lucky Engineer's Approach…



Burst Triggering for Upstream Measurements

Real World Complications

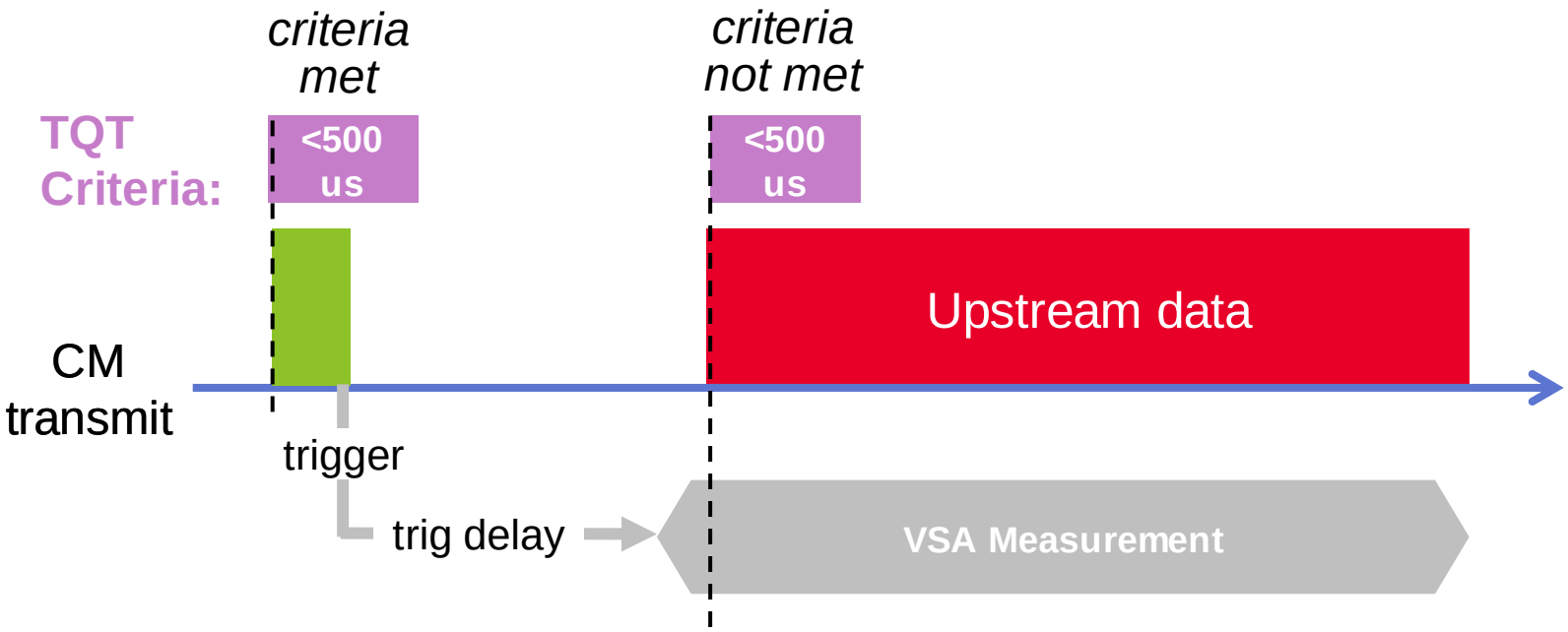


Traditional level-based trigger activates on every threshold-crossing, so burst durations appear to be <<1 us.

Freq Mask Trigger activates based on average power over 1K FFT interval.

Burst Triggering for Upstream Measurements

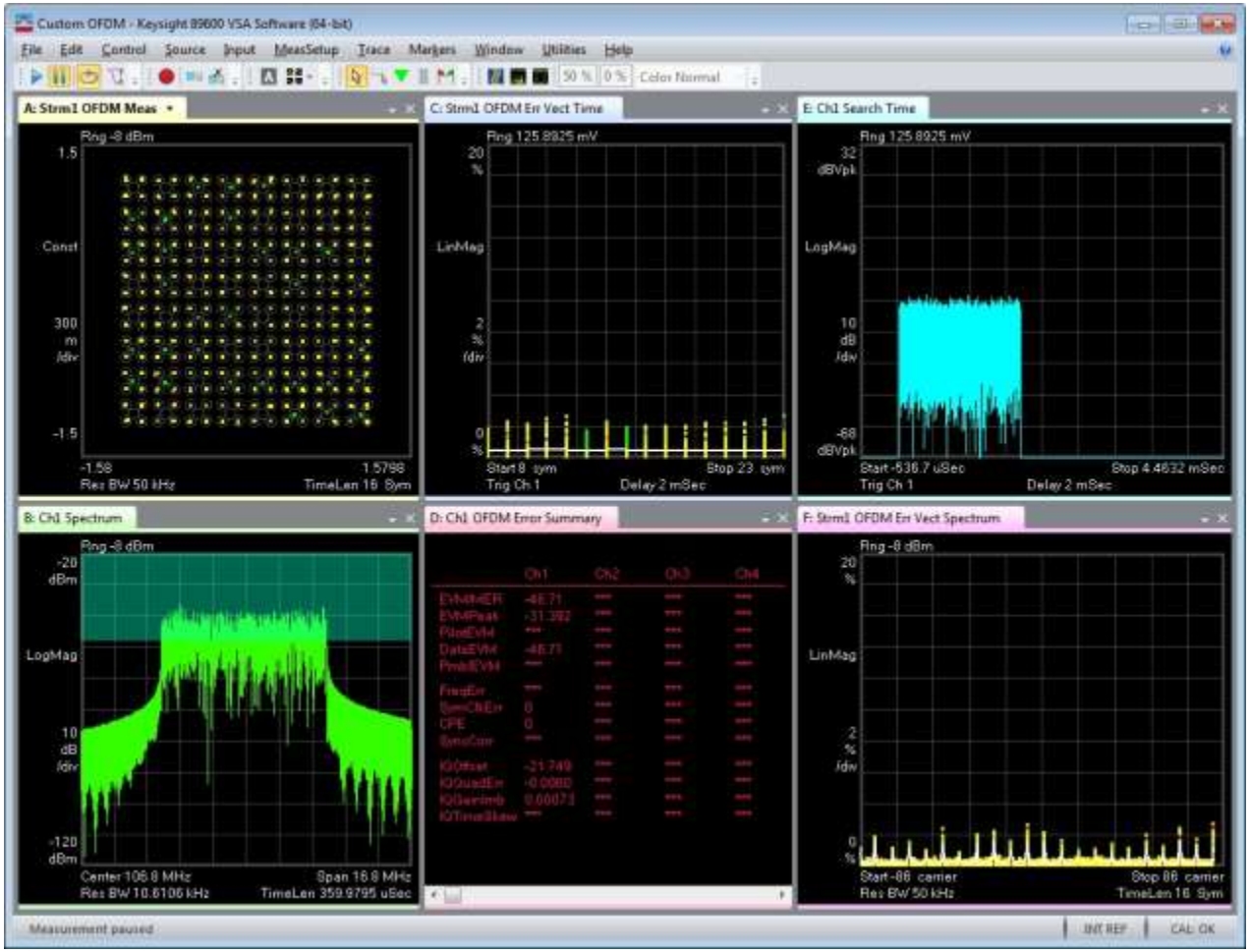
Real World Solution – Time Qualified Triggering (TQT)



1) Trigger in Freq Domain, not Time Domain.
2) Set Time Criteria: trigger when burst length is <500 us.
3) Add trigger delay to align VSA measurement with approx. start of data burst.

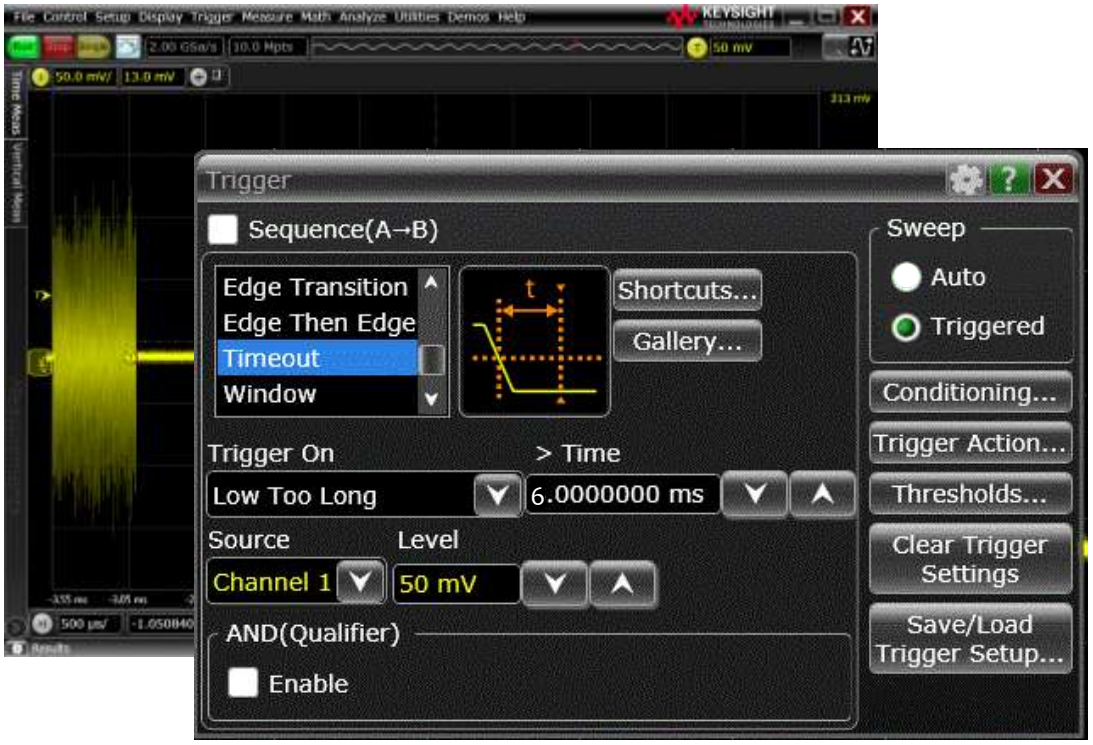
Burst Triggering for Upstream Measurements

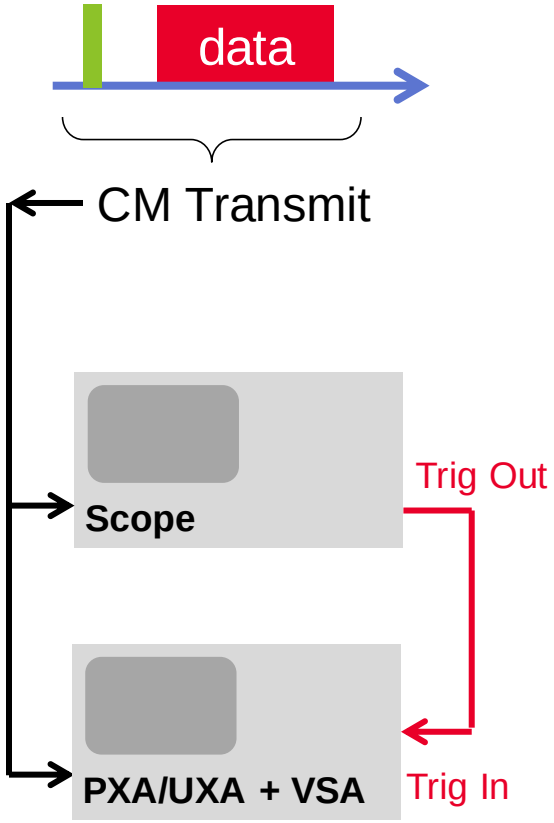
Demod Measurements on CM Data Burst



Burst Triggering for Upstream Measurements

Alternate Implementation: PXA/UXA + Scope





- Scope triggers on *gap > 6 ms*, (which only occurs after a data burst).
- VSA adds negative trig delay to position measurement at start of data burst.

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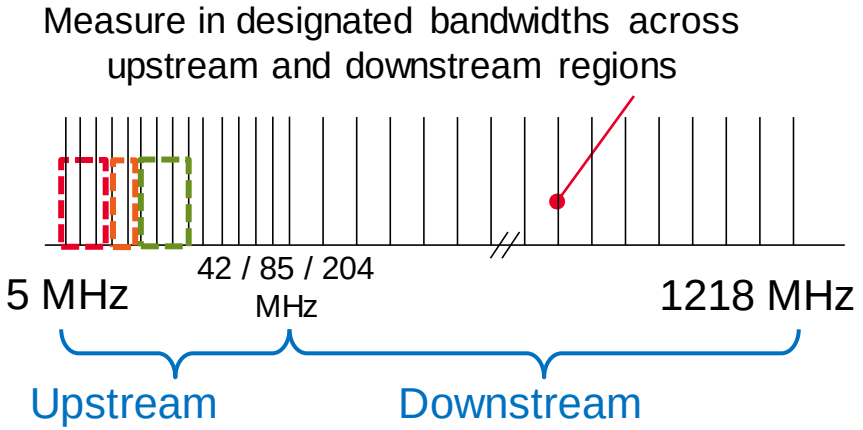
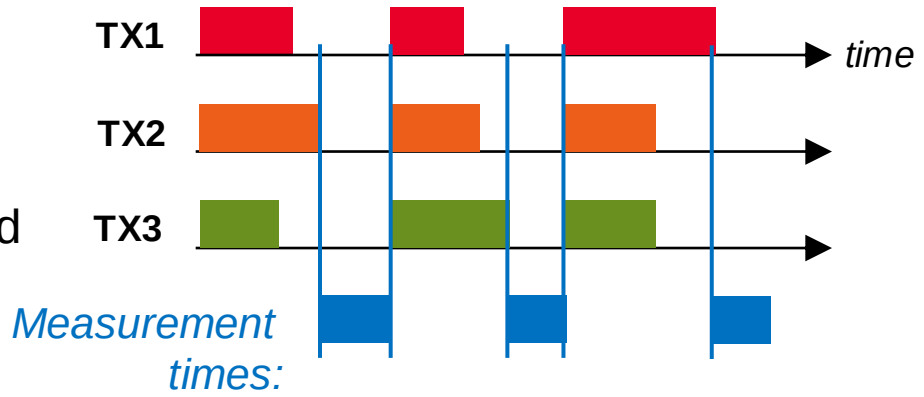
Interburst Noise and Spurious

– Ref: §7.4.12.5.1 *Spurious Emissions*

– What's normal:
  - well-defined offsets, bandwidths, test limits, etc.
  - tests in both upstream and down-stream frequency bands.
  - tests for both discrete spurs and integrated noise.

– What's new:
  - measurements must be triggered to occur only at times when no upstream bursts are present.

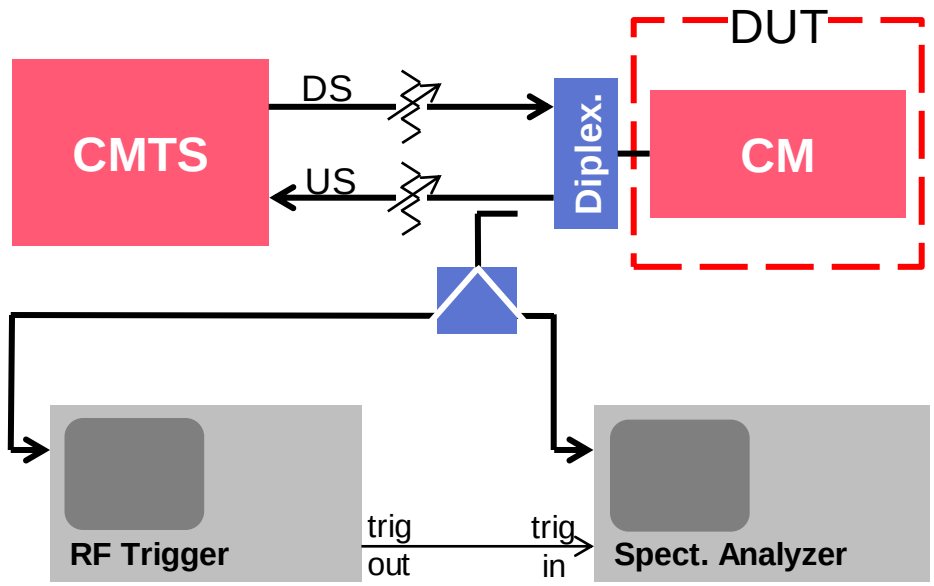




Interburst Noise and Spurious

– Problem: how to measure signals in one band while triggered by (the absence of) signals in a band that is hundreds of MHz away?

– Solution: 1.218 GHz span requires two instruments
  - RF Trigger detects CM transmissions and outputs a trigger signal,
  - Spectrum Analyzer performs triggered spectrum measurements.



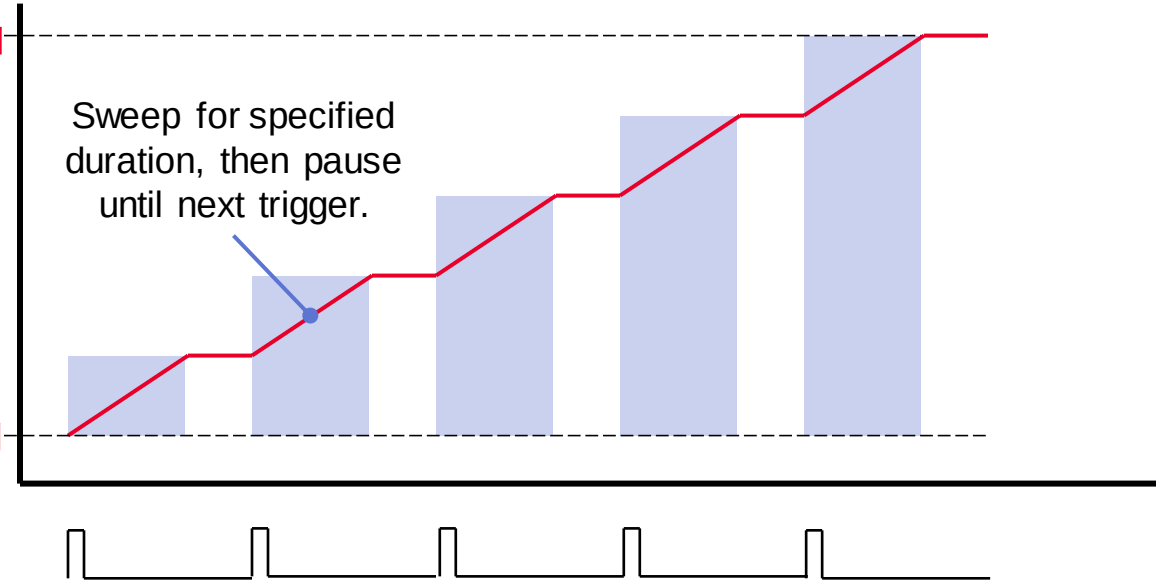
Interburst Noise and Spurious

Signal Analyzer Requirements

Requirements:
- Freq range: 5 to 1218 MHz
- RBW: 160 kHz, 4 MHz
- Gated LO sweep

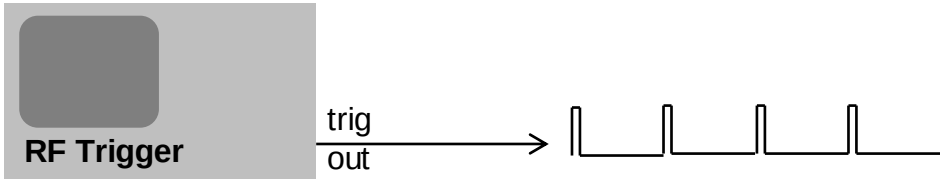
Recommendations:
- Keysight UXA or PXA Signal Analyzers

"Gated LO Sweep"



Interburst Noise and Spurious

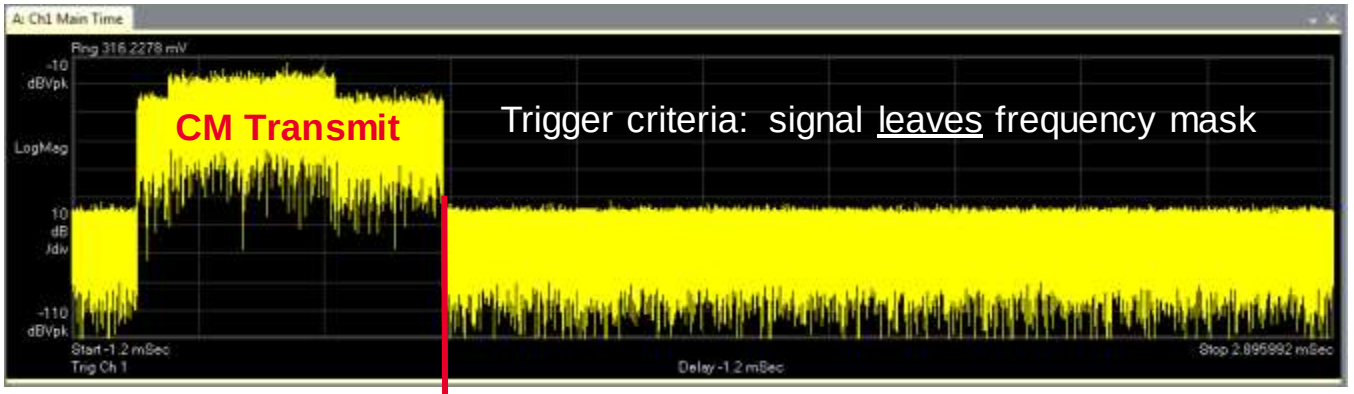
Obtaining a Trigger Signal



Device	Features
Signal Analyzer (e.g. MXA/PXA/UXA with RTSA option.)	• Mid-perf models suitable. • Frequency Mask Triggering (FMT). • 160 MHz IF BW.
Oscilloscope (e.g. Infiniium S-Series)	• Mid-perf models suitable. • “Timeout” triggering mode. • Wide BW supports all upstream configs, but requires that non-CM signals be isolated (e.g. diplexer).

Interburst Noise and Spurious

Trigger Settings



Shown: UXA with Freq. Mask Triggering
Alternative: Scope triggers if low >10 us.

RF Trigger

Trigger Out

time

Spect. Analyzer

Trigger Mode External
Sweep Mode Gated LO

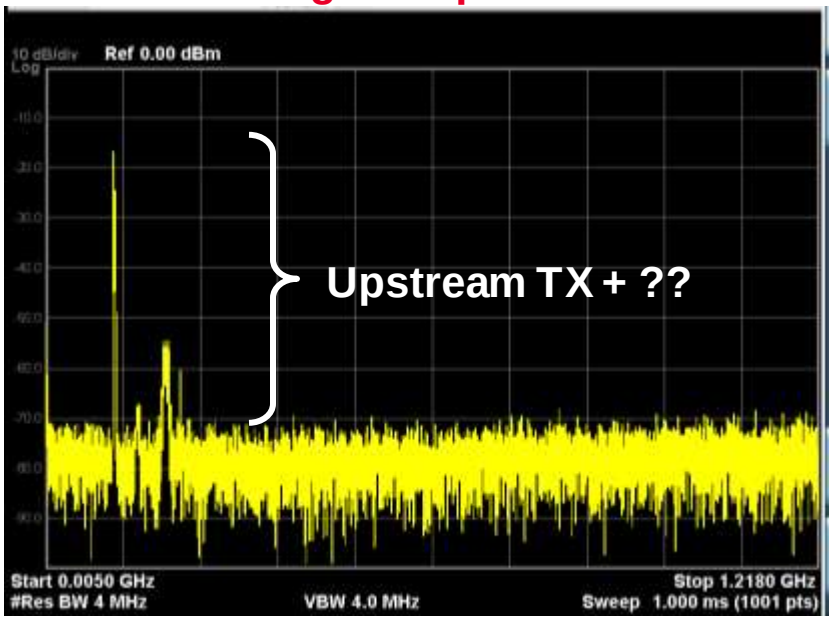
Gate Delay 0~few us (settling time)

Gate Length < minimum gap length.

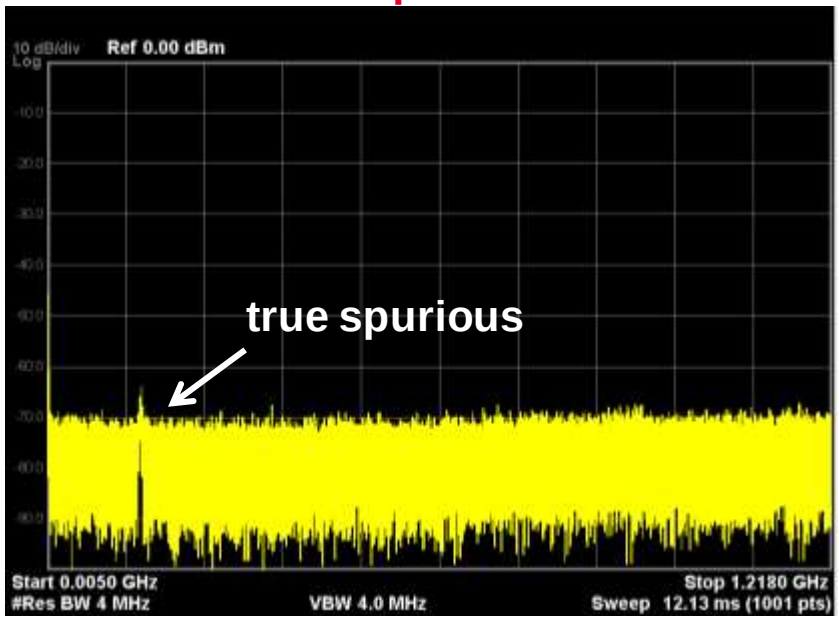
Interburst Noise and Spurious

Benefits of Gated LO Sweep

Free Running Sweep



Gated L.O. Sweep



Test Conditions

Upstream bands (5-204 MHz):

a) total emissions integrated in 160 kHz BW, in dBc.
b) total emissions integrated in 4 MHz BW, in dBmV.
c) any discrete spurs, in dBmV.

Downstream band (204-1218 MHz):

a) total emissions integrated in 4 MHz BW, in dBmV.
b) any discrete spurs, in dBmV.

KEYSIGHT TECHNOLOGIES

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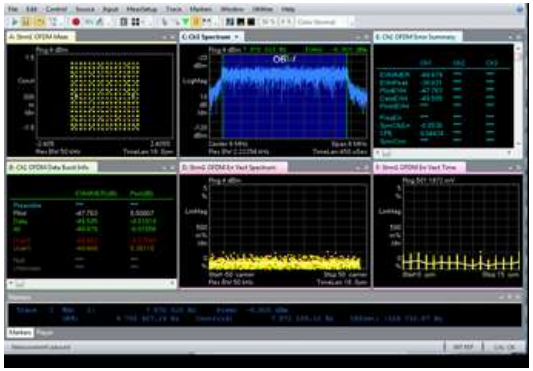
Learn More About DOCSIS 3.1

Additional Resources

- Recorded Webcast – "Viewing Upstream and Downstream DOCSIS 3.1 Signals "
  - www.keysight.com/find/wirelesswebcasts
- Recorded Webcast – "DOCSIS Signal Generation and Analysis"
  - www.keysight.com/find/wirelesswebcasts
- Application Brief – "Quickly Validate Designs for DOCSIS 3.1 Compliance"
  - http://literature.cdn.keysight.com/litweb/pdf/5991-4301EN.pdf?id=2447935
- VSA – www.keysight.com/find/VSA
- Future Webcasts – www.keysight.com/find/events



KEYSIGHT TECHNOLOGIES