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Introduction

DOCSIS 3.1 enables a new generation of cable-based broadband services by increasing data throughput to an unprecedented 10 Gbit/s downstream and 1-2 Gbit/s upstream. This is accomplished by means of a highly bandwidth-efficient new PHY layer, based on orthogonal frequency division multiplex (OFDM) modulation. This new PHY layer is compatible with existing DOCSIS 1.0-3.0 single-carrier QAM (SC-QAM) channels, allowing operators to deploy both within the same system.

As might be expected, the high spectral efficiency of OFDM comes at a cost in complexity. Even engineers with broad experience in the SC-QAM PHY will find the signals challenging to test and verify, with new parameters to be measured, new setups and procedures for doing so, and even new troubleshooting methods needed to diagnose problems.

This app note describes the key RF tests for DOCSIS 3.1 CMTS and CM devices, giving practical guidance for implementing them with commercially-available test instruments. The procedures are derived from two main documents:

CM-SP-PHYv3.1 DOCSIS 3.1 Physical Layer Specification (PHY Spec)
CM-TP-PHYv3.1-ATP DOCSIS 3.1 Physical Layer Acceptance Test Plan (ATP)

Both of these documents are published by Cable Television Laboratories, Inc. The PHY Spec is a public document, and can be downloaded from www.cablelabs.com. The ATP is available under NDA to CableLabs member companies only.

The tests described here are those most commonly required in engineering, prototype or certification labs, or in early manufacturing. Whereas the ATP covers the specific test conditions and pass/fail limits for device certification, the emphasis here is on implementation, i.e. how to set up the test equipment, which display types to use, and how to interpret and evaluate the results obtained.

Readers with no background in OFDM may wish to begin with the overview provided in the Keysight App Note titled “OFDMA Introduction and Overview”, available from http://literature.cdn.keysight.com/litweb/pdf/5991-4596EN.pdf.
DOCSIS 3.1 Upstream Signal Measurements

DOCSIS 3.1 upstream PHY overview:
- Two OFDMA signal formats:
  - 2K FFT mode with up to 1900 subcarriers, 50 kHz spacing. Symbol lengths from 21 to 26 us.
  - 4K FFT mode with up to 3800 subcarriers, 25 kHz spacing. Symbol lengths from 41 to 46 us.
- To support multiple-access (OFDMA), individual CM's transmit on a subset of the available subcarriers, as granted by the CMTS. Units of allocation are called "minislots", which consist of 8 or 16 contiguous subcarriers, for 2K or 4K mode respectively. A full 95 MHz bandwidth upstream channel comprises 237 minislots.
- Upstream spectrum begins at 5 MHz and extends to 42, 65, 85, 117 or 204 MHz, depending on system configuration. Upstream channel bandwidth is set by restricting the number of minislots available for allocation, e.g. minislots 0-104 for 42 MHz bandwidth, minislots 0-161 for 65 MHz, etc.
- Upstream signals are bursted, with two general categories of bursts:
  - Data bursts – for user payload data and certain system-level messages. Unless otherwise indicated, the test procedures in this app note are intended for use with these bursts.
  - Management bursts - usually short, specially-formatted bursts used for ranging, channel characterization, resource requests, etc.
- Upstream data is sent in frames of 6 to 16+ symbols, with lengths of approx. 120 to > 800 us. While single frame bursts are most common, multiple frames can be concatenated, resulting in burst lengths exceeding several milliseconds.
- Upstream pilot subcarriers are assigned to fixed locations, determined by the "pilot pattern" system parameter. Pilot density can range from approximately 3% of subcarriers to over 40%.

1. Burst power
DOCSIS 3.1 upstream signals present a unique challenge for power measurements. Not only are the signals bursted, but the power within a burst can change substantially from symbol to symbol. This is due to the resource allocation process, whereby the CM transmits only on the minislots (groups of subcarriers) granted specifically to it by the CMTS. Thus, even though the average power per subcarrier generally remains constant during the burst, the number of active subcarriers can - and often will - vary by symbol, and thus the total power.

As a result, a burst power measurement must be performed over an agreed-upon time period and over a specific range of subcarriers or minislots. This dependency on two domains at once calls for use of a vector signal analyzer (VSA) such as the Keysight 89600.

In the following VSA display, the spectrum (top trace) portrays the signal as observed during a 1 ms time record. The corresponding time waveform (bottom trace) shows that the signal is not constant during this time – it includes periods when the burst is at full power, at partial power and entirely off. Thus, the frequency domain power reading between the green band-power markers is not the desired result, because the displayed value of -1.941 dBm represents the average power during the entire 1 ms period.
Burst power measurements are generally defined as the power transmitted during the ON interval only, so this measurement needs to be constrained in the time domain.

In the following trace, markers select only the active burst time, resulting in a power measurement of +1.499 dBm. This is better, but it is still not the desired result, because the selected time period includes both a higher power region with many active subcarriers, followed by a short, low power region with only a few active subcarriers. The small burst in this case is a REQ burst, appended to the data burst and visible on the left side of spectrum display above. Thus, the measured power is still not the desired value, because it is the average of these two levels.
Finally, the time markers are adjusted to include only the period when the actual upstream grant is active. This is the correct measurement of the data burst power: +2.441 dBm.

**Converting 50 Ω to 75 Ω, and dBm to dBmV**

While CM and CMTS signal levels are generally given in voltage units (dBmV), most RF test equipment displays results in units of power (dBm) into a given termination impedance. Conversion between these two schemes is based on the following equations:

When starting from an RF measurement made with a 75 Ω instrument:

\[ \text{dBmV} = \text{dBm} \times \frac{75}{50} + 48.75 \text{ dB} \]

When starting from an RF measurement made with a 50 Ω instrument and impedance converter:

\[ \text{dBmV} = \text{dBm} \times \frac{75}{50} + 48.75 \text{ dB} - 1.76 \text{ dB} + \text{conversion loss (dB)} \]

The -1.76 dB factor accounts for the fact that a given voltage represents different power levels depending on whether the impedance is 50 or 75 Ω. The conversion loss represents the attenuation of the impedance conversion device, which ranges from 0.5-1.0 dB for a matching transformer to 7.48 dB for a resistive “minimum loss pad”. Note that the latter are often specified as having 5.72 dB loss, which is actually the sum of the conversion loss and the -1.76 dB factor described above. It is important not to include this factor twice.

Example - using a 50 Ω signal analyzer with a 5.72 dB minimum loss pad for impedance matching:

- Measured signal level = -20 dBm
- dBmV = -20 dBm + 48.75 - 1.76 + 7.48 dB
  = +34.47 dBmV

![Figure 3. Time-limited burst power shows the average power during only the full-power interval.](image-url)
2. Upstream spectral purity

These tests measure the levels of noise, spurious and other undesirable signals at the CM transmitter output. Complete verification requires a series of tests across several frequency bands, with setup conditions, measurement procedures and pass/fail limits varying as a function of the band. Purity is measured under both transmit (burst ON) and non-transmit (burst OFF) conditions, with separate setups and limits for each case.

Noise and spurious with burst ON

As shown in the diagram below, the various measurement bands consist of:

- The Adjacent band, a region 400 kHz wide beginning at center of the first inactive (null) subcarrier beyond the edge of the upstream signal;
- The Upstream band, extending from the outer edge of the Adjacent band to the edge of the CM's upstream operating region, i.e. 5 MHz (lower) or 42, 65, 85, 117 or 204 MHz (upper); and
- The Downstream band, extending from the upper edge of the Upstream band to 1218 MHz.

Additionally, there is a 2 MHz region extending outward from each edge of the active OFDM signal, where all spectral measurements must be made in synchronous mode, which is described in more detail below. For now, notice that this region includes all of the Adjacent band, plus the first 1.6 MHz of the Upstream band. This means that the Upstream band will usually need to be measured in two segments, one using synchronous and the other using non-synchronous measurements.

Within each band, two types of measurements are made: a) integrated noise power, consisting of all spectral emissions, summed over a specified bandwidth; and b) the peak magnitude of any discrete spurious signals.

The test matrix for the most common modem configuration is summarized in the table below. Pass/fail limits are found in the DOCSIS 3.1 PHY Specification section 7.4.12.5, which also provides test setups for other modem configurations.
### Table 1. Test matrix for upstream noise & spurious (burst ON)

<table>
<thead>
<tr>
<th>Band</th>
<th>Measurement Region</th>
<th>Synchronous?</th>
<th>Test #1: Integrated Noise Power</th>
<th>Test #2: Discrete Spurious</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjacent</td>
<td>0-400 kHz</td>
<td>Yes</td>
<td>Total power in a single 400 kHz band</td>
<td>Search entire region using RBW = 50 kHz (2K)</td>
</tr>
<tr>
<td>Upstream² (Sync region)</td>
<td>400 kHz to 2.0 MHz</td>
<td>Yes</td>
<td>Total power in a single 1.6 MHz band</td>
<td>Search entire region using RBW = 25 kHz</td>
</tr>
<tr>
<td>Upstream² (Non-sync region)</td>
<td>2.0 MHz to limits of CM range: a) 5-42 MHz b) 5-65 MHz c) 5-85 MHz d) 5-117 MHz e) 5-204 MHz</td>
<td>No</td>
<td>Total power in specified bands², stepped contiguously across meas. region: a) in 1.6 MHz bands b) in 3.2 MHz bands c) in 3.2 MHz bands d) in 9.6 MHz bands e) in 12.8 MHz bands</td>
<td>Search entire region using RBW = 25 kHz</td>
</tr>
<tr>
<td>Downstream²</td>
<td>Upstream band upper edge to 1218 MHz</td>
<td>No</td>
<td>Total power per 4 MHz band, stepped contiguously across meas. region</td>
<td>Search entire region using RBW = 30 kHz³</td>
</tr>
</tbody>
</table>

1. Frequencies shown as offsets from the outermost active subcarrier; all other frequencies are absolute. If the upstream signal includes internal exclusion bands, Adjacent band measurements are also required from each edge of these regions.
2. Upstream and Downstream bands are further broken down into sub-bands, each with its own pass/fail limits. However, the measurement procedure and setup apply as shown for the entire band.
3. Upstream band noise power is the sum of the power in the 1.6 MHz measured synchronously, plus the power in the remaining bandwidth (if any) measured non-synchronously.
4. Recommended RBW, not a spec requirement.

### Triggering

*Burst-ON* measurements must be triggered or time-gated so that they are performed only during the active portion of the burst. However, it is not sufficient to simply sync the start of the measurement to the rising edge of the RF envelope; the measurement must be fully completed before the end of the burst. The VSA’s ability to display both spectrum and waveform simultaneously is invaluable here.

In the display shown, the spectrum in the upper trace corresponds to the 12.7 us waveform segment in the lower trace. A 1 us trigger delay positions the measurement within the stable portion of the burst, eliminating any spectrum artifacts associated with turn-on or turn-off transients.

Some test cases involve channel bonding, i.e. where the CM is configured to transmit multiple OFDMA channels, with or without additional SC-QAM channels. These test cases have similar triggering requirements, except that the tests must be performed during periods when all required channels are active. Because there is no mechanism within DOCSIS to force upstream channels into time-alignment, these burst-ON measurements depend on the statistical likelihood that such alignment will occur with some regularity. Signal analyzer triggering should be used to continuously monitor the CM output and initiate a measurement when this occurs.
Integration bandwidth: Noise power in the non-synchronous regions is measured as a series of band-power measurements, summing the power over bandwidths of 1.6, 3.2, 9.6 or 12.8 MHz, depending on the upper frequency limit of the CM. With the 89600 VSA, these measurements can be performed in either of two ways, as shown on the accompanying display:

Band power approach: Trace A displays the active signal and its adjacent spectrum, using the default RBW for the chosen span. The band power markers are set to a width of (e.g.) 1.6 MHz, and compute the total power within that band. To complete the measurement, the markers are stepped across the measurement range in 1.6 MHz steps, and a result value is recorded for each step.

Custom-RBW approach: Trace B displays the same spectrum, but with the RBW set manually to 1.6 MHz bandwidth. Each trace point now represents the total power in a 1.6 MHz band. The advantage to this approach is that the entire measurement region – potentially hundreds of individual bands – can now be measured and verified in a single display update, simply by checking that no individual trace point exceeds the spec limit.

While the second approach is clearly more efficient, care must be taken to ensure that it is truly equivalent to the band power approach. In particular, note the different time record length (TimeLen) values for the two measurements. Trace A shows the average spectrum during a 12.7 microsecond time record; the Trace B measurement covers 2.4 microseconds. These lengths do not necessarily need to be equal, as long as both occur entirely within the active portion of the burst, and as long as the waveform statistics are substantially random for both (a potential issue when measuring repetitive bursts, such as those from an arbitrary waveform generator). A practical approach for ensuring equivalency is to start with both measurements running side-by-side, and then adjust the span and bandwidth parameters of the custom-RBW measurement until its results match those of the band power measurement.

Synchronous ACP measurements: Noise and distortion measurements in the Adjacent band (0–400 kHz) begin at one subcarrier spacing (25 or 50 kHz) from the outermost active subcarrier. However, OFDM signals naturally exhibit significant sinX/X modulation sidebands extending into this region, which are visible when viewed on a traditional spectrum analyzer (Figure 7, top trace).

The spurious ACP specification is not meant to include these sidebands, but rather to measure only the unwanted noise and distortion that may accompany them. In order to separate these components, spurious measurements at offsets of 2 MHz or less are performed synchronously – that is, the incoming signal is sampled at the same frequency and in phase with the underlying OFDM sample clock. As shown in the bottom trace, this suppresses all orthogonal (modulation-related) energy, leaving only the noise and spurious products.

Synchronous analysis produces a set of discrete spectrum points at the OFDM subcarrier spacing, as shown in Trace B. Because the RBW of these points is equal to their spacing, no spectral energy is missed. Integrated noise power is computed as the sum of these points over the specified measurement region. Discrete spurious affect the magnitude of the point in which they fall.

The 89600 VSA with option BHM (DOCSIS 3.1 Modulation Analysis) performs this measurement automatically, with results reported on the Error Summary table in units of dBc relative to transmit power.

Users of option BHF (Custom OFDM Analysis) can perform the same measurements by configuring 40 or 80 null subcarriers (resource type = 4) on either side of the signal. When Display Null Subcarriers is selected under Advanced Demod Properties, these empty subcarriers are displayed and can be read and tabulated manually.
Noise and spurious with burst OFF

Cable modems must also be tested for spurious emissions during the time periods between bursts. As before, two tests are performed: a) integrated noise and spurious power, and b) discrete spurious emissions. Separate measurement setups are provided for the Upstream and Downstream bands, with pass/fail limits further broken down by sub-band. Because no OFDM signals are present during these tests, synchronous sampling techniques are not needed.

The test matrix for Burst OFF emissions is shown in Table 2. Pass/fail limits are found in the DOCSIS 3.1 PHY Specification section 7.4.12.5.

<table>
<thead>
<tr>
<th>Band</th>
<th>Measurement Region</th>
<th>Synchronous?</th>
<th>Test #1: Integrated Noise Power</th>
<th>Test #2: Discrete Spurious</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream</td>
<td>5.0 MHz to upper end of CM range, e.g.: 42, 65, 85, 117 or 204 MHz</td>
<td>No</td>
<td>Total power per 160 kHz band, stepped contiguously across meas. region.</td>
<td>Search entire region using RBW = 30 kHz¹</td>
</tr>
<tr>
<td>Downstream</td>
<td>Upstream band edge to 1218 MHz</td>
<td>No</td>
<td>Total power per 4 MHz band, stepped contiguously across meas. region</td>
<td>Search entire region using RBW = 30 kHz¹</td>
</tr>
</tbody>
</table>

¹ Recommended RBW, not a spec requirement.

Triggering: Noise and spurious measurements must be made in the time intervals between upstream bursts. These bursts might include one or two OFDMA upstream carriers, with or without additional legacy SC-QAM carriers. The signal analyzer’s trigger input sees the sum of all signals within its current span width; when the combined signal drops down to the analyzer’s noise floor, this indicates that all bursts are OFF. Triggering on the falling edge of the combined signal envelope will thus align the measurement correctly, but requires care to set up correctly.
The following display shows the spectrum of an upstream band with two active OFDMA channels. They are not time-synchronized, so the instant when they are both off will occur at unpredictable intervals.

![Figure 11. Upstream spectrum with two active OFDMA channels](image)

A simple level-based trigger, configured as described above for the falling edge of the combined waveform, might seem reasonable, but is likely to be unreliable. Because OFDM waveforms are noise-like, they have millions of rising and falling edges per second. This makes it nearly impossible for a basic trigger function to distinguish between normal waveform variations and the desired burst edges.

The preferred trigger method uses frequency mask triggering (FMT). As shown below, a simple mask covers the entire measurement region. The trigger criteria is set to “Leave”, which means that the analyzer will trigger as soon as all signals have left the mask, i.e. when all carriers are off.

![Figure 12. Frequency Mask Trigger configuration for burst OFF triggering](image)
The resulting measurement now shows the empty upstream spectrum as it exists between bursts. The analyzer has been configured with a 160 kHz RBW, so the integrated noise power can be read directly from the trace. For spur searching, re-configure the RBW to 30 kHz.

Figure 13. Upstream spectrum with burst OFF triggering

Spurious measurements in the downstream band are further complicated by the fact that some measurement frequencies are 1000 MHz or more above the upstream signals used for triggering. Because of this wide frequency span, these measurements will often require two instruments – one to detect the trigger condition, and the other to perform the actual measurement, as shown in the following diagram.

Figure 14. Burst OFF triggering setup using wide-bandwidth oscilloscope
In this setup, the oscilloscope is configured for Timeout triggering, meaning that it will initiate a trigger only after the input signal(s) have remained below the set threshold for a given amount of time (10 us, in this example). As explained above, this identifies the point in time when all upstream carriers are off.

The scope's trigger output is sent to the spectrum analyzer, which is configured in FFT Gated Sweep mode. Here, the analyzer sweeps across its programmed span in a series of spectrum segments, one segment per trigger. Because the spectra are FFT-based, the measurement time per segment (i.e. “Gate Length”, shown here as 457.5 ns) is less than 1 symbol, which guarantees that the segment will be fully measured before the next upstream burst begins.

In the example display, note that the RBW has been manually set to 4.0 MHz. This satisfies the requirements for integrated noise and spurious measurements in the downstream band. For discrete spurious measurements, the RBW would simply be re-configured to 30 kHz.

Figure 15. Downstream band is measured in a single wide-BW sweep, using time-gating.
3. Modulation Error Ratio (MER)

The DOCSIS 3.1 PHY specification defines modulation fidelity in terms of Modulation Error Ratio, an industry-standard metric that computes the ratio of desired signal power to the combined power of in-channel noise and distortion. General background on MER measurements is widely available, including Keysight Application Note 1455 “Equalization Techniques and OFDM Troubleshooting” (publication number 5988-9440). In particular, note the chapters that illustrate how the VSA’s various MER displays (MER vs. time, MER vs. subcarrier, etc.) can provide useful insights for optimizing and troubleshooting signal performance.

MER measurements are performed by a specialized form of demodulator, which recovers the incoming signal, re-creates an ideal version of it, and then subtracts it from the incoming signal so that only the residual noise and distortion remains. Setup requires configuring this demodulator to match the signal under test, including the parameters shown here in the 89600 VSA menu box.

Most of these parameters can be auto-detected by the software, once the user has entered the CM’s Pilot Pattern, Bit Loading and Burst Length.

**Synchronization:** MER readings are very sensitive to the sample clock frequency of the receiver or signal analyzer. A sample clock difference of only a few tenths of a ppm between CM and analyzer can degrade MER by 5-6 dB or more. While tracking and compensating for the actual sample clock frequency can optimize MER, this is not technically permitted by the DOCSIS 3.1 PHY spec. Thus, for standards-compliant MER measurements, the VSA’s “Compensate Symbol Clock Error” setting must be turned OFF under Advanced Demod Properties.

Instead, the sample rate for MER measurements must be derived from the actual downstream signal. This is achieved by locking the VSA’s frequency reference to the CMTS master reference, rather than to an independent (internal or external) frequency standard. Several techniques for accomplishing this are described in the next section, under the heading “Synchronizing the VSA to the CMTS Master Clock”.

**Equalization:** depending on the test case, the required MER measurements are performed with or without an equalizer in the signal analysis path. When present, an equalizer measures and compensates for linear distortion in the signal under test - frequency response variations, including ripple caused by reflections - leaving only the non-linear distortion, such as noise, intermod, spurs, compression, etc.

The two VSA configurations used for CM MER testing are:

*Non-equalized* – these MER measurements are used to verify the CM’s pre-equalization function. In this procedure, the VSA first measures the frequency response of the upstream signal. The resulting complex coefficients are then sent to the CM and used to pre-equalize the frequency response of the transmitted signal. The CM, transmitting with its pre-equalizer ON, should theoretically output a perfectly flat signal, as measured by the VSA with its equalizer OFF.

However, as of this writing, no commercial CM’s actually offer the ability to import pre-equalization coefficients. Until this is implemented, the accepted convention is to perform this test as a conventional MER measurement, i.e. with the CM’s pre-equalizer turned OFF and the VSA’s equalizer turned ON.
Partially equalized – in this case, MER is measured using the compensations described above, except that any reflections occurring greater than 200 nanoseconds from the main signal must remain uncompensated, and thus permitted to degrade the measured MER.

To illustrate this, consider the Impulse Response display shown here for a typical CM transmitter. (Impulse response is simply the inverse FFT of the channel frequency response, which converts it to a time domain representation. This type of view is useful for observing reflections).

The fully-equalized MER for this signal was 44.1 dB. A discrete reflection is observed at T = +2.0 us and -50.8 dBc. Because it is outside the ±200 ns window, this reflection must not be compensated by the VSA’s equalizer. The effect of this can be computed by adding its power back into the equalized MER result, i.e.:

\[
\text{MER}_{\text{partialEQ}} = -10 \times \log(10^{-\text{MER}_{\text{fullEQ}}/10} + 10^{\text{P}_{\text{Refl}}/10})
\]

\[
\begin{align*}
\text{MER}_{\text{partialEQ}} &= -10 \times \log(10^{-44.1/10} + 10^{-50.8/10}) \\
&= 43.3 \text{ dB}
\end{align*}
\]

Figure 17. Impulse response showing reflection at +2.0 us
The DOCSIS 3.1 PHY Acceptance Test Plan describes several approaches for computing partially-equalized MER. VSA's that provide DOCSIS 3.1 MER measurements will generally include the ability to perform these calculations internally, allowing the user to choose from among full, partial or non-equalized measurements.

**Test Set Calibration:** The DOCSIS 3.1 PHY specification allows the CM’s MER result to be corrected for residual MER contributed by the test fixturing and related interconnections. However, a closer examination of the underlying math suggests a minimal benefit for this incremental effort.

According to DOCSIS 3.1 ATP guidelines, the residual MER of the test set must be at least 6 dB better than the device under test. Thus, to measure a CM with MER in the region of 50 dB, the test set must have a residual MER no worse than 56 dB. This worst-case contribution would degrade measured MER by about 1.3 dB. In theory, this loss would be regained by measuring the test set residual and subtracting it from the uncorrected MER reading.

From a practical standpoint, however, few test sets will contribute anywhere near this amount, because they are typically composed of passive components only. Less residual means less potential improvement. Furthermore, the process of characterizing the test set’s residual MER – which must be done separately for each test frequency, bandwidth and power level – would require a calibration signal source at least 6 dB better, i.e. a 62 dB MER source, which is not commercially available.

---

### 4. Frequency and timing accuracy

DOCSIS 3.1 Cable Modem tests verify two key frequencies: 1) the RF channel frequency, and 2) OFDM subcarrier spacing, derived from the sample (or symbol) clock rate of the OFDM modulator. These frequencies are fairly straightforward to measure on an absolute basis, using a signal analyzer synchronized to a known frequency standard. In fact, most VSA's provide numeric readouts of both channel frequency error and symbol clock error as part of their DOCSIS 3.1 modulation analysis results.

However, in the DOCSIS architecture, CM’s do not contain their own frequency reference, but are instead frequency-locked to the CMTS downstream signal. This means that upstream frequency accuracy must be measured and verified relative to the downstream reference, rather than relative to the VSA’s own frequency reference. For example, if the downstream frequency is in error by 1 ppm, then a correctly-synchronized upstream signal should also exhibit the same 1 ppm error, plus or minus the tolerances permitted by the DOCSIS 3.1 PHY specification.
CM frequency accuracy measurements therefore require two setup conditions: a) the CM must be connected and registered to a CMTS; and b) the signal analyzer must use a frequency reference that is derived from the master frequency reference of the CMTS. Techniques for doing so are discussed in the section below, “Synchronizing the VSA to the CMTS Master Clock”.

The DOCSIS 3.1 PHY specs refer to worst case subcarrier frequency error. Because OFDM subcarriers are too closely-spaced to be measured individually, this error must be derived from two other VSA measurements: Channel Frequency Error and Symbol Clock Error. To understand how these quantities are all related, consider the following OFDM signal characteristics:

As shown in the diagram, channel frequency errors and symbol clock errors affect subcarrier frequencies differently. Channel frequency errors simply shift all subcarriers by the same amount and in the same direction. Symbol clock errors have a cumulative effect on subcarrier frequencies, because they impact the subcarrier spacing (where subcarrier spacing = symbol clock freq/ FFT size). For example, if the correct spacing is 50 kHz, the subcarrier frequencies should lie at 50 kHz, 100 kHz, 150 kHz, etc. relative to subcarrier #0. But with a 1 kHz spacing error, the actual subcarrier frequencies would be 51 kHz, 102 kHz, 153 kHz, etc. - with the error increasing in proportion to the subcarrier number.

The frequency error for any given subcarrier, then, is simply the sum of the channel frequency error plus the subcarrier spacing error multiplied by the subcarrier number. Based on the above descriptions, it should be clear that the worst-case subcarrier frequency error will always occur at one of the two outer subcarriers, so only these two cases need to be evaluated (as shown in Error Summary table above).
Synchronizing the VSA to the CMTS master clock

Depending on the capabilities of the CMTS, several approaches are available for synchronizing the signal analyzer to the CMTS reference.

**CMTS Master Reference:** some CMTS units provide hardware access to their master frequency reference via an output connector or test point. If so, this reference signal is simply supplied to the signal analyzer’s external frequency reference input. Because it is now locked to the CMTS, the analyzer’s frequency accuracy readings are inherently referenced to the CMTS master clock, and can be used without modification.

**Shared Reference:** Some CMTS units, while not providing a master reference output, do have a reference input, allowing them to be synchronized to an external frequency source. In these cases, the signal analyzer and CMTS need only to be connected to the same source, based on the principle that two devices synchronized to the same reference are inherently synchronized to each other. As above, the analyzer’s frequency accuracy readings can now be used without modification.

**RF Reference:** the DOCSIS 3.1 PHY specification requires that a CMTS support two independently configurable downstream channels. It also specifies a mandatory test mode whereby a channel outputs a single CW carrier. Although primarily intended to support phase noise testing, this carrier can also be used as a frequency reference for the DOCSIS signal analyzer, because it is derived from the CMTS master clock.

In the example shown, one downstream channel is used for active communication with the CM, while the other is configured in the CW test mode. Its output is set to 400 MHz; an off-the-shelf ÷8 clock divider converts this to 50 MHz, which is then fed to the frequency reference input of the signal analyzer. Thus synchronized, the analyzer’s frequency accuracy readings can now be used without modification. In most cases, it will be desirable to output the CW signal from a separate hardware port, so that its power level can be set independently from the downstream OFDM signal.
Synchronization when no CMTS frequency reference is available

When there is no access to any master-referenced CMTS signals, CM frequency accuracy can still be determined analytically, using a two-step process. First, the CMTS downstream signal is demodulated, and its absolute frequency accuracy is determined. Then, the CM’s upstream signal is similarly analyzed, and its frequency accuracy compared to that of the CMTS. The two should exhibit the same accuracy, within the PHY spec limits.

With the CM connected and registered to the fully warmed-up CMTS, proceed as follows:

Step 1 – connect the analyzer to the CMTS TX output and configure it to demodulate the downstream signal. When a stable constellation is achieved, note the downstream symbol clock error, in ppm (ClkErr\textsubscript{CMTS}). This represents the basic accuracy of the CMTS master reference, relative to the frequency reference of the signal analyzer.

Step 2 – now connect the analyzer to the CM TX output, configure for upstream signal analysis and measure the symbol clock error, again in ppm (ClkErr\textsubscript{CM}).

Step 3 – the CM symbol clock error relative to the CMTS is computed as:

\[
\text{ClkErr(\text{relative})}_{\text{CM}} = \text{ClkErr}_{\text{CM}} - \text{ClkErr}_{\text{CMTS}}, \text{ with all values in ppm.}
\]

Note that any frequency error introduced by the analyzer appears in both terms, and simply drops out of the equation.

Example:

- measured CMTS symbol clock error = −0.25 ppm
- measured CM symbol clock error = +0.10 ppm
- CM relative symbol clock error = +0.35 ppm

Step 4 – the CM’s channel frequency error must also be expressed relative to the CMTS. In this case, the relevant equation is:

\[
\text{FreqErr(\text{relative})}_{\text{CM}} = \text{FreqErr}_{\text{CM}} - (\text{CM}_{\text{freq}} \times \text{ClkErr}_{\text{CMTS}})
\]

where

- FreqErr\textsubscript{CM} = measured CM channel frequency error, Hz
- CM\textsubscript{freq} = nominal upstream channel frequency, MHz
- ClkErr\textsubscript{CMTS} = measured CMTS symbol clock error, ppm

Example:

- measured CM channel freq error = +15.5 Hz
- measured CMTS symbol clock error = +0.10 ppm
- upstream channel frequency = 54 MHz
- CM relative channel freq error = +15.5 – (54 * 0.10) = +10.10 Hz

The CMTS symbol clock error indicates the proportional error of the CMTS master frequency reference, which governs both the symbol clock and the downstream channel frequencies. In a perfectly synchronized system, the CM upstream channel at 54 MHz would exhibit the same proportional error, so it would appear 0.1 ppm higher, i.e. a frequency error of +5.4 Hz. The measured error of +15.5 Hz thus represents the sum of this error plus an additional 10.1 Hz error contributed entirely by the CM.
The above approach simulates synchronized measurements of the CM frequency and sample clock rate to an acceptable degree of accuracy. Measurements of Upstream MER and Adjacent Channel noise and spurious must likewise be synchronous, and can also be simulated with a few additional steps.

Step 5 – note the CMTS sample clock (symbol clock) error obtained in the downstream demod measurement of step 1. When configuring the CM measurement, manually introduce the same error in the upstream sample clock frequency, where:

\[
\text{Upstream sample clock} = 102.4 \text{ MHz} \times (1 + \frac{\text{CMTS Sample Clock Error}}{10^6})
\]

With this setting, all upstream demod measurements, including MER and synchronous ACP, will now be based on the actual sample rate of the CMTS. Any additional frequency error introduced by the CM will degrade the device results – as intended by the PHY test requirements.

Figure 25. Approach for simulating synchronized measurements of Upstream MER and ACP when CMTS frequency reference is unavailable.
5. Demodulator-Based Power Measurements

Power per subcarrier

Power measurements on individual OFDM subcarriers may be occasionally useful, but can be problematic for several reasons.

First, the orthogonal subcarriers are spaced too closely to be separated using a conventional spectrum analyzer—they require at least a basic OFDM demodulator. Secondly, the power of an individual subcarrier is not constant, but varies with the constellation value being transmitted on that subcarrier during that symbol interval. The diagram illustrates a subcarrier varying over four symbols; for outer constellation points, the instantaneous power is high, for inner points, the power is low—in some cases, more than 10 dB lower. Because of this wide power range, it will usually require hundreds of symbols to obtain a stable reading of the average constellation magnitude.

The VSA’s Channel Response display simplifies this measurement greatly. The trace data, as shown here, represents the frequency response of the signal, with one data point provided per subcarrier. This data is useful because of how it is derived:

a) as each subcarrier’s magnitude is measured, it is compared to the ideal magnitude for the detected constellation point, so that the result is simply the deviation from ideal. This means that a subcarrier’s symbol-to-symbol readings will only vary over a range of a few tenths of a dB, regardless of the constellation data being transmitted. This greatly reduces the need for averaging;

b) the entire trace is also normalized, i.e. scaled such that the average is 0.00 dB. This 0 dB magnitude corresponds to the total power reading displayed on the VSA’s Error Summary trace, once it has been converted to a per-subcarrier value.

Thus, the absolute power reading for any given subcarrier is simply:

\[
\text{Subcarrier}_n \text{ Power (dBm)} = \text{Total power (dBm)} - 10 \times \log(\text{no. of active subcarriers}) \pm \text{chan. response}_n (\text{dB})
\]

For the example trace shown, the absolute power for subcarrier # 700 is computed as:

\[
\text{Power}_{700} = -18.365 \text{ dBm} - 10 \times \log(1900) + 0.119 \text{ dB} = -51.033 \text{ dBm.}
\]
Power per symbol

The DOCSIS 3.1 PHY specification requires upstream symbol power to remain constant to within 0.1 dB for the duration of an entire burst (i.e. assuming a fixed minislot allocation). This is true even for mixed mode scenarios, where other OFDM or SC-QAM channels may be bursting on or off at the same time.

Verifying constant power thus requires symbol-by-symbol power measurements, which can be implemented in either of two ways.

The time-domain approach utilizes a band power measurement on the (triggered) burst waveform. The interval between the markers is set to one symbol duration, calculated as:

Symbol duration = FFT size * (1 + Cyclic Prefix)/102.4 MHz

The readout shows the average power during the interval. To perform the power stability test, the band power markers are stepped across the burst in one symbol increments, and the power readings recorded.
While the time-domain approach is simple to implement, it is not always suitable for mixed-mode measurements. This is because the time-domain display shows the combination of all signals within the analyzer’s IF bandwidth (approximately 1.20 - 1.28x the frequency span setting). Thus, when additional upstream carriers are present in that span width, the power in their waveforms is added to that of the signal under test. For this reason, mixed-mode measurements are best performed in the subcarrier domain, following demodulation.

Both traces on Figure 30 portray the same demod result, known as OFDM IQ Meas. This is the demodulator’s main output, consisting of one complex data point per subcarrier per symbol. The lower trace plots this data on I vs. Q axes, resulting in the familiar constellation display. The upper trace plots exactly the same data, but using axes of log magnitude vs. subcarrier number. The magnitude varies across the trace because the constellation points vary in their distance from the constellation origin.

Band power markers can be applied to the upper trace to compute the average power of any or all subcarriers. Marker positions are defined by subcarrier number; for the example shown, the center subcarrier is set to 1024 and the width to 1900, thus including all active subcarriers. Adjacent channel energy is not included, because it lies outside the measurement band.

This trace type normally includes data for all subcarriers and all symbols. To measure one symbol at a time, use the Demod Properties, Time menu. As shown here, the Result Length is set to demodulate the entire 11-symbol burst, while the Measurement Interval is set to display only 1 symbol, with an offset from the burst start of 5 symbols.

By default, OFDM IQ Meas data is shown as normalized; that is, the I-Q data is internally scaled such that the average magnitude across the entire measurement interval is 1.000. This means that the band power result will be in dB, not dBm, and will generally be quite close to 0.00 dB. Because this test is concerned with symbol-to-symbol variations, not absolute power levels, the results can therefore be used as-is.

Lastly, make certain that Pilot Amplitude Tracking is not enabled for this measurement. When active, it normalizes the I-Q data separately for each symbol, and would therefore obscure the power variations that this test is specifically intended to detect.
DOCSIS 3.1 downstream PHY overview

Key characteristics of DOCSIS 3.1 downstream signals include:

- Two OFDM signal formats:
  - 4K FFT mode with up to 3800 subcarriers, 50 KHz spacing. Symbol lengths from 21 to 25 us.
  - 8K FFT mode with up to 7600 subcarriers, 25 KHz spacing. Symbol lengths from 41 to 45 us.
- Encompassed bandwidths ranging from 22 to 190 MHz, determined by the quantity of active subcarriers. Total channel bandwidth consists of the active subcarrier region plus variable guard bands on each side. Example: a nominal 192 MHz channel comprises 190 MHz of active subcarriers plus 1 MHz upper and lower guard bands. Guard bandwidth is specified in the PHY standard as a function of FFT size and symbol rolloff period, $N_{rp}$.
- Downstream spectrum covers at least 258 to 1218 MHz, but may be optionally extended within the range 108 MHz to 1794 MHz. Operators may also configure exclusion bands (regions of inactive subcarriers) in order to avoid interference from known external sources, or to provide space for legacy DOCSIS channels.
- Downstream transmissions are continuous, not bursted. Data is sent in contiguous frames of 128 symbols, using subcarrier modulation formats from 16 QAM to 4096 QAM, with 8192 QAM and 16384 QAM available for future use. Non-data subcarriers also utilize QPSK or BPSK.
- A PHY Link Control (PLC) band occupies an operator-selected 6 MHz region of the downstream channel. Within this region, 8 or 16 subcarriers continuously transmit key downstream PHY parameters, which are decoded and utilized by CM’s when initially connecting.
- OFDM pilots are BPSK modulated and boosted by 6 dB relative to the average constellation power. They come in two types:
  - Continuous – 16 to 128 pilots in fixed locations. Some of these locations are pre-determined (e.g. those in the 6 MHz PLC band), while others are determined by the CMTS and communicated to the CM via PLC message.
  - Scattered – spaced every 128 subcarriers, these shift to the right by one subcarrier position every symbol, so that every subcarrier serves as a pilot at least once per frame.
1. CMTS output power measurements

Output power level is one of the most basic CMTS parameters, and most test procedures include one or more steps where it must be measured. Although a standalone power meter could be used for these tests, it actually offers little or no advantage in return for being an added piece of test equipment. The required accuracy is readily achievable with most high-performance signal analyzers, such as those already needed for other CMTS tests. In addition, these analyzers can also perform the band-limited power measurements needed in some procedures.

Measuring power in the frequency domain:

Most transmit (TX) power measurements are based on a spectrum display of the input signal. Unlike steady-state or narrow-BW signals, wideband DOCSIS downstream signals cannot be measured using the display marker alone, because it only reads the power in a single resolution bandwidth (RBW), centered on the marker. Instead, DOCSIS power must be computed as the sum of hundreds or thousands of measurement points across signal’s bandwidth.

Fortunately, most signal analyzers have built-in functions that perform this summation automatically. This may be a dedicated channel power function, or it may use band power markers; in either case the user simply defines a measurement band, choosing either center/ span or start/stop frequencies sufficient to insure that the input signal fits entirely within it.

Figure 33. Band power markers sum power in OFDM channel only, ignoring adjacent channels
In Figure 33, the green band power markers have been configured to measure power in a ~200 MHz band, centered on the 190 MHz wide downstream OFDM carrier at 602.4 MHz. The power in the measurement band is read directly from the display as 11.593 dBm (also see “Converting 50 Ω to 75 Ω and dBm to dBmV” earlier in this note).

Because OFDM signals have a much higher peak-to-average ratio than legacy SC-QAM signals, averaging will generally be needed to obtain a stable result. As a general rule, result variance will decline in proportion to the square root of the number of readings averaged.

Notice that the OFDM channel is not the only signal present in this spectrum. Blocks of 6 MHz SC-QAM signals are located adjacent to the signal under test (a common test configuration). However, only the power between the markers is included in the result; this is therefore considered to be a band-limited or frequency selective power measurement, generally not possible using a standalone power meter.

**Signal analyzer sampling effects:** an important principle of OFDM modulation is that subcarriers are only orthogonal when sampled at a specific rate and timing. In all other cases they are non-orthogonal, meaning that their energy is no longer confined to a single frequency, but appears dispersed in the frequency domain. This can affect the spectrum appearance in unexpected ways.

Here, the VSA spectrum display shows a DOCSIS 3.1 downstream signal with continuous pilot subcarriers spaced regularly across the spectrum. The pilots stand out because of their +6 dB power boost. The varying magnitudes suggest a possible problem, but this is not actually the case. The variations occur because (in this mode) the VSA’s sampling rate has been internally chosen to optimize spectrum analyzer performance, rather than to preserve subcarrier orthogonality. As a result, the power of some subcarriers is spread across two or more bins, causing the pilot levels to appear as if they are varying. Fortunately, the total power of the subcarriers is unaffected by this dispersion, so the accuracy of the overall TX power measurement is fully preserved.
Measuring power in the time domain:

CMTS TX power may also be measured in the time domain, with results derived directly from the input waveform. These measurements will generally match those obtained from spectrum measurements, with a few key differences:

- Time domain power measurements are frequency selective, but to a lesser degree than spectrum-based measurements. The measurement bandwidth is determined by the analyzer’s digitizer bandwidth, which is equal to the current span setting plus an additional 20-28% (hardware-dependent). Thus, if other carriers are present in the region immediately adjacent to the displayed span, some of their power may be included in the measurement.
- Averaging does not smooth out time domain measurements; instead, stable readings are achieved by measuring over longer time periods. The minimum recommended measurement interval is one-half of an OFDM symbol, or approximately 10 us.
- Band power markers may be used on the time domain display, as shown here, with the start and stop locations set in units of time (i.e. time offset from start of acquisition). Note that, for time domain traces, the band power markers display the average power across the selected region, rather than the sum.

Time-domain power measurements offer several unique capabilities:

a) The ability to view power on a symbol-by-symbol basis, simply by adjusting band power markers to appropriate width and time offset;

b) The ability to view power variations over time, such as might occur when other carriers are switched on or off, or due to AC hum/ripple, or as intentionally commanded from the CMTS console.

Figure 35. Band power markers measure the average power of a single downstream symbol
Measuring Power of Individual Subcarriers and Symbols:
Power measurements on individual subcarriers or symbols require use of the analyzer’s DOCSIS 3.1 demodulator. Because it samples synchronously, magnitude and phase readings are accurate for each subcarrier in each symbol. For a detailed discussion of these measurements, see “Demodulator-Based Power Measurements” in the Upstream Measurements section of this note.

Additional Notes:

– CMTS power specifications are usually given in dBmV, i.e. dB relative to 1 millivolt, measured in a 75 ohm environment. RF signal analyzers generally report in dBm, i.e. dB relative to 1 milliwatt into 50 ohms. For guidance on converting these measurements to the desired units, see “Converting 50 Ω to 75 Ω and dBm to dBmV” earlier in this note.

– In several CMTS test procedures, power is expressed in dBc, i.e. relative to the power in the 6 MHz band containing the PLC. This reference power is measured by setting the band power markers to the center of the PLC region (200 kHz above the PLC index frequency), with a span width of 6 MHz. Because the PLC region has more pilot subcarriers than other regions, its power will be about 0.6 or 0.3 dB higher than the overall signal average, for 4K or 8K systems respectively.

2. Spurious Emissions
Every DOCSIS 3.1 CMTS must be tested to insure that it is not transmitting noise, spurious or distortion products in frequency bands reserved for other devices. These tests are performed in several bands, with measurement conditions and test limits determined as a function of the band. These tests are summarized in the table below.

Table 3. Test matrix for downstream noise & spurious

<table>
<thead>
<tr>
<th>Test Region</th>
<th>Frequencies</th>
<th>Required Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjacent band¹</td>
<td>0 - 750 kHz</td>
<td>Total band power</td>
</tr>
<tr>
<td></td>
<td>750 kHz - 6 MHz</td>
<td>Total band power</td>
</tr>
<tr>
<td>Second adjacent</td>
<td>6 - 12 MHz</td>
<td>Total band power</td>
</tr>
<tr>
<td>Third adjacent</td>
<td>12 - 18 MHz</td>
<td>Total band power</td>
</tr>
<tr>
<td>Wideband²</td>
<td>5 M - 47 M</td>
<td>Total power in a 6 MHz measurement band, stepped contiguously across region.</td>
</tr>
<tr>
<td>Low</td>
<td>47 M - 1218 M²</td>
<td></td>
</tr>
<tr>
<td>Mid</td>
<td>1218 M - 3000 M</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>6 MHz exclusion band within signal under test.</td>
<td>Total power in center 400 kHz of exclusion band, relative to power in 6 MHz PLC band, scaled to 400 kHz.</td>
</tr>
</tbody>
</table>

¹. Frequencies shown are relative to channel block edge or exclusion band edge (see text).
². Frequencies shown are absolute
³. Excluded from test region: a) signal under test; b) first/second/third adjacent channels; c) 2nd and 3rd harmonics of signal under test.
**Test configurations:** Noise and spurious measurements are performed with the CMTS transmitting in a variety of channel configurations, as shown here. Other configuration variables include 4K vs. 8K FFT, window rolloff length ($N_{rp}$, which determines guard band width), and transmit power level.

Within each channel block, channels are spaced such that their guard band edges touch (the SC-QAM block is treated as having zero-width guard bands). Adjacent band power measurements are performed on the block as a whole, extending from the outermost guard band edges. Exact channel frequencies are provided in the DOCSIS 3.1 PHY ATP document, and have been computed to align one edge of the block with the 6 MHz CEA channel grid.

A variety of terms are used to describe the OFDM channel, both here and in the DOCSIS 3.1 governing documents. These include:

- **Encompassed spectrum:** total bandwidth between the first and last active subcarriers of a channel, equal to the number of subcarriers x subcarrier spacing.
- **Channel block:** spectrum region containing one or more channels; channel block width is the sum of encompassed spectra plus all associated guard bands.
- **Modulated spectrum:** encompassed spectrum less the bandwidth of any internal exclusion bands.
- **Occupied spectrum:** total bandwidth of all 6 MHz CEA channels containing one or more OFDM subcarriers (thus always a multiple of 6 MHz). While a full-BW 4K signal will always encompass 190 MHz of spectrum (3800 subcarriers x 50 kHz), its occupied bandwidth may be 192 MHz or 198 MHz, depending on its guard band widths and/or how it is positioned relative to the CEA channel grid.
Adjacent band noise and spurious:

These measurements are relatively straightforward, using the VSA to sum the power in the prescribed 750 kHz or 6 MHz adjacent bands. However, care must be taken to locate these measurement bands appropriately for the signal configuration under test. As mentioned above, measurements begin at the outer edges of the overall channel block, and are thus separated from the encompassed or active spectrum by the guard band width. This width is dependent on the window rolloff factor \( N_{rp} \) and the FFT size, as shown in the following table (ref: PHY v3.1, Appendix V):

<table>
<thead>
<tr>
<th>Roll-Off Period, ( N_{rp} ) samples</th>
<th>Guard Band Width, MHz (4K FFT)</th>
<th>Guard Band Width, MHz (8K FFT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>64</td>
<td>3.575</td>
<td>3.3375</td>
</tr>
<tr>
<td>128</td>
<td>1.875</td>
<td>1.7125</td>
</tr>
<tr>
<td>192</td>
<td>1.325</td>
<td>1.1625</td>
</tr>
<tr>
<td>256</td>
<td>0.975</td>
<td>0.9875</td>
</tr>
</tbody>
</table>

Example: in this display, a full-BW 4K OFDM signal is centered at 1102 MHz. Window roll-off is 128 samples. In the top trace, the band power markers measure the power in the 6 MHz PLC band (–23.217 dBm) to serve as the reference power for the ACP measurement, which is in dBc.

The lower trace shows the same spectrum, but with the frequency axis zoomed to show the adjacent channel region. The band power markers are set for the 0 - 750 kHz portion of the first adjacent channel. The two marker frequencies are computed as:

Right marker: lower edge of channel block:
\[ = 1102 \text{ MHz} - \left(\frac{\text{encompassed spectrum}}{2}\right) - \text{guard band} \]
\[ = 1102 - 190/2 - 1.875 \text{ MHz} \]
\[ = 1005.125 \text{ MHz} \]

Left marker: lower edge of channel block – 750 kHz:
\[ = 1005.125 - 0.750 \]
\[ = 1004.375 \text{ MHz} \]

The ACP in this band is therefore:
\[ = (–85.193 \text{ dBm}) - (–23.217 \text{ dBm}) = –61.976 \text{ dBc} \]
Notice that dBc result is the difference between the PLC reference power, measured in a 6 MHz bandwidth, and the adjacent channel power, measured in a 750 kHz bandwidth. It is not necessary to adjust either result for the difference in measurement bandwidth, because the test limits in the PHY spec (Table 7-38) already include this adjustment.

The test is then repeated 3 more times, with the band power markers set for −0.75 to −6 MHz, −6 to −12 MHz and −12 to −18 MHz, all relative to the lower channel block edge. A duplicate set of band power measurements is then performed beginning at the upper channel block edge, i.e. 1102 + 190/2 + 1.875 = 1198.875 MHz. In all cases, the test limits vary as a function of offset from the signal.

These measurements can be performed using the analyzer’s band power, channel power or adjacent channel power (ACP) functions. When using band power, insure that the analyzer’s resolution bandwidth (RBW) is set to no greater than 10% of the measurement band width, e.g. an RBW of 600 kHz or less for a 6 MHz measurement band.

The ATP includes several test cases to verify adjacent band power in exclusion bands (gaps) configured within the signal under test. These gaps consist of an 18 MHz exclusion band surrounded by guard bands appropriate for the OFDM signal configuration. The total gap width thus ranges from approximately 20 to 25 MHz, with ACP measurements performed only over the inner 18 MHz.

ACP measurements in the internal gap use the same series of bands and frequency offsets as are used externally to the channel block, i.e. 0-750 kHz, 750 kHz-6 MHz, 6-12 MHz, etc. However, as shown below, these bands extend from both edges of the gap, and thus overlap at every point. For this reason, the test limit for each band within the gap is the sum of test limits for two measurement bands – i.e. one extending from each edge of the gap.

![Diagram showing ACP test limits within the 18 MHz internal exclusion band](image)

**Band B test limit** = limit for 0.75-6 MHz offset + limit for 12-18 MHz offset * (5.25/6.00)
Wideband noise and spurious:

These are an extension of the adjacent channel measurements made earlier, again checking total power in a 6 MHz bandwidth stepped contiguously across the measurement range. The test frequencies extend from the point where the adjacent channel measurements end, i.e. from the channel block edges ± 18 MHz, and continue to the specified frequency limits (47 MHz on the lower end, 3.0 GHz on the upper).

Wideband measurements are generally easier and quicker when performed as swept spectrum measurements. Simply set the analyzer’s sweep to match the required start and stop frequencies, and manually select a 6 MHz RBW. Each point on the resulting trace now represents a 6 MHz band power measurement, and each must be below the spec limits. Note that the analyzer’s RBW setting may refer to its 3 dB, 6 dB or equivalent noise bandwidth. For standards compliance, select the latter.

Inband noise and spurious:

For this measurement, the downstream signal is configured with a 6 MHz wide internal exclusion band. The band’s location should be near the center of the signal under test, and must satisfy the other rules listed in PHY 7.2.5.2. The signal analyzer is then zoomed in to this band, and a band power measurement performed over the center 400 kHz. Test limits for this value are given in the PHY spec, and are given in dBr, i.e. relative to the average power of the 6 MHz PLC region.

In this example, the ACP reference is configured for 6 MHz bandwidth and positioned over the PLC region. The Channel 1 ACP markers are set to 400 kHz bandwidth, and are offset such that the lower marker lies in the middle of the exclusion band. The upper marker is off-screen, and not used.

Figure 40. Inband noise and spurious measurement showing correct placement of the ACP markers
The ACP readout at the bottom shows the relative power to be 64.566 dB. However, because the measurement bandwidths are not equal, a scaling factor of $10\log(6.0/0.4)$ must be applied. Thus, the actual ACP result here is $-64.566 \text{ dB} - (-11.76 \text{ dB}) = -52.81 \text{ dB}$. 

The gradual rolloff of the OFDM spectrum into the exclusion band is due to modulation sidebands. These are naturally-occurring artifacts present in all OFDM signals, and their width is inversely proportional to the signal's windowing factor or rolloff period ($N_{rp}$). For DOCSIS 3.1, inband spurious measurements are specified for $N_{rp}$ values of 256, 192, 128 (shown above) and 64 samples. However, an $N_{rp}$ value of 64 samples will result in sidebands more than 3 MHz wide, which means they will occupy the entire 6 MHz exclusion band. This will limit inband noise measurements to about $-45 \text{ dB}$, whereas spec limits may be as low as $-50 \text{ dB}$. In practice, this measurement configuration will usually be omitted.

3. Modulation error (MER)

The high-density modulation formats used in DOCSIS 3.1 require extraordinarily high signal to noise ratios. To verify transmitted signal quality, CMTS units are tested for modulation error ratio (MER) over a wide variety of output conditions. MER is essentially an in-channel SNR measurement, performed on the active signal under well-defined conditions.

**Performance considerations:** MER specifications for downstream signals approach 50 dB in some configurations. This requires measuring noise and distortion products at least 50 dB below individual subcarrier levels, which themselves may be up to 39 dB below the total transmit power. Thus, a 50 dB MER measurement can require > 89 dB of dynamic range from the signal analyzer hardware. This performance is achievable with high-end analyzers such as the Keysight PXA and UXA, but requires careful attention to setup, considering the following:

**Input signal level:** for a typical signal analyzer with an input noise density of $-150 \text{ dBm/Hz}$, the total noise power in a 190 MHz channel will be $-150 + 10 \log(190e6)$ = $-67 \text{ dBm}$. To achieve MER measurements of 50 dB or more, the analyzer will thus require an input signal level of at least $(-67 + 50) = -17 \text{ dBm}$. To check whether a given setup is noise-limited, reduce the input level by 1 dB; if the MER decreases by the same amount, this indicates that the measurement is at or near the analyzer's noise floor.

**Analyzer range:** best dynamic range is always achieved with the signal as near full-scale as possible. The 89600 VSA simplifies this with a single range setting that controls both RF and IF gain. In general, simply reduce the range until the OVL (overload) annunciator appears on the VSA display. If results improve with further range reduction, it is legitimate to use that setting, regardless of the OVL indication. However, it is very important to re-check input ranging whenever changes are made to the input signal or analyzer span width. For example, activating additional OFDM or SC-QAM channels may increase total power to the analyzer input, and thus require down-ranging. Conversely, if the total CMTS output power remains constant, it will be divided among more channels, reducing the OFDM channel power and thus require up-ranging.
RF Filtering: in fully-loaded test configurations – those including additional OFDM and SC-QAM channels – the analyzer might require so much down-ranging as to limit the MER measurement range. In these cases, external bandpass filters are recommended (and permitted by the spec) as a way to reduce the out-of-band power to the analyzer, and thus allow use of a lower, more optimal range setting.

Multicarrier filtering: even with adequate input power and optimal ranging, very close-in adjacent carriers can still leak through into the OFDM demodulator, degrading the MER measurement. In these cases, simply activate the VSA's Multicarrier filter, found under Demod Properties, Advanced. This provides additional bandpass filtering at the demodulator input, greatly attenuating the adjacent signals with only a slight impact on measurement speed.

Note: multi-carrier filtering is provided with the 89600 VSA option BHM DOCSIS 3.1 demodulator only, and not with option BHF Custom OFDM demodulator. See below for a comparison of these two options.

Phase noise optimization: because phase noise has a significant impact of MER, it is important to minimize the amount contributed by the analyzer hardware. For DOCSIS 3.1 measurements performed using Keysight PXA or UXA signal analyzers, go to the VSA's Input menu and select "Extensions". Then select “Best Wide Offset” under Phase Noise Optimization.
Choosing a VSA Demodulator: MER measurements begin with demodulation of the OFDM signal. The 89600 VSA supports demodulation of both coded and uncoded DOCSIS 3.1 signals, depending on the options chosen. As explained below, working with coded signals provides the greatest flexibility and ease-of-use, and is recommended for most users. However, some users – particularly those with legacy or first-generation test setups – may still prefer the uncoded approach.

Demodulating coded signals: Coded signals are those which contain the low-level message fields used by a DOCSIS 3.1 CM to automatically configure itself for the incoming downstream signal. These fields are contained in structures such as the PLC, OCD, and DPD. For testing purposes, coded signals are typically obtained from an actual DOCSIS 3.1 CMTS, or from an advanced waveform generation tool such as Keysight N7623B Signal Studio for Digital Video. Analysis is provided by 89600 VSA option BHM, DOCSIS 3.1 Modulation Analysis.

Demodulator setup is simplified by auto-detection routines. Basic OFDM parameters such as FFT size, CP length and PLC location are detected automatically from the input waveform. The PLC is then decoded, providing access to the OFDM Channel Descriptor (OCD) and Downstream Profile Descriptor (DPD) messages. With this information, the VSA can then finalize all demod settings and ultimately process the actual payload codewords, enabling BER measurements.

The resulting 89600 VSA display, shown below, provides basic and advanced MER readings, plus a large selection of numeric and graphical results to help the user examine and understand even the subtlest aspects of the signal. Additional tables show the detected OFDM parameters, decoded data fields, BER summary, etc.
Additional MER notes:

- Successful self-configuration depends on the VSA being able to locate and decode the OCD and DPD messages contained in the PLC. However, these messages may be present in only a small percentage of downstream frames. To locate them more quickly, temporarily increase Result Length (found under Demod Properties, Time) from 128 symbols (1 frame) to 1280 symbols (10 frames), until these fields are detected and demodulation is successful. The supplied VSA macro *DocsisFastDetection* performs this automatically, manipulating these and other analyzer settings to quickly acquire, detect and decode the needed PLC data. (See the 89600 VSA Help function for instructions on loading and running macros).

- Once decoded, the OCD and DPD data will be retained and used to configure subsequent measurements. The analyzer’s “PLC Decoding Info” display, however, will always indicate whether an OCD and/or DPD was found in the current measurement update.

- To maximize MER measurement speed: a) use the minimum span width that is compatible with the input signal; e.g. a 200 MHz span for a 190 MHz channel; b) once demod settings are finalized, click “Copy Auto to Manual” and de-select Automatic configuration under Initial Settings and PLC Settings; and c) only activate BER Analysis as needed.

- Other choices available under Demod Properties include the option of training the equalizer using preamble and pilots only, or preamble, pilots and data. The latter choice will provide a slightly better MER reading in most cases, and is permitted by the PHY standard.
Demodulating uncoded signals: These are the simplified signals created by first-generation DOCSIS 3.1 waveform generation tools, such as Keysight M9099 Waveform Creator and SystemVue. They are physically accurate signals, with the correct OFDM parameters, pilot placements, PLC structure, etc., but their data subcarriers are populated with random data only, typically using a single modulation format. Uncoded signals are convenient for stimulus/response testing of two-port devices such as amplifiers, RF converters, lasers, etc.

Uncoded signals are analyzed using 89600 VSA software option BHF, Custom OFDM Modulation Analysis. As shown here, this flexible demodulator can be manually configured for virtually any OFDM signal format, by means of user-entered data fields that precisely define all aspects of the physical signal.

Keysight provides a free DOCSIS 3.1 Configuration Wizard to configure option BHF data for uncoded DOCSIS 3.1 signals. Users select their desired downstream or upstream signal parameters, and the utility outputs a setup file ready for importing into the 89600 VSA.

VSA displays for uncoded signals are similar to those provided with option BHM, except that DOCSIS 3.1-specific tables and readouts are not provided.

Other uses for MER measurements:

- Calibrated SNR: because MER is fundamentally a signal-to-noise measurement, it offers a simple and accurate way to verify the calibrated SNR levels required for receiver BER / PER testing. Expressed as a decibel value, it relates the measured (noise + distortion + spurious) power to the measured signal power. Thus, rather than computing SNR from separate measurements of input signal power, noise source power, RF combiner loss, etc., the MER value can be used as-is to show the same quantity.

- Pilot verification: DOCSIS 3.1 signals contain hundreds of BPSK pilot subcarriers, each of which is modulated according to a specific binary sequence. Validating these patterns could be a tedious, data-intensive process, except for the fact that the sequence is already built into the VSA’s DOCSIS personality, and used to compute pilot MER. Thus, if a particular pilot is supposed to be transmitting +1 at a given symbol time, but is transmitting -1 instead, it will appear as a distinct error spike for that subcarrier during that symbol. To detect pilot errors most easily: a) view error as EVM instead of MER (Demod Properties, Advanced), because positive peaks stand out better visually; and b) view the error symbol-by-symbol, using the Measurement Interval and Measurement Offset settings under Demod Properties.
Test Instruments for DOCSIS 3.1

Keysight Technologies offers a variety of solutions for DOCSIS 3.1 signal generation and analysis. For more information about coded vs. uncoded DOCSIS signals, see the MER section under Downstream Signal Measurements.

1. Signal analysis

**Software:** DOCSIS 3.1 signal analysis is performed by Keysight’s 89600 Vector Signal Analysis software in conjunction with a wide range of hardware front ends. The front ends tune and digitize the signal under test, with the resulting I-Q samples streamed to the software for analysis, or for capture in a variety of PC-compatible formats.

The 89600 VSA software measures both DOCSIS 3.1 upstream and downstream signals, in either coded (opt. BHM) or uncoded (opt. BHF) formats. A wide variety of measurement types and user-selectable display formats provide deep insights into signal performance, and have established the 89600 VSA as the industry standard for SW-defined vector signal analysis.

![Figure 46. Keysight 89600 VSA software analyzes DOCSIS 3.1 plus hundreds of other signal formats.](image-url)
The VSA software runs as a separate PC application, either within the instrument or on an external computer. This brings key advantages, including:

- The ability to switch quickly and easily among various hardware front ends, depending on test requirements (e.g. for reasons of frequency coverage, measurement bandwidth, RF performance, etc.)
- A single user interface scheme that remains consistent across all supported front-end hardware.
- The ability to move measurement results, displays and even captured signals back and forth between the test bench and PC-based engineering tools.

**Hardware:** The following Keysight products are recommended for DOCSIS 3.1 signal analysis.

Keysight’s X-series signal analyzers include two high-performance models suitable for DOCSIS 3.1 analysis.

The UXA offers superior phase noise, DANL and dynamic range, at measurement bandwidths up to 1 GHz. Typical MER performance for DOCSIS 3.1 signals is 50-58 dB. The PXA provides excellent RF performance at measurement bandwidths of up to 510 MHz. With option EP0 (Enhanced Phase Noise LO), typical MER performance is also in the 50-58 dB range.

Both analyzers are available with a wide range of options, including real-time signal analysis, frequency mask triggering, low-noise preamplifiers and frequency range extensions to 50 GHz.

With an RF bandwidth of 1.4 GHz, the Keysight U5303A two-channel 1.6 GSa/s digitizer offers the resolution and dynamic range required for the most demanding DOCSIS 3.1 MER measurements. With both channels interleaved, the resulting 3.2 GSa/s rate extends the MER range by an additional 3 dB.

Direct digitizing of the input signal eliminates the spectrum artifacts sometimes associated with down conversion, such as L.O. feedthrough. Its compact form factor and economical price makes it well-suited for manufacturing test.

The U5303A digitizer is also available in a PXI form factor as Keysight model M9202A.
2. Signal generation

**Software:** Keysight offers waveform generation solutions for both coded and uncoded DOCSIS 3.1 waveforms.

N7623B Signal Studio for Digital Video: Option Lxx generates fully-coded DOCSIS 3.1 downstream waveforms which contain all the low-level MAC messages required for auto-configuring receivers. Use it for stimulus/response testing in conjunction with the 89600 VSA Software, DOCSIS 3.1 option BHM.

M9099 Waveform Creator Software: Option DCS generates uncoded arbitrary waveforms for both upstream and downstream DOCSIS 3.1. These may be downloaded as-is to supported signal generators, or they may be combined with other waveforms to create realistic spectrum environments including other OFDM or SC-QAM carriers, cellular and other interfering signals, calibrated noise levels or even real-world signals captured using the 89600 VSA software.

**Hardware:** waveforms created by the above software can be downloaded and output on the following signal generators:

With 14-bit resolution up to 8 GSa/s and 12-bits to 12 GSa/s, the M8190A generator outputs extremely pure up- and downstream signals with industry-leading MER. Its wide RF bandwidth allows it to create complex spectrum scenarios covering the entire DOCSIS frequency range and beyond. RF performance is excellent, with up to 90 dBC spurious free dynamic range.

The MXG series offers 3 GHz or 6 GHz models, with modulation bandwidths of up to 160 MHz. Other options provide enhanced dynamic range and/or phase noise performance, for better MER.

For additional information on these and other DOCSIS-compatible products, and for assistance in configuring one to meet your specific requirements, please consult your local Keysight sales representative or go to [www.keysight.com](http://www.keysight.com).

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