Characterizing Network Problems Using DOCSIS® 3.1 OFDM RxMER Per Subcarrier Data

A Technical Paper prepared for SCTE•ISBE by

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Introduction

Receive modulation error ratio (RxMER) has long been a powerful metric for cable network maintenance and troubleshooting. A limitation to single carrier quadrature amplitude modulation (SC-QAM) RxMER is that the reported value doesn't give an indication of why that value is what it is, or what kind of impairment might exist.

The DOCSIS® 3.1 specifications [1] define several operational measurements that can be reported by the cable modem and cable modem termination system (CMTS) or converged cable access platform (CCAP). One important modem performance parameter is orthogonal frequency division multiplexing (OFDM) RxMER per subcarrier, which can be plotted to show a graph of all subcarriers' RxMER performance. Based on real-world observations of data from production cable networks and subsequent lab testing to recreate and validate the observations, a number of specific impairments can be identified that point to faults in the underlying network. Not only does the identification of these problems assist with maintenance and troubleshooting of the network, but various impairments identifiable in the RxMER per subcarrier plots can impact subscriber service and result in lower throughput and performance than expected. Plus, due to the sensitivity of the RxMER per subcarrier measurement, it can find impairments in the network before they adversely impact customer service, and before repairs become costly.

This paper includes discussions about a number of impairments that have been observed, describes the findings when recreated in a laboratory environment, and explains how the observed results point to potential cable network faults. Examples include:

- Amplitude ripple in the channel in the frequency domain can under certain conditions cause amplitude ripple in RxMER per subcarrier graphs.
- Interference caused by long term evolution (LTE) and other ingress can be correlated to specific frequencies by observing the impact on the RxMER per subcarrier graphs.
- SC-QAM signals adjacent to OFDM signals can cause a rolloff at the edges of the RxMER per subcarrier graph.

Production network examples are presented that show how analysis of RxMER data collected from cable modems can be used to identify and locate specific cable network impairments, resulting in an improved subscriber service performance and experience.

Content

1. What is MER?

For a single QAM carrier or a single OFDM subcarrier, modulation error ratio (MER) is the ratio of average signal constellation power to average constellation error power – that is, digital complex baseband signal-to-noise ratio (SNR).[1] Indeed, MER is often called SNR. From a high-level perspective, the following formula defines MER (refer to Figure 1):

$\text{MER} = 10\log_{10}(\text{average symbol power}/\text{average error power})$

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[1] For more information about MER, see [2], [3], and [6] through [10] in the bibliography.

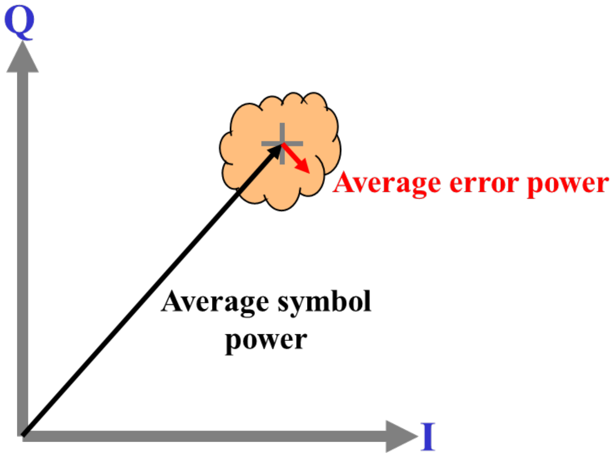


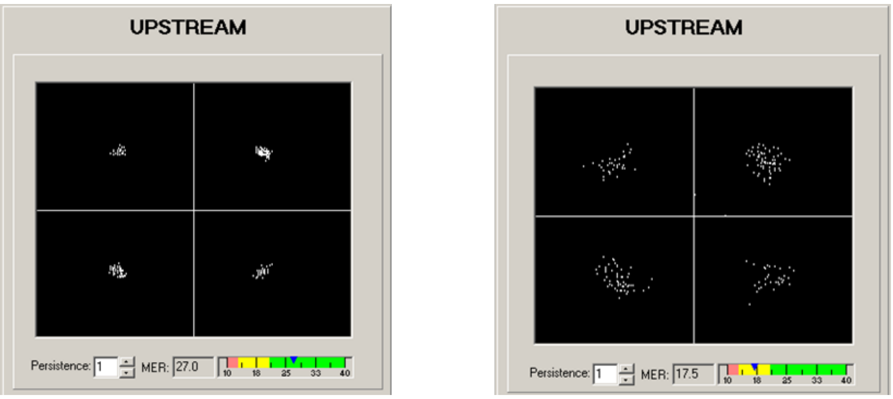
Figure 1. MER is the ratio of average symbol power to average error power.

A more precise mathematical definition of MER is

$$MER = 10\log_{10}\left[\frac{\sum_{j=1}^{N}\left(I_j^2 + Q_j^2\right)}{\sum_{j=1}^{N}\left(\delta I_j^2 + \delta Q_j^2\right)}\right]$$

where *I* and *Q* are the real (in-phase) and imaginary (quadrature) parts of each sampled ideal target symbol vector, and δI and δQ are the real (in-phase) and imaginary (quadrature) parts of each modulation error vector. This definition assumes that a long enough sample is taken so that all the constellation symbols are equally likely to occur. Note: The numerator in the above equation can be replaced with a constant if the constellation power is known, as is the case in DOCSIS 3.1 OFDM RxMER where all constellations have average power = 1.

In effect, MER is a measure of how "fuzzy" or spread out the symbol points in a constellation are. For example, Figure 2 shows two quadrature phase shift keying (QPSK) data constellations, one with high MER (left), the other with low MER (right).



Persistence: 1 MER: 27.0

Persistence: 1 MER: 17.5

Figure 2. The symbol points in the left constellation are tightly grouped, indicating higher MER (27 dB). The symbol points in the right constellation are diffuse (spread out), indicating lower MER (17.5 dB).

RxMER is the MER as measured in a digital receiver after demodulation of a given QAM carrier or OFDM subcarrier, after adaptive equalization.

RxMER is affected by the carrier-to-noise ratio (CNR); phase noise in the transmitter or receiver; linear distortions such as micro-reflections, amplitude ripple, and group delay; non-linear distortions such as composite triple beat, composite second order, and common path distortion; in-channel ingress; laser clipping; and just about anything else that degrades the channel through which the signal is transmitted. Its usefulness lies in the fact that it is a bottom-line measurement at the receiver slicer, just before forward error correction (FEC) decoding. An RxMER computation based on blind slicer decisions would produce inaccurate results at low SNR due to slicer symbol errors. This would be particularly important with the strong low density parity check (LDPC) coding used in DOCSIS 3.1 OFDM, which allows the link to operate at low SNR values where slicer errors are a normal occurrence, and are corrected by the FEC decoder. As we will see, the DOCSIS 3.1 OFDM RxMER per subcarrier metric uses the pilot subcarriers, which have known modulation values, so no slicer errors occur and the measurement is accurate over a wide dynamic range.

1.1. SC-QAM RxMER

When a QAM receiver in a set-top box, cable modem, CMTS upstream burst receiver, or a test instrument computes RxMER for an SC-QAM signal, the value reported is for just that signal – for instance, a 6 MHz-wide downstream DOCSIS signal. Figure 3 shows an example in which the reported RxMER for an SC-QAM signal on CTA[2] channel 19 is 38.3 dB. A detailed explanation of how a QAM receiver computes RxMER can be found in [2].

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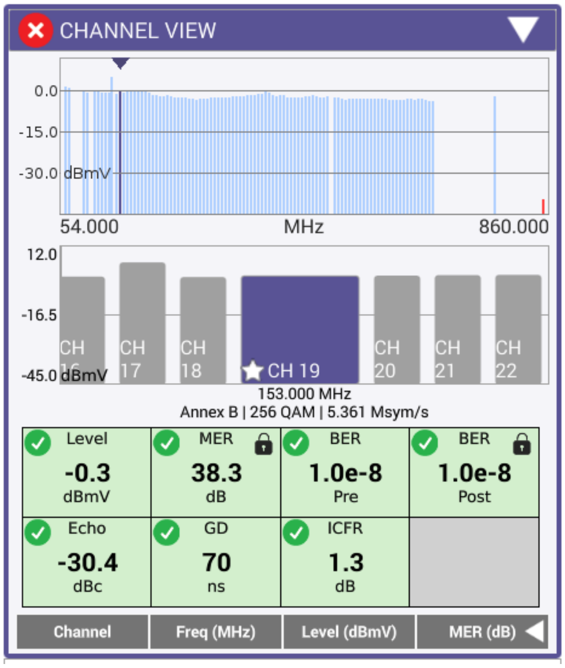
[2] The Consumer Technology Association's CTA-542-D R-2018 standard [4] defines channel plans and frequencies used for 6 MHz-wide channels in cable networks.



153.000 MHz
Annex B | 256 QAM | 5.361 Msym/s

Level -0.3 dBmV	MER 38.3 dB	BER 1.0e-8 Pre	BER 1.0e-8 Post
Echo -30.4 dBc	GD 70 ns	ICFR 1.3 dB	

Figure 3. Example test equipment screen shot showing 38.3 dB RxMER for an SC-QAM signal on CTA channel 19.

While SC-QAM RxMER is a useful tool for characterizing the health of the signal and/or the network, the reported value doesn’t give an indication of why the value is what it is. If the reported RxMER is low, one cannot determine from just the RxMER value what kind of impairment(s) might exist.

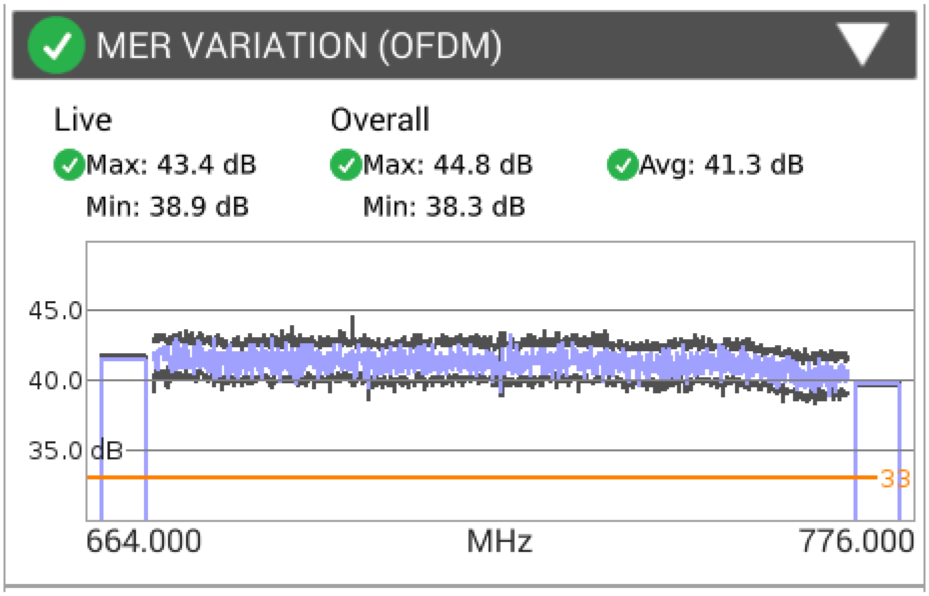
1.2. OFDM RxMER Per Subcarrier

RxMER is even more useful with DOCSIS 3.1 OFDM signals, because an OFDM signal comprises up to several thousand subcarriers, each of which is a narrow-bandwidth QAM signal with its own RxMER measurement value. However, trying to manage a list of RxMER values for thousands of subcarriers would be unwieldy and impractical. Consider the tabular list in Table 1, from an operational DOCSIS 3.1 cable modem. The far left column is the subcarrier number in hexadecimal notation (hex). The 8-bit hex values to the right are RxMER values in ¼ dB increments, (two digits represent RxMER for a subcarrier). The zeros at the start and end are nulled for the excluded subcarriers including the taper regions. In practice a list of RxMER values per subcarrier like this would have to be converted from hex to decimal (in dB) to be useful (e.g., subcarrier #1 RxMER = 41.25 dB, subcarrier #2 RxMER = 41.5 dB, subcarrier #3 RxMER = 41.75 dB…subcarrier #7600 RxMER = 41.25 dB, etc.).

Table 1 - Example tabular list of OFDM per-subcarrier RxMER values reported by a DOCSIS 3.1 cable modem. The original list has been shortened.

```
Number of SubCarriers : 8192
1st Active SubCarrier    : 296
# of Active SubCarriers : 7600
Tx Time                  : 0h:04m:56s ago
Rx Time                  : 0h:04m:55s ago
OFDM Profile Failure Rx                  : 172h:26m:55s ago
MER Poll Period   (min)                  : 5
Recommend Timeout (min)                  : 120
Unfit Timeout    (min)   : 5
Source                   : OPT
Sub-   RxMER
Carrier
0x0000  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x0020  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x0040  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x0060  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x0080  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x00A0  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x00C0  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x00E0  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x0100  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x0120  00000000 00000000 A5A6A7A6 A7A6A8A6 A4A8A7A6 AAA4A6A3 A6A5A6A8 A8A8A4A7
0x0140  A7ABA6A7 A4A1A6A3 A8A6A6A7 A6A3A5A7 A7A4A6A3 A5A3A7A3 A3A6A3A7 A4A5A8A2
0x0160  A49FA3A6 A7A5A3A7 A8A8A4A4 A4A5A5A7 A7A6A5A7 A79FA7A1 A3A6A5A9 A6A9A5A4
0x0180  A7ABA5A7 A3A6A8A2 A5A7A9A8 A1A8A5A4 A6A5A2AC A7A6A2A5 A7A6A3A5 A4A5A5A6
0x01A0  A8A4A3A6 A3A6A5A7 A5A6A7A4 A8A8A8A6 A8A2A7A4 A8A4A3A5 A6A8A5A8 A4A3A3A2
0x01C0  A6A3A3A5 A7A2A3A3 A6AAA3A4 A7A9A5A5 A6A3A3A7 A5A4A1A8 A3A7A1A8 A7A4A6A6
0x01E0  A0A1A5A5 9FA7A7A5 A7A5A6A3 A5A6A3A8 A4A5A4A4 A7A2A0A3 A1A7A6A5 A7A6A4A7
0x0200  A5A8A5A2 A5A4A7A6 A6A7A5A7 A5A59FAA A6A6A5A3 A7A4A1A5 A5A6A2A6 A2A3A5A4
0x0220  A2A7A3A2 A8A5ABA3 A7A8A4AA A4A4A6A4 A8A3A1A5 A3A6A4A6 9FA7A5A6 AAA4A7A2
0x0240  A5A3A3A6 A5A4A9A2 A7A5A6A6 A8A7A2A5 A2A7A6A6 AAA7A7A6 A5A9A4A2 A7A8A4A5
0x0260  A6AAA5A5 A4A6A9A5 AAA3A7A4 A6A1A8A3 A4A4A8A7 A7A5A4A3 A6A7A8A9 A5A6A4A6
0x0280  A3A4A4A1 A7A4A7A6 A9A5A6A6 A3A2A4A6 A2A7A7A4 ABA5A3AB A2A7A3A4 A5A4A7A4
0x02A0  A3A1A3A5 A3A7A7A0 A7A6A5A5 A7A2A5A8 A7A4A5A5 A9A9A5A4 A4A7A2A6 A4A2A6A2
0x02C0  A4AAA6A4 A0A4AAA6 A3A6A6A7 A3AAA4A5 A6A3A8A6 A6A3A4AB A9A2AAA6 A6A5A5A4
0x02E0  A9A5A6A3 A9A4A8AA A6A4A7A5 A8A5A0A6 A4A5A6AA A1A2A5A6 A9A5A3A8 A8A4A3A5

<data deleted>

0x1D00  A4A5A5AB A8AAA5AB A4A5A3A8 A6A9A6A6 A7A9ABA6 A7A8A4A5 ABA6A8A9 A7A6A6A4
0x1D20  AAA5A7A9 A5A9A6A7 A8A7A8A2 A5AAA9A7 A8AAAAA8 A6A5A5AA A4AAA6A6 A6A6A8A7
0x1D40  A8A7A8A7 A5A9A5A4 A5A69BA9 AAA9A7A4 ACA9A8A7 A6A5A7A9 A4A9A9AB A5A7A7A5
0x1D60  ABA7A4A5 A6A4AEA4 A8A9A3A6 A3A4A9AA A6A8A9A8 AAA6A8A9 A9A5A4A7 A8A6A7A8
0x1D80  AAACA9A6 A6A6A6A6 A3A4A6A7 A5A9A5A8 AAA4AAA9 A5A6A6A7 A8A7AAA7 A9A7A8A8
0x1DA0  A5A3A8A6 A7A7A7A7 AAA6A6A9 A5AAA5A5 A8A7A7A6 A9A7A3AA ACA7A8AA A7A5A9A7
0x1DC0  A9A5ABA5 A7A6A8A6 A6A9ABA8 A7A6A6A7 AAA5A6AB A5A5A8A6 A9A5ACAA A6A6A6A3
0x1DE0  A6A2A39F A7A7A9A8 A6A5A8A8 A6A5A7A7 A9A5A9A9 A7A6A7A8 A3A8A5A4 A4A9A7AA
0x1E00  A7ABA5AA A7AAA8A7 A7A7A7A9 A5A8A7A7 A5A6A7A6 A6A7A8AA A7A5A8A7 A6A3A8AA
0x1E20  A7A7A7A8 A4A8A6A9 A2A9A5A8 A6A4A6A7 A9A6A9A9 A6A7A5AC A8A4A7A6 A7A9A5AA
0x1E40  A9A5A7AA A7A9A3A8 A7A6A6A9 A8A7A4A8 A8A6A7AB AAA5A8A6 AAAAA6A6 A9A8A5A4
0x1E60  A9A9A8AA AAA4A5A3 A7A7A9A6 A7A4A5A3 A6A6A6A5 A8A6ABA8 AAA5A7A8 9DA7A7A7
0x1E80  A9A8A6A8 A5AAA8A6 A6A7A8A6 A9A5AAA6 A6A8A4A8 A9A4A5AD A7A6A8A8 A8A9A7A8
0x1EA0  ACA9A7A7 A7A9A8A8 A7A5A8AA A5A3ADA8 A9A6A5A6 AAA6A6A7 A6A5A8AB ACA8A7A9
0x1EC0  A9AAA8A9 A6A7A7AA A5A7A8A7 A7AAA6A9 A7AAA9A7 A4ACA8A5 00000000 00000000
0x1EE0  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x1F00  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x1F20  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x1F40  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x1F60  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x1F80  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x1FA0  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x1FC0  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
0x1FE0  00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000


SC RxMER Distribution (Excluded SCs counted as 0):
Each *: 2%
>44dB:   0.03%
  44dB: **  4.63%
  43dB: *********************** 45.32%
  42dB: *********************** 44.50%
  41dB: **  4.81%
  40dB:   0.59%
  39dB:   0.09%
  38dB:
  37dB:
  36dB:
  35dB:
  34dB:
  33dB:
 <33dB:

        --------------------------------------------------100
              Percent of Subcarriers
```

Instead of dealing with a cumbersome list of RxMER per subcarrier values, it is much more convenient to plot the per-subcarrier RxMER on a graph, showing frequency or subcarrier numbers in the horizonal axis, and RxMER in decibels in the vertical axis. Figure 4 illustrates an example. As will be shown later, plotting OFDM RxMER per subcarrier data on a graph can be used to identify and characterize a number of impairments.



✓ MER VARIATION (OFDM)

Live
✓Max: 43.4 dB
Min: 38.9 dB

Overall
✓Max: 44.8 dB
Min: 38.3 dB

✓Avg: 41.3 dB

Figure 4. RxMER per subcarrier plot for a 96 MHz-wide OFDM signal.

1.2.1. Description of RxMER per Subcarrier Measurement

One of the reasons the OFDM RxMER measurement is useful under a wide range of conditions is the way it is computed. As mentioned earlier, the measurement does not rely on the OFDM signal's data subcarriers, which with their strong LDPC decoding and potentially high constellation densities, are subject to slicer symbol errors and thus cannot provide a reliable measurement of RxMER when a given subcarrier has low SNR. Rather, the cable modem measures the RxMER using pilots and PHY link channel (PLC) preamble symbols, which have known values regardless of SNR.

In the DOCSIS 3.1 OFDM downstream, the scattered pilots scan across all active subcarriers, repeating the scan every 128 OFDM symbols. When the scattered pilots land on a continuous pilot or PLC preamble symbol, they adopt the value of the continuous pilot or PLC preamble symbol. We can use the name "scan pilots" to cover all three cases: scattered pilot, continuous pilot or PLC preamble symbol. The scattered pilots and continous pilots are BPSK-modulated with real part = +/-2 and imaginary part = 0. Thus, they have power = 4, or $10\log_{10}(4) = 6.02$ dB higher than the data subcarrier constellations, which have average power = 1, or $10\log_{10}(1) = 0$ dB. The PLC preamble symbols are BPSK with real value +/-1 (and imaginary part = 0). Thus, they have power = 1, which is the same as the QAM data subcarrier constellations; that is, the PLC preamble is not boosted.

When a scattered pilot – which has a known BPSK value – lands on a data subcarrier location, an accurate measurement of the RxMER of that subcarrier over a wide range of SNR can be performed. For example, if narrowband ingress causes a given subcarrier to have a very low SNR, the RxMER measurement will still be accurate at that subcarrier because the ingress cannot cause the symbol value to be interpreted in error (recall that the value is known ahead of time), and the error vector, though large due to the strong ingress, will correctly indicate the difference between the received and true symbol.

Thus the RxMER of all active subcarriers across the entire OFDM signal is periodically measured over time. If some subcarriers cannot be measured by the cable modem – for instance, in exclusion bands – the modem indicates that condition by reporting empty values in the measurement data for those subcarriers.

RxMER was carefully defined for the purposes of this measurement as the ratio of the average power of the ideal QAM constellation (numerator of the ratio, always equal to 1) to the average error vector power (denominator of the ratio). The error vector is the difference between the equalized received value and the known correct “scan pilot” value. For additive noise, the noise vector amplitude is not affected by the symbol amplitude, that is, whether or not the symbol is boosted. With this definition, since the numerator is the power of the QAM constellation rather than the “scan pilot” power, the RxMER measurement yields the true QAM RxMER even when the pilots are boosted by 6 dB relative to the data subcarriers. That is, for the case of additive noise, the pilot boost (in the case of scattered or continuous pilots) or lack of boost (in the case of PLC preamble symbols) is taken into account by design and no further compensation of the measurement is necessary to remove the effect of the pilot boosting. For some types of noise, such as phase noise, there may be some dependence of the error vector amplitude as a function of symbol amplitude, and a correction to RxMER may be necessary to reflect the actual noise on the data subcarriers as opposed to the boosted pilots.

The following example will help make this definition clear: For an ideal additive white Gaussian noise (AWGN) channel, an OFDM signal containing a mix of QAM constellations with CNR = 35 dB on the QAM data subcarriers, will yield an RxMER measurement of nominally 35 dB averaged over all subcarrier locations. That is, RxMER is defined to match the CNR. Figure 5 illustrates how the “scan pilots” are used to compute RxMER per subcarrier. The figure shows the case of scattered or continous pilots, which are boosted by 6 dB relative to data symbols, and a 4096-QAM data constellation.

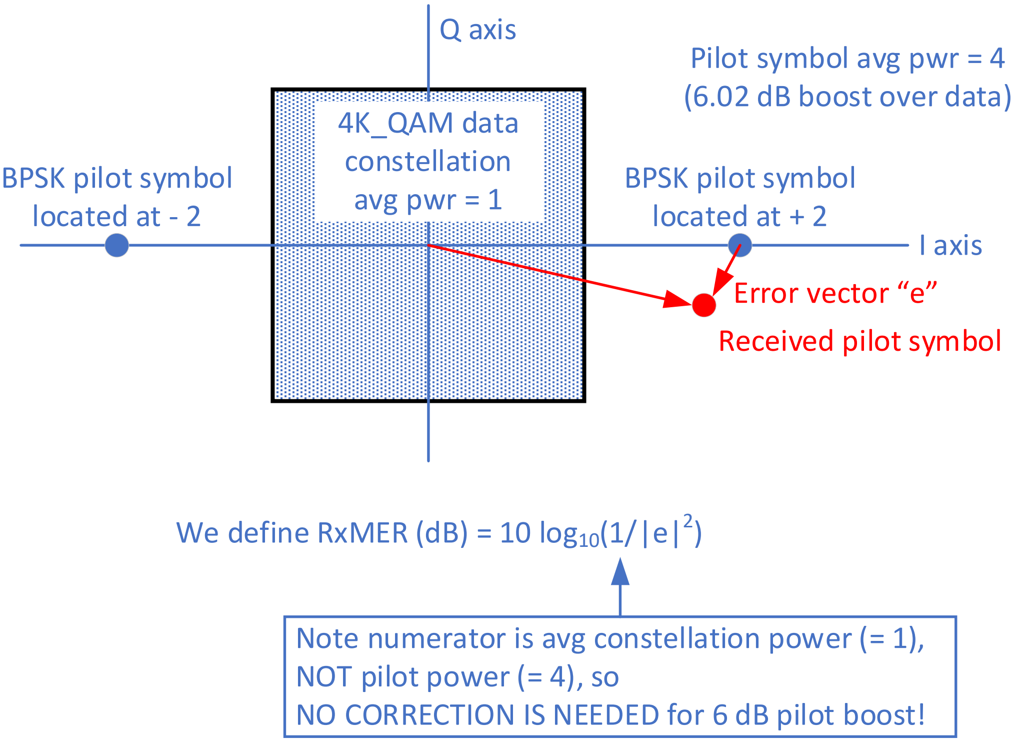
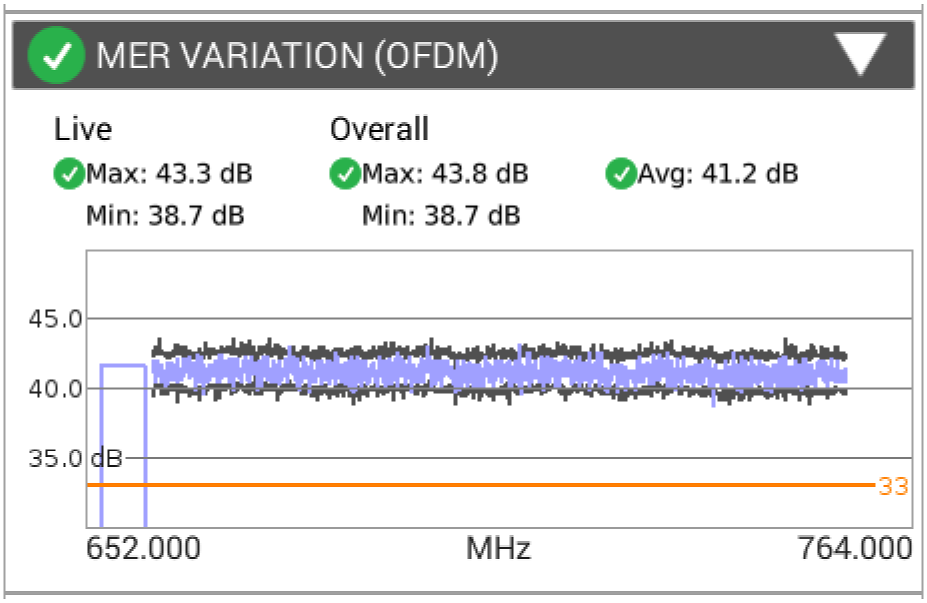


Figure 5. OFDM RxMER computation.

2. Impairment Identification

A graph of RxMER per subcarrier is a useful tool for identifying and characterizing a variety of impairments. Figure 6 shows an impairment-free example of RxMER per subcarrier for a 96 MHz-wide OFDM signal, captured using a DOCSIS 3.1 cable modem-equipped field meter. This particular capture was made by one of the authors [Hranac] on his subscriber drop, which is connected to a 4 dB, two-port end-of-line tap after a node+3 cascade. The OFDM signal is carried in the upper end of the cable network's downstream spectrum.



MER VARIATION (OFDM)

Live
✓Max: 43.3 dB
Min: 38.7 dB

Overall
✓Max: 43.8 dB
Min: 38.7 dB
✓Avg: 41.2 dB

Figure 6. RxMER per subcarrier graph for a 96 MHz-wide OFDM signal.

2.1.1. Simulated Ingress

One impairment of interest to cable operators is in-channel ingress. When ingress is present in an OFDM signal, it can be identified by a reduction of RxMER on the subcarriers that overlap the ingress. Figure 7 shows an example graph of RxMER per subcarrier for a 96 MHz-wide OFDM signal, in which simulated ingress from an idealized 10 MHz-wide LTE signal causes an approximately 10 dB reduction in RxMER on the affected subcarriers (an example with real ingress is included in Section 2.1.3).

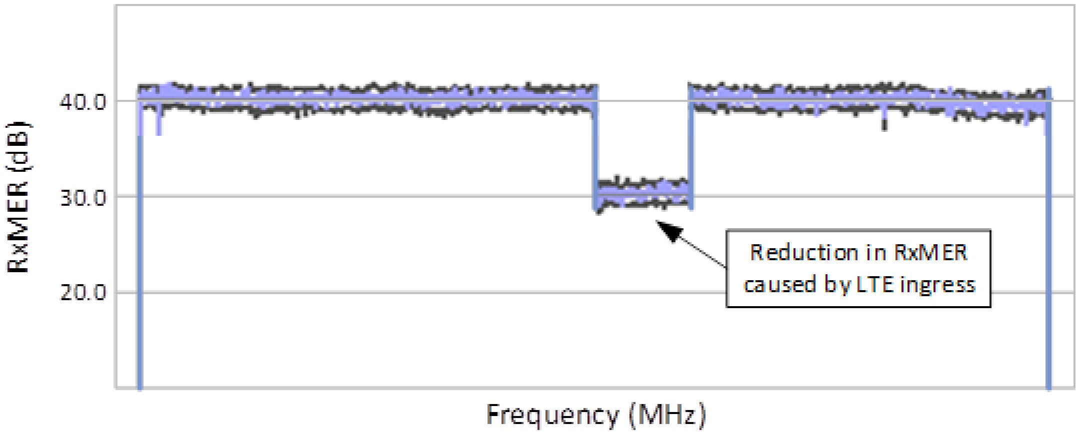


Figure 7. OFDM RxMER per subcarrier plot showing simulated ingress and its impact on the affected subcarriers.

2.1.2. Inverted Plot and Equalized Noise Floor

An inverted graph of RxMER versus subcarrier frequency (that is, -RxMER per subcarrier) gives a plot of the underlying noise (including ingress) in the channel relative to the signal, after receive equalization. Figure 8 shows the OFDM signal and simulated ingress from Figure 6, but with the RxMER plot inverted.

The y-axis may be labeled "-RxMER (dB)" or "Equalized Noise Floor (dBc)"; both are equally descriptive of the data being plotted.

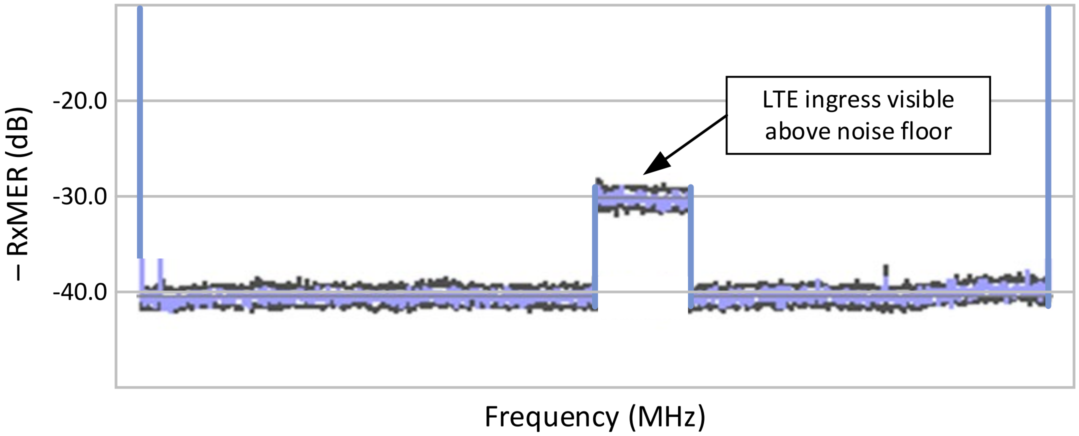


Figure 8. Inverted plot of RxMER per subcarrier.

The value of inverting the RxMER per subcarrier plot is that the graph now shows the equalized noise and ingress underneath the OFDM channel.

2.1.3. Impairment Examples

This section includes examples of RxMER per subcarrier graphs with a variety of impairments observed in production cable networks.

Figure 9 is captured data that shows ingress in an OFDM signal, and its impact on RxMER per subcarrier. This example is more typical of what the effect of real ingress looks like. (Note: In Figure 9 and some subsequent figures, the parallel horizontal red lines are standard deviation plot bars and the horizontal black line in between is the average value.)

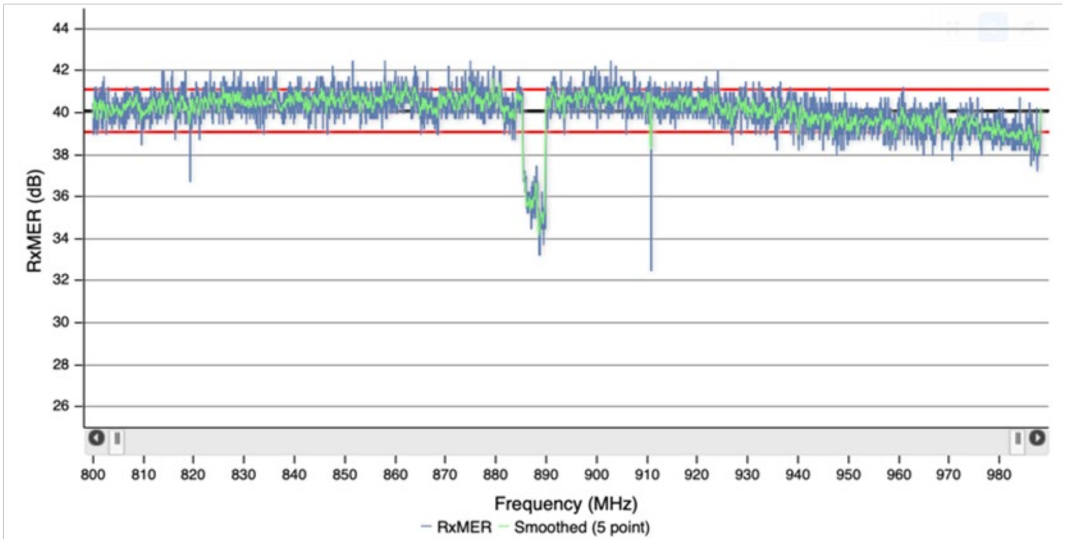


Figure 9. OFDM RxMER per subcarrier graph showing ingress interference at about 890 MHz.

Figure 10 shows an example of "edge rolloff" in the RxMER per subcarrier graph. The reduction in RxMER at the left edge of the OFDM signal is caused by a combination of the presence of an adjacent SC-QAM signal and the configuration of the cyclic prefix samples (N_{cp}) and rolloff period samples (N_{rp}), which affect how much the edge of the OFDM spectrum overlaps the adjacent signal. This phenomenon is discussed in more detail later in this paper.

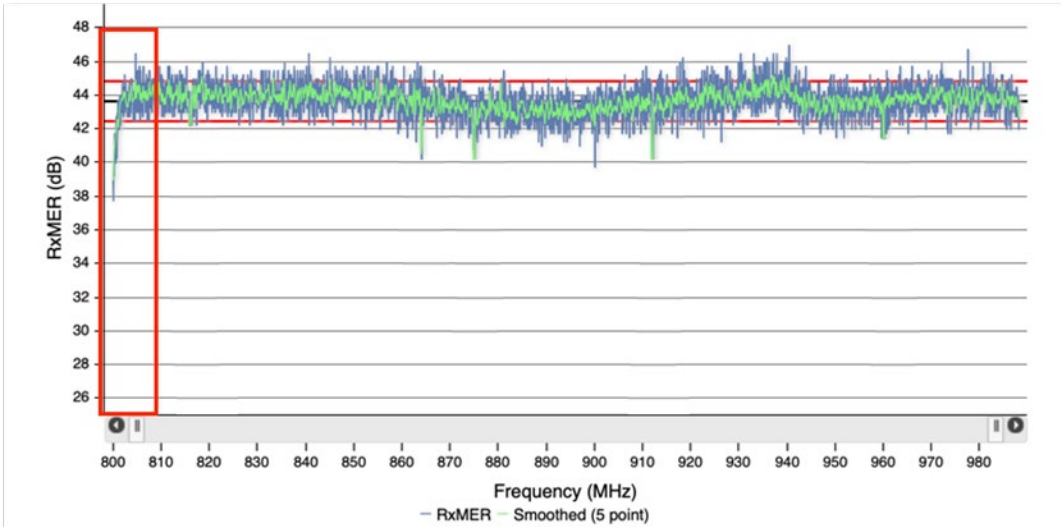


Figure 10. "Edge rolloff" visible at the left edge of the RxMER per subcarrier plot.

Figure 11 shows a combination of impairments, and the presence of an exclusion band from 759.85 MHz to 763.55 MHz. Starting at the left side of the graph, RxMER "edge rolloff" is visible. Ingress is evident at several frequencies within the OFDM signal, and the overall RxMER per subcarrier decreases from left-to-right, suggesting possible CNR degradation and/or cable network frequency response problems.

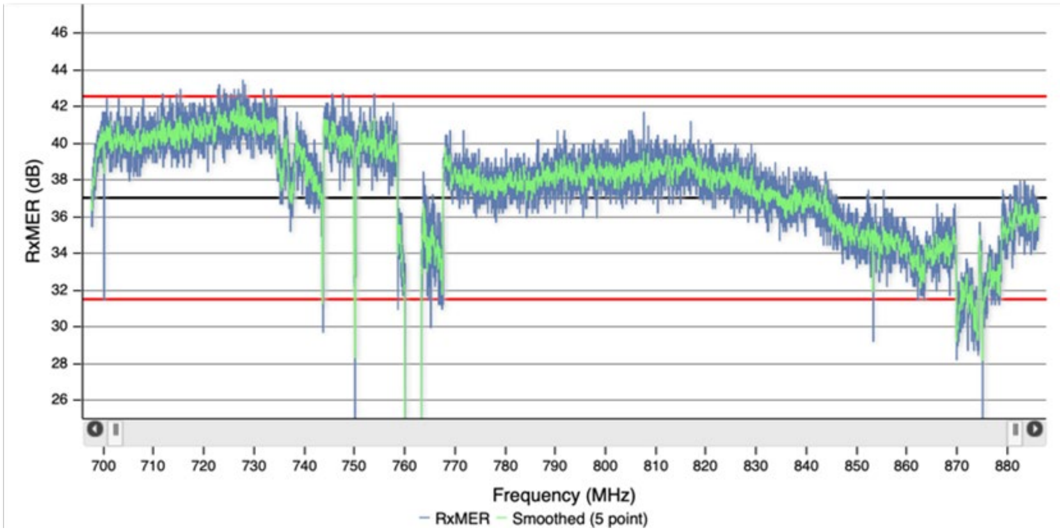


Figure 11. Multiple impairments are evident in this RxMER per subcarrier graph (see text), along with an exclusion band from 759.85 MHz to 763.55 MHz.

Figure 12 shows an example in which a reflection caused amplitude ripple to be visible in the RxMER per subcarrier graph. This phenomenon is discussed in detail later in this paper.

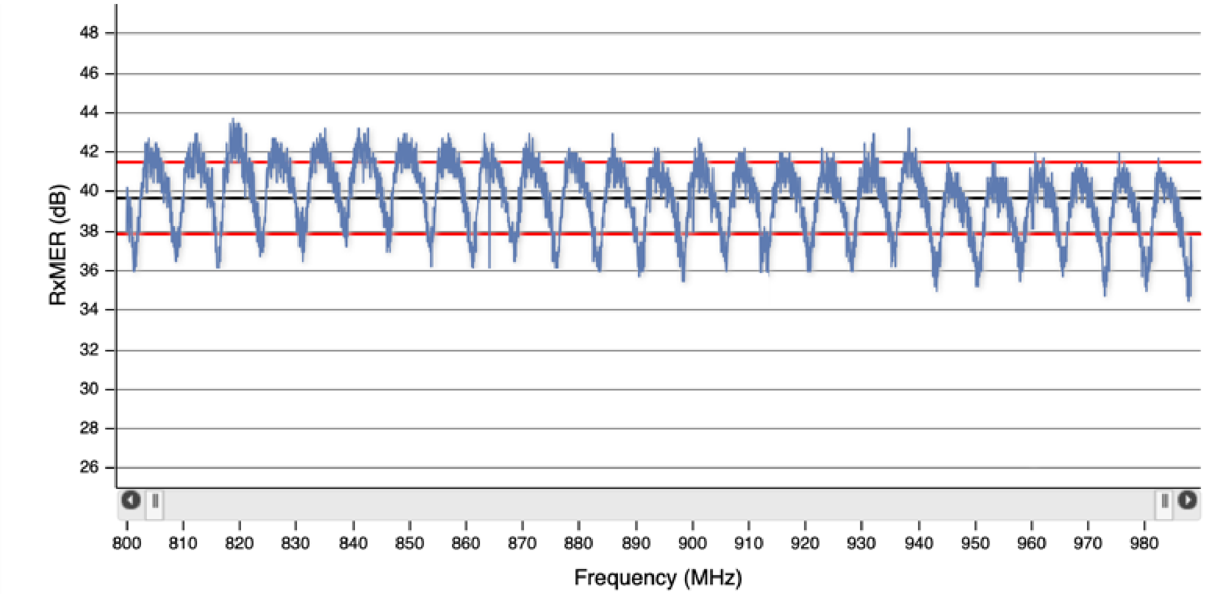


Figure 12. RxMER per subcarrier graph with amplitude ripple caused by an impedance mismatch-related reflection.

3. Lab Testing

A reduction in RxMER per subcarrier when the CNR is low, or when ingress affects certain subcarriers, is expected behavior. Amplitude ripple and edge rolloff in RxMER per subcarrier graphs warranted further investigation, because those phenoemena were found to not appear consistently when the underlying mechanisms that cause them occur. Testing was done in CableLabs and Akleza test labs to recreate amplitude ripple and edge rolloff, and develop a better understanding of why and when those impairments appear.

3.1. Amplitude Ripple

The appearance of amplitude ripple in the frequency domain – for instance, as viewed on a spectrum analyzer or a broadband sweep display – occurs when an impedance mismatch (or impedance mismatches) causes a reflection (or reflections). Under some circumstances amplitude ripple can also appear in an RxMER per subcarrier graph. Lab testing was done to better characterize this phenomenon. Figure 13 shows high-level block diagrams of equipment configurations used for five different amplitude ripple test scenarios.

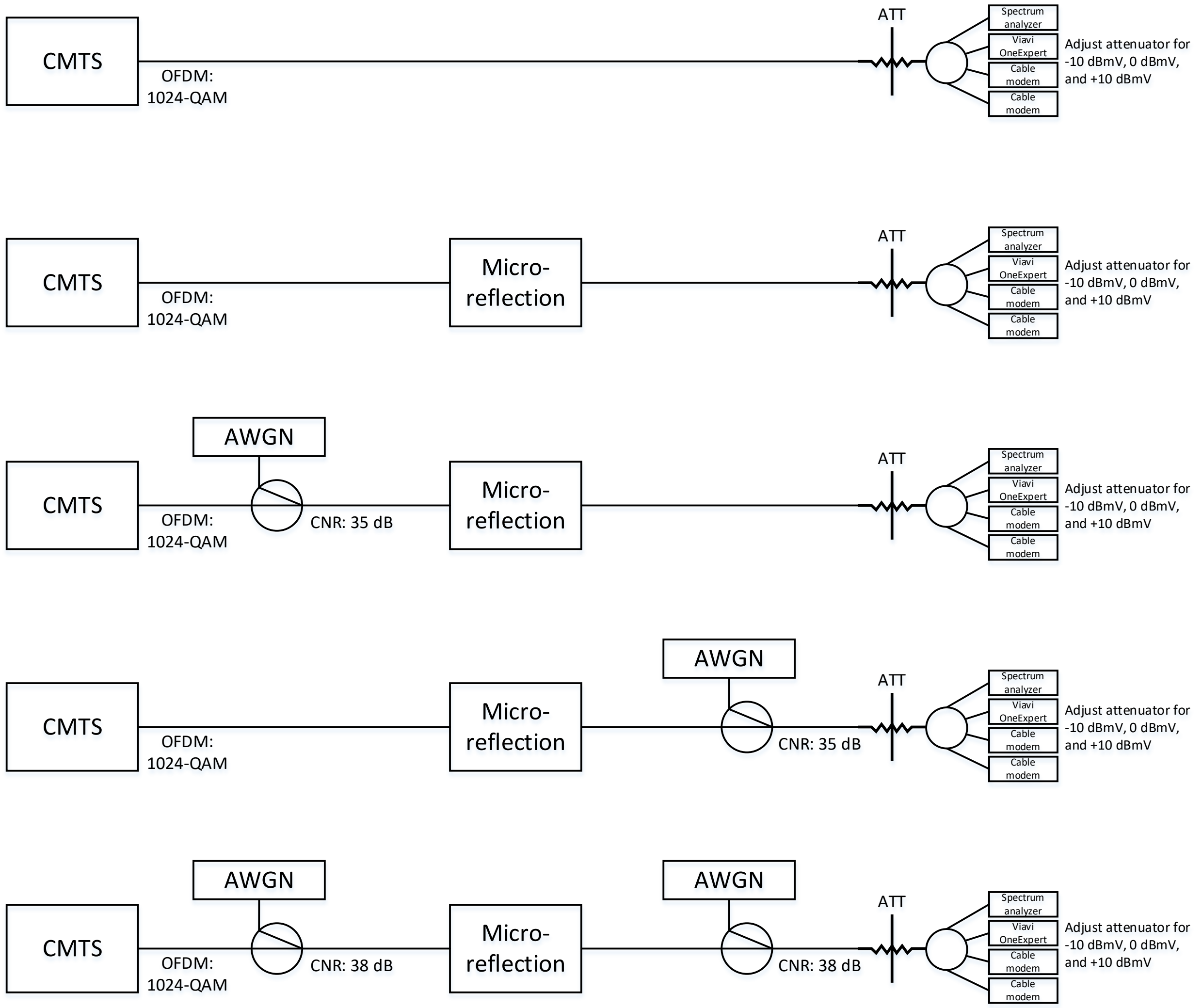


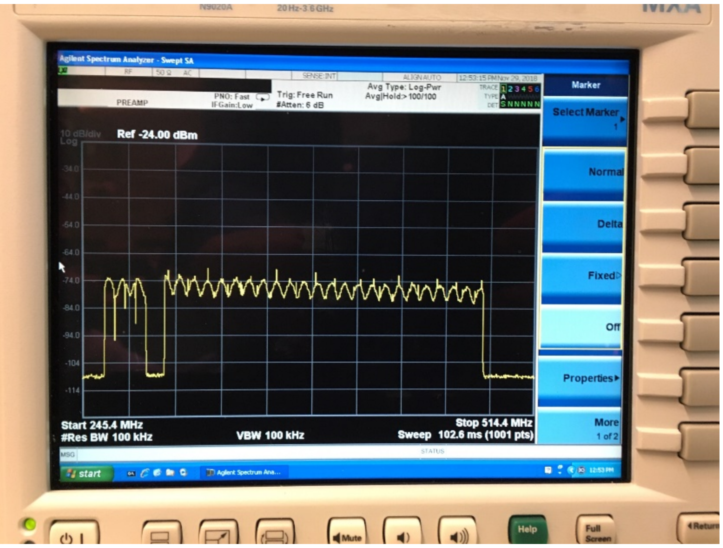
Figure 13. Equipment configurations for RxMER per subcarrier amplitude ripple testing.

The micro-reflection in Figure 13 was set up to produce amplitude ripple with approximately 8 MHz spacing. Data captured during the lab testing included the frequency domain display on a spectrum analyzer; and all of the following from one or more of the cable modems (including a field instrument with an embedded DOCSIS 3.1 cable modem): channel estimate, RxMER per subcarrier, and OFDM channel power – that is, power per 6 MHz.[3] Data was captured with the RF input power (OFDM channel power) to the modems at -10 dBmV, 0 dBmV, and +10 dBmV. The AWGN source was configured for wideband output, and adjusted to produce an aggregate CNR of 35 dB.

The OFDM signal was 192 MHz wide (292 MHz to 484 MHz), with 190 MHz encompassed spectrum, N_{rp} = 256 (0.975 MHz taper region width), 50 kHz subcarrier spacing, and Profile A set to 1024-QAM.

The captured test results are summarized graphically in the Appendix as Test Case 1A, Test Case 1B, Test Case 1C, Test Case 2A, Test Case 2B, and so on, where "A," "B," and "C" refer to RF input levels of -10 dBmV, 0 dBmV, and +10 dBmV per 6 MHz respectively. Test Case 1, 2, 3, 4, and 5 refer to the five configurations shown in Figure 13.

The following figures highlight RxMER per subcarrier measurement results for Test Case 3B and 4B (see the Appendix for all Test Case results). The figures here show how amplitude ripple in the frequency domain (Figure 14) sometimes does not cause amplitude ripple to appear in an RxMER per subcarrier graph (Figure 15), and sometimes does (Figure 16). In both of these test cases, the nominal OFDM channel power at the input to the modem was 0 dBmV (Figure 17). An important takeaway from the lab testing is confirmation that amplitude ripple in the channel in the frequency domain will not always result in visible amplitude ripple in an RxMER per subcarrier graph. For the why behind this, refer to Section 3.1.1.



PNO: Fast
IFGain:Low
Trig: Free Run
#Atten: 6 dB
Avg Type: Log-Pwr
Avg|Hold:> 100/100
Ref -24.00 dBm
Start 245.4 MHz
#Res BW 100 kHz
VBW 100 kHz
Stop 514.4 MHz
Sweep 102.6 ms (1001 pts)

Figure 14. Test Case 4B spectrum analyzer capture (the frequency domain ripple in the channel was the same for Test Case 3B).

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[3] OFDM channel power is expressed in terms of the power per CTA channel – that is, the power per 6 MHz. The total power is ***Power per CTA channel + 10log$_{10}$(Number of occupied CTA channels)*** for that OFDM channel. When discussing OFDM signal level (channel power) in this paper, the stated value is the average power per 6 MHz, unless otherwise noted.

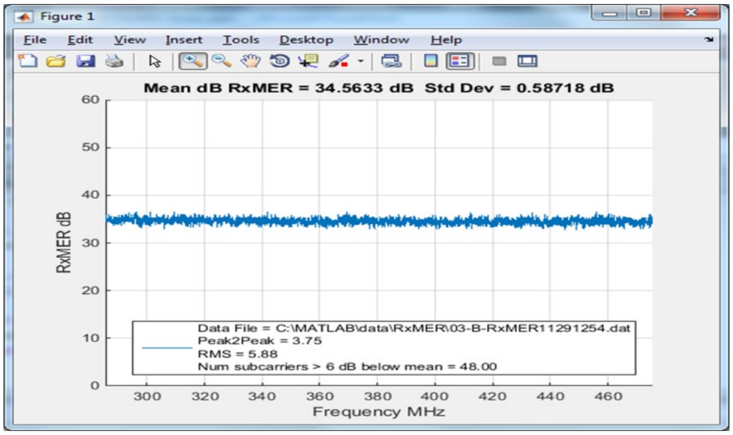


Figure 15. Test Case 3B RxMER per subcarrier graph showing little or no amplitude ripple.

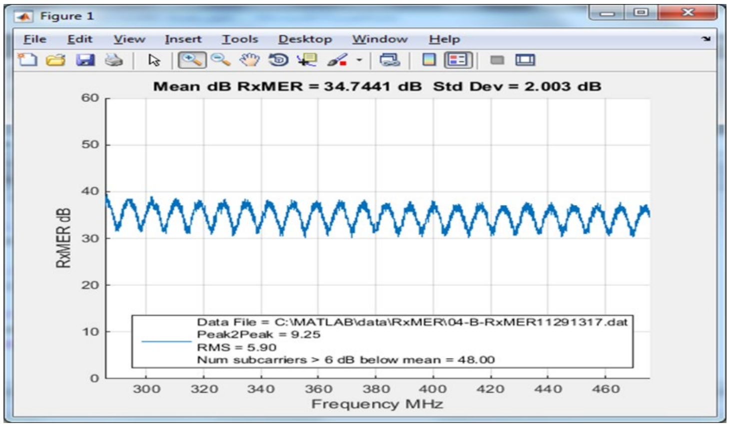
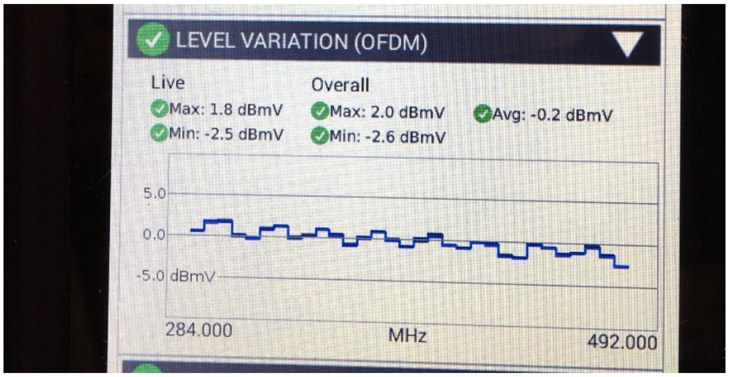


Figure 16. Test Case 4B RxMER per subcarrier graph showing amplitude ripple.


LEVEL VARIATION (OFDM)

Live
✓Max: 1.8 dBmV
✓Min: -2.5 dBmV

Overall
✓Max: 2.0 dBmV
✓Min: -2.6 dBmV
✓Avg: -0.2 dBmV

Figure 17. Test Case 4B OFDM channel power (the OFDM channel power was the same for Test Case 3B).

3.1.1. Amplitude Ripple Test Results Discussion

When the dominant noise (e.g., from optical fiber links and amplifiers) occurs before the source of a reflection – as was the situation with Test Case 3 – one will usually not see amplitude ripple in a graph of

RxMER per subcarrier. In contrast, when the dominant noise occurs after the source of a reflection, amplitude ripple will be visible in a graph of RxMER per subcarrier. There are some exceptions, as can be seen in the figures in the Appendix. The following explains why the location of dominant noise relative to a reflection affects the visibility of RxMER per subcarrier amplitude ripple.

Figure 18 is a block diagram of a test system for an OFDM signal, showing sources for an OFDM signal and SC-QAM signals; a noise injection point ("Noise 1") before the source of an echo (reflection); an echo creation circuit with frequency response H(f); and a second noise injection point ("Noise 2") after the echo circuit. A cable modem is shown as two functional blocks: an analog front end (AFE, including an A-D converter and amplifiers) and an adaptive equalizer, the latter labeled $H(f)^{-1}$, indicating that its purpose is to invert the echo channel response. A noise source, "Noise 3", represents the noise added internally to the modem, often described by the noise figure of the modem[4]. A modem's typical noise figure can be as good as 5 dB to 10 dB, but could be higher, especially when attenuation is inserted by the AFE at high input signal power. Signal and noise observation points A, B, and C are labeled.

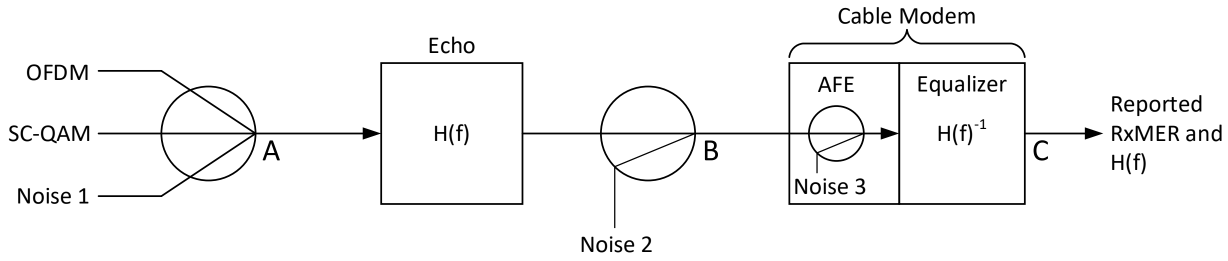


Figure 18. OFDM signal test system block diagram.

Figure 19 illustrates signals at points A, B, and C for test conditions with no SC-QAM signals, Noise 1 active, and Noise 2 quiet. At point A, the OFDM signal is flat; Noise 1 is flat, and kT is ever-present. At point B the echo has put a ripple in both the OFDM signal and Noise 1. At point C the channel estimate coefficients H(f) and RxMER per subcarrier are both reported with different MIBs. Note that the RxMER has been flattened by the equalizer since Noise 1 has passed through both the echo channel and its inverse, resulting in no net echo at the modem slicer. This happens automatically when the cable modem's equalizer flattens the OFDM signal. The resulting RxMER per subcarrier plot will be a function of the level of Noise 1 relative to the noise floor of the cable modem. If Noise 1 is very small, the modem's noise floor may be dominant and some ripple may be seen in the RxMER per subcarrier plot; if Noise 1 is much higher than the internal modem noise floor, the cable modem's internally generated noise will not contribute appreciably to the RxMER plot, which will be flat. Elements that contribute to the internally generated modem noise are amplifier noise, bits of precision in the A-D converter, phase noise, quantizing error in digital computations, etc.

---

[4] Noise power spectral density kT, where k is Boltzmann's constant ($1.38 * 10^{-23}$ joules/kelvin) and T is the effective noise temperature in kelvin. After the modem AFE, T is elevated above the standard temperature $T_0 = 290$ K due to the noise added by the modem.

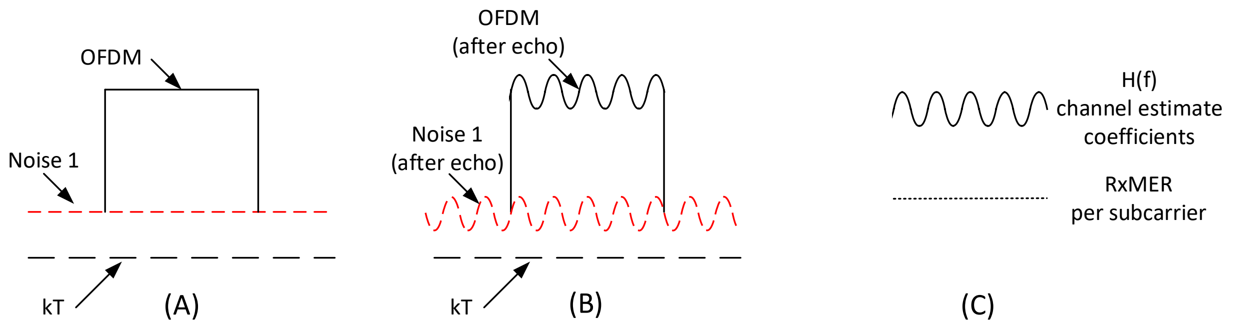


Figure 19. Test conditions with Noise 1 injected before the source of an echo (reflection). As seen at observation point (B) both Noise 1 and the OFDM signal have amplitude ripple, but the modem's adaptive equalizer removes the channel effect so that at observation point (C) the RxMER-per-subcarrier plot does not show ripple. In this figure, the horizontal axis is frequency, and the vertical axis is relative amplitude in decibels.

Figure 20 illustrates signals at observation points A, B, and C for test conditions with no SC-QAM signals, Noise 1 quiet, and Noise 2 active. At point A the OFDM signal is flat and noise is kT background noise. At point B, the OFDM signal has an echo, but Noise 2 is flat since it was injected after the echo creation circuit. At point C the channel estimate coefficients H(f) and RxMER per subcarrier are reported. However, equalization has been applied to the injected flat Noise 2, giving it an inverse channel response, which exhibits ripple. The RxMER will exhibit the original (uninverted) channel ripple. This is because RxMER is a signal-to-noise ratio (SNR), with N in the denominator. So the ripple was inverted twice: once by the inverse channel equalizer and once in the RxMER computation. Since two inversions yield a non-inversion, we see the original ripple signature in the RxMER plot.

Note that in determining whether or not a ripple is observed in RxMER, it matters whether the elevated random noise experienced the echo or not, illustrated by the differences in Figure 18(C) and Figure 19(C). Furthermore, if the OFDM signal level is very weak at the input to the cable modem, the background noise kT will become the dominant noise component in RxMER, and the ripple in the RxMER-per-subcarrier plot will be diminished.

To summarize: If the noise passes through both the echo and the inverse equalizer, these two filtering operations will cancel and the RxMER-per-subcarrier plot will NOT show channel ripple. If the noise does not pass through the echo but does pass through the inverse equalizer, the RxMER WILL show channel ripple, and the ripple in the RxMER-per-subcarrier plot will be upright (same polarity as the channel estimate coefficients, that is, not inverted).

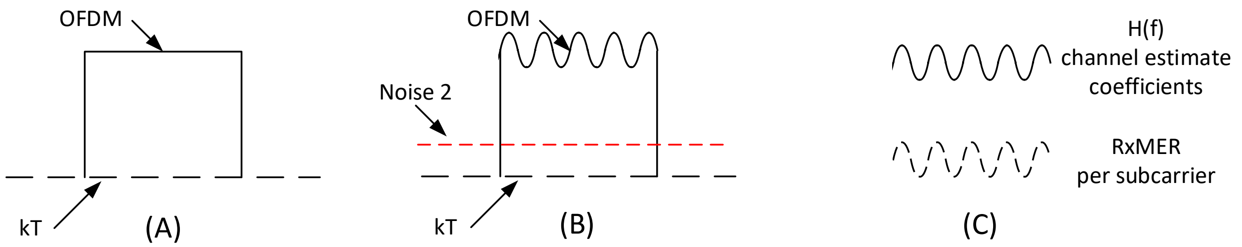


Figure 20. Test conditions where Noise 2 is injected after the source of an echo (reflection). At observation point (B), Noise 2 does not have ripple because it did not pass through the echo. However, the modem's RxMER-per-subcarrier plot does have amplitude ripple (C) because the noise passed through the receive equalizer H(f)-1. In this figure, the horizontal axis is frequency, and the vertical axis is relative amplitude in decibels.

3.2. RxMER Edge Rolloff

Observations from production cable networks and subsequently recreated in test lab environments have shown that the presence of an SC-QAM signal adjacent to an ODFM signal can cause a degradation of the reported RxMER values in the subcarriers near the edge of the OFDM signal, depending upon the configuration of the cyclic prefix and rolloff period parameters. When looking at a graph of RxMER per subcarrier, this effect can present itself as rolloff at the band edge(s) of the OFDM channel as shown in the highlighted areas in Figure 10 and Figure 21.

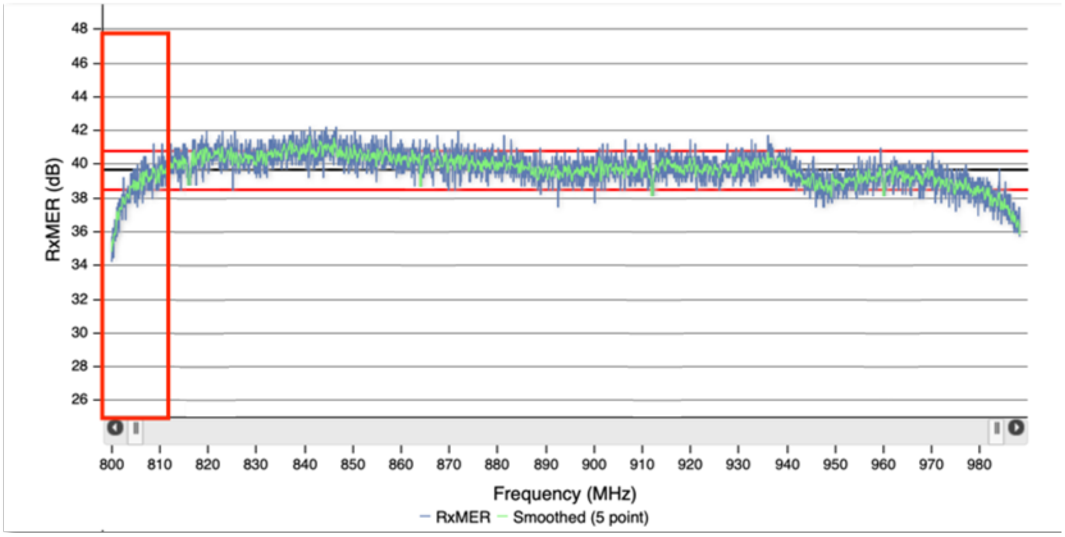


Figure 21. Another example of edge rolloff in an RxMER per subcarrier graph.

In the aforementioned examples, the signals were aligned on standard CTA channel boundaries with an SC-QAM signal adjacent to the OFDM signal. N_{cp} was configured to 192 and N_{rp} to 128. Figure 22 shows an example spectrum capture with the same signal conditions including N_{cp} and N_{rp} settings for the OFDM signal as in Figure 21; the taper region width is 1.875 MHz. Even though the RF spectrum shows a guard band of sorts between the SC-QAM and OFDM signals, the OFDM taper region extends into the lower adjacent channel, introducing degradation, although possibly minimal. In this example, energy from the adjacent SC-QAM signal also leads to interference in the first few subcarriers of the OFDM signal, resulting in the edge rolloff in the RxMER per subcarrier graph visible in Figure 10 and Figure 21.

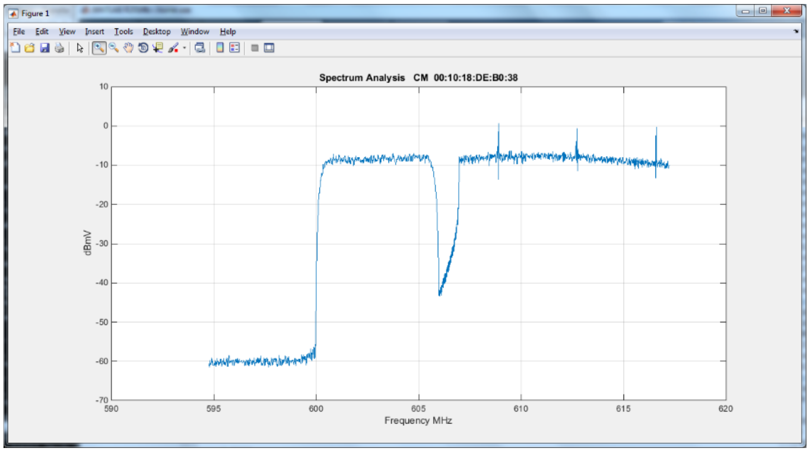


Figure 22. Example spectrum capture of an SC-QAM signal adjacent to an OFDM signal. Note the OFDM signal's taper region, which extends into part of the SC-QAM signal.

While degradation of the RxMER of the first few OFDM subcarriers does not have a meaningful impact on overall performance or throughput, changing the configuration of cyclic prefix and rolloff period can help. In particular, proper configuration of N_{rp} can sharpen the OFDM signal's spectral edges in the frequency domain (that is, reduce the taper region width). Figure 23 shows a graph of RxMER per subcarrier after adjusting Ncp to 1024 and Nrp to 256. This is data from the same modem as shown in Figure 10, but with the new cyclic prefix and rolloff period settings.

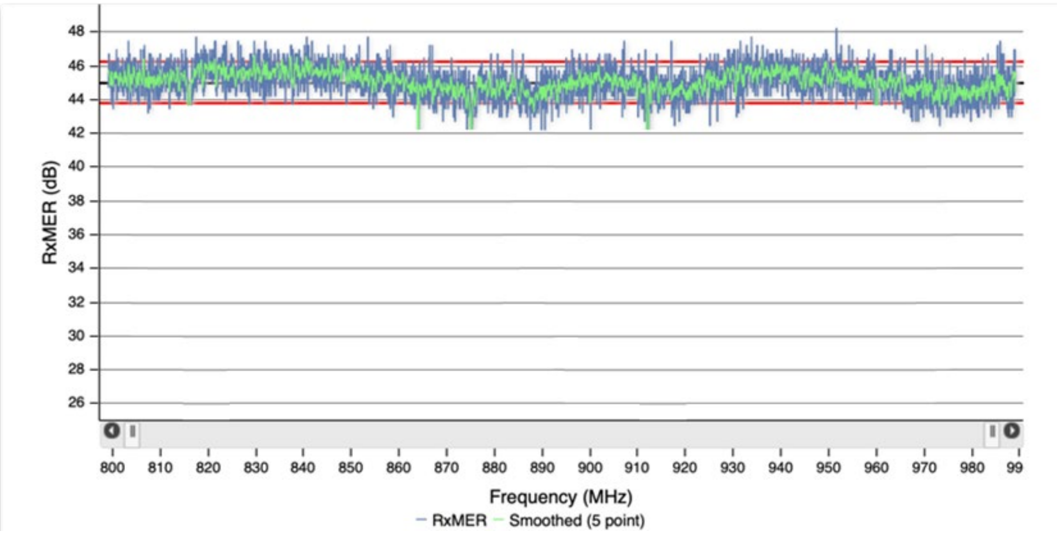
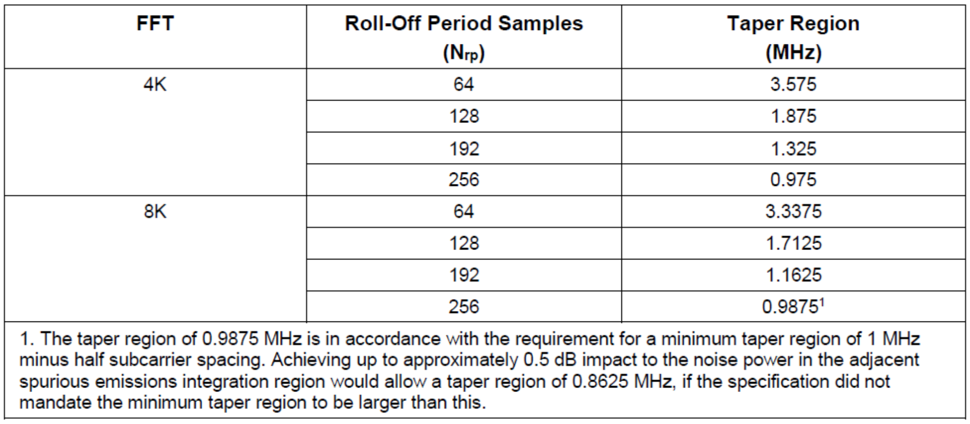


Figure 23. RxMER per subcarrier graph after reconfiguring N_{cp} and N_{rp}.

One can avoid or minimize adjacent channel interference and OFDM RxMER per subcarrier edge rolloff by properly configuring the OFDM signal's N_{cp} and N_{rp} values. Appendix V of the DOCSIS 3.1 Physical Layer Specification includes a table showing taper region width versus N_{rp} setting (see Figure 24). If the channel(s) adjacent to the edge(s) of the OFDM signal will be occupied, then an OFDM band edge exclusion should be should be configured in accordance with the table in Figure 23. From the table in

Figure 24, maximum N_{rp} = 256 will yield a taper region width of either 0.975 MHz or 0.9875 MHz, depending on subcarrier spacing. Keep in mind the DOCSIS requirement that the N_{rp} value must be less than the N_{cp} value.



FFT	Roll-Off Period Samples (N_{rp})	Taper Region (MHz)
4K	64	3.575
	128	1.875
	192	1.325
	256	0.975
8K	64	3.3375
	128	1.7125
	192	1.1625
	256	0.9875[1]
1. The taper region of 0.9875 MHz is in accordance with the requirement for a minimum taper region of 1 MHz minus half subcarrier spacing. Achieving up to approximately 0.5 dB impact to the noise power in the adjacent spurious emissions integration region would allow a taper region of 0.8625 MHz, if the specification did not mandate the minimum taper region to be larger than this.		

Figure 24. Table 75 from Appendix V of the DOCSIS 3.1 Physical Layer Specification [1].

3.2.1. *RxMER Edge Rolloff Discussion*

During the field observations and lab testing done for this paper, the edge rolloff was not always consistently visible in a graph of RxMER per subcarrier. Under some conditions the rolloff was seen, but other times the rolloff was not seen, despite the same configuration (existence of adjacent SC-QAM signal, same N_{cp} and N_{rp} settings, etc.). Indeed, field observations indicated that some modems in the same node service area displayed the edge rolloff, while others did not, including two modems that were in homes next door to each other.

Preliminary results suggested that factors such as the total power at the input to the modem, the presence of a micro-reflection, and even cable modem make/model (and silicon vendor) appeared to affect visibility of the rolloff. However, additional testing showed that when performing multiple RxMER captures from a given modem, in some cases the edge rolloff was not consistently present. Further investigation showed that with the intermittent rolloff in a cable modem, the visual impact in the RxMER band edges was notable; quantitatively, the impact to the link was minmal, but this has not been characterized. The impact to the link can be reduced to zero if the bit loading for the affected subcarriers is reduced by one or two bits, and the cost of this reduction in throughput is less than 0.1 bits per Hz (less than 0.5%). For the same transmission parameters, a different cable modem showed consistent band edge rolloff which was more severe than the modem which showed intermittent rolloff. Note that reducing the bit loading for a few (e.g., 100) subcarriers, impacts throughput much less than increasing N_{cp}.[5]

A DOCSIS 3.1 cable modem, usually employing a system on a chip, constantly adjusts several parameters to optimize throughput of a downstream OFDM channel and minimize frame errors. Adjustments may include tracking loops for receive carrier frequency/phase and timing (selection of the samples used in FFT processing); and channel tracking (adaptive equalization). These dynamic adjustments may result in seemingly intermittent behavior under certain signal conditions while the receiver is actually maintaining tight, near optimal link performance. An analogous situation occurs in

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[5] Optimization of N_{cp} and N_{rp} settings is important because larger values add overhead, which in turn impacts usable throughput.

SC-QAM where an adaptive equalizer may exhibit some frequency response fluctuation or path wander while maintaining consistent performance throughout.

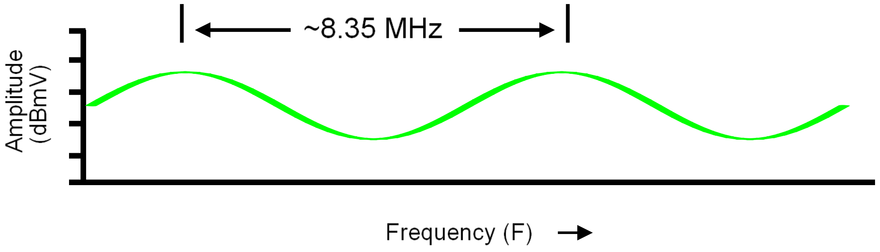
4. Using RxMER per Subcarrier Data for Maintenance and Troubleshooting

CableLabs' PNM Best Practices [5] document outlines a fault localization process based on correlating pre-equalization or full band capture data from cable modems based on their network topology. The procedure identifies the point along a shared path where a fault or anomaly indicator changes. This is a similar process that field technicians use to determine the area of a fault using field test meters where reading are taken while working upstream from a fault until the impairment is no longer visible. The area where this change occurs gives an indication of the location of the cable plant that must be contributing to the fault. With the advent of PNM software tools capable of taking readings from existing cable modems, the determination of the approximate fault location can now be achieved without having to roll a truck, making the technician's troubleshooting efforts much easier.

As described in the previous sections, OFDM RxMER per subcarrier data can indicate impairments related to cable plant faults such as an echo or reflection resulting in amplitude ripple in the RxMER per subcarrier plot. By analyzing results from cable modems that show amplitude ripple in the RxMER per subcarrier caused by a reflection, the area of the impairment can be isolated when correlated with the shared network path. Comparing the reported RxMER per subcarrier of devices on the same shared path, a boundary can be determined where a problem exists and where it does not. The fault therefore must be between the last device showing the fault and the first device not showing the fault.

Additionally, the peak-to-peak frequency spacing of the amplitude ripple can be used to compute the approximate length of an "echo tunnel," the distance between two impedance mismatches (e.g., and amplifier and a tap full of water). This echo tunnel length can then be used to further narrow down the possible location of the fault along the shared path.

Figure 25 shows the formula for computing the echo tunnel length based on the peak-to-peak frequency spacing of amplitude ripple.



Length in feet:
$L = 492 * (VF/F_{MHz})$
$L = 492 * (0.85/8.35)$
$L = 50.08$ feet
where:
L = length in feet
VF = velocity factor of the cable (velocity of propagation expressed in decimal form)
F_{MHz} = frequency spacing of amplitude ripple in megahertz

Figure 25. Amplitude ripple-to-echo tunnel length calculation.

Figure 26 shows a real-world example from a production network and the resulting analysis and findings. Cable modem icons are shown along with an overlay of the cable plant in the area. This area shows a number of DOCSIS 3.1 cable modems connected to an amplifier [A] that all show a similar and significant amplitude ripple in a plot of their RxMER per subcarrier data. This amplitude ripple is however not seen on any cable modem connected to the other outputs of the amplifier and directional coupler show at point [B]. This analysis would therefore indicate that the cause of the impairment is located on the interconnecting trunk cable [C].

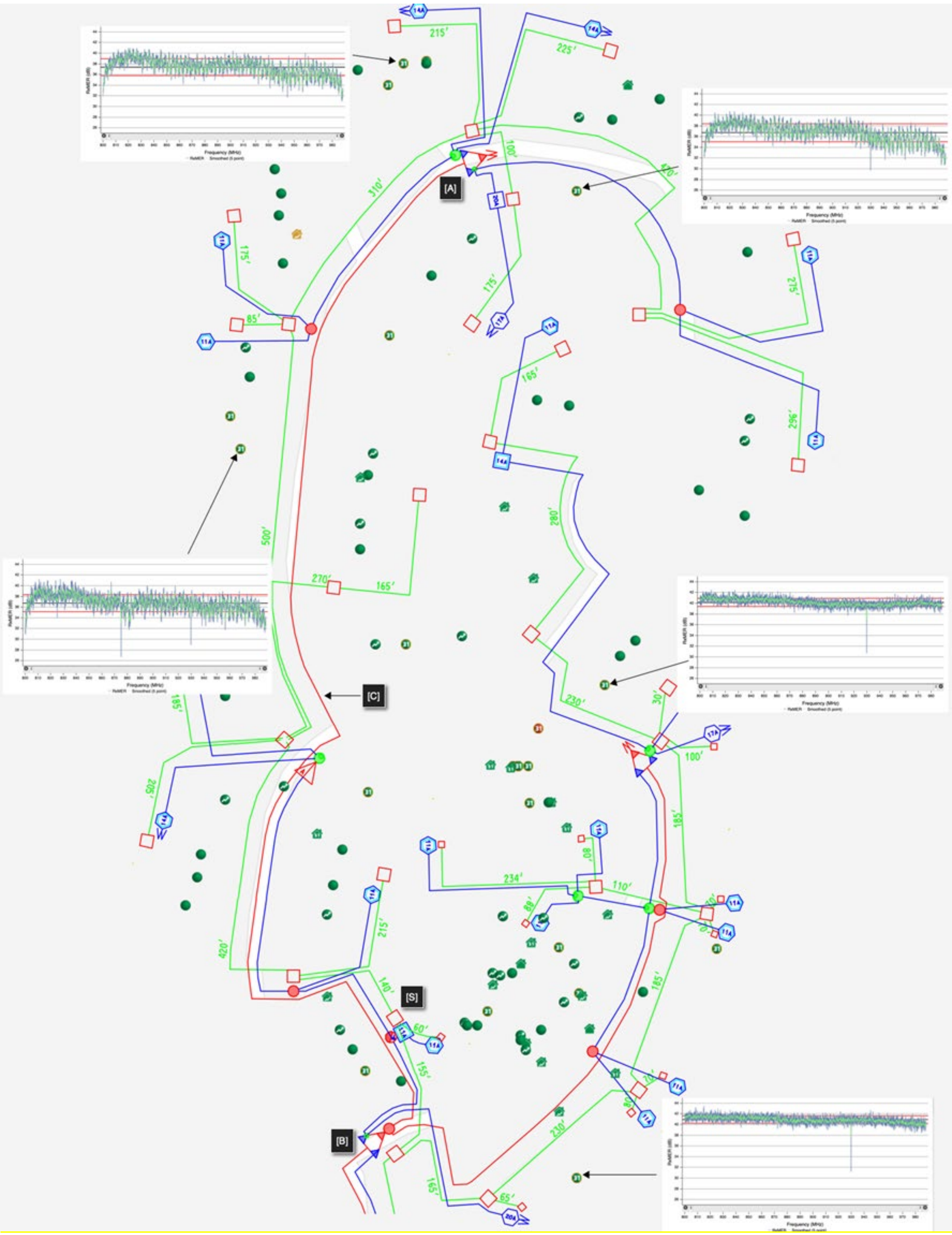


Figure 26. System map with RxMER per subcarrier data.

The trunk cable in this area is underground, however above-ground trunk block splices are located at different points along the path in pedestals. The locations of these pedestals with block splices are indicated with red boxes such as shown at [S].

Zooming into the RxMER per subcarrier and measuring the peak-to-peak distance in MHz shows a periodicity of approximately 3 MHz as illustrated in Figure 27. (There also appears to be at least one other ripple visible in the graph.)

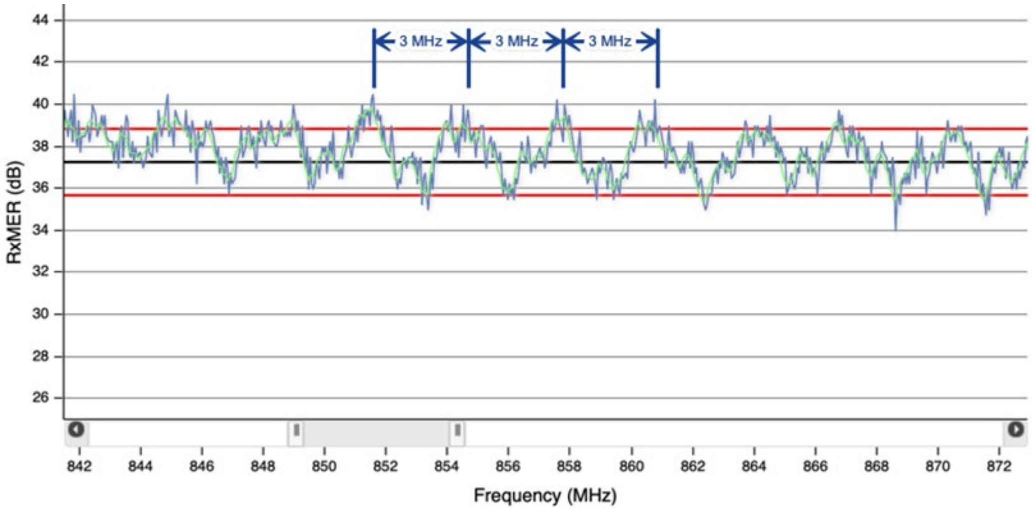


Figure 27. Close-up of RxMER per subcarrier amplitude ripple periodicity.

Using the amplitude ripple length calculation formula shown in Figure 25 one can compute the approximate length of the echo tunnel impacting this part of the network. The velocity of propagation for the trunk cable being used in this particular system is 93%. Plugging these values into the formula results in a calculated echo tunnel length of about 152.5 feet.

The cable plant diagram shown in Figure 26 shows a trunk span of 155 feet between the amplifier [B] and the first splice block [S] on the impaired trunk. A field maintenance crew was dispatched to the area and after verifying the RxMER per subcarrier responses reported were consistent with what was being reported by their field meters, they proceeded to inspect and replace the trunk block splice [S] shown in Figure 28 and Figure 29.

Figure 28. Technician troubleshooting RxMER per subcarrier amplitude ripple.

Figure 29. Trunk splice removed from network.

While no obvious impairment was visually apparent, a refresh of the RxMER per subcarrier data for the impacted cable modems attached to this trunk showed that fault had been corrected and that the average RxMER per subcarrier increased by 2 dB after replacing the splice (see Figure 30). The technicians also replaced a suspect directional coupler and second splice, which helped improve the response somewhat.

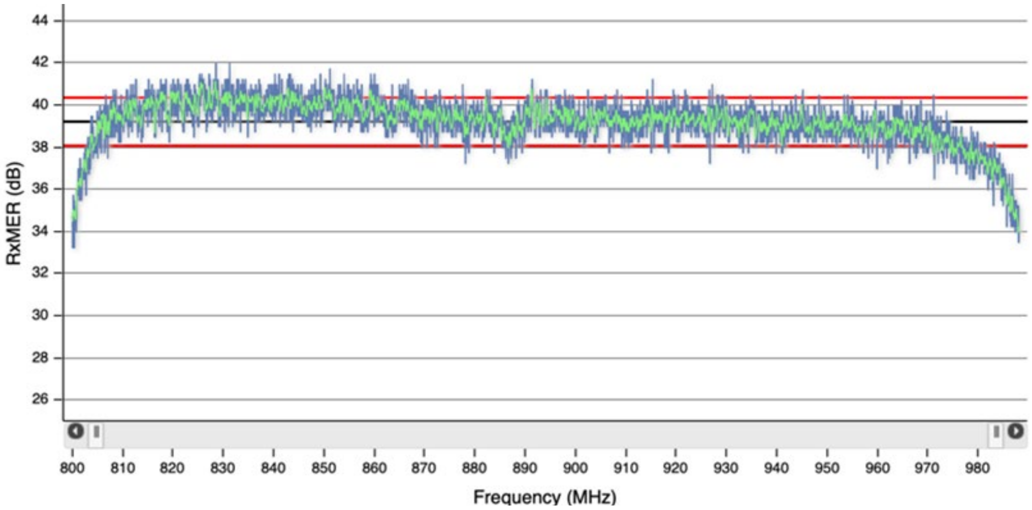


Figure 30. RxMER per subcarrier after replacing splice.

The same general techniques described in this section to determine the location of an impairment can also be used for other types of interference visible in the RxMER per subcarrier data. For example, if there is an indication of LTE ingress, this is caused by degradation of shielding effectiveness due to a cable crack, loose or corroded connector, etc. By isolating those modems that show this interference the general area of the source of the fault can be found. If the problem is visible on the cable modem from one home but not a neighboring home, then most likely the fault is in the drop cable or in the home itself. If, however, interference is visible across a number of cable modems in an area, then the fault is most likely farther upstream in a section of cable on the common path. As in the previous example, by examining data from a number of points progressively farther upstream on the common path, one can determine the location between where the interference is visible and where it isn't. This then defines the bounds of the area to investigate and locate the problem.

5. Areas for Further Investigation

One area for additional investigation is field and lab testing to characterize the impact of nonlinear distortions – composite second order, composite triple beat, and noise-like composite intermodulation distortion – on RxMER per subcarrier. For instance, if an OFDM signal's RxMER per subcarrier was found to unexpectedly improve deeper in an amplifier cascade, that might be an indication of the presence of nonlinear distortion(s).

Another area for further investigation is related to impairment testing using one or more SC-QAM signals under an OFDM signal to simulate ingress. Some testing using this method has shown that as the underlying SC-QAM signal amplitude was increased, the RxMER on the affected subcarriers decreased as expected. However, as the "interference" amplitude increased even more, in one cable modem the RxMER on all subcarriers started to decrease, but on another vendor's modem there was no observed RxMER decrease outside of the interference region. Additional testing could be done to determine whether this behavior is consistent and repeatable.

One other area for further investigation is evaluation of the effectiveness of DOCSIS 3.1's frequency domain interleaving and LDPC FEC when in-channel ingress is present and when the SNR is several dB above the threshold for the modulation order in use. When the overall SNR margin is high, some testing has shown that a block of noise (e.g., 6 MHz to 12 MHz wide) used to simulate ingress has little or no effect on overall throughput until the RxMER on the affected subcarriers is well below the known margin for the modulation order (profile) in use. There is a tradeoff with respect to the bandwidth of the interference relative to the bandwidth of the OFDM signal and the amount of SNR margin. Additional testing could more accurately quantify interleaving and FEC performance vs the level and bandwidth of the interference..

Conclusion

SC-QAM RxMER has long been an important and useful metric for cable operators, but it does have limitations. The ability to take advantage of DOCSIS 3.1 OFDM RxMER per subcarrier data is even more useful and goes beyond the limitations of SC-QAM RxMER. Graphs of OFDM RxMER per subcarrier can in many instances be used to identify the type(s) of impairment(s) affecting the network, and nicely complements other tools for maintaining optimum performance, maximum throughput, and overall subscriber satisfaction.

Abbreviations

ACI	adjacent channel interference
A-D	analog-to-digital
AFE	analog front end
AWGN	additive white Gaussian noise
CableLabs	Cable Television Laboratories
CCAP	converged cable access platform
CMTS	cable modem termination system
CNR	carrier-to-noise ratio
CTA	Consumer Technology Association
dB	decibel
dBmV	decibel millivolt
DOCSIS	Data-Over-Cable Service Interface Specifications
FEC	forward error correction
I	in-phase
ISBE	International Society of Broadband Experts
LDPC	low density parity check
log	logarithm
LTE	long term evolution
MER	modulation error ratio
MHz	megahertz
MIB	management information base
N_{cp}	cyclic prefix samples
N_{rp}	rolloff period samples
OFDM	orthogonal frequency division multiplexing
PLC	PHY link channel (also physical layer link channel)
PNM	proactive network maintenance
Q	quadrature
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying
RF	radio frequency

RxMER	receive modulation error ratio
SC-QAM	single carrier quadrature amplitude modulation
SCTE	Society of Cable Telecommunications Engineers
SNR	signal-to-noise ratio

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[7] Hranac, R., “Making MER Better: Part 2” (September 2009 *Communications Technology*)

[8] Hranac, R., “Making MER Better: Part 1” (August 2009 *Communications Technology*)

[9] Hranac, R., “Equalized or Unequalized? That is the Question” (February 2007 *Communications Technology*)

[10] Hranac, R., “Modulation Error Ratio” (January 2007 *Communications Technology*)

Appendix

6. Appendix I – Lab Test Results

The following figures highlight data measured during the lab testing. A variable attenuator was set to obtain three nominal levels (power per 6 MHz) at the cable modem inputs (-10 dBmV, 0 dBmV, and +10 dBmV) for each test case. The figures in this section detail the following four parameters.

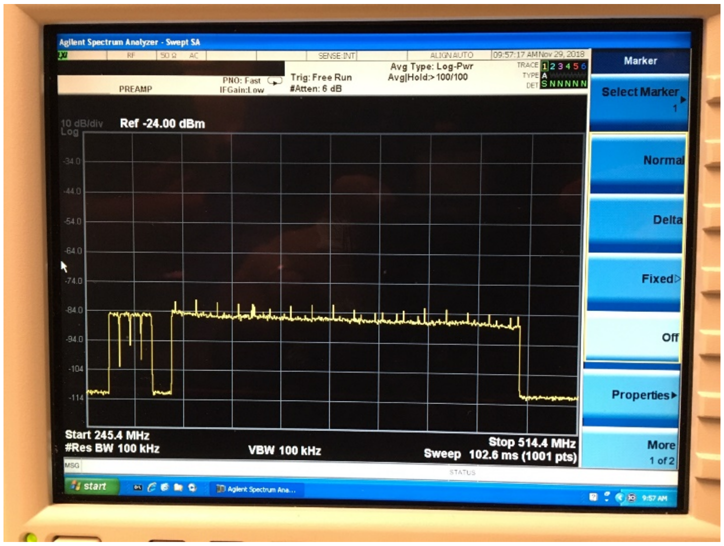
Spectrum analyzer screen capture – A spectrum analyzer was tuned to the OFDM signal under test to show the signal in the frequency domain. The analyzer display was photographed for each test case.

Channel estimate – The downstream channel estimate coefficients (a cable modem's estimate of the downstream channel response) were obtained from a modem in the lab test setup and plotted in graph form.

RxMER per subcarrier – This data for each OFDM subcarrier was obtained from a modem in the lab test setup (same modem used for channel estimate) and plotted in graph form.

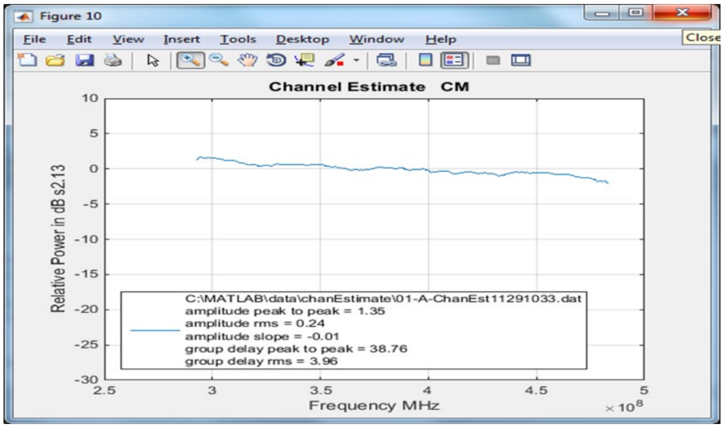
OFDM channel power –A screen capture of OFDM channel power (the RF power per CTA channel) was taken from a Viavi OneExpert field meter. Each short horizontal line represents the power per 6 MHz segment of the OFDM signal.

6.1. Test Case 1A



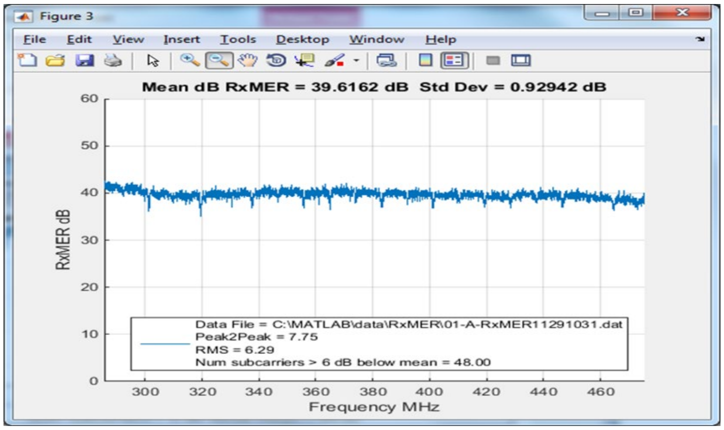
PNO: Fast
IFGain:Low
Trig: Free Run
#Atten: 6 dB
Avg Type: Log-Pwr
Avg|Hold:> 100/100
Ref -24.00 dBm
Start 245.4 MHz
#Res BW 100 kHz
VBW 100 kHz
Stop 514.4 MHz
Sweep 102.6 ms (1001 pts)

Figure 31. Test Case 1A spectrum analyzer screen capture.



C:\MATLAB\data\chanEstimate\01-A-ChanEst11291033.dat
amplitude peak to peak = 1.35
amplitude rms = 0.24
amplitude slope = -0.01
group delay peak to peak = 38.76
group delay rms = 3.96

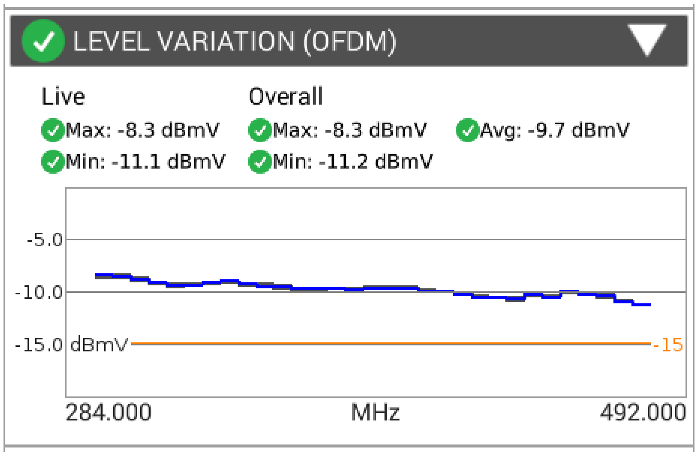
Figure 32. Test Case 1A channel estimate.



Mean dB RxMER = 39.6162 dB Std Dev = 0.92942 dB

Data File = C:\MATLAB\data\RxMER\01-A-RxMER11291031.dat
Peak2Peak = 7.75
RMS = 6.29
Num subcarriers > 6 dB below mean = 48.00

Figure 33. Test Case 1A RxMER per subcarrier.



Live
✓ Max: -8.3 dBmV
✓ Min: -11.1 dBmV

Overall
✓ Max: -8.3 dBmV
✓ Min: -11.2 dBmV
✓ Avg: -9.7 dBmV

Figure 34. Test Case 1A OFDM channel power (nominal -10 dBmV).

6.2. Test Case 1B

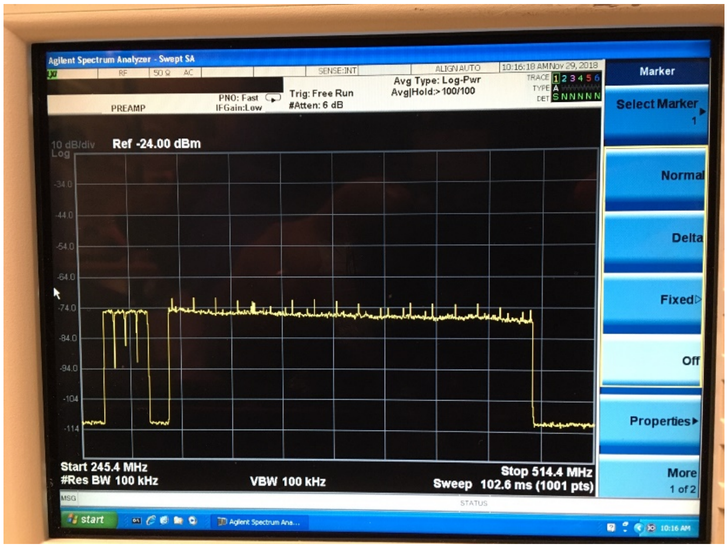


Figure 35. Test Case 1B spectrum analyzer screen capture.

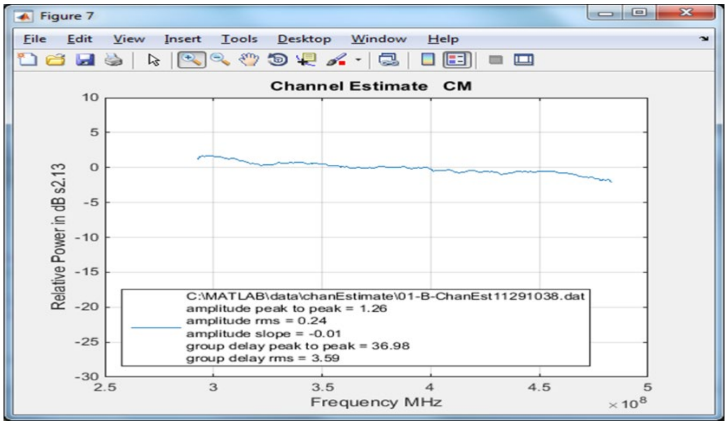


Figure 36. Test Case 1B channel estimate.

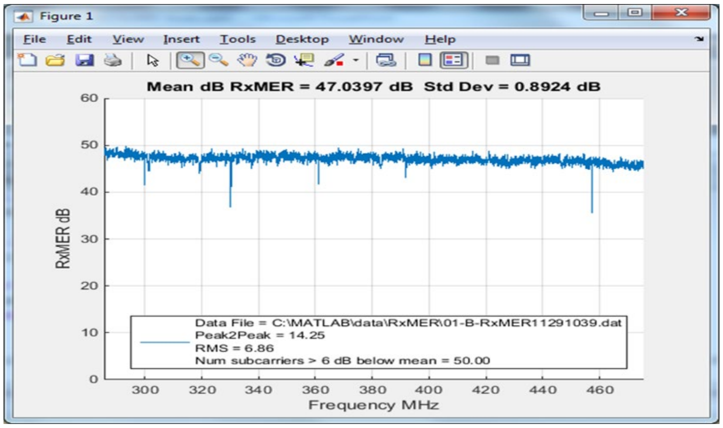
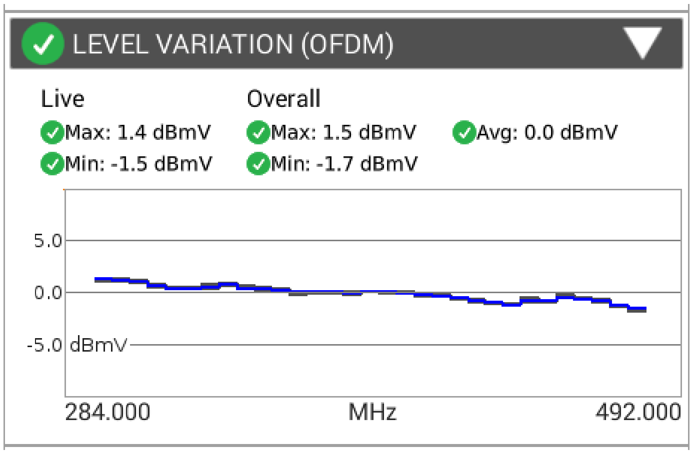


Figure 37. Test Case 1B RxMER per subcarrier.


✓ LEVEL VARIATION (OFDM)

Live
✓ Max: 1.4 dBmV
✓ Min: -1.5 dBmV

Overall
✓ Max: 1.5 dBmV
✓ Min: -1.7 dBmV
✓ Avg: 0.0 dBmV

Figure 38. Test Case 1B OFDM channel power (nominal 0 dBmV).

6.3. Test Case 1C

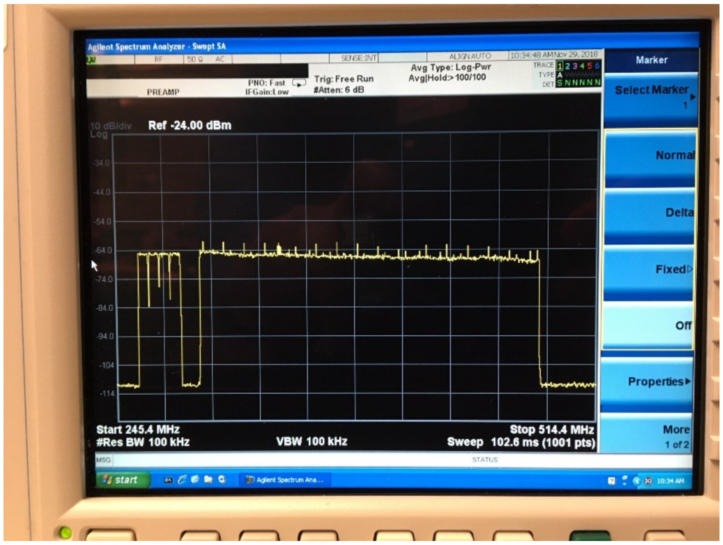

Agilent Spectrum Analyzer - Swept SA
RF 50 Ω AC SENSE:INT ALIGN AUTO 10:34:48 AM Nov 29, 2018
PREAMP PNO: Fast IFGain:Low
Trig: Free Run
#Atten: 6 dB
Avg Type: Log-Pwr
Avg|Hold:> 100/100
TRACE 1 2 3 4 5 6
TYPE A
DET S N N N N N
10 dB/div Log Ref -24.00 dBm
Start 245.4 MHz
#Res BW 100 kHz
VBW 100 kHz
Stop 514.4 MHz
Sweep 102.6 ms (1001 pts)

Figure 39. Test Case 1C spectrum analyzer screen capture.

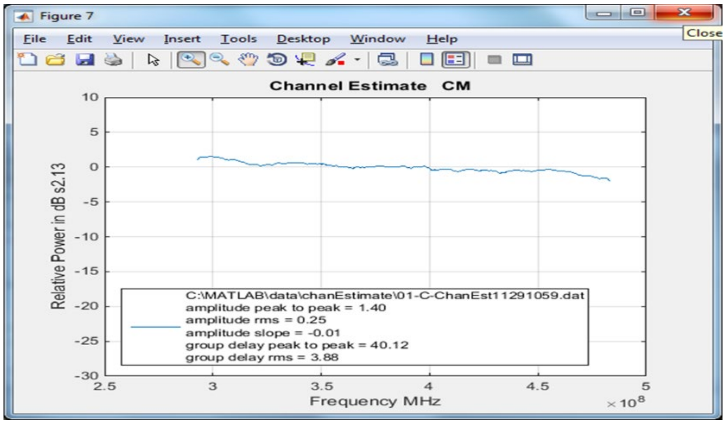

C:\MATLAB\data\chanEstimate\01-C-ChanEst11291059.dat
amplitude peak to peak = 1.40
amplitude rms = 0.25
amplitude slope = -0.01
group delay peak to peak = 40.12
group delay rms = 3.88

Figure 40. Test Case 1C channel estimate.

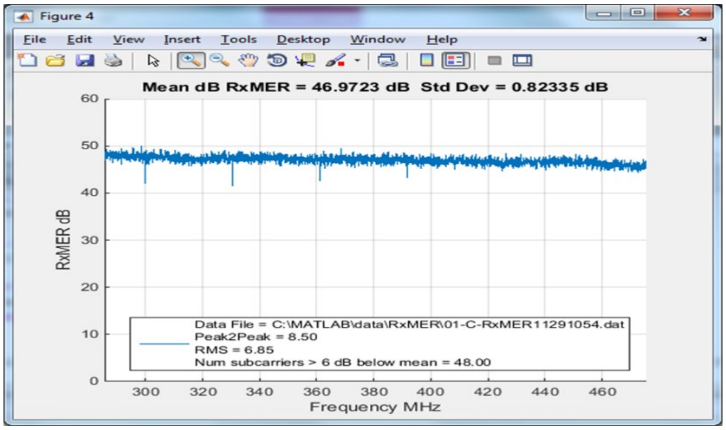


Figure 41. Test Case 1C RxMER per subcarrier.

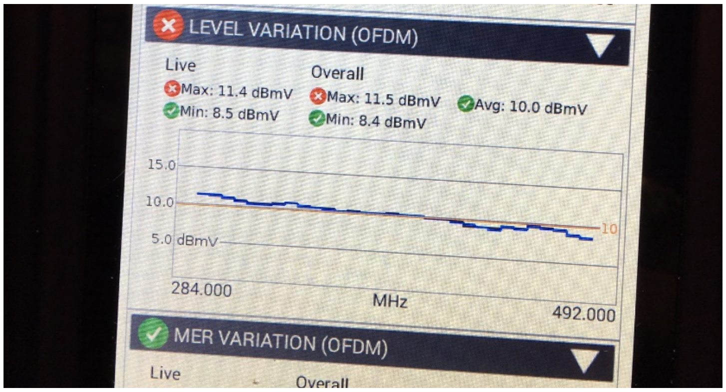


Figure 42. Test Case 1C OFDM channel power (nominal +10 dBmV).

6.4. Test Case 2A

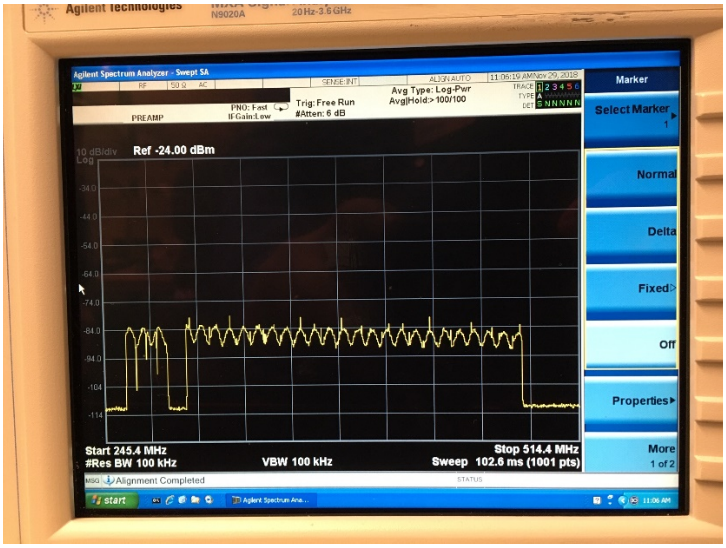
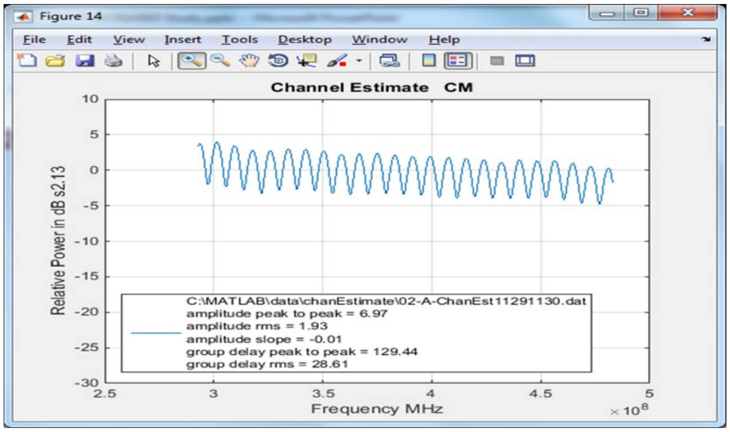
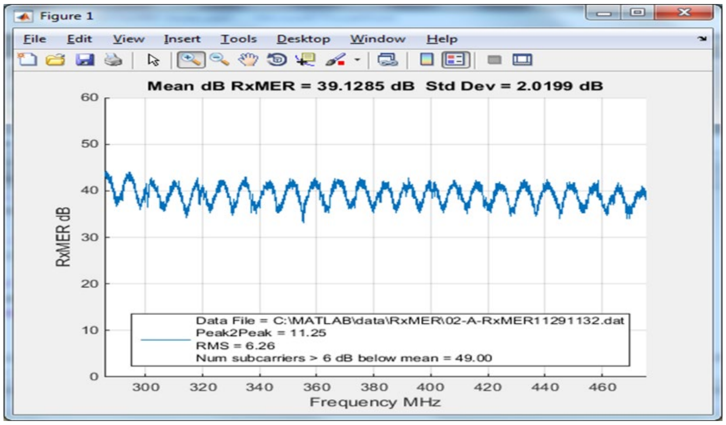


Figure 43. Test Case 2A spectrum analyzer screen capture.



C:\MATLAB\data\chanEstimate\02-A-ChanEst11291130.dat
amplitude peak to peak = 6.97
amplitude rms = 1.93
amplitude slope = -0.01
group delay peak to peak = 129.44
group delay rms = 28.61

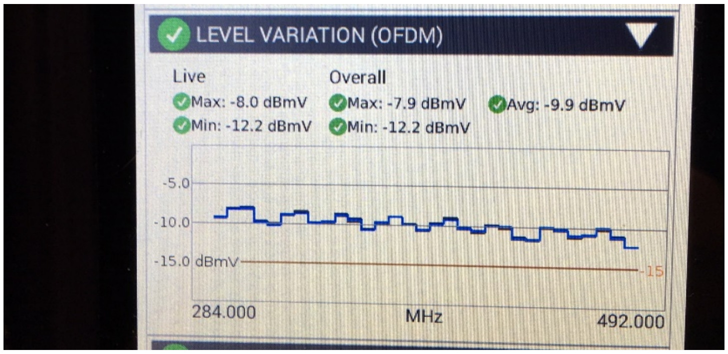
Figure 44. Test Case 2A channel estimate.



Mean dB RxMER = 39.1285 dB Std Dev = 2.0199 dB

Data File = C:\MATLAB\data\RxMER\02-A-RxMER11291132.dat
Peak2Peak = 11.25
RMS = 6.26
Num subcarriers > 6 dB below mean = 49.00

Figure 45. Test Case 2A RxMER per subcarrier.

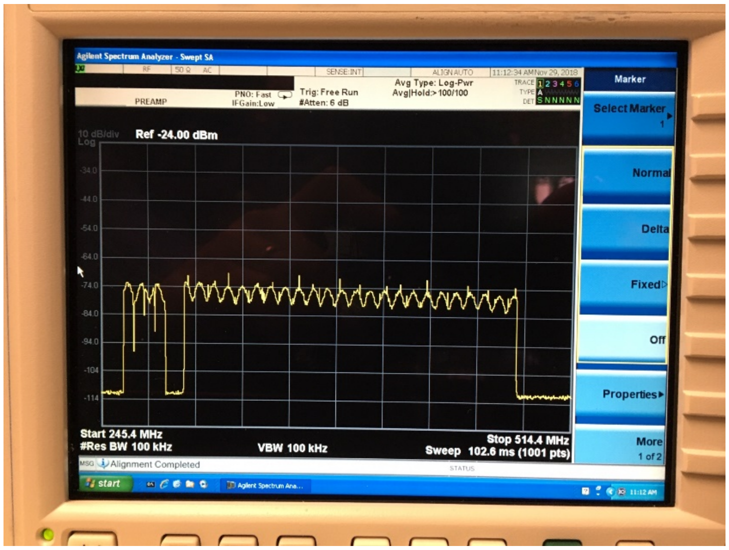


Live
✓ Max: -8.0 dBmV
✓ Min: -12.2 dBmV

Overall
✓ Max: -7.9 dBmV
✓ Min: -12.2 dBmV
✓ Avg: -9.9 dBmV

Figure 46. Test Case 2A OFDM channel power (nominal -10 dBmV).

6.5. Test Case 2B



Agilent Spectrum Analyzer - Swept SA

RF 50 Ω AC SENSE:INT ALIGN AUTO 11:12:34 AM Nov 29, 2018

PREAMP

PNO: Fast

IFGain:Low

Trig: Free Run

#Atten: 6 dB

Avg Type: Log-Pwr

Avg|Hold:>100/100

10 dB/div Log Ref -24.00 dBm

Start 245.4 MHz

#Res BW 100 kHz

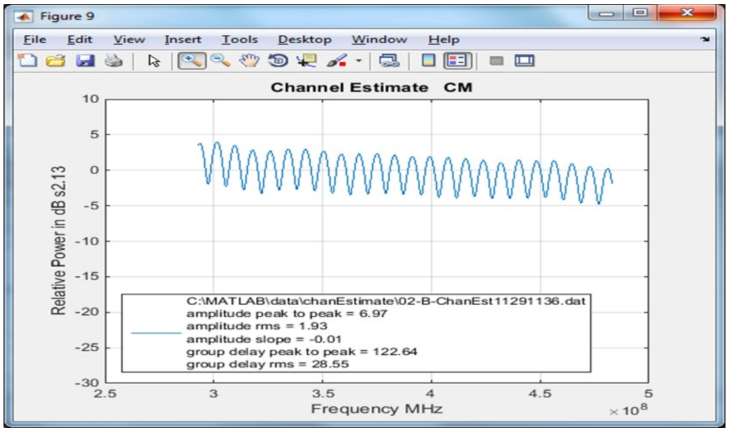
VBW 100 kHz

Stop 514.4 MHz

Sweep 102.6 ms (1001 pts)

Alignment Completed

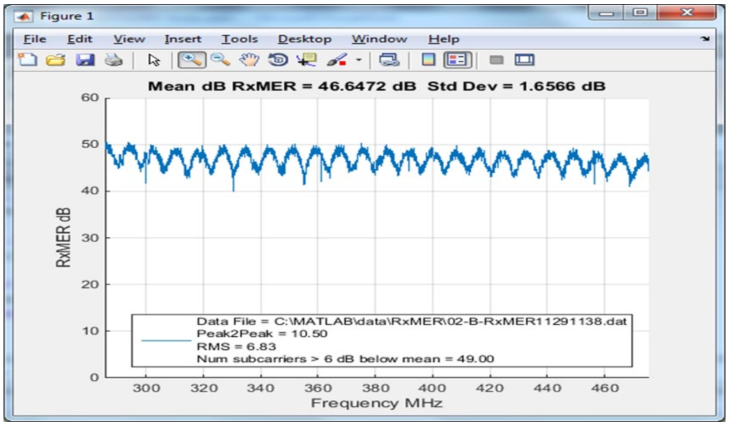
Figure 47. Test Case 2B spectrum analyzer screen capture.



Channel Estimate CM

C:\MATLAB\data\chanEstimate\02-B-ChanEst11291136.dat
amplitude peak to peak = 6.97
amplitude rms = 1.93
amplitude slope = -0.01
group delay peak to peak = 122.64
group delay rms = 28.55

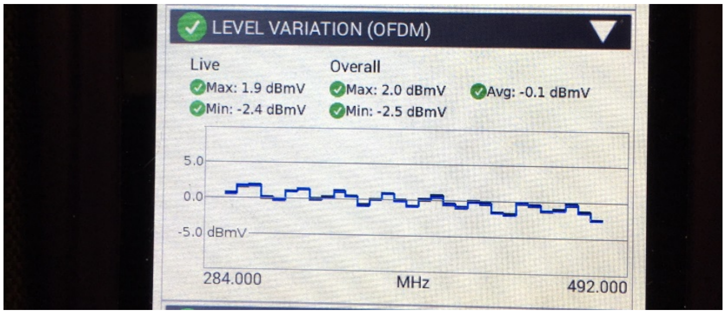
Figure 48. Test Case 2B channel estimate.



Mean dB RxMER = 46.6472 dB Std Dev = 1.6566 dB

Data File = C:\MATLAB\data\RxMER\02-B-RxMER11291138.dat
Peak2Peak = 10.50
RMS = 6.83
Num subcarriers > 6 dB below mean = 49.00

Figure 49. Test Case 2B RxMER per subcarrier.

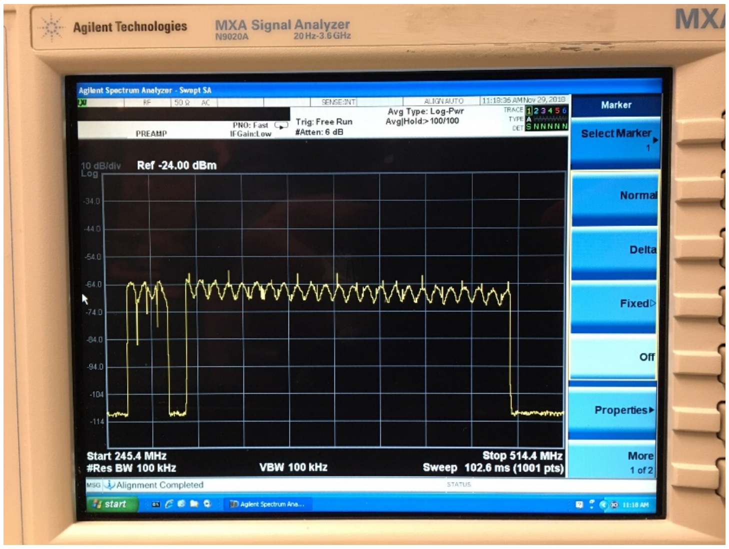

LEVEL VARIATION (OFDM)

Live
Max: 1.9 dBmV
Min: -2.4 dBmV

Overall
Max: 2.0 dBmV
Min: -2.5 dBmV
Avg: -0.1 dBmV

Figure 50. Test Case 2B OFDM channel power (nominal 0 dBmV).

6.6. Test Case 2C


Agilent Spectrum Analyzer - Swept SA

PNO: Fast
IFGain:Low
Trig: Free Run
#Atten: 6 dB
Avg Type: Log-Pwr
Avg|Hold:>100/100
11:18:36 AM Nov 29, 2018

Ref -24.00 dBm

Start 245.4 MHz
#Res BW 100 kHz
VBW 100 kHz
Stop 514.4 MHz
Sweep 102.6 ms (1001 pts)

Alignment Completed

Figure 51. Test Case 2C spectrum analyzer screen capture.

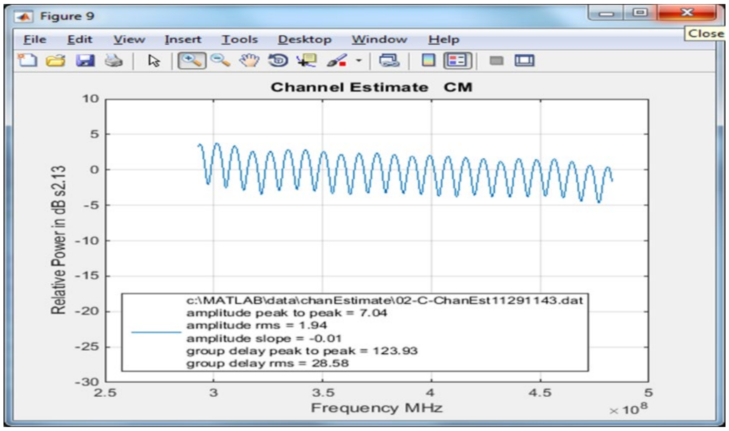
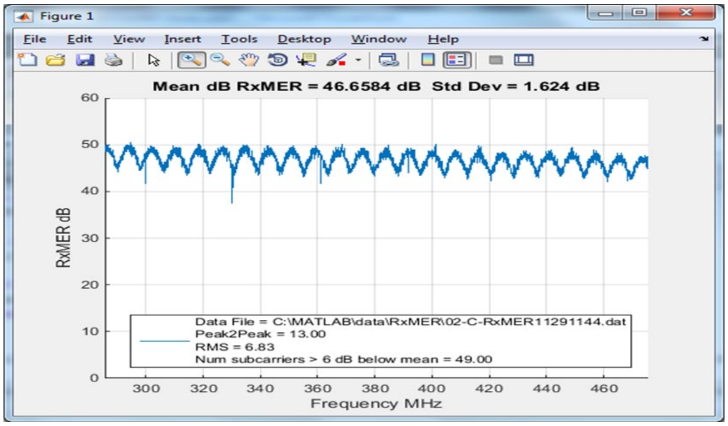

c:\MATLAB\data\chanEstimate\02-C-ChanEst11291143.dat
amplitude peak to peak = 7.04
amplitude rms = 1.94
amplitude slope = -0.01
group delay peak to peak = 123.93
group delay rms = 28.58

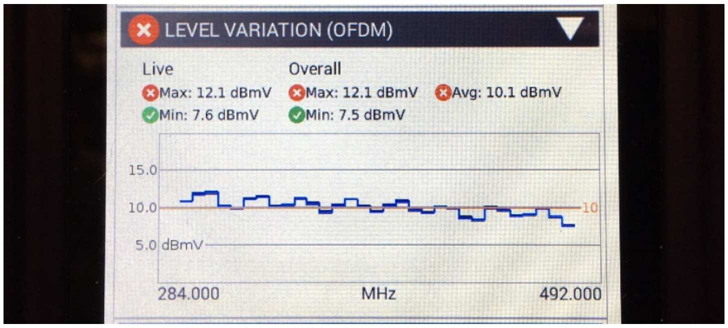
Figure 52. Test Case 2C channel estimate.



Mean dB RxMER = 46.6584 dB Std Dev = 1.624 dB

Data File = C:\MATLAB\data\RxMER\02-C-RxMER11291144.dat
Peak2Peak = 13.00
RMS = 6.83
Num subcarriers > 6 dB below mean = 49.00

Figure 53. Test Case 2C RxMER per subcarrier.

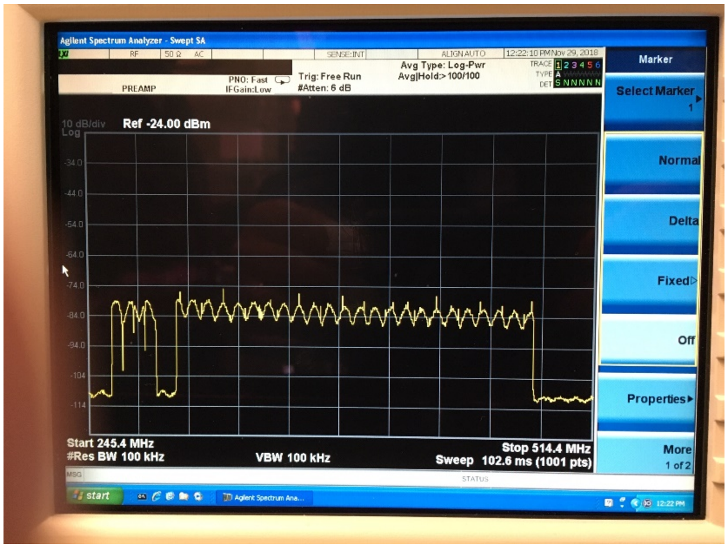


Live
Max: 12.1 dBmV
Min: 7.6 dBmV

Overall
Max: 12.1 dBmV
Min: 7.5 dBmV
Avg: 10.1 dBmV

Figure 54. Test Case 2C OFDM channel power (nominal +10 dBmV).

6.7. Test Case 3A

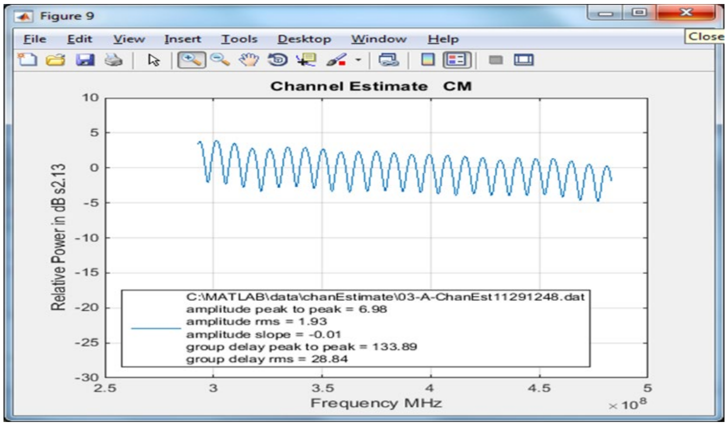


PREAMP
PNO: Fast
IFGain:Low
Trig: Free Run
#Atten: 6 dB
Avg Type: Log-Pwr
Avg|Hold:>100/100
12:22:10 PM Nov 29, 2018

Ref -24.00 dBm

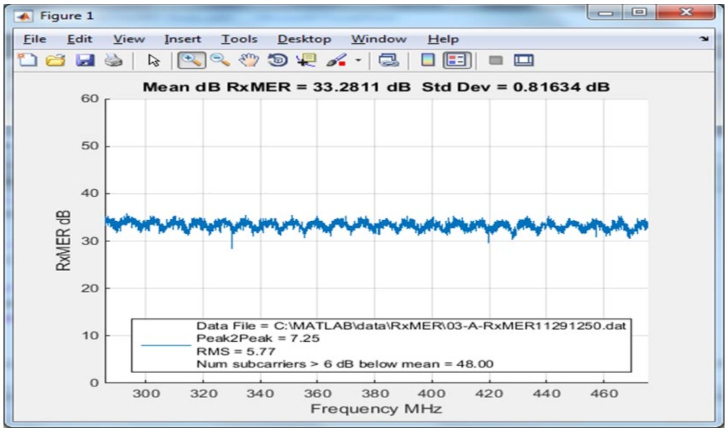
Start 245.4 MHz
#Res BW 100 kHz
VBW 100 kHz
Stop 514.4 MHz
Sweep 102.6 ms (1001 pts)

Figure 55. Test Case 3A spectrum analyzer screen capture.



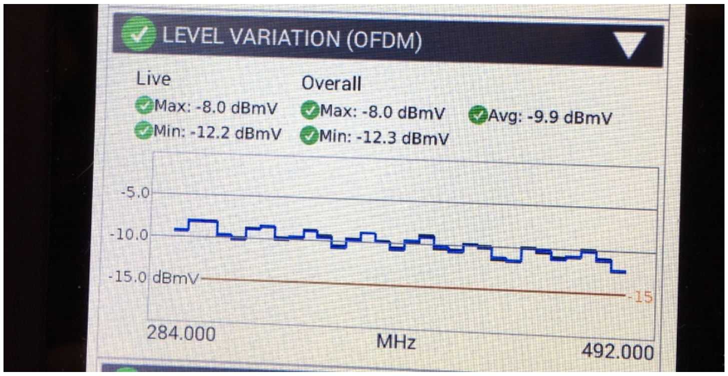
C:\MATLAB\data\chanEstimate\03-A-ChanEst11291248.dat
amplitude peak to peak = 6.98
amplitude rms = 1.93
amplitude slope = -0.01
group delay peak to peak = 133.89
group delay rms = 28.84

Figure 56. Test Case 3A channel estimate.



Data File = C:\MATLAB\data\RxMER\03-A-RxMER11291250.dat
Peak2Peak = 7.25
RMS = 5.77
Num subcarriers > 6 dB below mean = 48.00

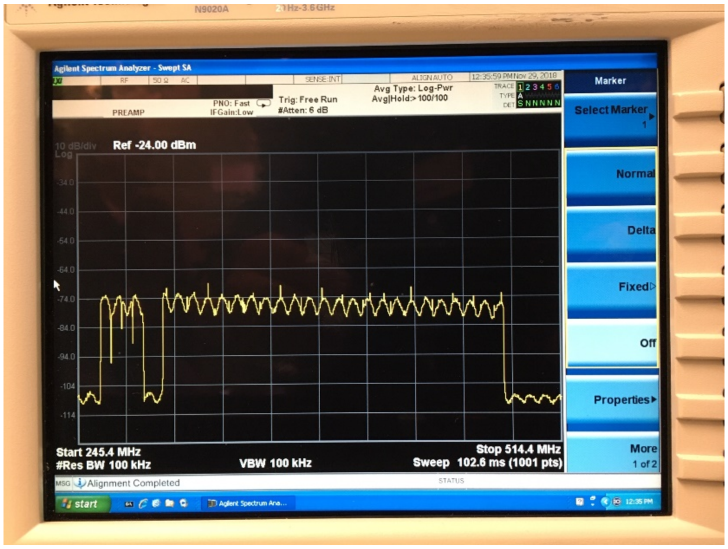
Figure 57. Test Case 3A RxMER per subcarrier.



Live
✓Max: -8.0 dBmV
✓Min: -12.2 dBmV
Overall
✓Max: -8.0 dBmV
✓Min: -12.3 dBmV
✓Avg: -9.9 dBmV

Figure 58. Test Case 3A OFDM channel power (nominal -10 dBmV).

6.8. Test Case 3B


Agilent Spectrum Analyzer - Swept SA

PNO: Fast
IFGain:Low
Trig: Free Run
#Atten: 6 dB
Avg Type: Log-Pwr
Avg|Hold:> 100/100

Ref -24.00 dBm

Start 245.4 MHz
#Res BW 100 kHz
VBW 100 kHz
Stop 514.4 MHz
Sweep 102.6 ms (1001 pts)

Alignment Completed

Figure 59. Test Case 3B spectrum analyzer screen capture.

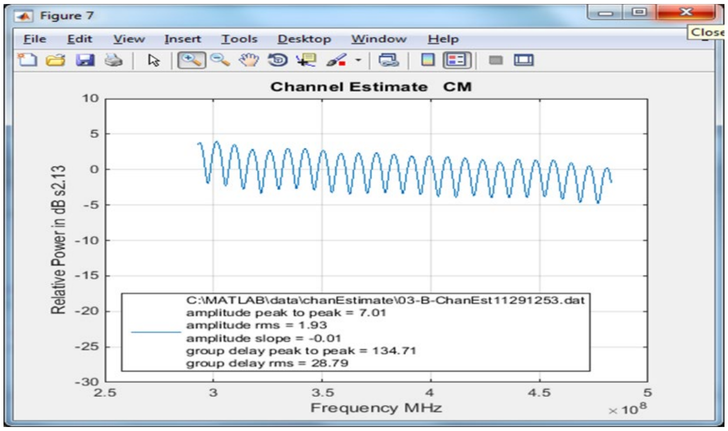
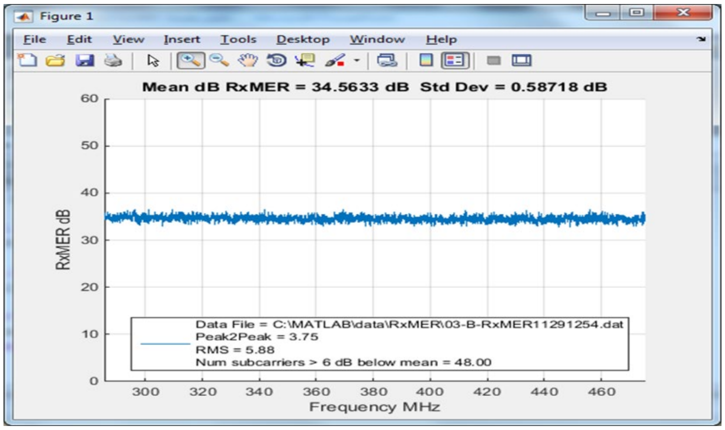
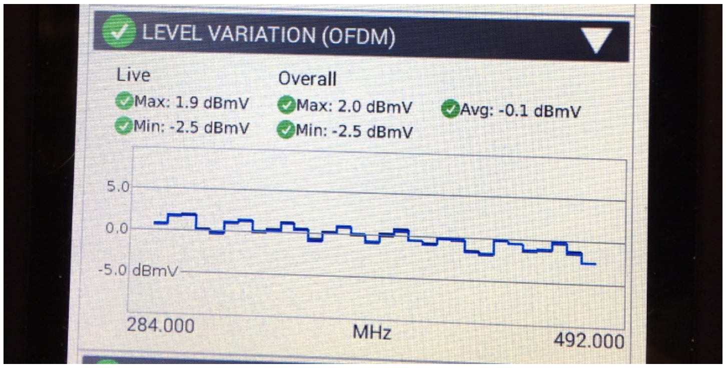

C:\MATLAB\data\chanEstimate\03-B-ChanEst11291253.dat
amplitude peak to peak = 7.01
amplitude rms = 1.93
amplitude slope = -0.01
group delay peak to peak = 134.71
group delay rms = 28.79

Figure 60. Test Case 3B channel estimate.


Mean dB RxMER = 34.5633 dB Std Dev = 0.58718 dB

Data File = C:\MATLAB\data\RxMER\03-B-RxMER11291254.dat
Peak2Peak = 3.75
RMS = 5.88
Num subcarriers > 6 dB below mean = 48.00

Figure 61. Test Case 3B RxMER per subcarrier.



Live
Max: 1.9 dBmV
Min: -2.5 dBmV

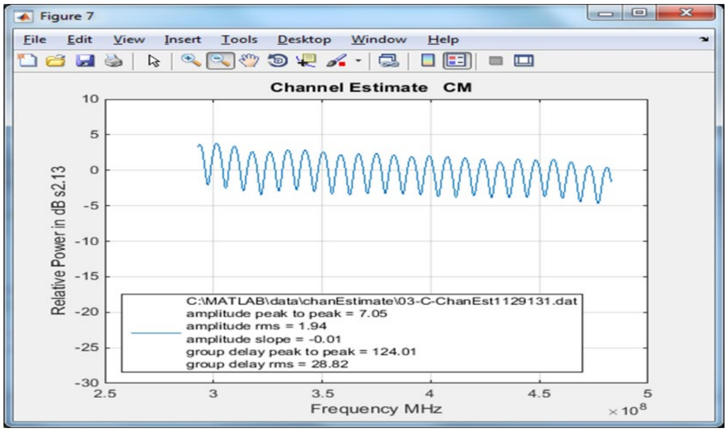
Overall
Max: 2.0 dBmV
Min: -2.5 dBmV
Avg: -0.1 dBmV

Figure 62. Test Case 3B OFDM channel power (nominal 0 dBmV).

6.9. Test Case 3C

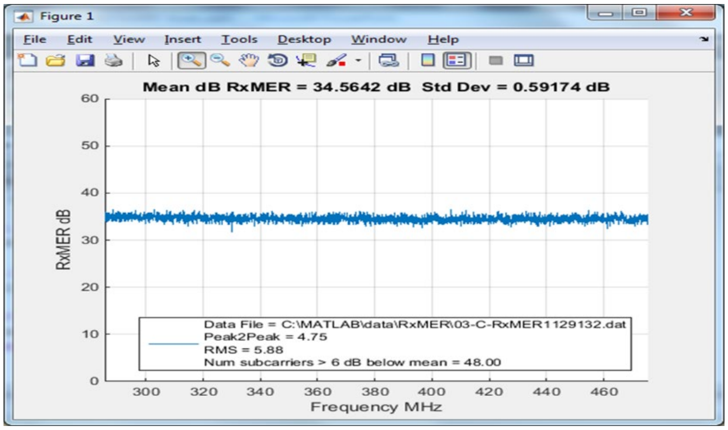
12:39:01 PM Nov 29, 2018
PREAMP
PNO: Fast
IFGain:Low
Trig: Free Run
#Atten: 6 dB
Avg Type: Log-Pwr
Avg|Hold:> 100/100
Ref -24.00 dBm
Start 245.4 MHz
#Res BW 100 kHz
VBW 100 kHz
Stop 514.4 MHz
Sweep 102.6 ms (1001 pts)
Alignment Completed

Figure 63. Test Case 3C spectrum analyzer screen capture.



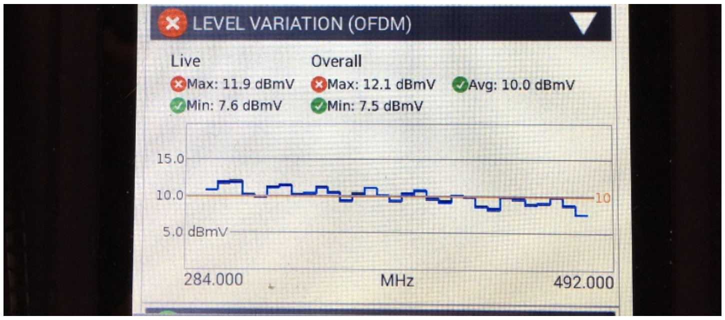
C:\MATLAB\data\chanEstimate\03-C-ChanEst1129131.dat
amplitude peak to peak = 7.05
amplitude rms = 1.94
amplitude slope = -0.01
group delay peak to peak = 124.01
group delay rms = 28.82

Figure 64. Test Case 3C channel estimate.



Data File = C:\MATLAB\data\RxMER\03-C-RxMER1129132.dat
Peak2Peak = 4.75
RMS = 5.88
Num subcarriers > 6 dB below mean = 48.00

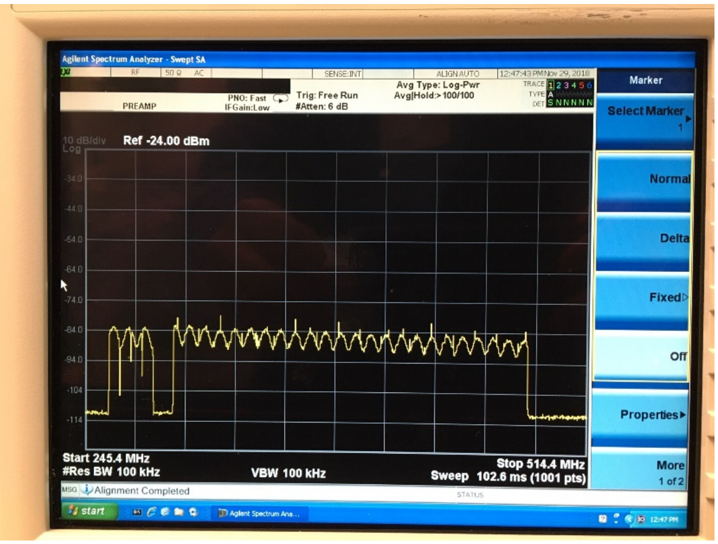
Figure 65. Test Case 3C RxMER per subcarrier.



Live
Max: 11.9 dBmV
Min: 7.6 dBmV
Overall
Max: 12.1 dBmV
Min: 7.5 dBmV
Avg: 10.0 dBmV

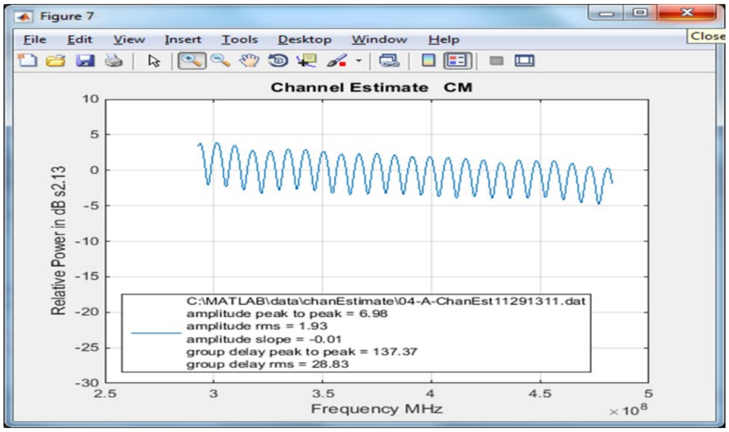
Figure 66. Test Case 3C OFDM channel power (nominal +10 dBmV).

6.10. Test Case 4A



RF 50 Ω AC SENSE:INT ALIGN AUTO 12:47:43 PM Nov 29, 2018
[redacted]
PREAMP
PNO: Fast
IFGain:Low
Trig: Free Run
#Atten: 6 dB
Avg Type: Log-Pwr
Avg|Hold:> 100/100
TRACE 1 2 3 4 5 6
TYPE A WWWWW
DET S N N N N N
Ref -24.00 dBm
Start 245.4 MHz
#Res BW 100 kHz
VBW 100 kHz
Stop 514.4 MHz
Sweep 102.6 ms (1001 pts)
MSG Alignment Completed
STATUS

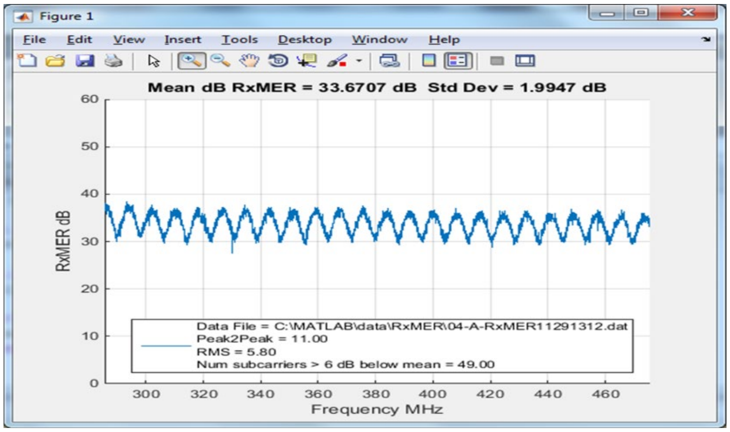
Figure 67. Test Case 4A spectrum analyzer screen capture.



Channel Estimate CM

C:\MATLAB\data\chanEstimate\04-A-ChanEst11291311.dat
amplitude peak to peak = 6.98
amplitude rms = 1.93
amplitude slope = -0.01
group delay peak to peak = 137.37
group delay rms = 28.83

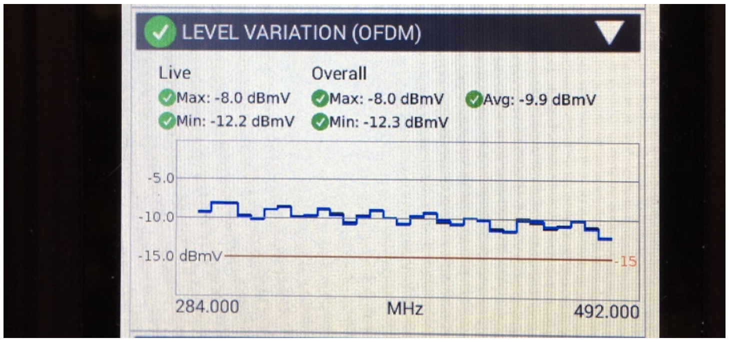
Figure 68. Test Case 4A channel estimate.



Mean dB RxMER = 33.6707 dB Std Dev = 1.9947 dB

Data File = C:\MATLAB\data\RxMER\04-A-RxMER11291312.dat
Peak2Peak = 11.00
RMS = 5.80
Num subcarriers > 6 dB below mean = 49.00

Figure 69. Test Case 4A RxMER per subcarrier.

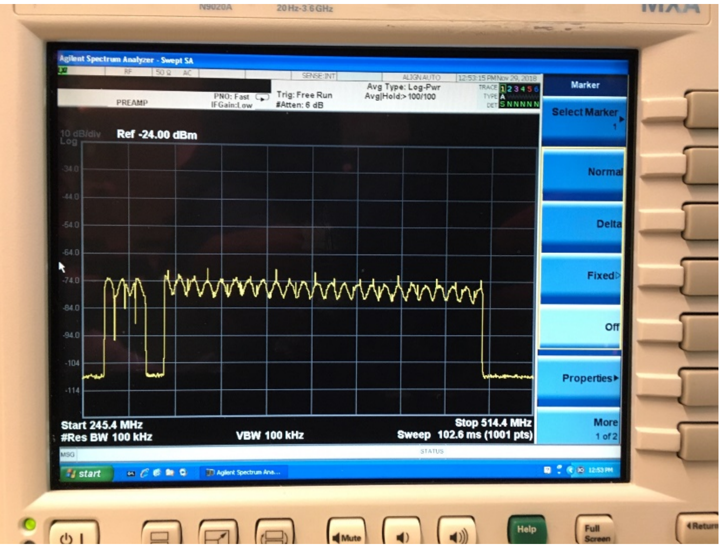


Live
✓ Max: -8.0 dBmV
✓ Min: -12.2 dBmV

Overall
✓ Max: -8.0 dBmV
✓ Min: -12.3 dBmV
✓ Avg: -9.9 dBmV

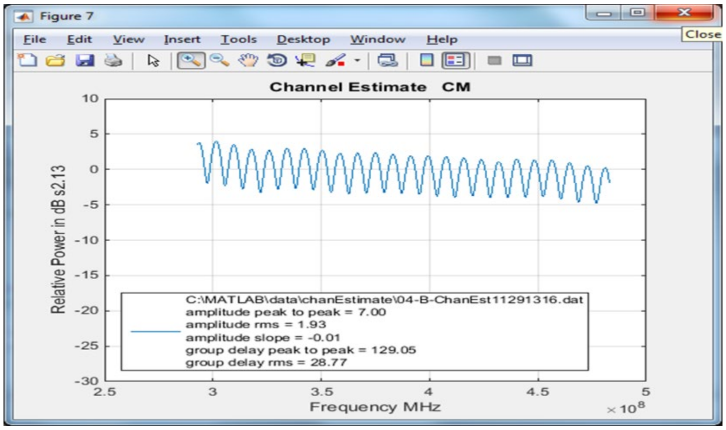
Figure 70. Test Case 4A OFDM channel power (nominal -10 dBmV).

6.11. Test Case 4B



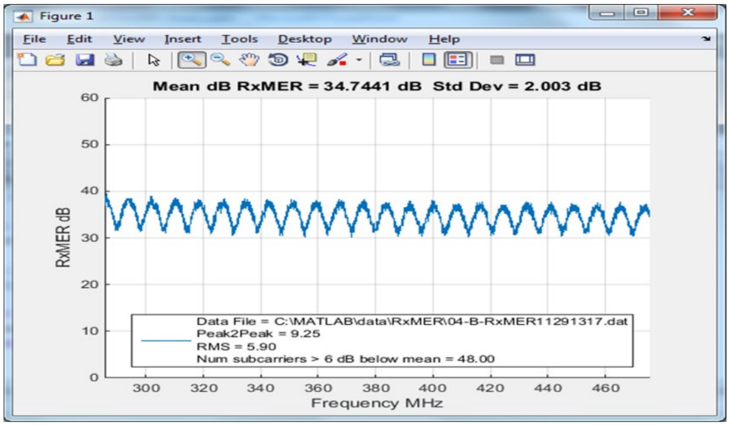
PNO: Fast
IFGain:Low
Trig: Free Run
#Atten: 6 dB
Avg Type: Log-Pwr
Avg|Hold:> 100/100
Ref -24.00 dBm
Start 245.4 MHz
#Res BW 100 kHz
VBW 100 kHz
Stop 514.4 MHz
Sweep 102.6 ms (1001 pts)

Figure 71. Test Case 4B spectrum analyzer screen capture.



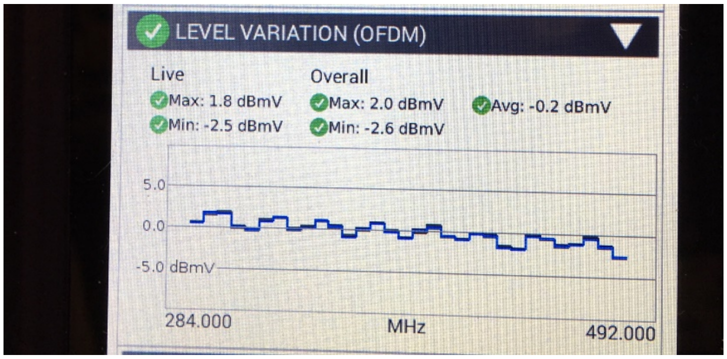
C:\MATLAB\data\chanEstimate\04-B-ChanEst11291316.dat
amplitude peak to peak = 7.00
amplitude rms = 1.93
amplitude slope = -0.01
group delay peak to peak = 129.05
group delay rms = 28.77

Figure 72. Test Case 4B channel estimate.



Data File = C:\MATLAB\data\RxMER\04-B-RxMER11291317.dat
Peak2Peak = 9.25
RMS = 5.90
Num subcarriers > 6 dB below mean = 48.00

Figure 73. Test Case 4B RxMER per subcarrier.


LEVEL VARIATION (OFDM)

Live
Max: 1.8 dBmV
Min: -2.5 dBmV

Overall
Max: 2.0 dBmV
Min: -2.6 dBmV
Avg: -0.2 dBmV

Figure 74. Test Case 4B OFDM channel power (nominal 0 dBmV).

6.12. Test Case 4C

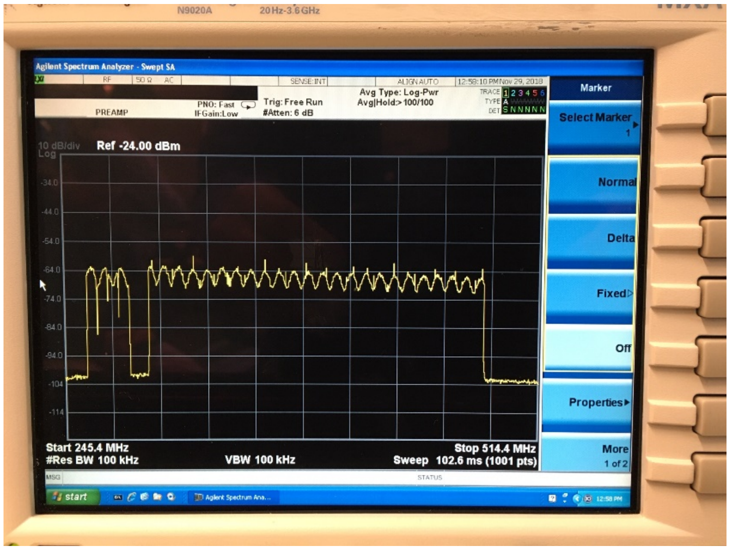

Agilent Spectrum Analyzer - Swept SA
RF 50 Ω AC SENSE:INT ALIGN AUTO 12:58:10 PM Nov 29, 2018
PREAMP PNO: Fast IFGain:Low
Trig: Free Run
#Atten: 6 dB
Avg Type: Log-Pwr
Avg|Hold:> 100/100
10 dB/div Log Ref -24.00 dBm
Start 245.4 MHz
#Res BW 100 kHz
VBW 100 kHz
Stop 514.4 MHz
Sweep 102.6 ms (1001 pts)

Figure 75. Test Case 4C spectrum analyzer screen capture.

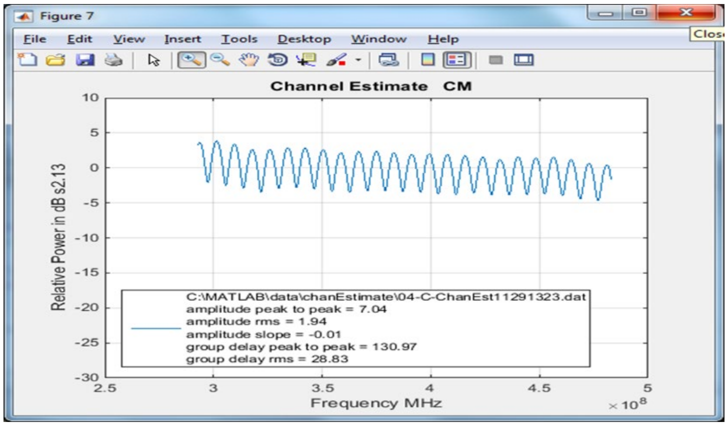

C:\MATLAB\data\chanEstimate\04-C-ChanEst11291323.dat
amplitude peak to peak = 7.04
amplitude rms = 1.94
amplitude slope = -0.01
group delay peak to peak = 130.97
group delay rms = 28.83

Figure 76. Test Case 4C channel estimate.

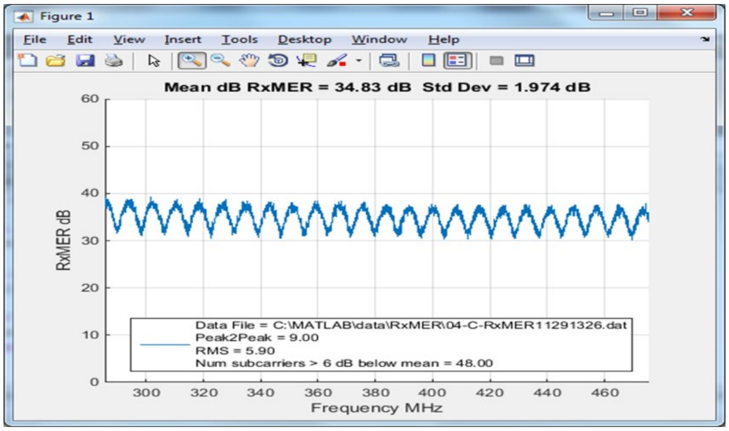


Figure 77. Test Case 4C RxMER per subcarrier.

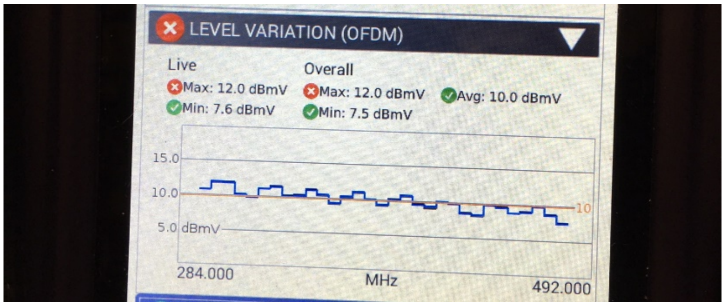


Figure 78. Test Case 4C OFDM channel power (nominal +10 dBmV).

6.13. Test Case 5A

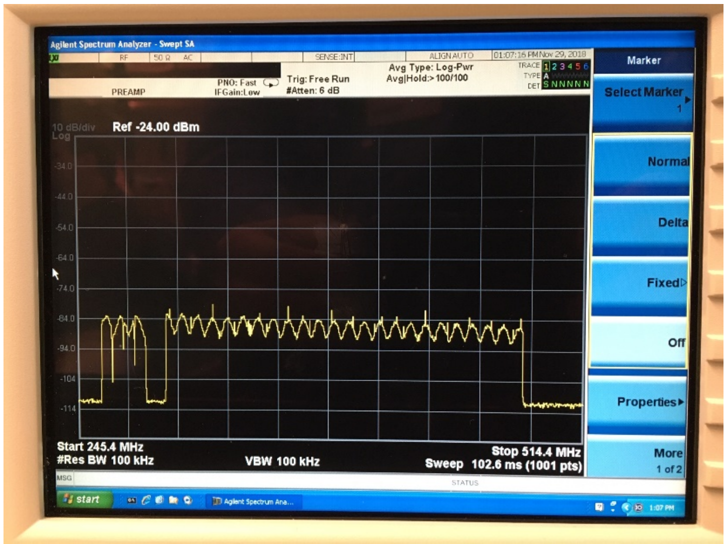
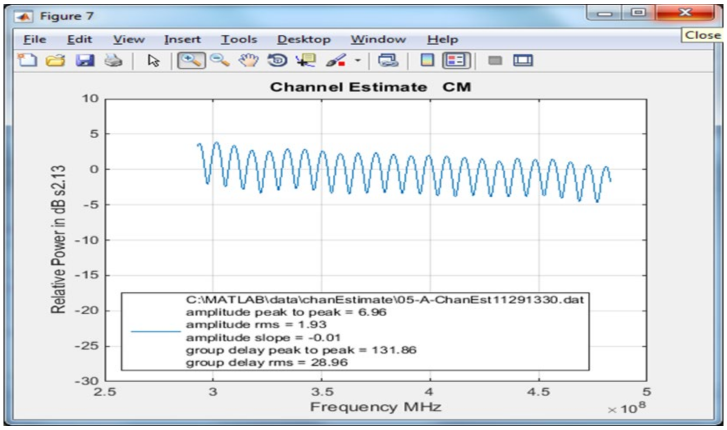
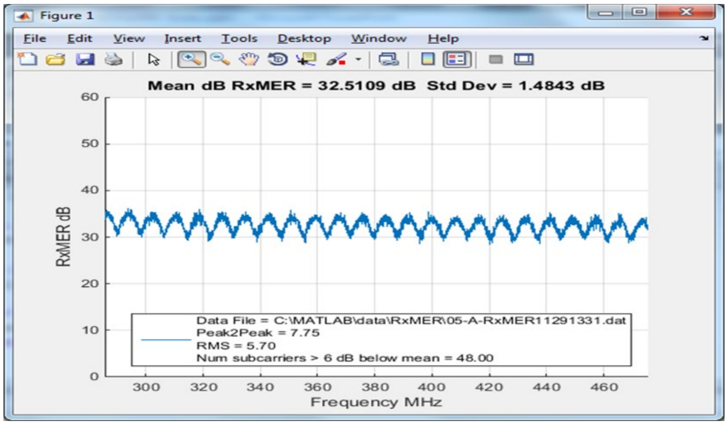


Figure 79. Test Case 5A spectrum analyzer screen capture.



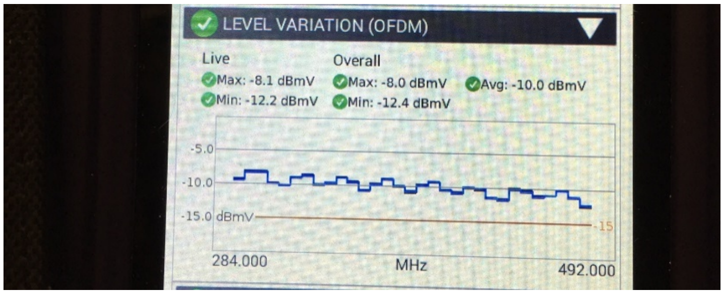
C:\MATLAB\data\chanEstimate\05-A-ChanEst11291330.dat
amplitude peak to peak = 6.96
amplitude rms = 1.93
amplitude slope = -0.01
group delay peak to peak = 131.86
group delay rms = 28.96

Figure 80. Test Case 5A channel estimate.



Data File = C:\MATLAB\data\RxMER\05-A-RxMER11291331.dat
Peak2Peak = 7.75
RMS = 5.70
Num subcarriers > 6 dB below mean = 48.00

Figure 81. Test Case 5A RxMER per subcarrier.



Live
Max: -8.1 dBmV
Min: -12.2 dBmV
Overall
Max: -8.0 dBmV
Min: -12.4 dBmV
Avg: -10.0 dBmV

Figure 82. Test Case 5A OFDM channel power (nominal -10 dBmV).

6.14. Test Case 5B


Agilent Spectrum Analyzer - Swept SA

PNO: Fast
IFGain:Low
Trig: Free Run
#Atten: 6 dB
Avg Type: Log-Pwr
Avg|Hold:> 100/100

Ref -24.00 dBm

Start 245.4 MHz
#Res BW 100 kHz
VBW 100 kHz
Stop 514.4 MHz
Sweep 102.6 ms (1001 pts)

Figure 83. Test Case 5B spectrum analyzer screen capture.

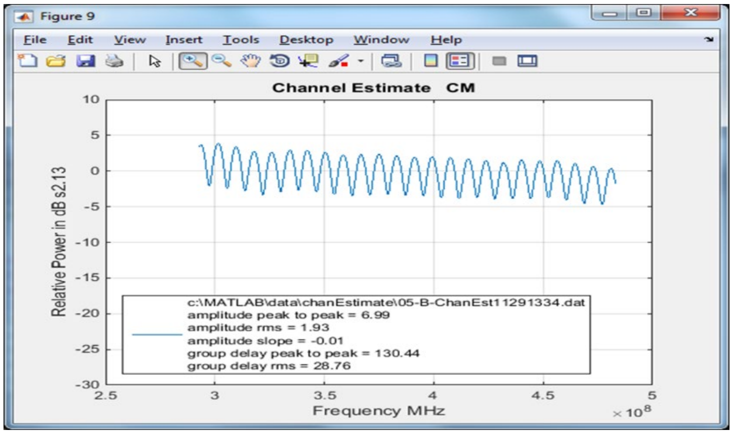
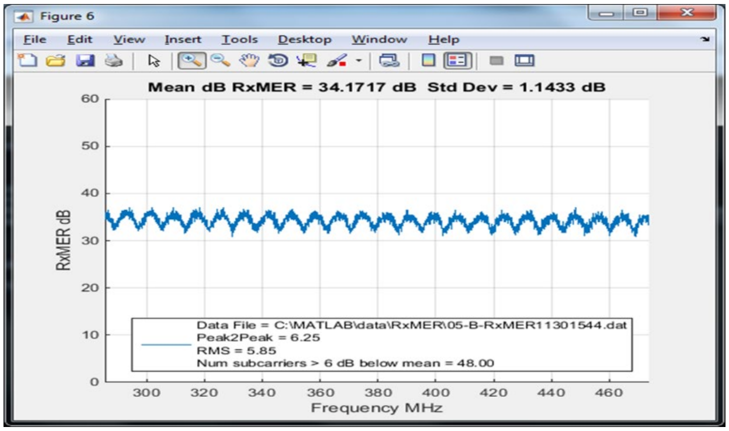
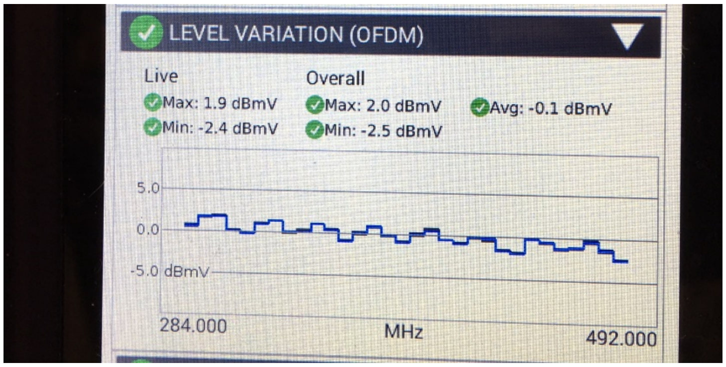

c:\MATLAB\data\chanEstimate\05-B-ChanEst11291334.dat
amplitude peak to peak = 6.99
amplitude rms = 1.93
amplitude slope = -0.01
group delay peak to peak = 130.44
group delay rms = 28.76

Figure 84. Test Case 5B channel estimate.


Mean dB RxMER = 34.1717 dB Std Dev = 1.1433 dB

Data File = C:\MATLAB\data\RxMER\05-B-RxMER11301544.dat
Peak2Peak = 6.25
RMS = 5.85
Num subcarriers > 6 dB below mean = 48.00

Figure 85. Test Case 5B RxMER per subcarrier.



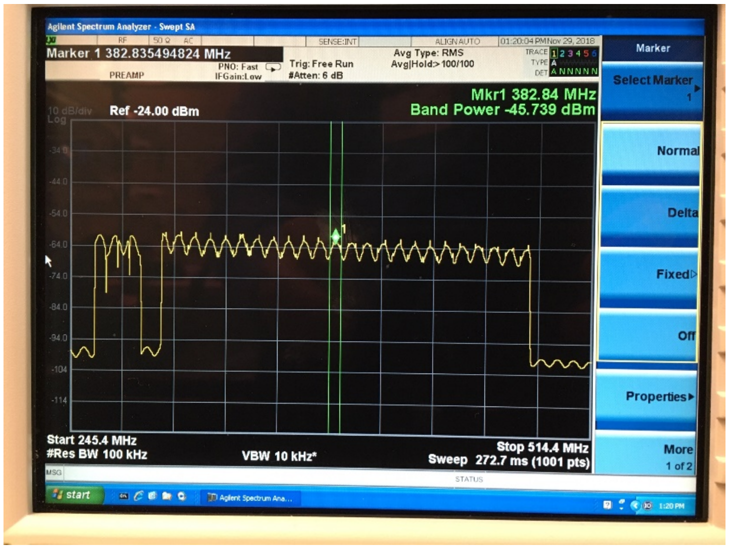
LEVEL VARIATION (OFDM)

Live
Max: 1.9 dBmV
Min: -2.4 dBmV

Overall
Max: 2.0 dBmV
Min: -2.5 dBmV
Avg: -0.1 dBmV

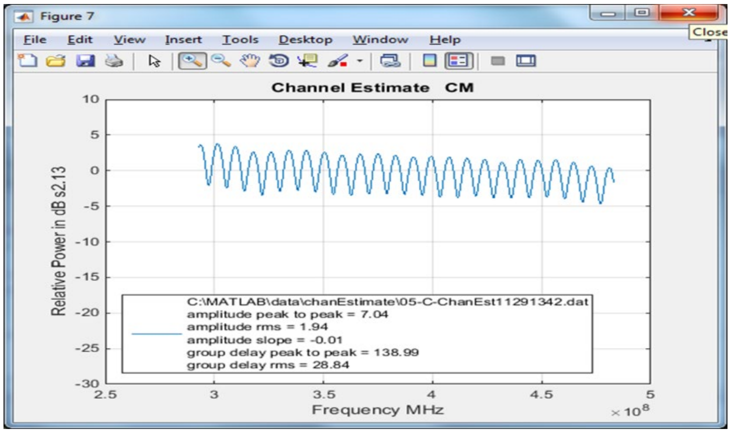
Figure 86. Test Case 5B OFDM channel power (nominal 0 dBmV).

6.15. Test Case 5C



Marker 1 382.835494824 MHz
Trig: Free Run
#Atten: 6 dB
Avg Type: RMS
Avg|Hold:>100/100
Mkr1 382.84 MHz
Band Power -45.739 dBm
Ref -24.00 dBm
Start 245.4 MHz
#Res BW 100 kHz
VBW 10 kHz*
Stop 514.4 MHz
Sweep 272.7 ms (1001 pts)

Figure 87. Test Case 5C spectrum analyzer capture.



C:\MATLAB\data\chanEstimate\05-C-ChanEst11291342.dat
amplitude peak to peak = 7.04
amplitude rms = 1.94
amplitude slope = -0.01
group delay peak to peak = 138.99
group delay rms = 28.84

Figure 88. Test Case 5C channel estimate.

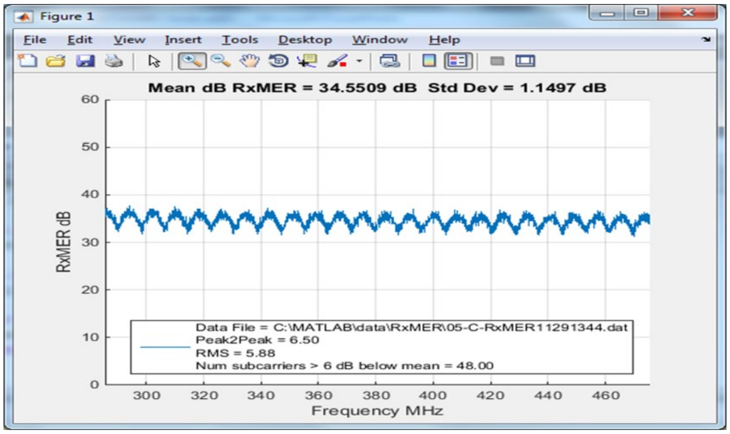


Figure 89. Test Case 5C RxMER per subcarrier.

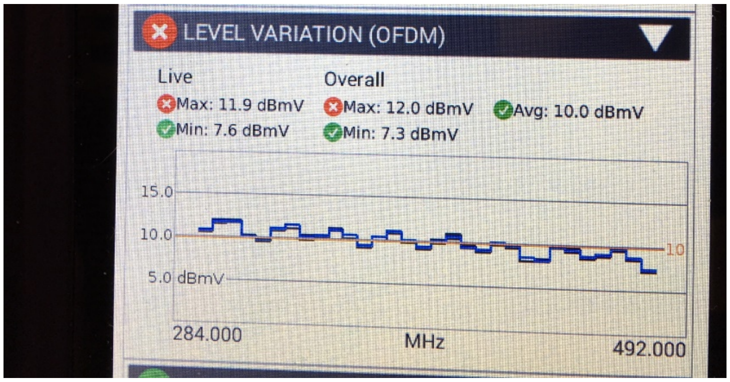


Figure 90. Test Case 5C OFDM channel power (nominal +10 dBmV).

7. Appendix II – Acknowledgements

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