OPTIMIZING UPSTREAM THROUGHPUT USING EQUALIZATION COEFFICIENT ANALYSIS

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Abstract

The current economic climate and increasingly competitive marketplace is driving cable operators to optimize utilization and efficiency of their upstream plant. However, a problem exists when more bandwidth is utilized, as more efficient, but also more sensitive, modulation schemes are leveraged. Impairments that had previously gone unnoticed now present a significant barrier. An understanding of these problematic impairments is critical in order to properly identify, estimate, isolate, and minimize their impact to support this critical transition cable operator's now face. A goal of this paper will be to expose these key impairments that must be managed, and present a strategy for successful optimization of bandwidth utilization and efficiency.

One powerful tool that cable operators have at their disposal is the transmit pre-equalization feature (Pre-Eq) of DOCSIS. Pre-Eq is mandated by CableLabs for interoperability among vendors, and is required of all certified cable modems (CMs) and cable modem termination systems (CMTSs). Its primary function is to mitigate impairments which severely degrade upstream DOCSIS signals. It is not uncommon for the Pre-Eq feature to achieve performance improvements such that Bit-Error-Rate (BER) and Modulation-Error-Ratio (MER) support near error-free operation in an upstream environment that would otherwise be unable to support the transmission at all. Additionally, Pre-Eq has helped DOCSIS upstream signals work in environments where some test equipment will not even work.

While repairing damaged waveforms for detection is the primary Pre-Eq function, in doing so the algorithm learns important information about impairments in the plant. Simple query and analysis of the Pre-Eq coefficients can reveal the dominant impairment for which the CM-CMTS link is compensating. Conclusions may be drawn regarding the impairment contributions, including Micro-Reflections, Group Delay Variation (GDV), and Amplitude Distortion (AD). A plurality of DOCSIS terminal devices, such as CMs, may be engaged in an effort to isolate and minimize a dominant impairment.

INTRODUCTION

This paper will discuss the identification of return path impairments that can be derived by a comprehensive understanding and careful analysis of the data obtained as part of the Pre-Eq function. Conclusions can be drawn based upon coefficient analysis of the DOCSIS 2.0 Pre-Eq settings that the CM-CMTS link collaborate to create. Limits at which Pre-Eq will fail will be provided for conditions of Micro-Reflection impairment only, and a combination of Micro-Reflection, GDV, and AD impairments. These failure thresholds identify at which point the channel is too impaired to function properly, or with reasonable margin. Definition of "reasonable" margin varies among cable operators, but identifying limits will empower cable operators with the tools necessary to ensure their return plant is within their criteria.

This paper will demonstrate a mathematical simulation, supported by laboratory verification, as well as live CATV plant tests, all of which were used to establish and validate the proposed limits. A systematic approach for isolating discussed impairments within a CATV plant will be proposed. This extension of the Pre-Eq information into the realm of HFC maintenance enables cable operators to identify suspect CATV plant components that may be contributing to an impairment problem, and thus take corrective action pro-actively.

EQUALIZATION

This section introduces the fundamental digital communications receiver function of equalization, and how the operation of the equalizer generates coefficient information that can be used for diagnostic purposes. While equalization is part of virtually all modern telecommunications platforms, for cable it is instrumental in proper return operation for advanced DOCSIS systems. In order to offer higher data rates to its subscribers in the competitive world of high-speed Internet access, operators must take advantage of the throughput benefits gained from leveraging more complex digital modulation schemes, such as 32-QAM and 64-QAM. Unfortunately, these schemes are also considerably more sensitive to digital communication channel impairments than the 16-QAM channels (maximum) they are replacing in the return band.

HFC Impairments

Equalizers are very powerful tools within the digital receiver, and they can hide a lot of sins. Relevant return path impairments that can be mitigated by equalization include Micro-Reflections, AD, GDV, and Narrowband Interference. Amplitude Distortion is also referred to as Attenuation Distortion (AD). GDV, a phase-related distortion, is also commonly referred to as Group Delay Distortion (GDD) or Envelope Delay Distortion (EDD) in the telephony world.

It is important to recognize that impulse and thermal noise will reduce the equalization algorithm's ability to mitigate these aforementioned impairments. These commonplace impairments introduce random amplitude and possibly decision errors that the equalization algorithm operates on. Successful application of coefficient analysis assumes that the CATV plant meets sufficient impulse and noise requirements necessary to support a desired modulation level use. However, the fact that some level of these noise contributors exists will introduce some error into the calculated Pre-Eq solution. These issues can be overcome with modifications to the Pre-Eq update approach, but as a closed loop system, it requires careful analysis of the plant conditions to ensure stability of operation.

Digital Signal Characteristics

The digital signal characteristics used to generate all of the data presented in this paper are as shown in Table 1. The 6.4 MHz DOCSIS channel bandwidth was chosen because its widened bandwidth makes it more sensitive to impairments. Of the two formats, clearly 64-QAM is the more sensitive of the two. This actually makes the more robust wideband 16-QAM particularly valuable as a diagnostic tool in this mode.

Table 1 - Signal Characteristics

16-QAM	64-QAM
5.12 Msym/sec	
6.4 MHz	
20.48 Mbps	30.72 Mbps

RRC Matching (α = 0.25)
Square Constellation (max/min = ±1v)

Equalization Fundamentals

Equalization is the process by which a digital communications receiver (in collaboration with transmitter in the Pre-Eq case) estimates the inverse of the digital communication channel response, $H_c(f)$, and applies it to the incoming signal. The process is as illustrated by the following transfer function equation [1].

`Eq 1 - Equalization Transfer Function`

$$H_e(f) = \frac{1}{H_c(f)} = \frac{1}{|H_c(f)|} e^{-j\vartheta_c(f)}$$

By using the inverse function, equalization attempts restore a received digital signal to an ideal response - canceling the impairment encountered in the digital communication channel. In doing so, equalization minimizes *inter-symbol-interference* (ISI). ISI is the mechanism whereby the frequency response distortions previously noted (AD, GDV) cause in the time domain, adjacent digital symbols to leak into one another and cause interference most clearly observed on an eye diagram.

DOCSIS Equalization

Pre-Eq is required for DOCSIS compliance. The endpoints of the DOCSIS link (CM and CMTS) collaborate to converge upon an estimate of the communication channel response and bias transmission in order to, ideally, cancel any impairment that may be present. While the Pre-Eq function significantly hardens the link to impairments, as an added bonus there is much more information that can be mined to help the operator more broadly. Understanding what communication channel impairments the DOCSIS link is attempting to cancel offers the operator with extremely valuable diagnostic data. The more DOCSIS compliant devices located throughout the HFC plant, the better equipped the cable operator is to use this information for proactive maintenance, potentially eliminating a source of subscriber calls.

DOCSIS 2.0 Pre-Eq uses twenty-four, symbol-spaced coefficients, also called taps. For example, a CMTS estimates the values of these coefficients and forwards this information to a CM via station maintenance messages. These coefficients are used for amplitude and phase correction over a twenty-four symbol period time window. There are several reasons for having equalization functionality in the transmitter in addition to the receiver that are out of scope of this paper. But, in general, the more complex and diverse a channel transfer function may be, the more well-suited it is to deploying equalization resources at both ends. Cable's return path has a large range of possible frequency response signatures even within a single RF leg of an HFC plant.

Coefficient Interpretations

DOCSIS 2.0 Pre-Eq coefficients are a list of 24 complex values and may be interpreted in multiple ways, as demonstrated in Figure 1 through Figure 5. The figures presented here represent a digital communications channel with negligible levels of impairment. These can be used as a baseline to aid in the impairment identification process.

Figure 1 is the magnitude of the equalizer's impulse response, $|h_e(t)|$. A single line at Tap = 0, known as the main tap, on the x-axis is the ideal response. In that case, whatever stimuli excite the channel is perfectly replicated. Calculation of impulse response magnitude is based upon complex tap values of DOCSIS 2.0 Pre-Eq and is shown in Eq 2.

Eq 2 - Impulse Response Magnitude

$$|h_e(t)| = 20\log_{10}|h_e(t)|$$

The main tap represents the desired symbol energy, while the remaining taps represent negligible correction magnitudes of < -35 dBc. The small random magnitudes of the non-zero taps are primarily due to simulated system noise.

For coefficient analysis of multiple CMs, it is helpful to break-down impulse response measurements into regions in which dominant impairments will have the greatest impact. Numerically sorting on these impaired regions facilitates efficient organization of similarly impaired CM groups, and this can help in diagnosing issues.

Two important regions of the impulse response to focus on are the *post-tap* region and the *main tap* region. Dominant micro-reflections typically impact the post-tap region, which consists of tap 1 through tap 16. Dominant AD and GDV typically impact the main-tap region, which consists of taps adjacent to the main tap, numbers -3, -2, -1, 1, 2, and 3.

Figure 2 is the phase of the equalizer's impulse response, $\theta_e(t)$. Calculation for phase is simply the argument of the complex tap values of DOCSIS 2.0 Pre-Eq and is shown in Eq 3. The impulse response phase appears randomized between $-\pi$ and π, except for the main tap whose phase correction is 0 radians. While this plot looks "noisy," recognize from the Magnitude response that the amplitude contribution of the randomly phased imperfections is negligible.

Eq 3 - Impulse Response Phase

$$\theta_e(t) = \arg(h_e(t))$$

Figure 3 is the equalizer's amplitude response, $|H_e(f)|$. Calculation for amplitude response is based upon a 1024-point, Fast Fourier Transform of the DOCSIS 2.0 Pre-Eq coefficients and is shown in Eq 4. Note that the equalizer's amplitude response is ideally constant throughout the channel's bandwidth, which is the Fourier result of the ideal impulse in Figure 1.

Eq 4 - Amplitude Response

$$|H_e(f)| = 20\log_{10}\left|h_e(t) \overset{FFT}{\leftrightarrow} H_e(f)\right|$$

Figure 4 is the equalizer's phase response, $\theta_e(f)$. Calculation for phase response is based upon a 1024-point, Fast Fourier Transform of the DOCSIS 2.0 Pre-Eq coefficients and is shown in Eq 5. Note that the equalizer's phase response is ideally linear throughout the channel's bandwidth.

Eq 5 - Phase Response

$$\theta_e(f) = \arg\left[h_e(t) \overset{FFT}{\leftrightarrow} H_e(f)\right]$$

Figure 5 is the equalizer's Group Delay (GD) response, $GD_e(f)$. Calculation of GD is based upon the phase response and is shown in Eq 6. Note that the equalizer's GDV is approximately 6 nsec across the channel's bandwidth. Group delay is anther way of describing the phase characteristics, but in a way more intuitively descriptive. Group delay represents the absolute time delay each frequency component across the band will endure. As such, it is the variation of this delay (non-flat delay) that matters most, as components of frequency arriving at different times at the opposite end of the channel result in distortion and ISI.

Eq 6 - Group Delay Response

$$GD_e(f) = -\left(\frac{\delta\theta_e(f)}{\delta f}\right)$$

The subsequent sections will show how communication channel impairments will uniquely impact the DOCSIS Pre-Eq coefficient interpretations discussed above.

MICRO-REFLECTION

This section introduces the micro-reflection impairment and how it impacts the DOCSIS Pre-Eq coefficients. As seen by a receiver, a micro-reflection is a copy of the transmitted signal, arriving late and with reduced amplitude. The result of the additional copy is the familiar image ghosting in analog video reception, but for digital communications this is ISI.

Micro-Reflection Fundamentals

Micro-Reflection sources are composed of pairs of HFC components separated by a distance of cable. What's important to understand about HFC components is that they facilitate the propagation of the signal copies in a variety of ways including return loss, isolation, mixing, and combining.

Figure 6 illustrates one of many possible micro-reflection source configurations. Two devices with poor return loss, acting as signal reflectors, are separated by a length of cable. The CM is acting as the second reflector, but any HFC component has the potential to achieve a similar result. The reflector return loss and the loss between the reflectors determine the amplitude of the micro-reflection. The delay encountered as a signal copy traverses the red path of Figure 6 will determine which equalizer tap is responsible for correction.

Note that the CM has as a design limit has a high return maximum loss value of 6 dB, meaning it may reflect up to 25% of its incident power. In the plant, design limits are typically significantly better, but over time will degrade as the plant ages and elements that contribute to good RF matching – connectors, cable, splitters, interfaces on PCBs – degrade.

QAM Signaling Impact

Micro-Reflection impairment impact may be measured on a spectrum analyzer as amplitude ripple. The peak-to-peak amplitude and frequency of the ripple, shown in Figure 7, are directly related to the micro-reflection impairment's amplitude and delay. One look at the frequency response signature quantifies the micro-reflection's parameters. In this case, the signal is impaired by a micro-reflection whose relative amplitude is -20 dBc and whose delay is 4 symbol periods.

In a QAM constellation, a micro-reflection causes the symbols to spread in a miniaturized pattern similar to the full QAM constellation itself. Additionally, phase distortion may cause the spread symbols to appear rotated. Consider first Figure 8 and Figure 9, which illustrate ideal constellation diagrams for 16-QAM and 64-QAM, respectively.

Now consider Figure 10. Figure 10 shows the effect of a micro-reflection on a16-QAM signal's constellation diagram. The micro-reflection's characteristics are those previously depicted in Figure 7. Note the spread throughout the symbol region on each 16-QAM point, and subsequently how now less additive noise has more likelihood of causing a symbol to jump a boundary and create a hard decision error than the Figure 8 case.

Figure 11 repeats the same micro-reflection scenario for 64-QAM. 16-QAM is less sensitive micro-reflections than 64-QAM because of reduced decision boundary size of 64-QAM for the same average transmit power. In other words, 16-QAM symbol size can spread more than 64-QAM. In comparing Figure 10 and Figure 11, the same level of micro-reflection impairment has spread the symbols of the 64-QAM constellation appreciably closer to the symbol boundaries than in 16-QAM constellation. The 64-QAM situation is clearly a catastrophic situation with some added noise unless some equalization processing is applied to undo the micro-reflection.

Pre-Eq Coefficient Analysis

A single dominant micro-reflection uniquely impacts the DOCSIS Pre-Eq coefficients. The post-tap region of the impulse response magnitude, illustrated in Figure 12, reveals the characteristics of the Figure 7 micro-reflection: amplitude -20 dBc relative to the main tap, and delay 4 symbol periods later than the main tap.

The impulse response phase reveals negligible phase distortion of both the desired symbol and the micro-reflection impairment.

The equalizer's amplitude response of Figure 13 shows the equalizer's amplitude response. This response derived should be compared to Figure 7 in the context of Eq 1.

The phase response shows some nonlinearity across the channel's bandwidth, especially when compared with Figure 4 phase response. The GD response of Figure 14 clarifies the additional phase distortion with appreciably higher GDV than was previously illustrated in Figure 5. Note equalizer's GDV is approximately 43 nsec across the channel's bandwidth, while the symbol duration itself is less than 200 nsec.

DOCSIS Micro-Reflection Assumptions

CableLabs has identified via the DOCSIS standards [2-5] certain assumptions regarding the nature of a single dominant echo or micro-reflection present in an HFC environment. DOCSIS compliant devices must interoperate at or below the values illustrated in the Figure 15.

AMPLITUDE DISTORTION (AD)

This section introduces the AD impairment and how it impacts the DOCSIS Pre-Eq coefficients. AD is undesirable variation in the communication channel's amplitude response resulting in distortion of the digital signal amplitude. Some common forms of AD include tilt, ripple, and roll-off.

AD Fundamentals

One common cause of AD in an HFC plant is upper return band-edge operation of digital signals, combined with long reaches of coaxial plant. Long reaches of coaxial plant accumulate multiple diplex filters from amplifiers and in-line equalizers. While individually contributing small attenuation versus frequency, when part of a deep RF amplifier cascade, the combination may contribute appreciable variation in a communication channel's magnitude frequency response. An example of amplitude roll-off has been provided in Figure 16.

QAM Signaling Impact

In a QAM constellation, amplitude roll-off causes the symbols to spread in a pattern similar in appearance to Additive White Gaussian Noise (AWGN). For reference, Figure 17 and Figure 18 are constellations for 16-QAM and 64-QAM respectively, which have been impaired by equivalent levels of AWGN.

Increasing AWGN contribution by 6 dB would show that 16-QAM is now just as close to the decision boundaries as 64-QAM was previously in Figure 18. Conversely, reducing AWGN contribution by 6 dB would show 64-QAM is now just as far away from the decision boundaries as 16-QAM was previously in Figure 17. Use of 6 dB demonstrates a well-known relationship between AWGN and modulation complexity on square constellations such as 16-QAM and 64-QAM. Each modulation order involves a 6 dB increased sensitivity to thermal noise from 16-QAM on up (for QPSK to 16-QAM it is closer to 7 dB).

The 6 dB relationship is isolated to the thermal noise impairment. Similar assumptions must *not* be made regarding the impairments discussed in this paper. Many such additional impairment relationships have been derived and discussed in the literature over time. For our case here, simulation and test is crucial for characterizing the true nature of the relationship which exists between these more complex impairments and modulation complexity, and in particular for multiple simultaneous impairments.

Figures 19 and 20 represent the 16-QAM and 64-QAM constellations that result from the amplitude roll-off illustrated in Figure 16. Note the appearance of these as compared to the AWGN cases in Figures 17 and 18.

As with prior impairments, 16-QAM is less sensitive to amplitude roll-off than 64-QAM because of reduced decision boundary size of 64-QAM. In comparing Figure 19 and Figure 20, the same level of amplitude roll-off impairment has spread the symbols of the 64-QAM constellation appreciably closer to the symbol boundaries than in 16-QAM constellation. And, again, the 64-QAM case is bordering on a catastrophic link result without some intervention.

Pre-Eq Coefficient Analysis

Amplitude roll-off uniquely impacts the DOCSIS Pre-Eq coefficients. The near main-tap region of the impulse response magnitude, illustrated in Figure 21, reveals main-tap spreading in the region of main tap +/- 3 taps. The amplitude response of Figure 22 reveals appreciable amplitude correction.

Lastly, there is linear phase and negligible GDV across the channel's bandwidth. Note equalizer's GDV is approximately 12 nsec across the channel's bandwidth.

GROUP DELAY VARIATION (GDV)

This section introduces the GDV impairment and how it impacts the DOCSIS Pre-Eq coefficients. GDV is undesirable variation in the communication channel's phase response resulting in distortion of the digital signal phase, or, as described, a variation in the propagation of frequency components of the signal across the channel.

GDV Fundamentals

As is the case for AD, one major cause of GDV in an HFC plant is upper-band-edge operation of digital signals, combined with long reaches of coaxial plant. The reasoning is the same as in the AD case. Note that filtering functions typically induce nonlinear phase responses as the band edges are approached, so the combination of AD and GDV in the same band region, understanding that diplex filtering is the cause, is perfectly expected. Different filter functions induce different GDV responses, just as different filter functions induce different stop-band characteristics. It is common that the sharper the roll-off, such as would be the case for long cascades, the worse the GDV will be.

QAM Signaling Impact

In a QAM constellation, GDV causes the symbols to spread in a pattern similar to what has already been illustrated for AWGN and AD.

As expected, 16-QAM is less sensitive to GDV than 64-QAM because of reduced decision boundary size of 64-QAM.

Pre-Eq Coefficient Analysis

GDV uniquely impacts the DOCSIS Pre-Eq coefficients. The main-tap region of the impulse response magnitude, shown in Figure 23, reveals main-tap spreading as was illustrated for the amplitude roll-off impairment. However, the amplitude response, shown in Figure 24, reveals appreciably less amplitude correction. Since the induced impairment is phase related, this makes sense.

Of course, there is an appreciable amount of phase variation in the impulse response phase and the phase response, while Figure 25 reveals appreciable GD correction over the GD correction present for the amplitude roll-off impairment scenario previously discussed. Note equalizer's GDV was approximately 30 nsec across the channel's bandwidth.

DOCSIS Group Delay Assumptions

CableLabs via the DOCSIS standards [2-5] has also made assumptions regarding the nature of GDV present in an HFC environment. DOCSIS compliant devices must interoperate under the estimated conditions illustrated in the Figure 26. The estimates shown in Figure 26 are based upon preliminary simulation and measurements of GDV and DOCSIS Pre-Eq interaction.

MAINTENANCE REQUIREMENTS

Understanding the point at which Pre-Eq will fail is the first step toward leveraging the diagnostic benefits of equalization coefficient analysis. Simulation and tests were performed of increasing single dominant micro-reflection impairment. The results of these tests reveal the highest micro-reflection impairment level that could be corrected by DOCSIS 2.0 Pre-Eq. 16-QAM and 64-QAM were both evaluated.

The test topology is illustrated in Figure 27. Seven amplifiers were cascaded with an optical link. The 6.4 MHz test signal was centrally located within a 5 – 40 MHz return path spectrum at 16 MHz center frequency, in order to minimize contributions from both the AD and GDV impairments contributed by the HFC network.

An Ethernet link was established between the subscriber side of the CM and the Wide Area Network (WAN) side of the CMTS. The Ethernet connectivity was continuously monitored as increases in micro-reflection impairment were introduced into the path between the CM and CMTS. Loss of Ethernet connectivity was assumed to be the point at which a High Speed Data (HSD) subscriber would log a service call with a cable operator.

Simulation and measurement for both 16-QAM and 64-QAM, illustrated in Figure 28 and Figure 29, reveal DOCSIS 2.0 mitigation of impairments is appreciably higher than what is assumed by DOCSIS to be present in the HFC environment. Additionally, there is a reduction of correction capability caused by a reduced decision boundary size as 16-QAM signals are migrated to 64-QAM. Note that this reduction is approximately 2 dB on average and not the 6 dB expected from QAM and AWGN impairment relationship previously discussed.

Simulation and test of increasing micro-reflection impairment were repeated with additional impairments, AD and GDV. AD and GDV contributions were increased by simply locating the test signal near the upper band edge of a 5 – 40 MHz return path spectrum, 36.8 MHz center frequency. Figure 30 and Figure 31 are measurements of the AD and GDV present at the upper band region of 5 – 40 MHz return path spectrum of the test topology illustrated in Figure 27. These results, illustrated in Figure 32 and Figure 33 for 16-QAM and 64-QAM respectively, reveal a negligible change in correction capability of the DOCSIS 2.0 Pre-Eq even with the additional impairments.

Overall, the results shown in Figures 28 through 33 are significant for the following reasons:

1. Discussed impairment levels can exceed DOCSIS HFC environmental assumptions and still be corrected by DOCSIS 2.0 Pre-Eq
2. Simulation results closely agree with laboratory measurement
3. Micro-Reflection impairment impact on modulation complexity is different from AWGN impairment impact

The HFC environment is dynamic in nature, with causes including changing loading conditions, component decay, weather, and routine maintenance practices. Allowing sufficient margin for this variation will allow the HFC environment to breath. However, exploiting the limits of acceptable performance and maintaining margin will optimize maintenance costs while also minimizing service calls.

In order to define the acceptable performance limits, simulation and measurement are necessary. However, simulation may bare the burden of exploring impairment permutations while minimizing the cost of testing resources. For example, the impact of multiple micro-reflection impairments can be studied and defined through simulation to establish acceptable performance limits which can then be verified in the laboratory and HFC environment.

Study of the single dominant micro-reflection and a combination of micro-reflection, AD, and GDV impairments has defined acceptable performance limits and behavior that is clearly different than assumptions.

Continued investigation of impairments and combinations thereof can complete the acceptable performance limit requirements of DOCSIS 2.0 Pre-Eq. Simulation can be leveraged to help manage the cost of defining these limits. And finally, an understanding of the impairment limits and relationships with modulation complexity will help cable operators define maintenance requirements and transition toward optimal upstream throughput by minimizing cost and service calls.

ISOLATION PROCESS

There may be many ways to take advantage of the wealth of information provided by Pre-Eq to isolate DOCSIS Pre-Eq related impairments. The following process has been proposed in order to isolate impairments using equalization coefficient analysis.

Step 1

Ensure that majority of DOCSIS links are supporting at least DOCSIS 2.0 with Pre-Eq enabled. The resolution of the 24-tap equalizer of DOCSIS 2.0 is better suited to identify impairments, compared to the 8-tap equalizer of DOCSIS 1.1.

Step 2

Query the DOCSIS 2.0 CM population using an SNMP query tool similar to *Modem Pre-Eq Response Tool*, illustrated in Figure 34. The Modem Pre-Eq Response Tool, which is software developed by Marc Morrissette of Motorola, has many useful features, the most important being the ability to query multiple DOCSIS terminal devices based on an IP address list. Periodic polls of coefficient values and other relevant physical layer (PHY) metrics are displayed and/or stored into a log file for post processing. This tool also provides users with a graphical view of either the impulse response or amplitude response for each CM poll.

Using tools like the Modem Pre-Eq Tool can help cable operators establish a baseline of performance, and identify problem DOCSIS links, based on CM IP addresses, within the HFC plant.

Step 3

Identify impairment problems by sorting, on increasing levels that sum the DOCSIS Pre-Eq regions previously defined. For example, determine which CMs experience the greatest amount of micro-reflection impairment by sorting on the levels which result from summing the taps located in the post-tap region.

Step 4

Understand the relevant Pre-Eq impairment problems, their impact, and how they originate in HFC plant. For example, one micro-reflection source has been discussed in the micro-reflection fundamentals section, but many possible permutations of micro-reflection sources must be understood for successful isolation.

Use results such as those in the maintenance requirements section to define what impairment levels will likely result in service calls, and consider these for potential areas to address proactively

Through repeated application of an isolation process, understand how much margin below service outages would optimize the cost/benefit ratio of proactive maintenance.

Step 5

Leverage the CM population to differentiate between CMs experiencing an impairment problem and those that are not. For example, a query of the CM population of the HFC coaxial feeder segment illustrated in Figure 35 reveals that CMs located off of amplifier 1 are reporting a micro-reflection problem, while CMs located off of amplifiers 2, 3, and T1 are not reporting a problem.

Step 6

Identify suspected HFC components using results from Step 4 and Step 5. As previously discussed, micro-reflection sources consist of pairs of HFC components separated by a distance of cable. Again referring to Figure 35, none of the CMs upstream from amplifier 1 are reporting a micro-reflection problem. Additionally, diplex filters make amplifiers located between suspected HFC components unlikely. Therefore, all of the HFC components fed from amplifier 1 are suspect.

Step 7

Inspect and repair as necessary all suspected HFC plant components resulting from Step 6. Again, referring back to the example provided in Figure 35. Inspection of the suspect HFC plant components show the micro-reflection source to be a combination of tap-to-output port isolation loss and an unterminated cable splice at the end of the amplifier 1 feeder run. This combination is what is contributing to the micro-reflections experienced by CMs 1A, 1B, and 1C. Properly terminating the splice reduces the micro-reflections to negligible amplitudes.

Step 8

Repeat CM population query multiple times and compare to baseline captured in Step 1 to ensure that the impairment problem has been eliminated and the improvements are sustainable.

CONCLUSION

The DOCSIS Pre-Eq function has enabled operators to deliver yet higher speeds of upstream service to the subscribers. The use of higher order modulation, with a strong push from DOCSIS tools such as equalization has made this a reality. However, the modulation order and bandwidth come at the expense of increased sensitivity to common HFC impairments. Not only does the Pre-Eq function ensure these higher speed links are robust, it also provides a wealth of insight into important plant characteristics. The type of characteristics is many of those that are of increased relevance as the upstream modulation complexity increases.

By fully understanding the Pre-Eq function and deploying some simple tools to perform equalization coefficient analysis on the data gathered by this function, it is possible to identify the dominant impairments for which the DOCSIS 2.0 Pre-Eq is compensating.

Single dominant micro-reflection will mostly impact the post-tap region of the impulse response magnitude, revealing the amplitude and delay characteristics of the micro-reflection source.

Dominant AD will mostly impact the main-tap region of the impulse response magnitude as well as the amplitude response.

Dominant GDV will mostly impact the main-tap region of the impulse response magnitude as well as the phase response.

Simulation and measurement are required to determine all of the points at which DOCSIS 2.0 Pre-Eq will work under various impairment combinations and levels.

Understanding the limits of DOCSIS 2.0 Pre-Eq will help cable operators establish when proactively maintaining the HFC plant will be most beneficial, leading to a refined process that helps cable operators leverage the benefits of DOCSIS Pre-Eq coefficient analysis.

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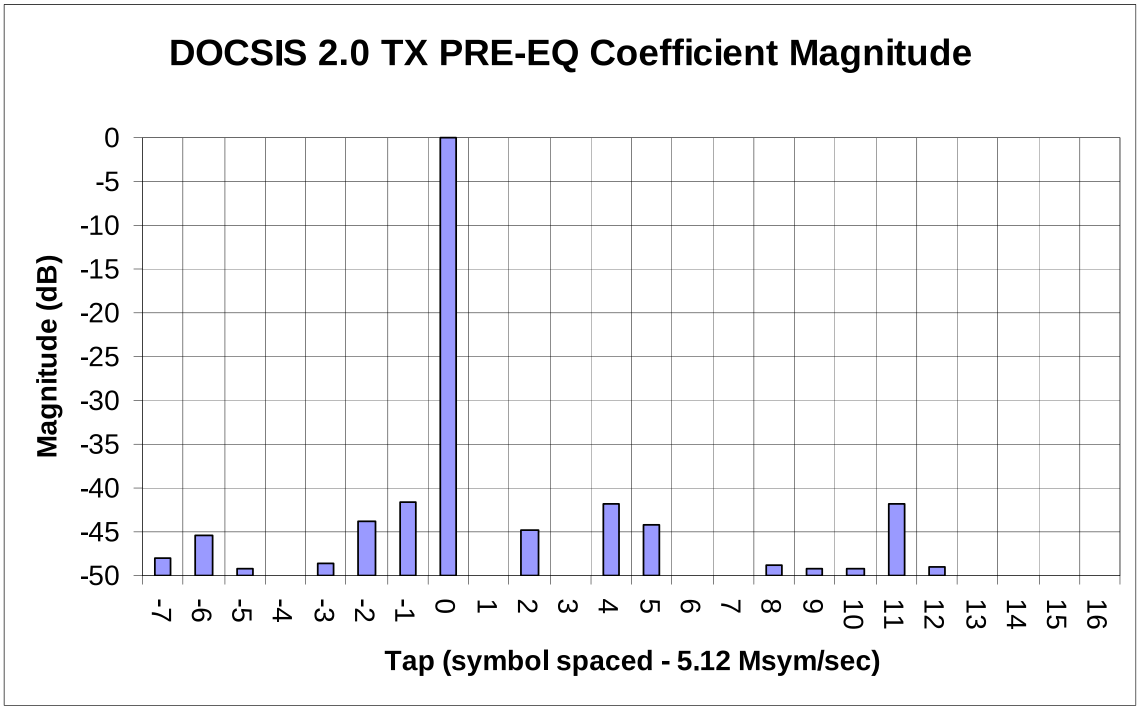


Figure 1 – Negligible Impairment – Impulse Response Magnitude

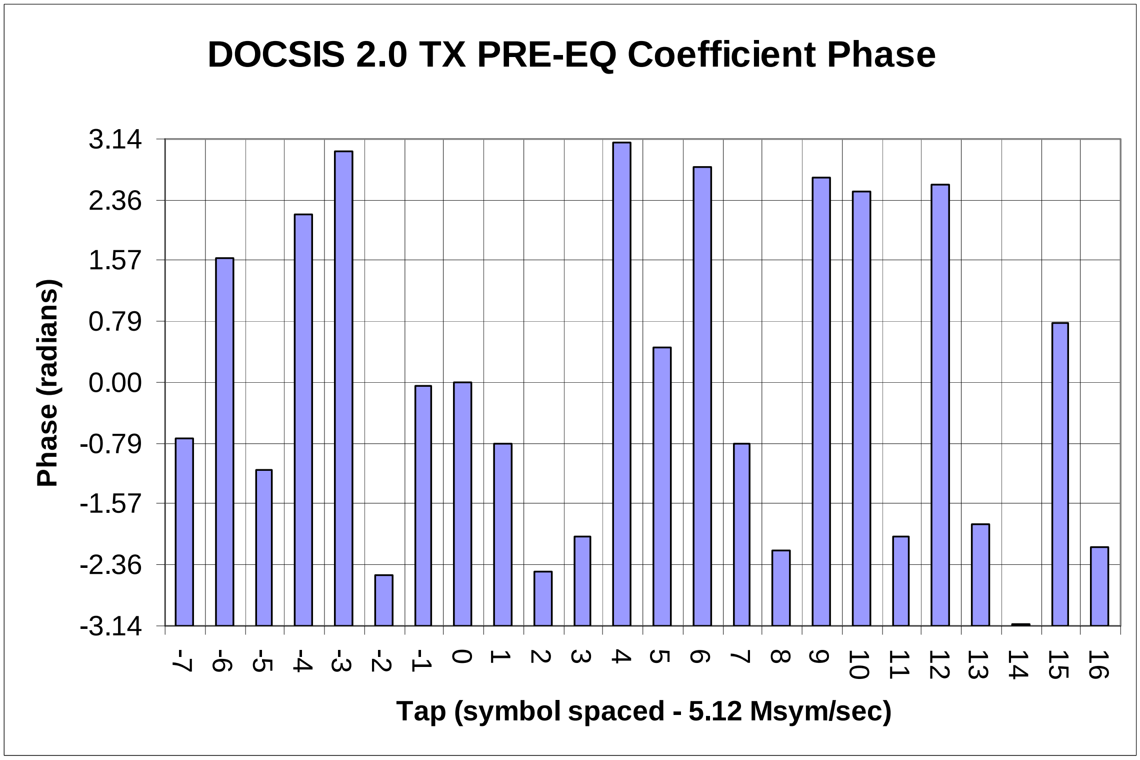


Figure 2 - Negligible Impairment – Impulse Response Phase

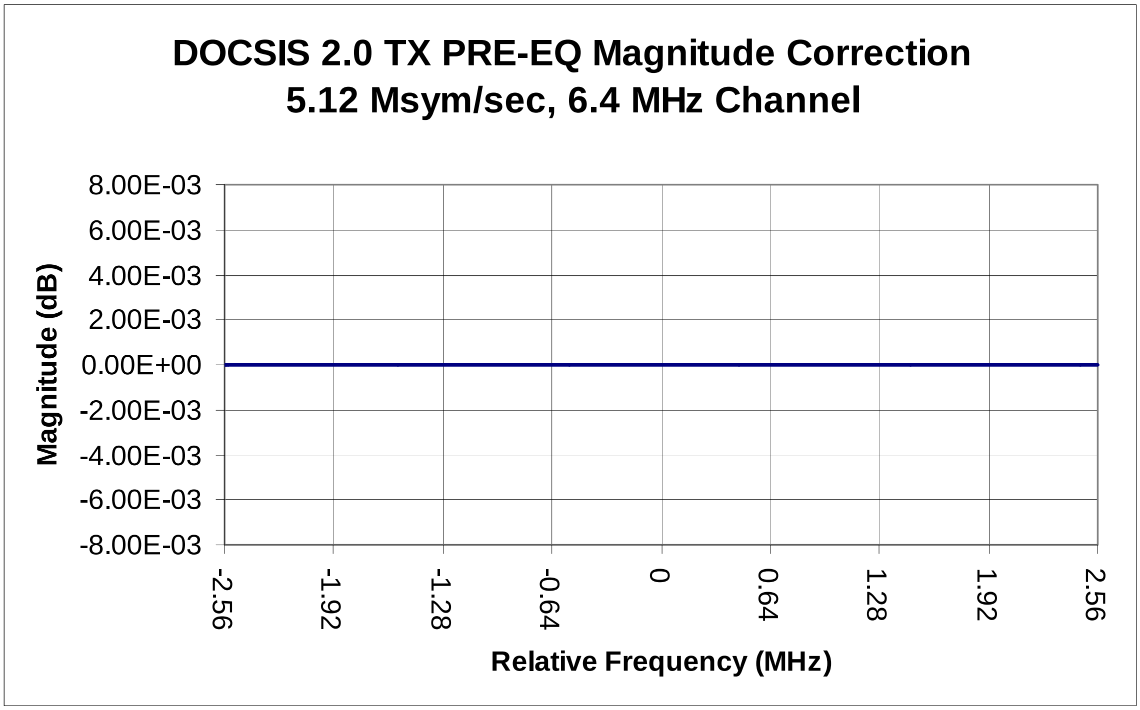


Figure 3 - Negligible Impairment – Amplitude Response

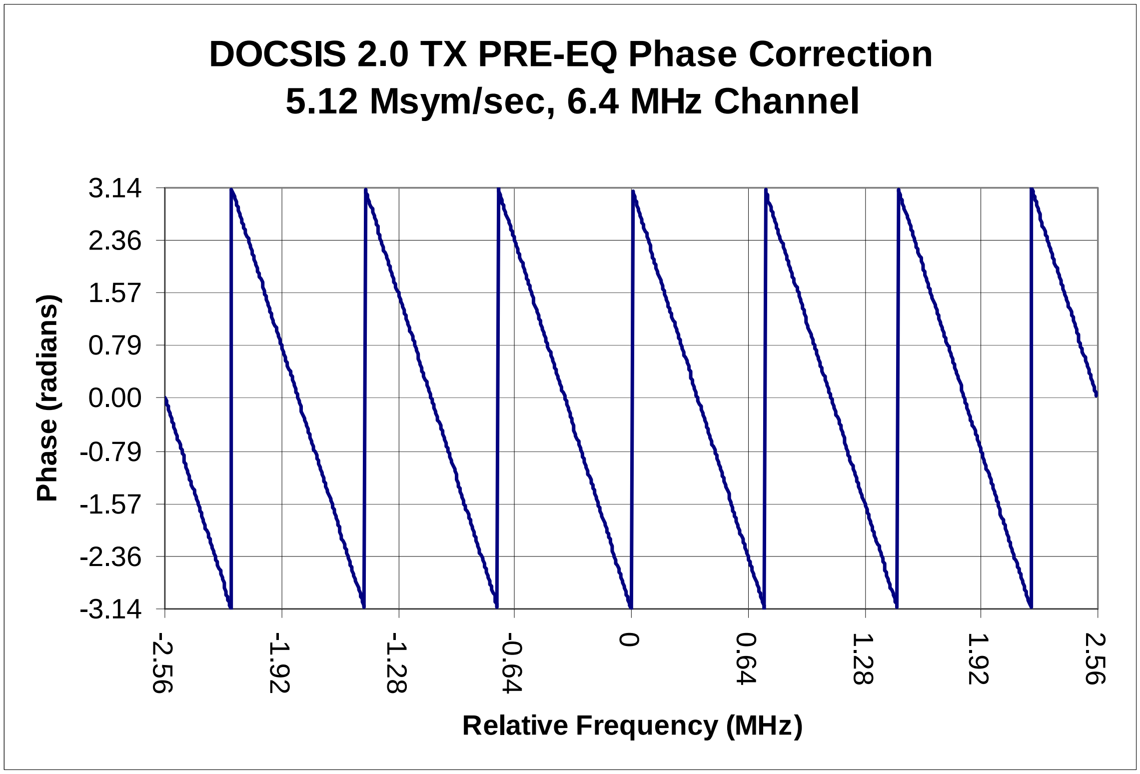


Figure 4 - Negligible Impairment – Phase Response

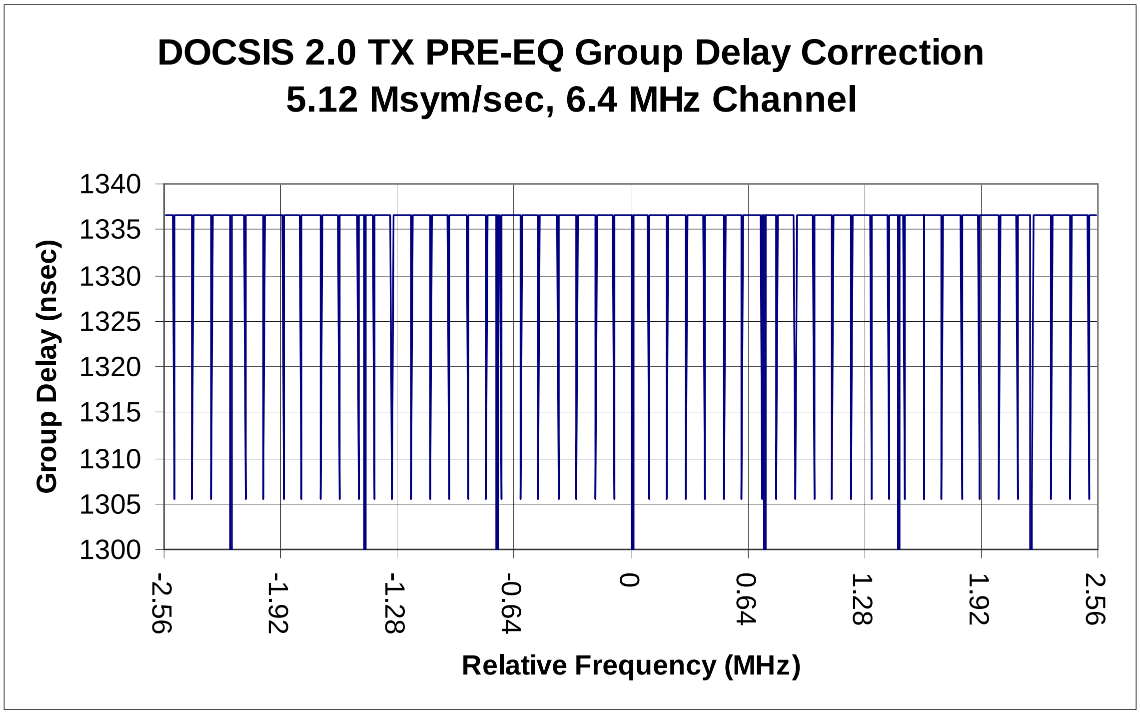


Figure 5 – Negligible Impairment – Group Delay Response

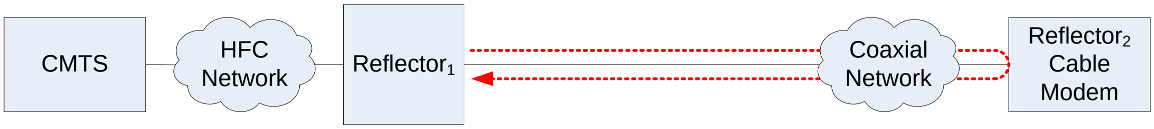


Figure 6 – Micro-Reflection Source

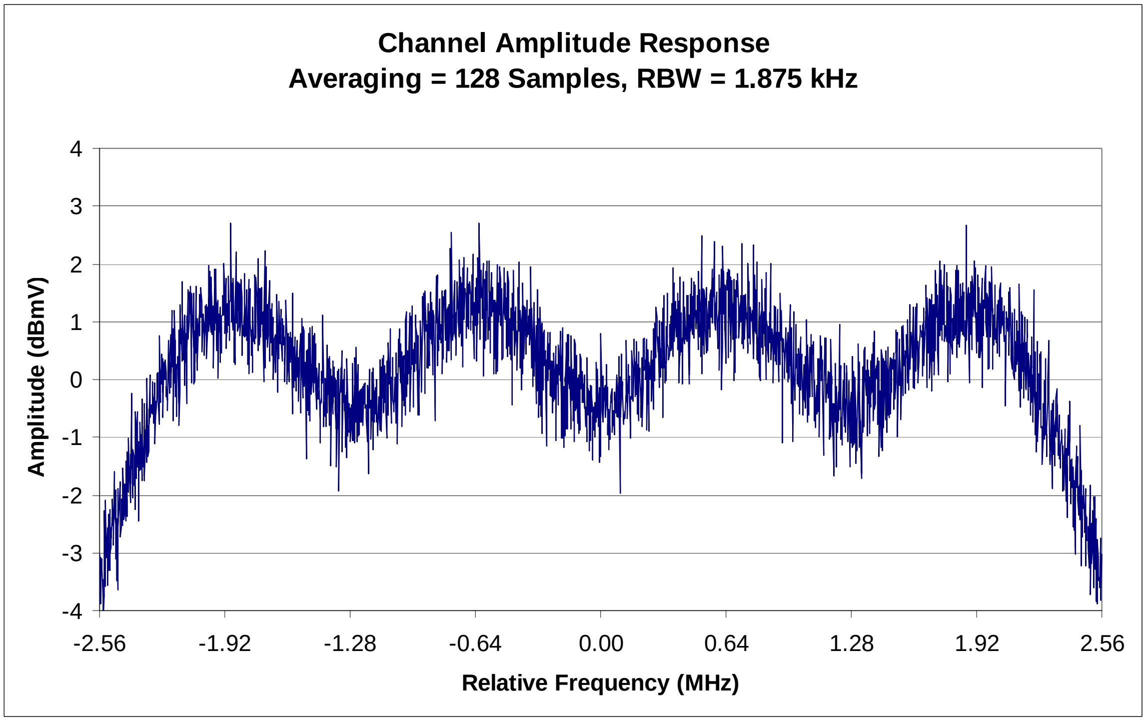


Figure 7 - Micro-Reflection Impairment – Channel Amplitude Response

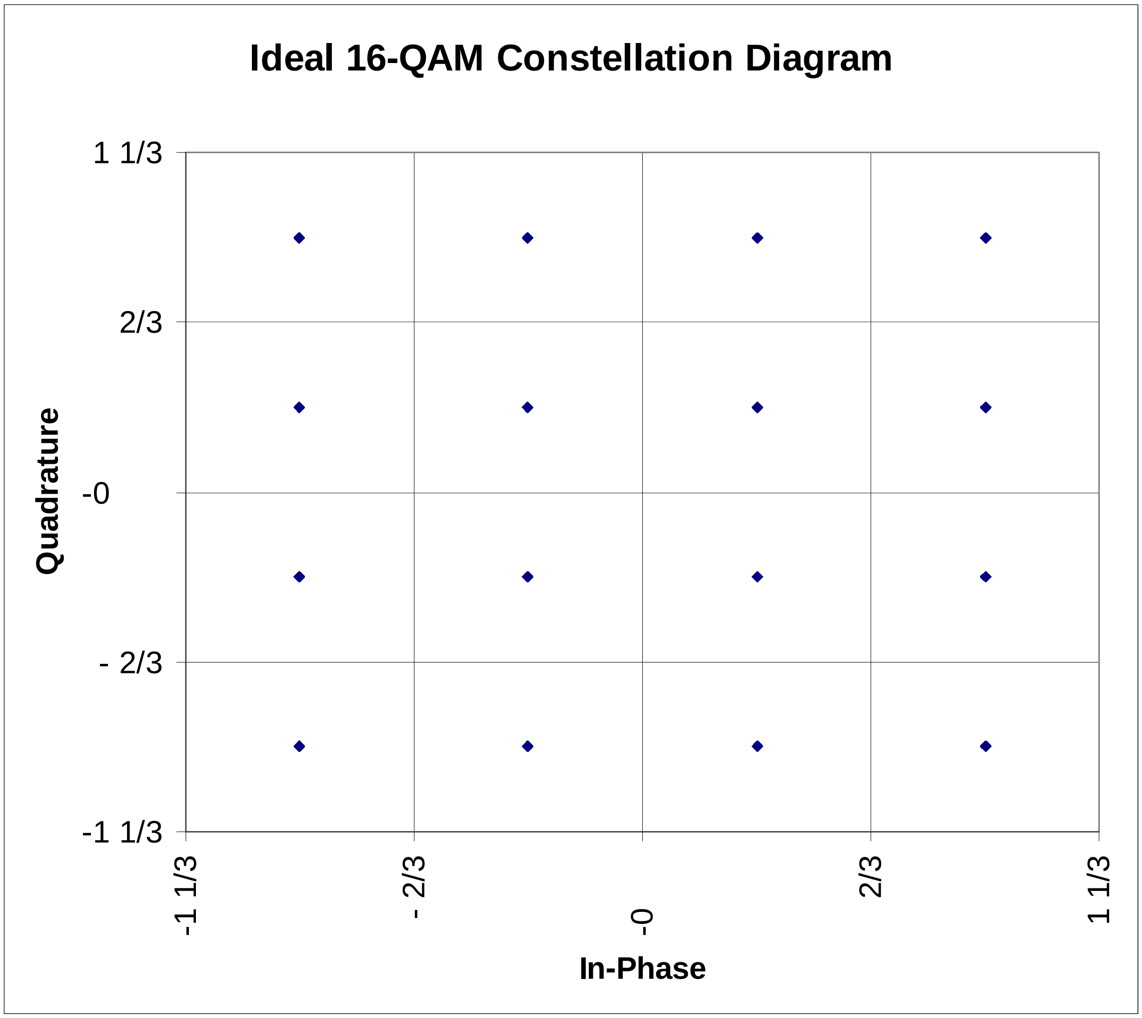
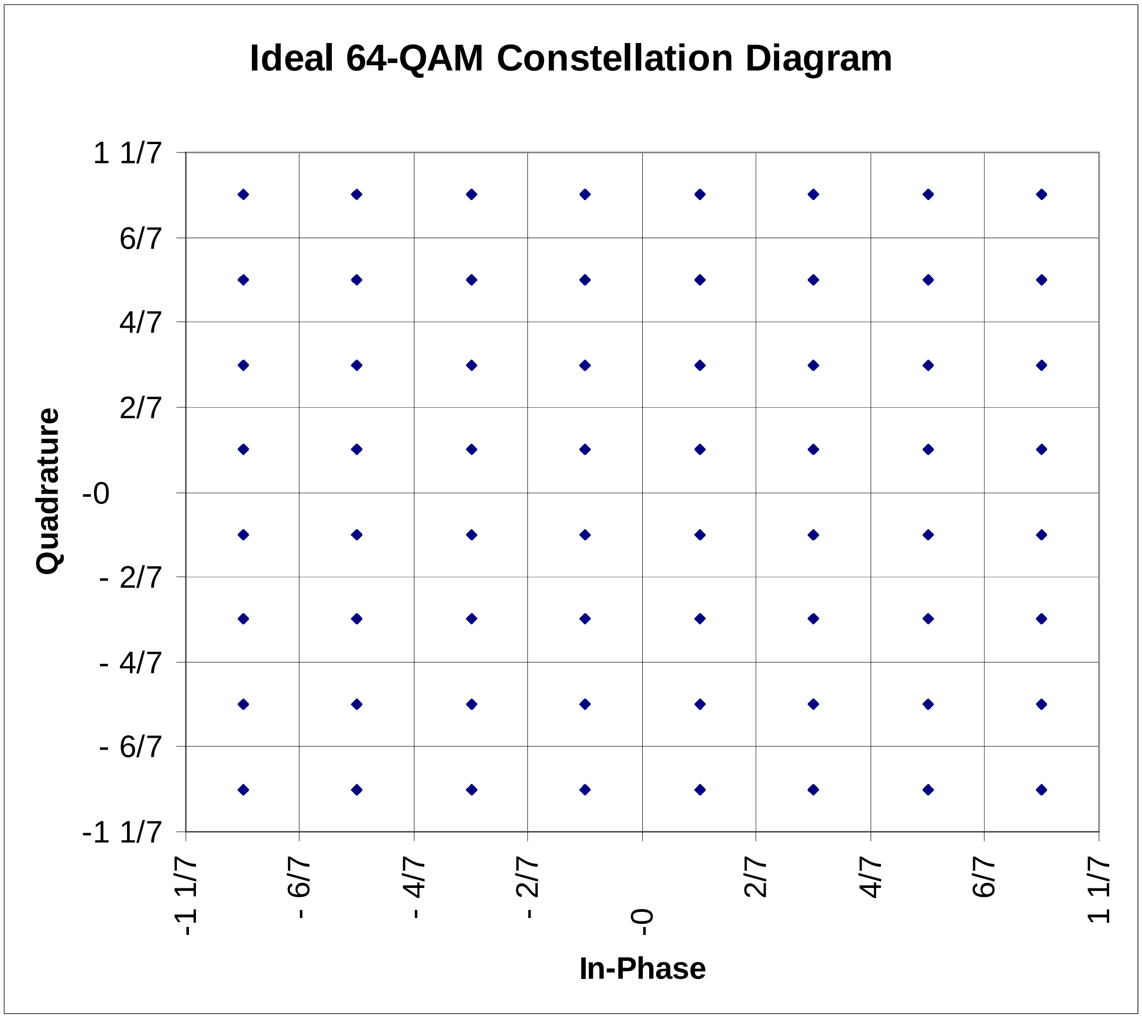


Figure 8 - Ideal 16-QAM Constellation



`Figure 9 - Ideal 64-QAM Constellation`

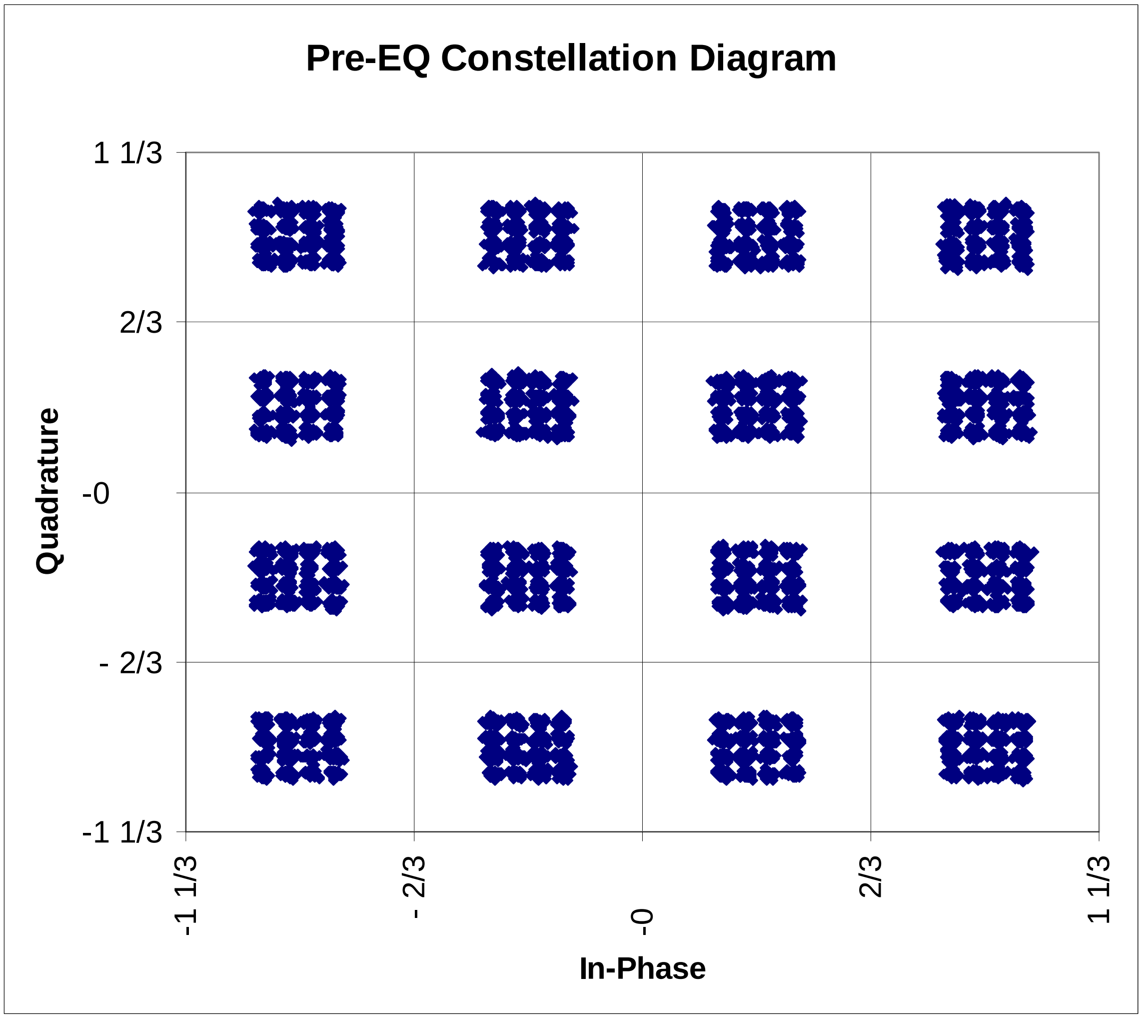


Figure 10 - Micro-Reflection Impaired 16-QAM Constellation

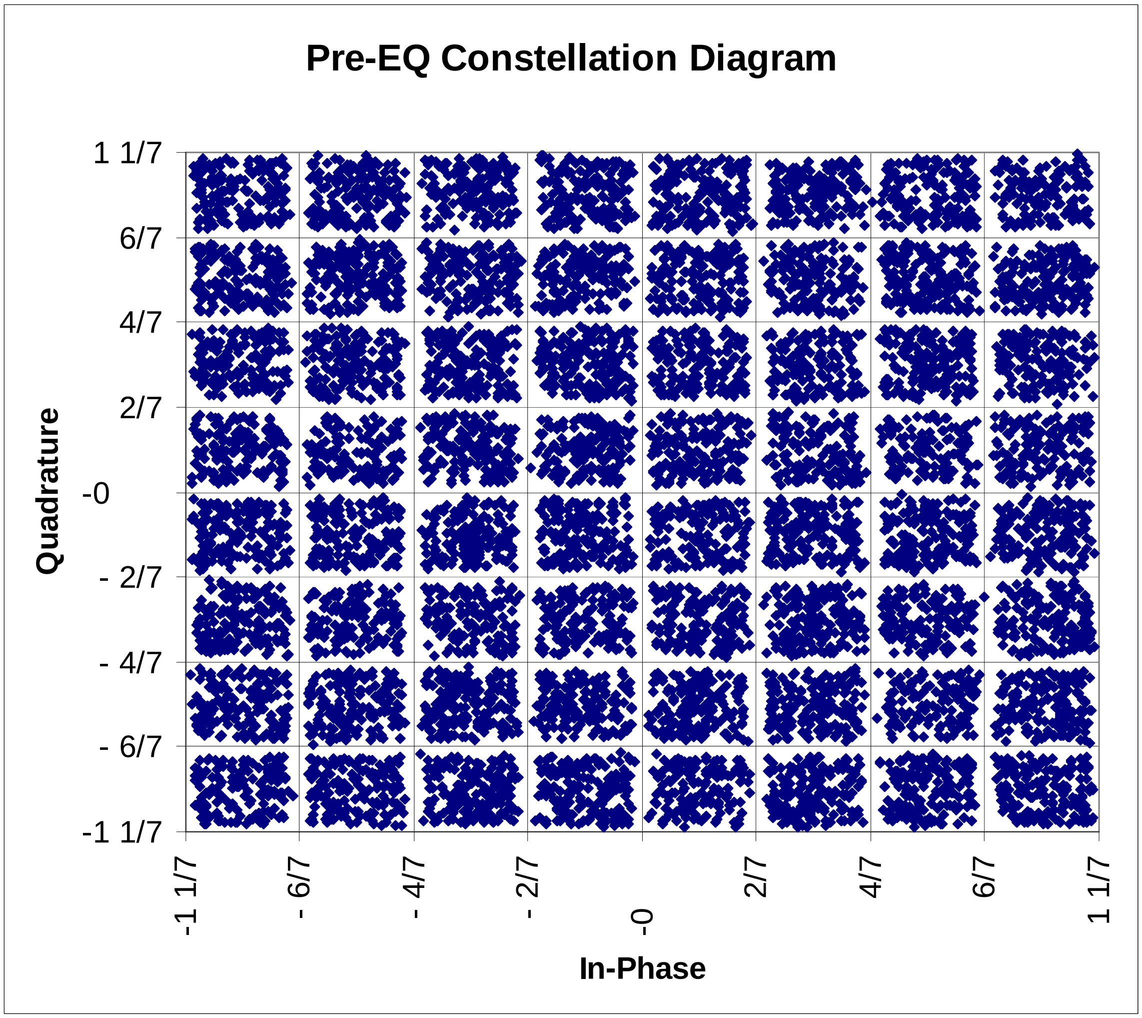


Figure 11 - Micro-Reflection Impaired 64-QAM Constellation

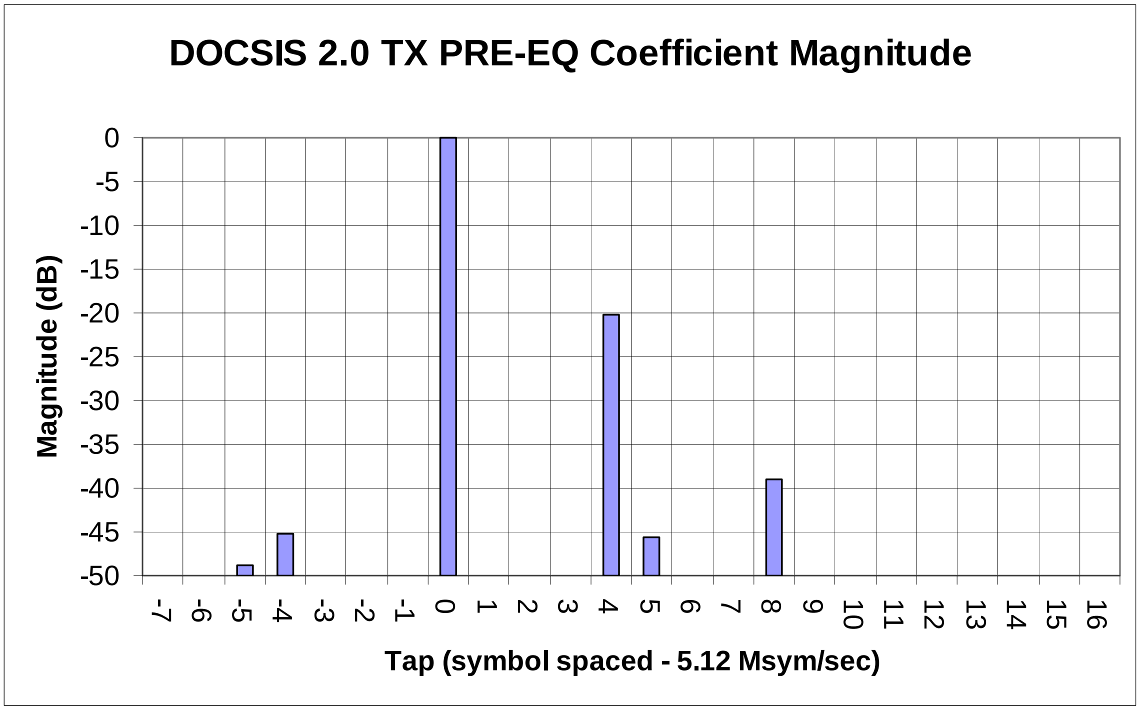


Figure 12 - Micro-Reflection Impairment –Impulse Response Magnitude

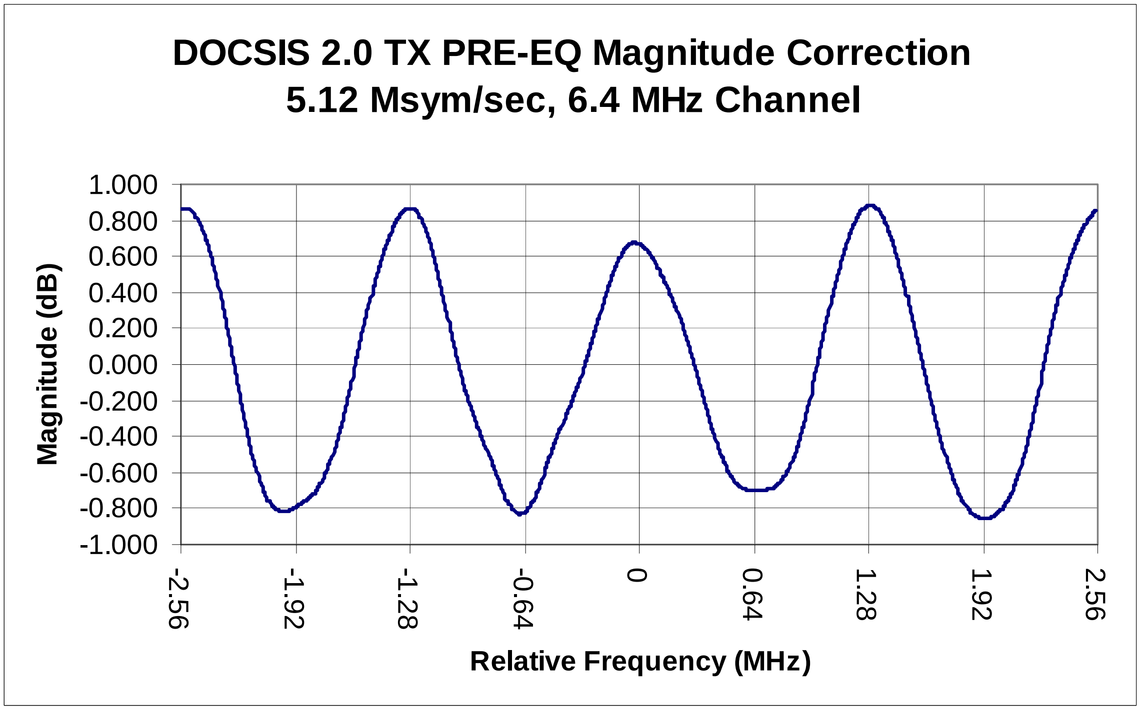


Figure 13 - Micro-Reflection Impairment – Amplitude Response

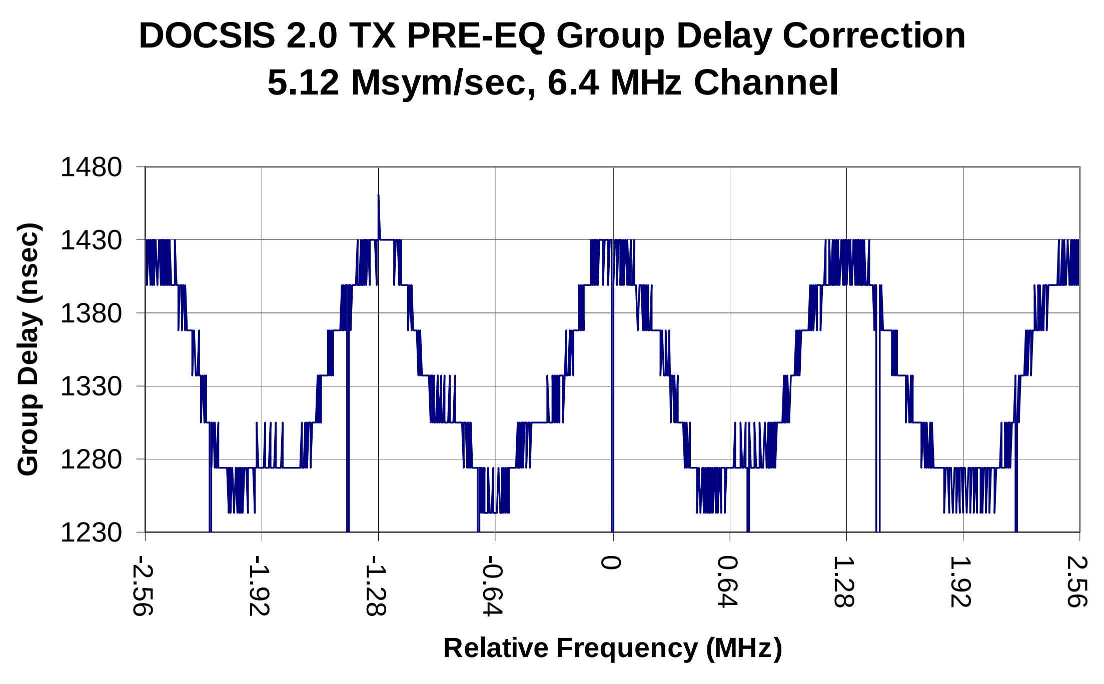


Figure 14 - Micro-Reflection Impairment – GDV Frequency Response

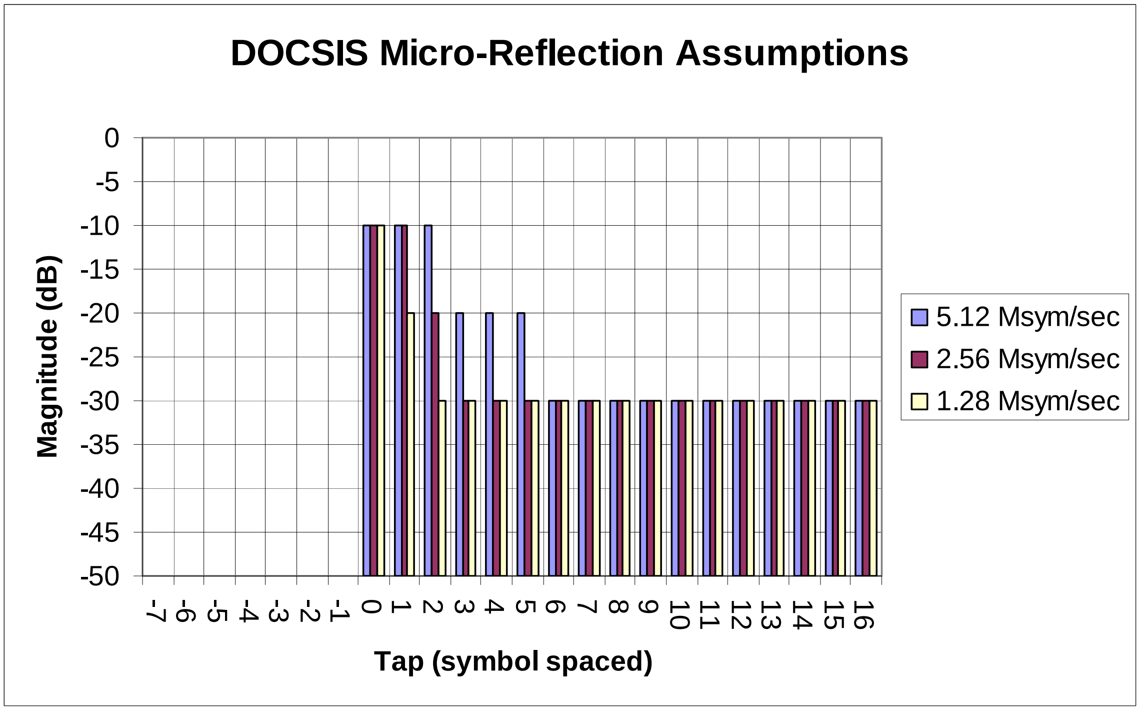


Figure 15 - DOCSIS Micro-Reflection Assumptions

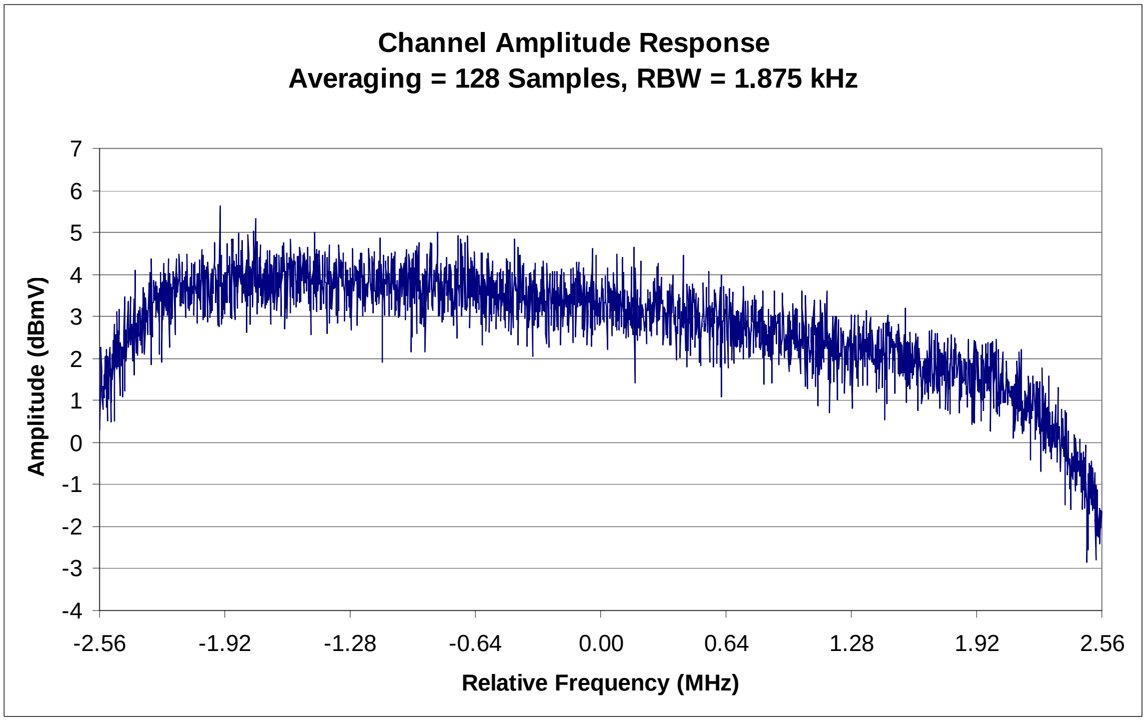


Figure 16 - Amplitude Roll-Off Impairment – Channel Amplitude Response

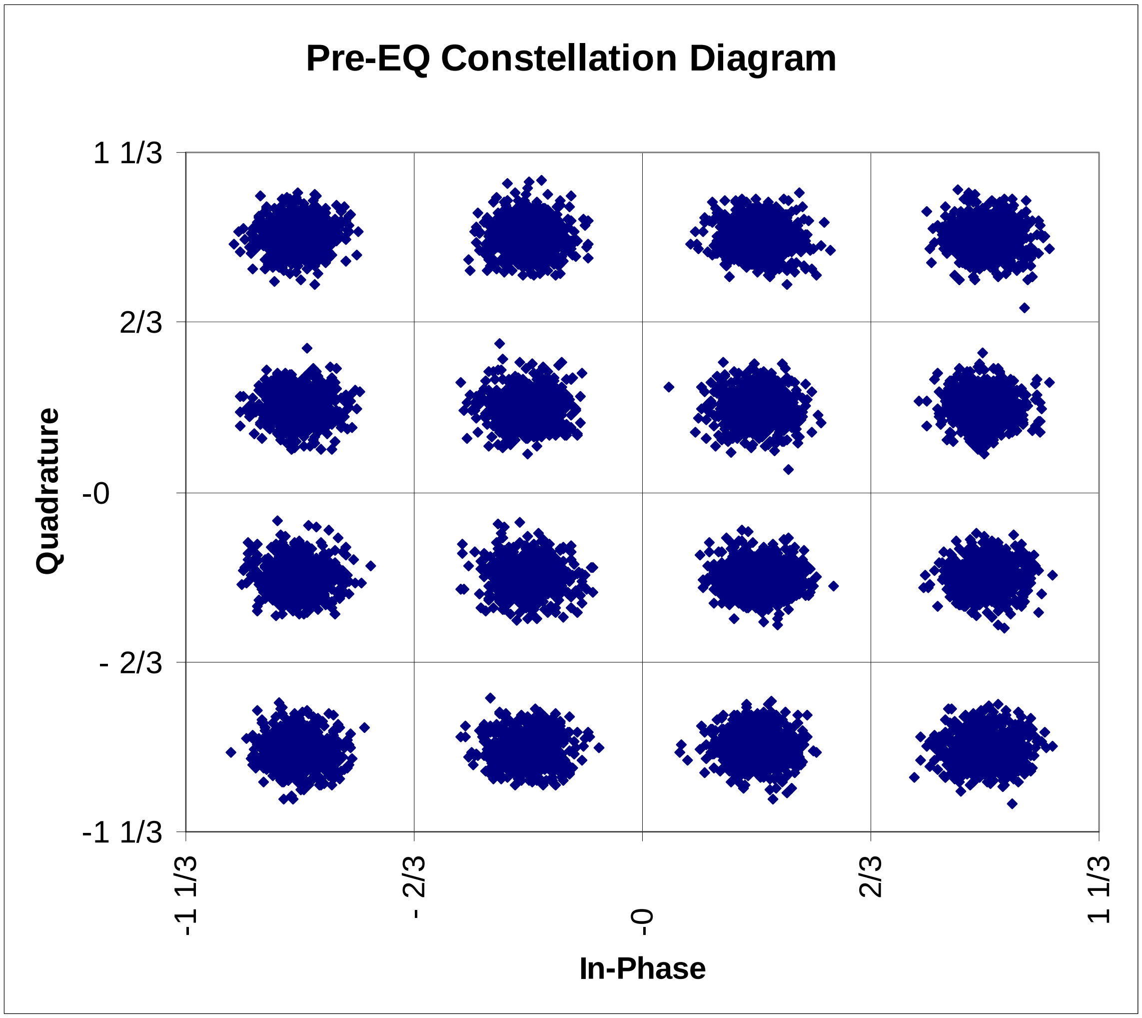
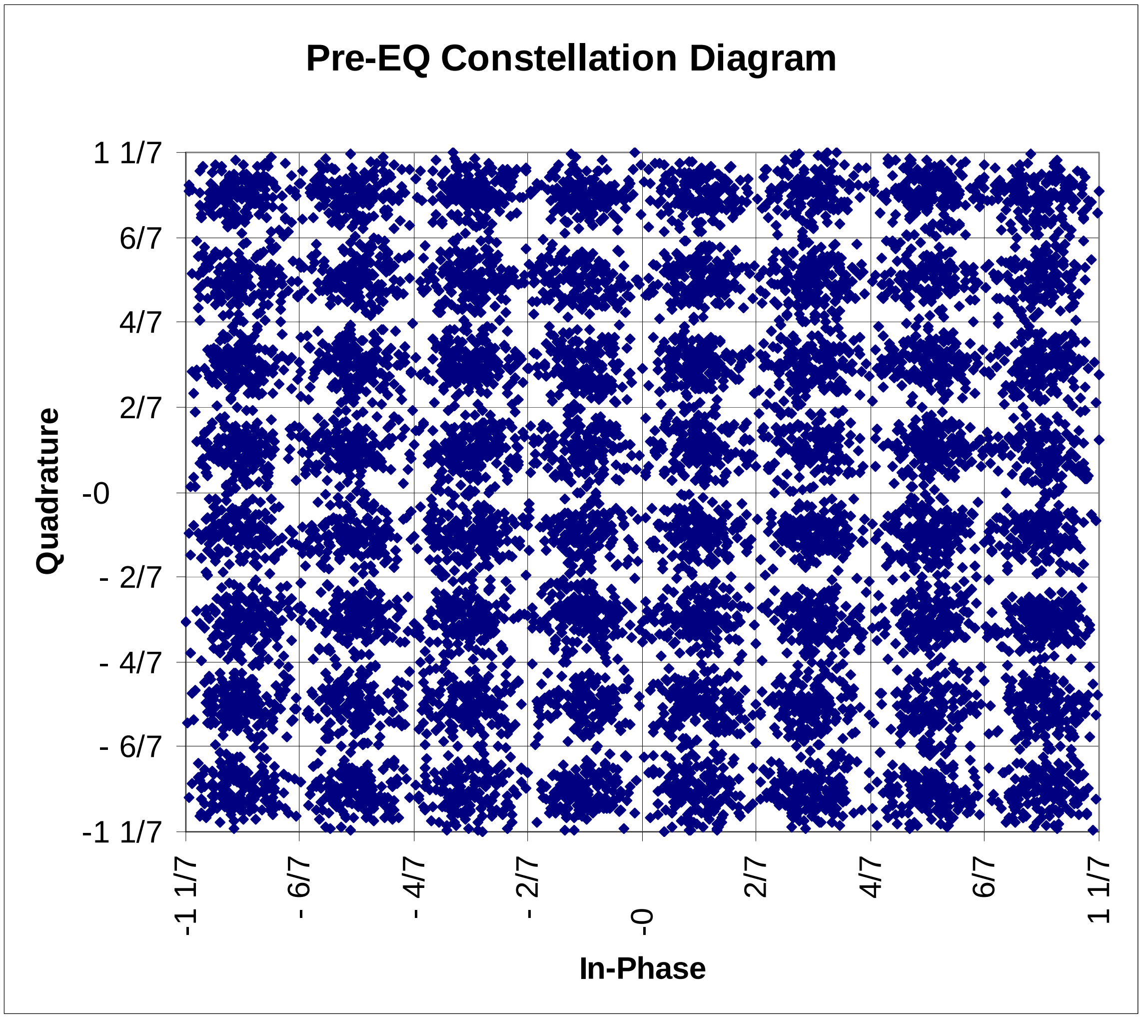


Figure 17 - AWGN Impaired 16-QAM Constellation



`Figure 18 - AWGN Impaired 64-QAM Constellation`

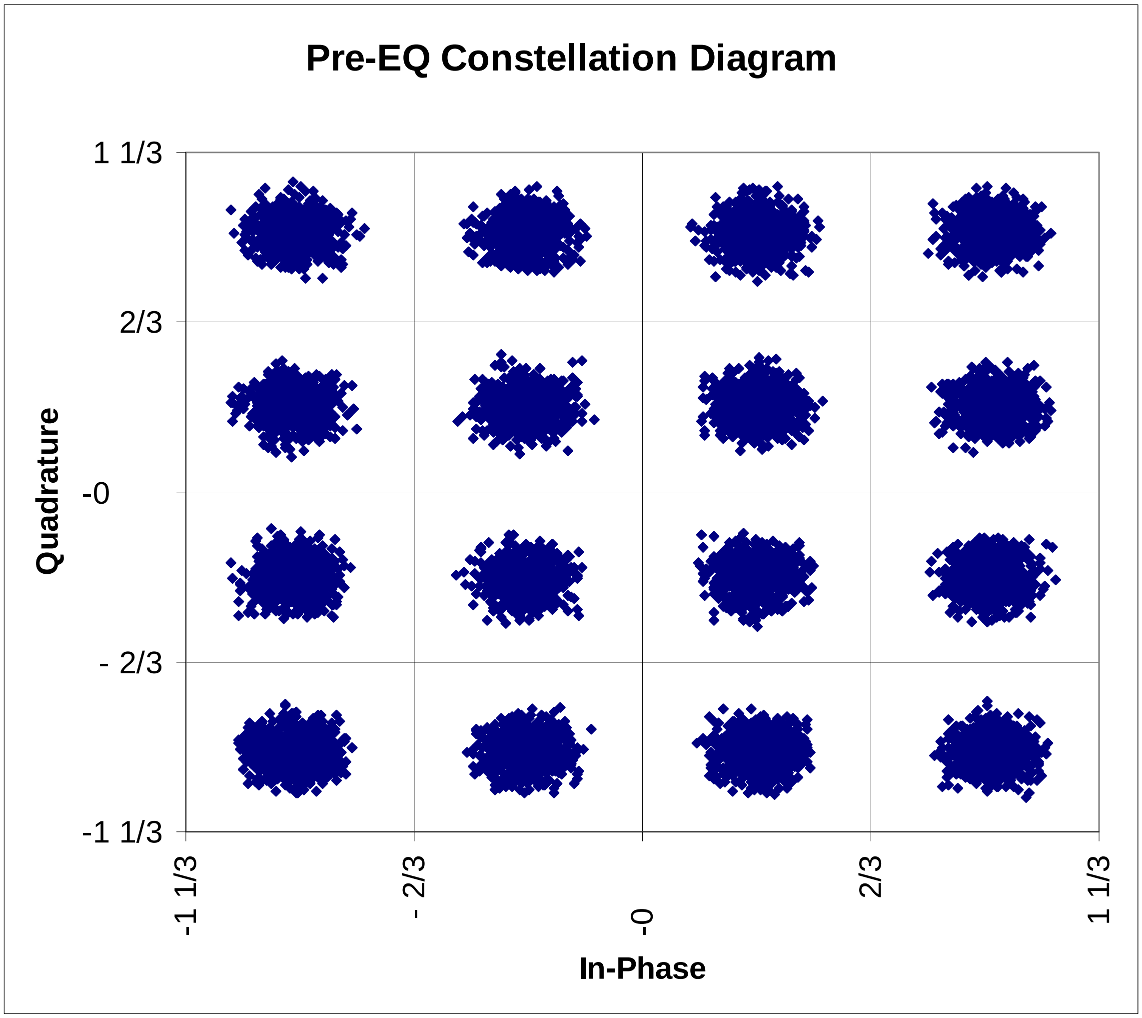


Figure 19 - Amplitude Distortion Impaired 16-QAM Constellation

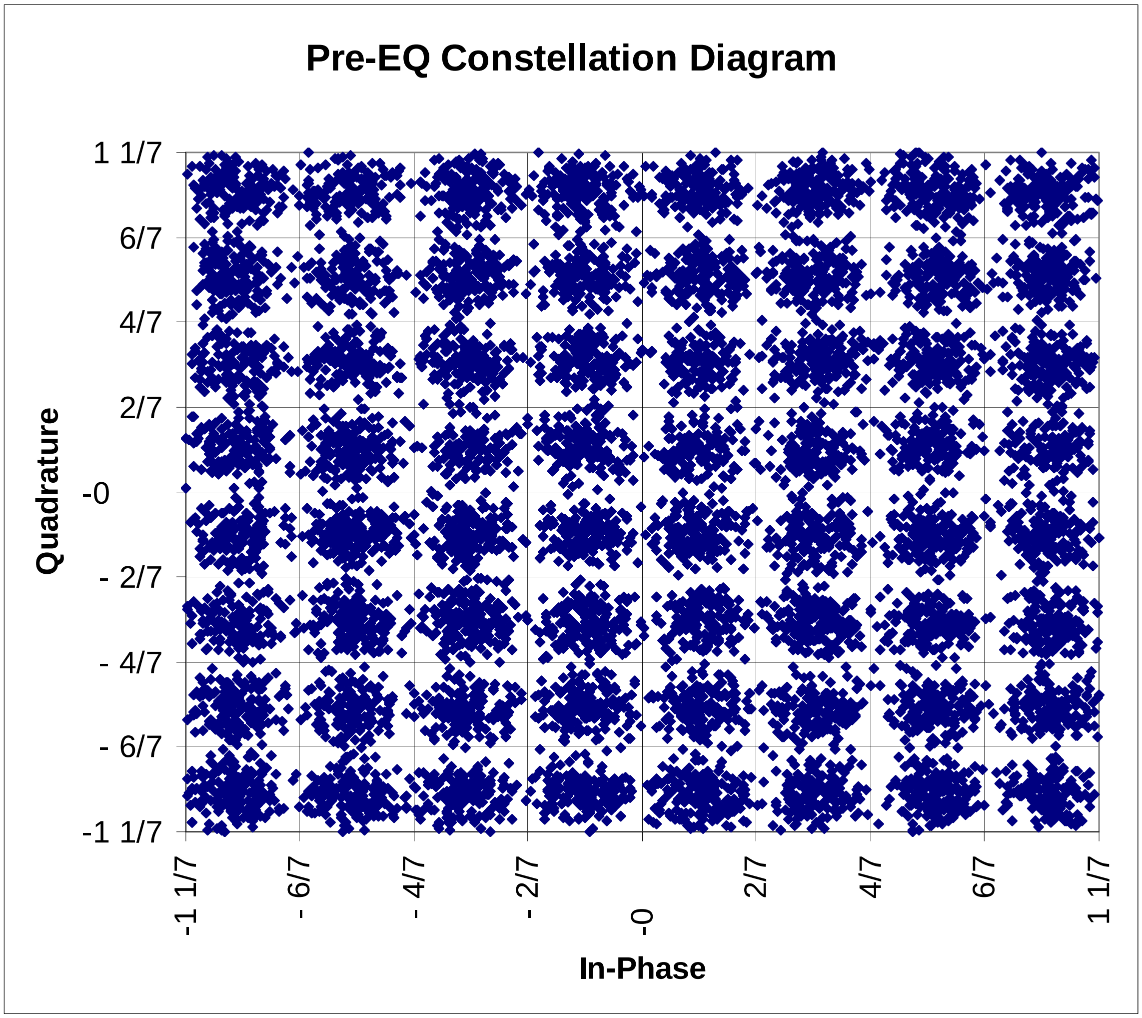


Figure 20 - Amplitude Distortion Impaired 64-QAM Constellation

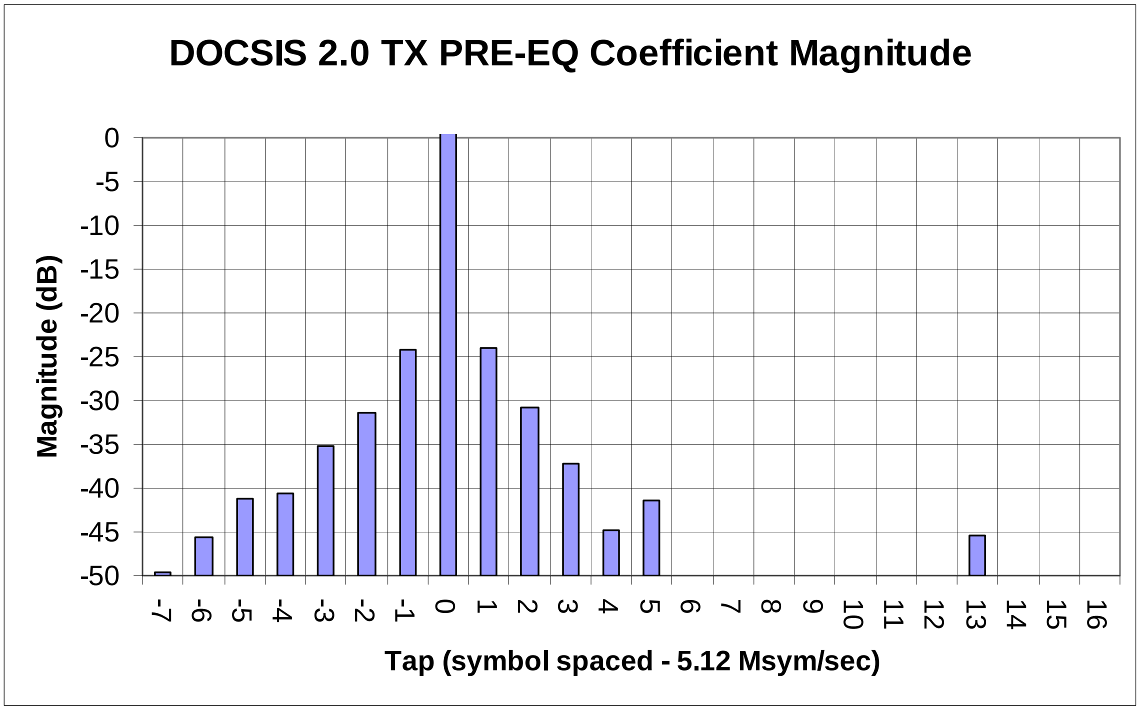


Figure 21 - Amplitude Distortion Impairment –Impulse Response Magnitude

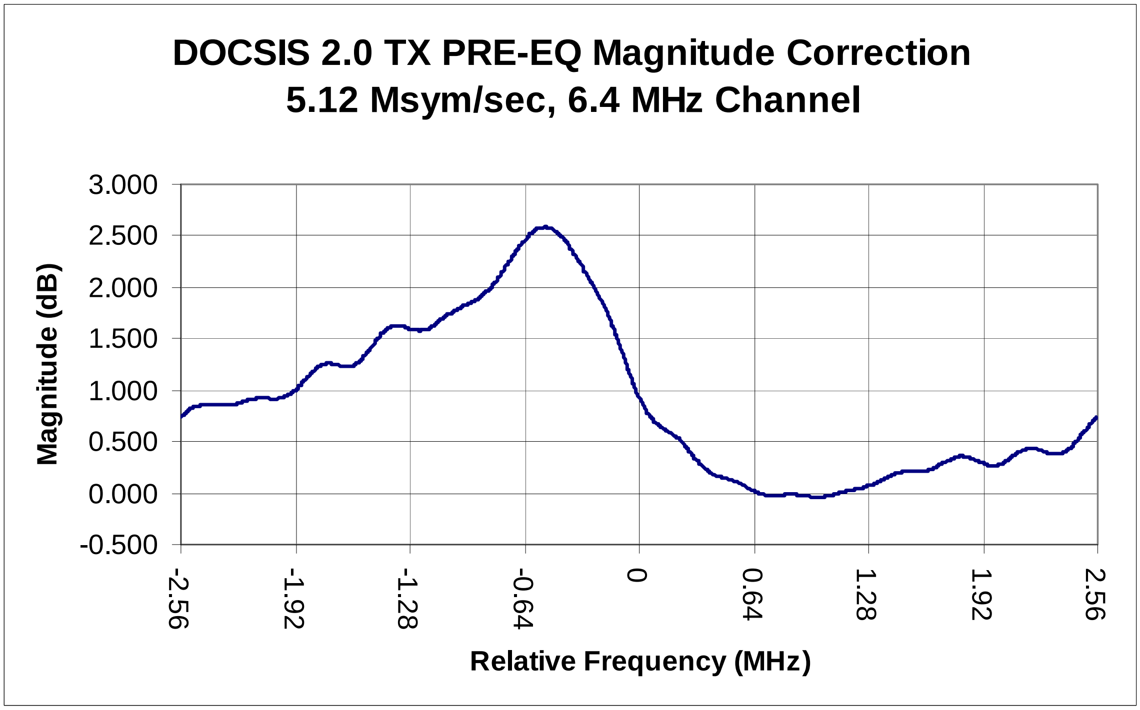


Figure 22 - Amplitude Distortion Impairment – Amplitude Response

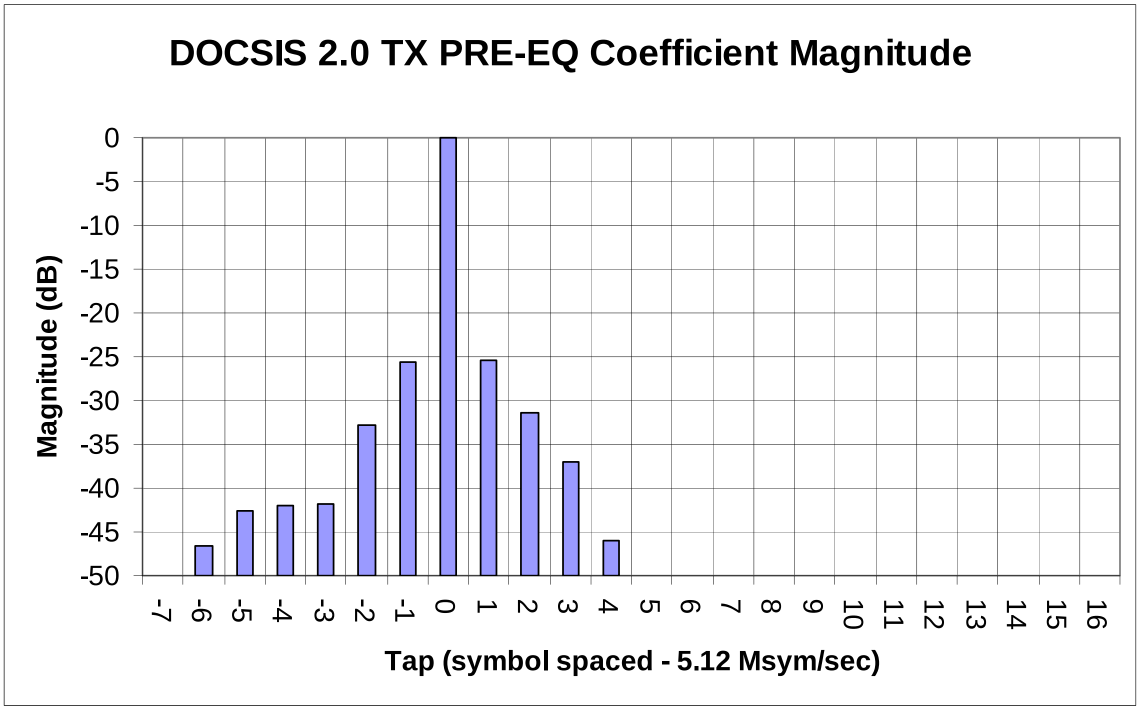


Figure 23 - Group Delay Variation Impairment - Impulse Response Magnitude

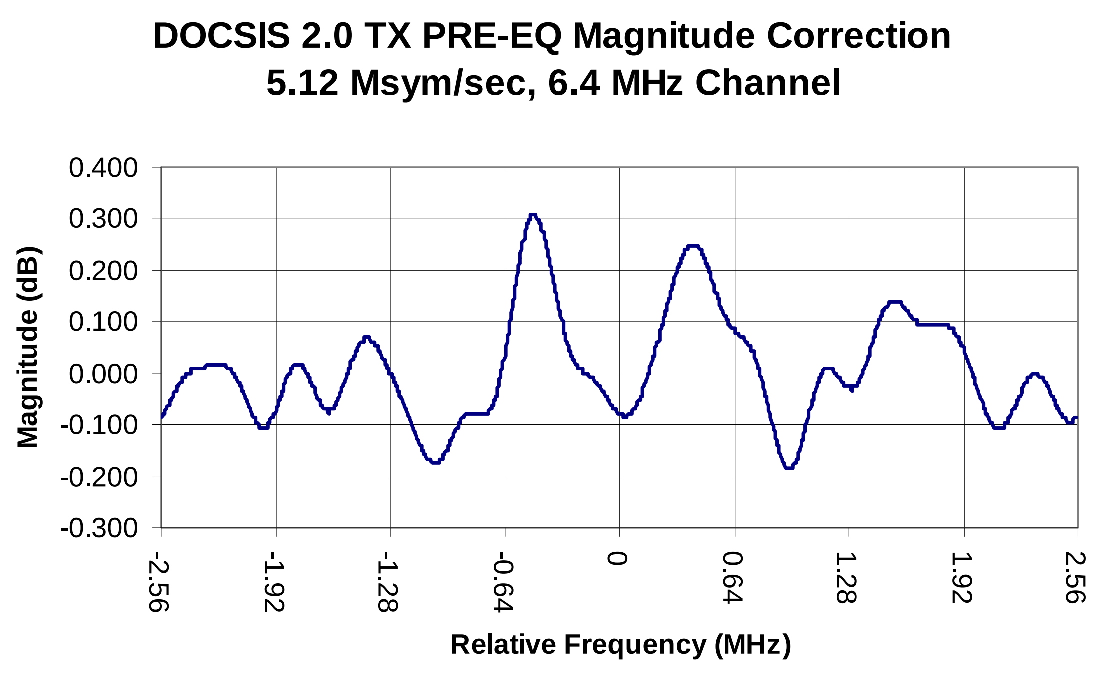


Figure 24 - Group Delay Variation Impairment - Amplitude Response

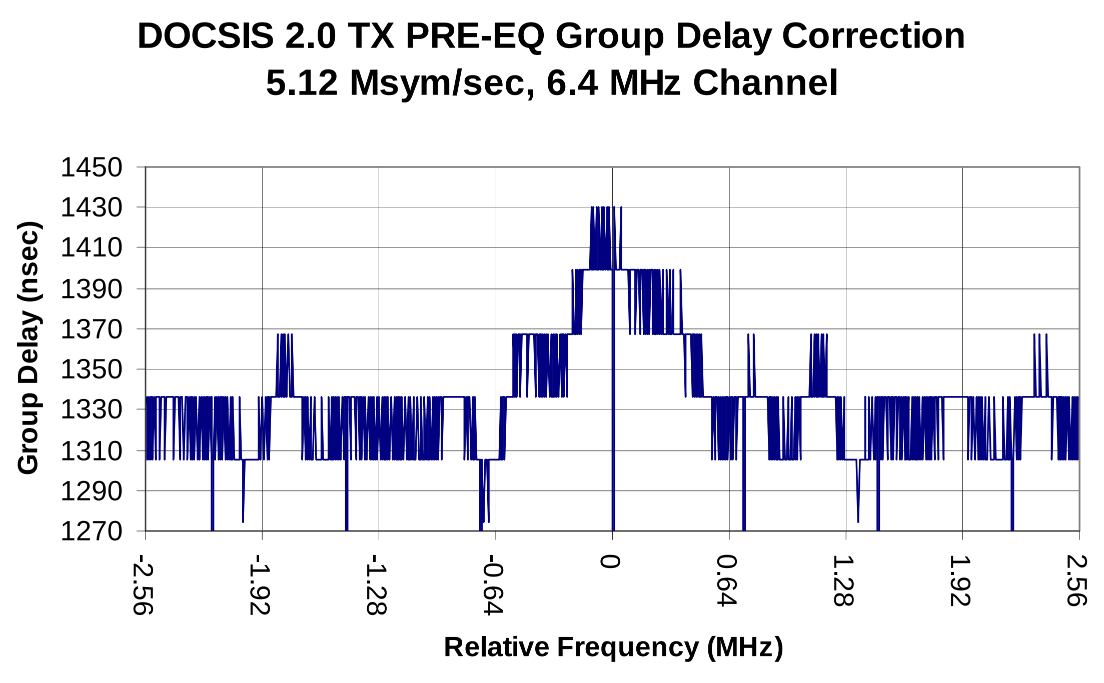


Figure 25 - Group Delay Variation Impairment - Group Delay Response

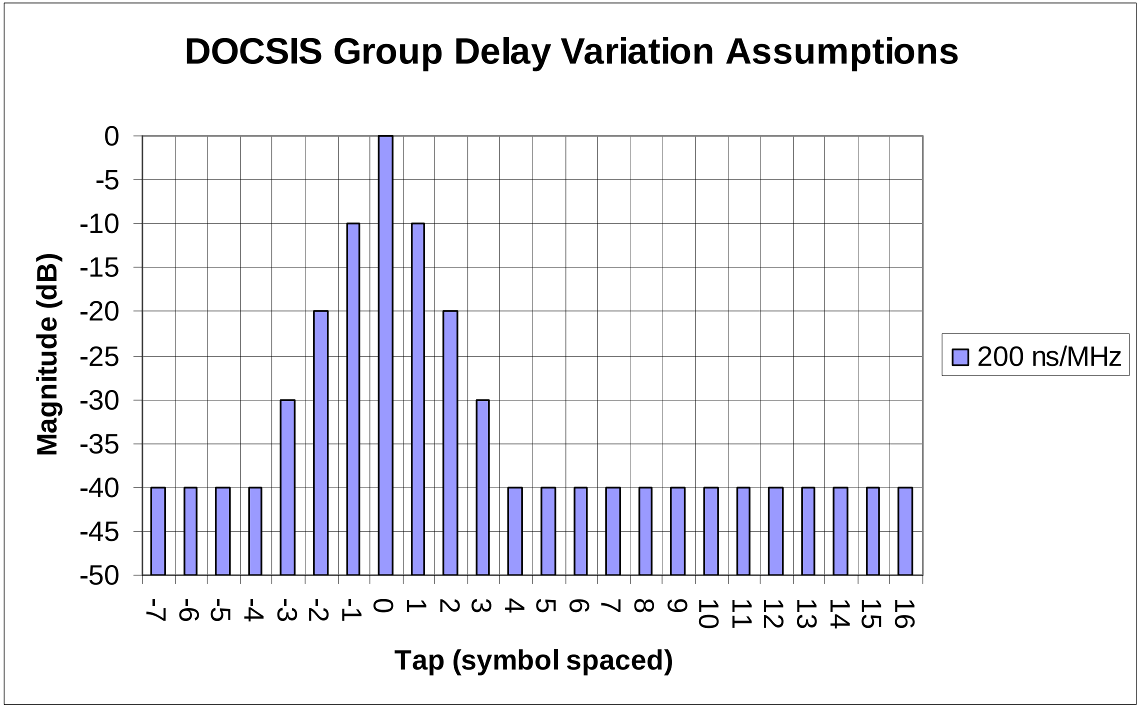


Figure 26 - DOCSIS Group Delay Variation Assumptions

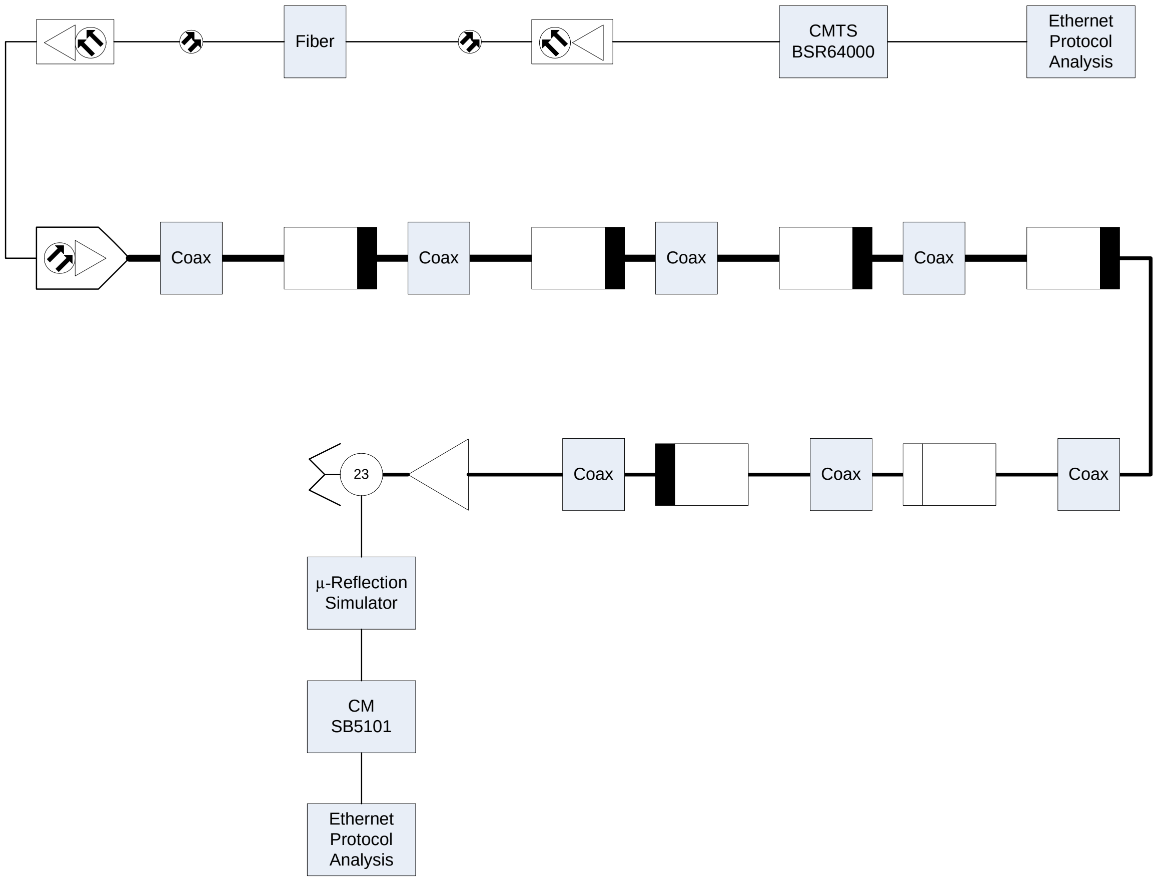


Figure 27 - Micro-Reflection Impaired Communication Channel Test Topology

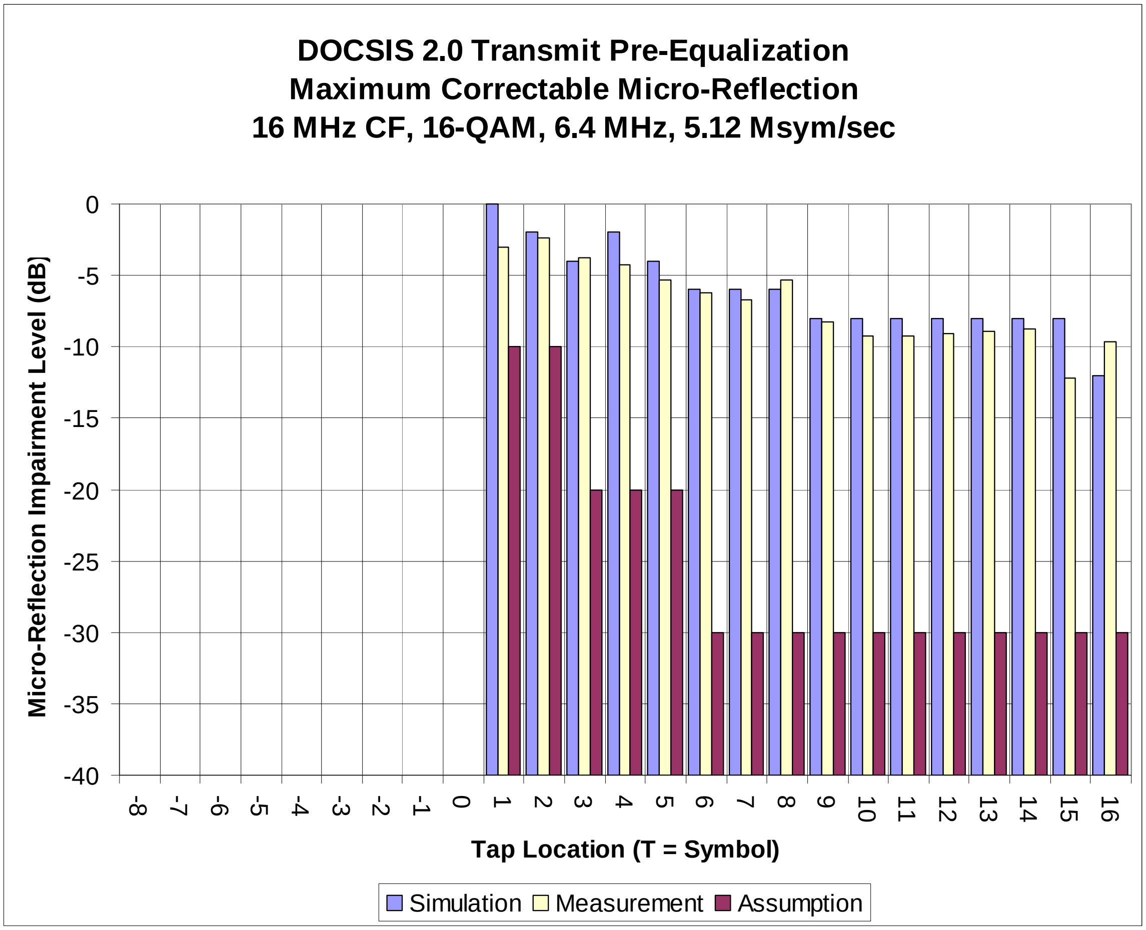


Figure 28 - Highest Correctable Micro-Reflection Using 16-QAM

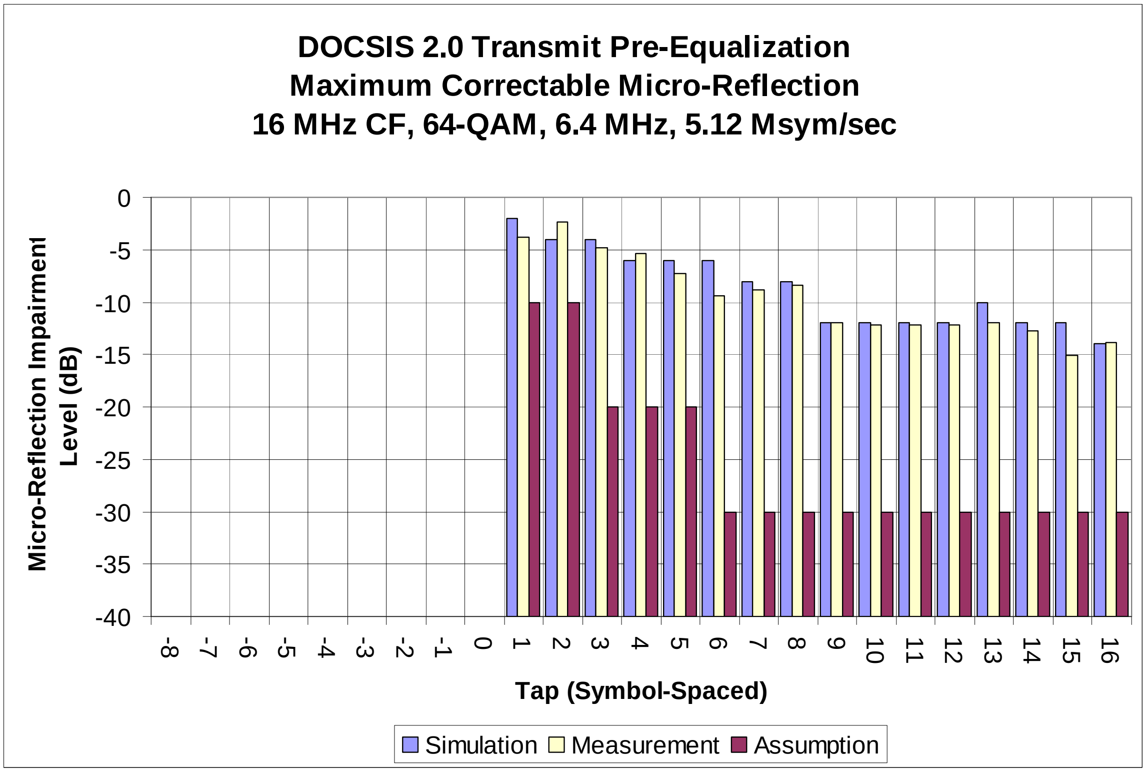


Figure 29 - Highest Correctable Micro-Reflection Using 64-QAM

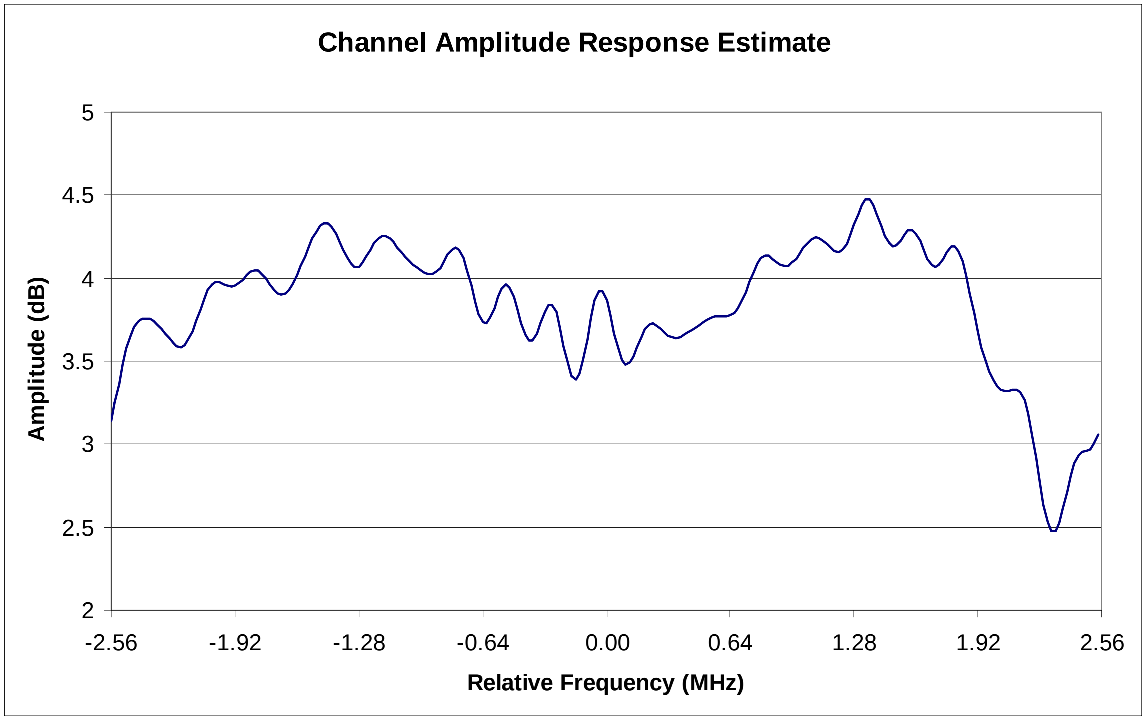


Figure 30 - Cascaded Amplitude Distortion Estimate, BW = 6.4 MHz, CF = 36.8 MHz

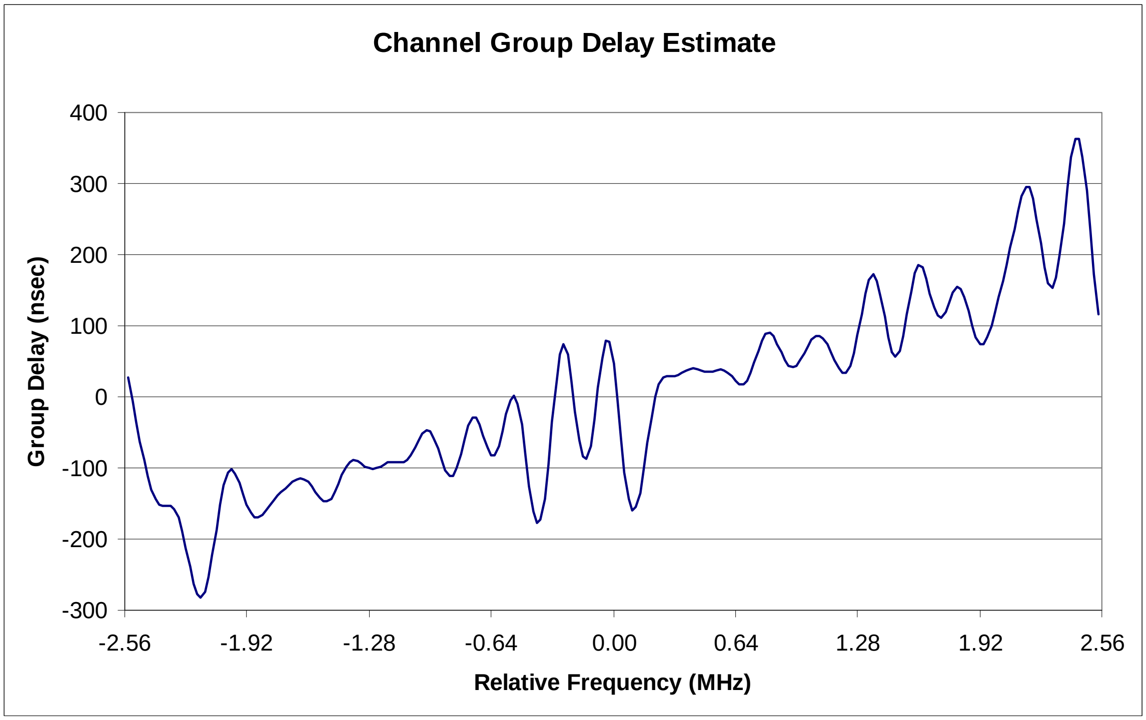


Figure 31 – Cascaded Group Delay Variation Estimate, BW = 6.4 MHz, CF = 36.8 MHz

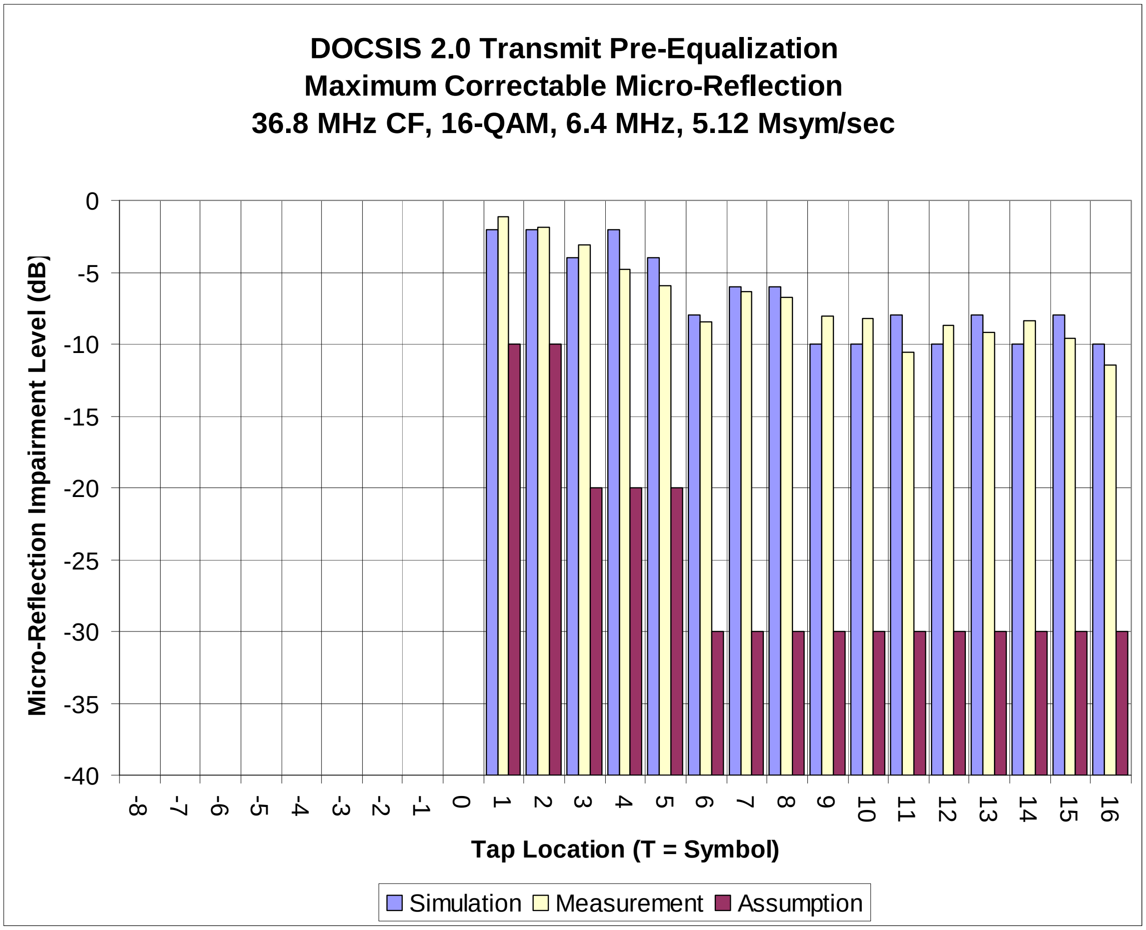


Figure 32 - Highest Correctable Micro-Reflection with Cascaded Amplitude Distortion and Group Delay Variation Using 16-QAM

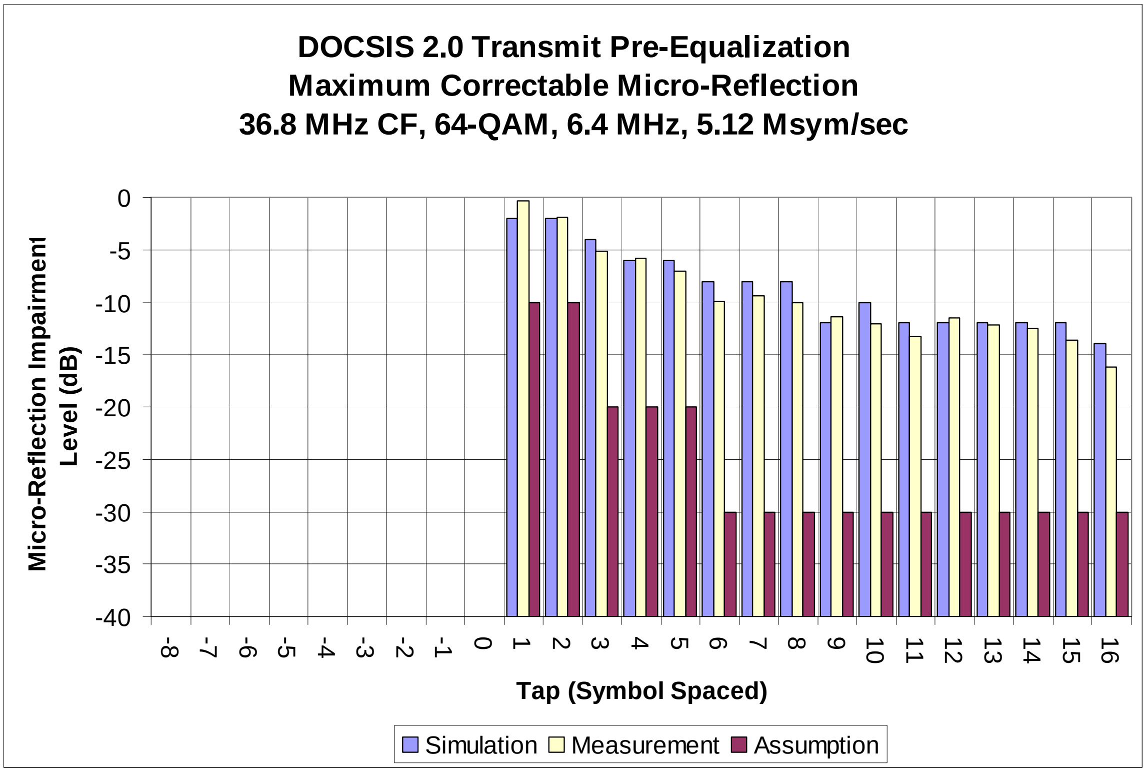
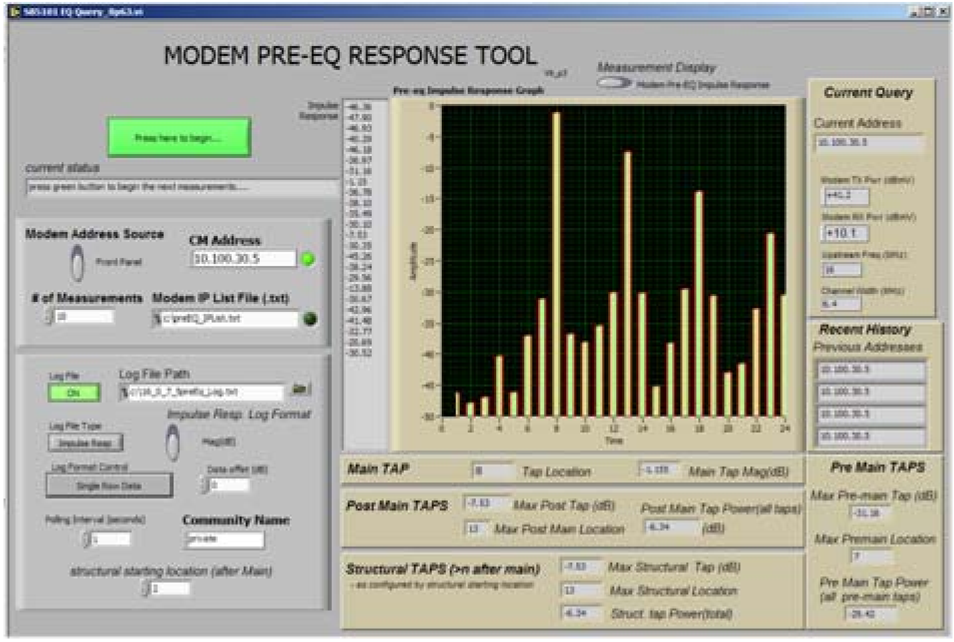


Figure 33 - Highest Correctable Micro-Reflection with Cascaded Amplitude Distortion and Group Delay Variation Using 64-QAM



current status: press green button to begin the next measurements....

Modem Address Source: Front Panel

CM Address: 10.100.30.5

Impulse Resp. Log Format: Mag(dB)

Community Name: private

Current Address: 10.100.30.5

Modem RX Pwr (dBmV): +10.1

Channel Width (MHz): 6.4

Main TAP: 8 Tap Location

Post Main TAPS: -7.53 Max Post Tap (dB)

13 Max Post Main Location

Post Main Tap Power(all taps): -6.34 (dB)

Structural TAPS (>n after main): -7.53 Max Structural Tap (dB)

13 Max Structural Location

-6.34 Struct. tap Power(total)

Figure 34 - Transmit Pre Equalization Query Tool

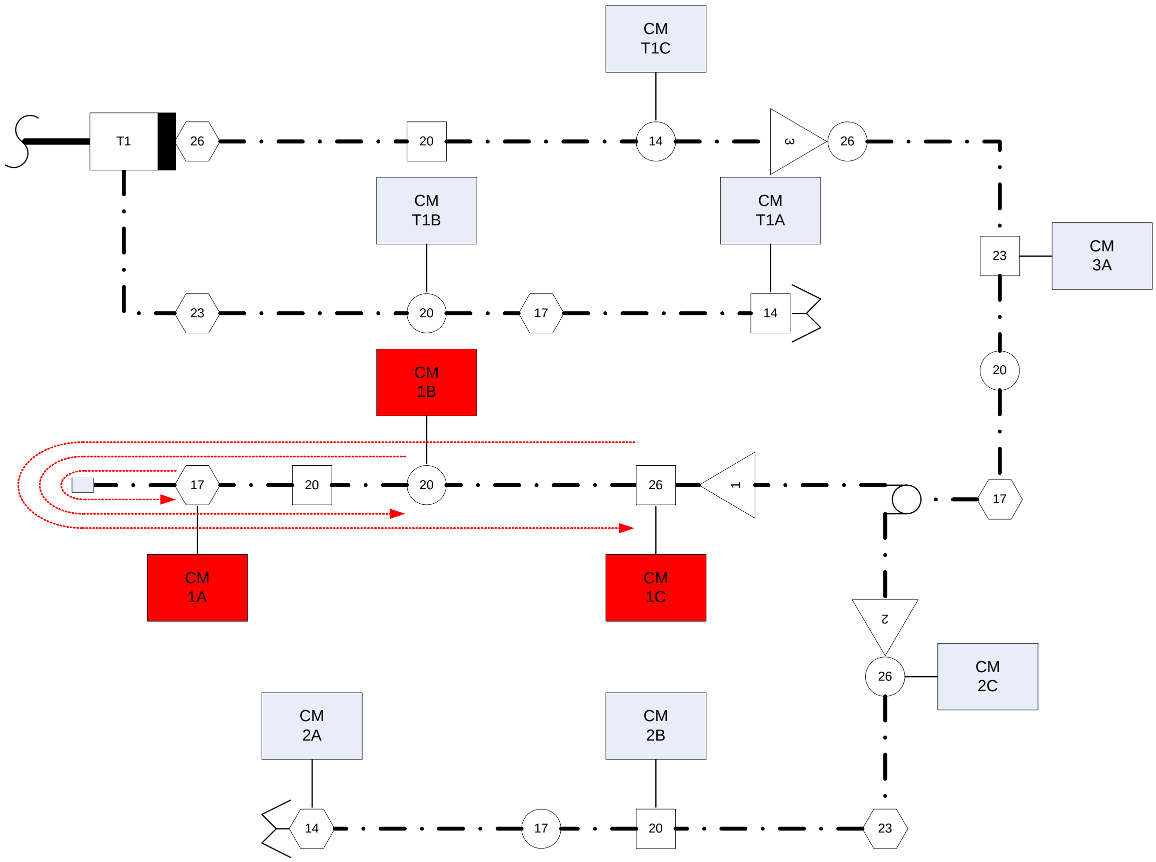


Figure 35 - Micro-Reflection Impairment Isolation Example