Water Can Run, But It Can't Hide

PNM Finds Soaked Cables

A Technical Paper prepared for SCTE by

Kathy Fox
Vice President, XOC
Comcast
Kathy_Fox@comcast.com

Jason Rupe, Principal Architect, CableLabs

Tom Williams, Distinguished Technologist, CableLabs

Jay Zhu, Senior Engineer, CableLabs

Ron Hranac, Chair, SCTE Network Operations Subcommittee

Nathan Zedan, RF Lab Manager, Comcast

James Kolcun, Director of Field Operations Standards, Comcast

Larry Wolcott, Fellow, Comcast

Table of Contents

Title **Page Number**

List of Figures

Title **Page Number**

List of Tables

Title **Page Number**

1. Introduction

The cable industry started taking advantage of proactive network maintenance (PNM) nearly a dozen years ago, and has shared results at many previous SCTE Cable-Tec Expos – so what's new in PNM for 2021? Water. Not the liquid itself, but what it can do to our subscriber drop plant and the services we provide over that plant. Operators have long been haunted by coaxial cable water ingress – since the very first days of the industry. Water ingress is nothing new, but it now has its own special tool in the PNM toolbox. In the grand scheme of things, that tool is a way to sharpen the focus on enhancing the customer experience and network performance, which is where PNM tends to take center stage. (Even, and perhaps especially, when it's raining.)

This paper reviews the progress of water detection, location, and severity assessment in the cable plant. The authors explore the background, motivation, theory and provide an outline for operators to evaluate their networks. In addition, there are field and lab examples which clearly illustrate the importance to customer experience, using customer testimony and speed test results as points of validation. Lastly, the authors provide information to help operators determine the future impacts when considering DOCSIS 4.0's features, such as extended spectrum (ES) DOCSIS and full duplex (FDX) DOCSIS.

2. Background

It has been said that one of the most versatile pieces of test equipment available to the cable industry is the spectrum analyzer. These are instruments that display signals in the frequency domain, and have been used for decades to install, validate, and troubleshoot service on cable networks.

Starting November of 2012, the DOCSIS 3.0 specification was expanded to include spectrum analyzer-like functionality in cable modems (CMs). This feature is known as full band capture (FBC) and is supported by most DOCSIS 3.0 and all 3.1 CMs. Since this time, most cable operator-deployed modems now have the FBC spectrum analysis capability.

This was an important moment for cable operators, creating the opportunity to automate a long-time manual process, known as sweeping. Prior to this time, technicians were required to manually connect broadband test equipment to take measurements of the RF plant. In addition to significantly improving operational efficiency and reducing costs, FBC allows cable networks to be monitored constantly, without a technician being present. This is important for diagnosing intermittent issues which can occur at odd times, often as the result of temperature or weather changes.

Among the earliest recognized impairments (Figure 1) was the standing wave, or more accurately, amplitude ripple which is caused by standing waves. These are characterized by a periodic, or predictably repeating waveform in the frequency response, which may be sinusoidal or scalloped. Standing waves can be classified by a number of parameters including their periodicity and magnitude.

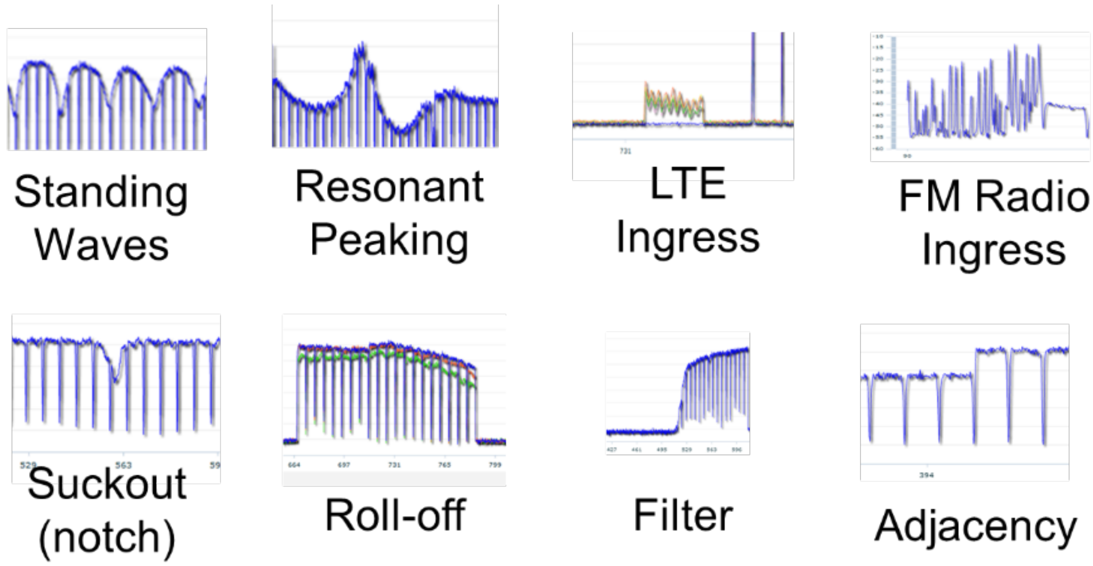


Figure 1 - Examples of impairments found using FBC (Source: Comcast)

As illustrated in Figure 1, there are several common RF impairments which can be detected and classified using FBC. However, there are a few impairment types which do not clearly fall into these general impairment categories. This typically occurs in the case of multiple problems resulting in a compound impairment. The detection software algorithms can become ineffective, sometimes detecting one or the other.

3. Cable RF Spectrum Fundamentals and Water

Some of the basic concepts of cable RF spectrum are illustrated in Figure 2. The horizontal axis represents the frequency spectrum, starting from 5 MHz and ending above 1000 MHz [1000 MHz is the same as 1 gigahertz (GHz.)] RF signals are precisely modulated and transmitted at specific frequencies, and their quality is measured using a variety of metrics: RF power, carrier- or signal-to-noise ratio, frequency response, and more.

For instance, we measure RF power (signal strength) using the decibel millivolt (dBmV) rather than watts. This is because the range of RF signal power in cable networks is very large, so, expressing those numbers in units of watts gets unwieldy. When comparing two values, we use units of the decibel (dB) because it represents a ratio, although it is logarithmic. One simple rule-of-thumb to remember when using decibels is that a 3 dB change in signal level represents a doubling or halving of RF power. For example, 50 dBmV is twice the power of 47 dBmV.

Notice in Figure 2 that all the RF signal levels across the spectrum are similar, making a nice flat line across the peaks of the signals. However, in Figure 3 there are significant power variations at different frequencies within the spectrum. When things are working properly, the levels should be relatively flat and sometimes may have a tilt in one direction or the other. The overall amplitude-versus-frequency performance of the spectrum is known as the “frequency response.”

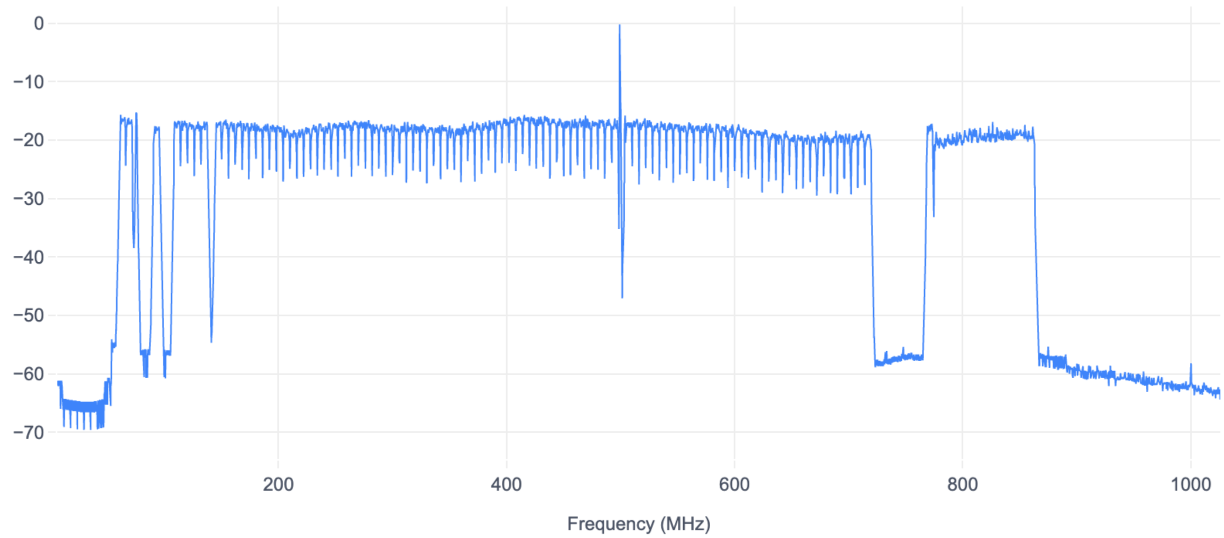


Figure 2 - Unimpaired frequency response

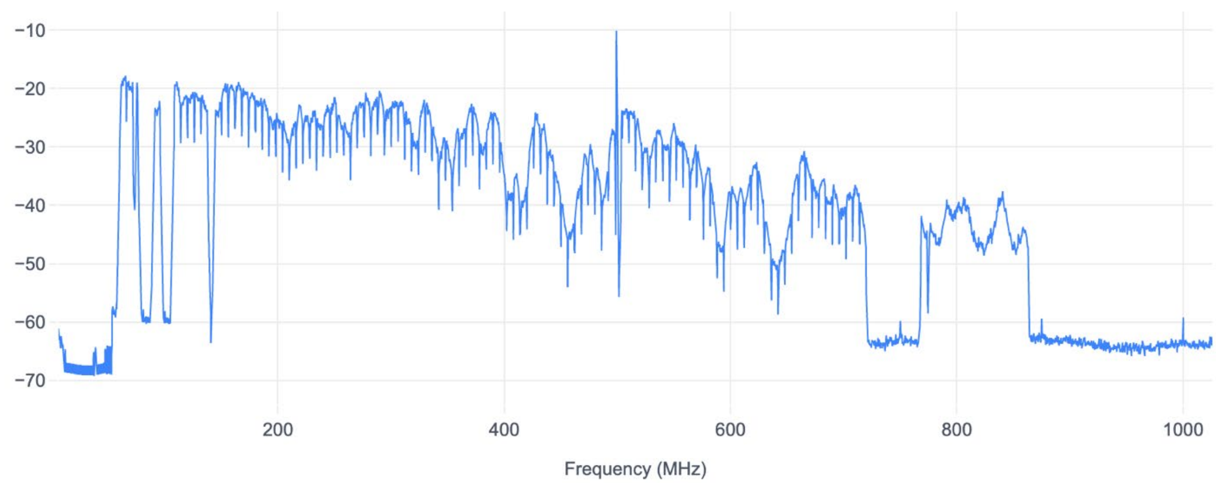


Figure 3 - Water impaired frequency response

When water enters coaxial cable, several things happen to create the distinctive frequency response shown in Figure 3. Why does water in coaxial cable have that effect on RF? The presence of water in the cable's dielectric changes the dielectric constant, which changes the velocity factor, characteristic impedance, and attenuation (see the Appendix for more information on the characteristics of coaxial cable). Further complicating the water-related degradation is the fact that the water is not uniformly distributed throughout the length of the cable. That, in turn, results in randomly distributed, localized variations in the cable's velocity factor, impedance (think micro-reflections) and attenuation, causing a non-periodic shape in the frequency response.

The severity of this problem will depend on the amount of water present in the cable and other factors such as temperature and system RF levels. These problems have been observed to coincide with rainy weather and tend to be variable, sometimes completely clearing when the water drains or evaporates. The amount of customer impact can be measured with downstream receiver power levels, tilt, per-channel RxMER, and codeword errors or packet loss, which may inform the repair prioritization.

To avoid confusion, another related but different impairment you should be familiar with is known as an amplitude ripple, commonly referred to as a "standing wave." This is especially important because the standing wave is somewhat like our water signature, but there are subtle and not-so-subtle differences. Standing waves are also caused by impedance mismatches and the resulting micro-reflections, but water is not present. Because there's no water to add *random* attenuation, the signal bounces and attenuates in a predictable manner. In the case of a standing wave, a repeating and *periodic pattern* can be seen in the frequency response. Standing waves tend to have a sinusoidal wave shape, but can sometimes have a sharp, scalloped appearance. A standing wave may affect all or part of the RF spectrum. These problems tend to be constant (non-variable) or change very little. The changes in standing waves are subject to environmental influence such as wind or temperature, which can influence the mechanical properties of the plant.

It is most common for our drop cables and taps to be impacted by the presence of water, but it could be feeder or distribution cable affecting multiple locations. Drop cables are easily damaged by squirrels chewing on the jacket and shielding and is very common in some areas. Hardline is also subject to animal chews, radial cracks and holes caused by all manner of hostile forces. It is important to distinguish between drop and hardline because these are sometimes two different repair categories, each requiring a different type of technicians to fix the problem. Generally, a drop cable signature will be common to all devices within a single location and would be repaired by an install/repair tech or business partner (contractor). Larger plant issues would be repaired by a network maintenance technician and can disrupt service for a larger segment of our network. The latter often requires additional attention to scheduling and notification to help limit the negative impacts to customers.

From the customer's perspective, excessive RF signal attenuation is typically experienced as diminished quality and reliability of their internet or video experiences – or, in some cases, it renders those services unusable. What gets affected depends on the specific frequency which is impacted by the impairment. Conventional DOCSIS, video or other system signals can be used to evaluate the severity of the problem. However, given the transient nature of water in our cable systems, these types of problems can be temporal and associated with weather. Therefore, time and environmental components can be used to help with predictability. For example, additional resources may be allocated to a service area in advance of a rainy season.

3.1. Water Migration - Peripheral Damage

In addition to the cable, which is often a primary victim of water ingress, it's also common for the water to migrate and damage peripheral components. When additional network elements are damaged, multiple problems can become compounded and worsened. Among the most common examples are taps, splitters, splices, block splices and all the different filters and pads installed in the drop network.

3.1.1. *Water Damaged Tap*

In the following example, a water-soaked drop was the primary source of water ingress. However, the tap was physically located at a lower elevation on the pole than where the water entered the cable. With water accumulating over time and the influence of gravity, the water eventually migrated into the tap. A closer look at Figure 4 clearly shows water droplets in the upper left and lower right corners of the tap faceplate. The circuit also shows rust and other signs of corrosion. The subsequent frequency responses were captured before and after the faceplate was replaced. The FBC spectrum in Figure 5 represents a typical high-frequency roll-off starting around 500 MHz, becoming dramatically worse at 750 MHz (nearly 30 dB). In this case, the OFDM channel was significantly impacted, causing severely degraded service performance. Figure 6 shows the frequency response improvement after replacing the water-damaged faceplate.

Figure 4 - Water-soaked tap faceplate, water droplets visible

(Courtesy of James Medlock, Akleza)

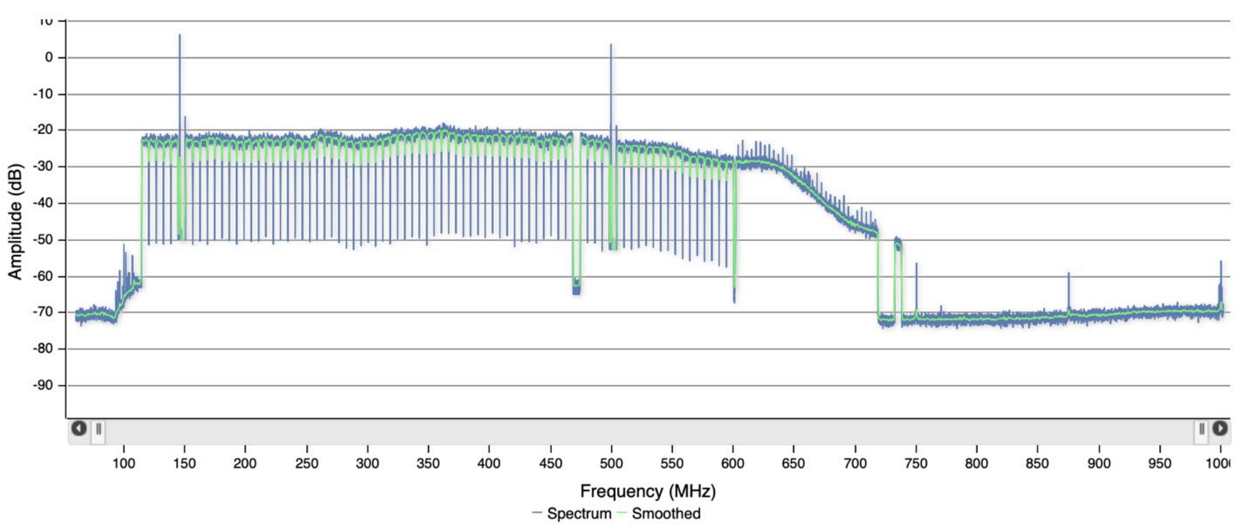


Figure 5 - Roll-off frequency response of water damaged tap port
(Courtesy of James Medlock, Akleza)

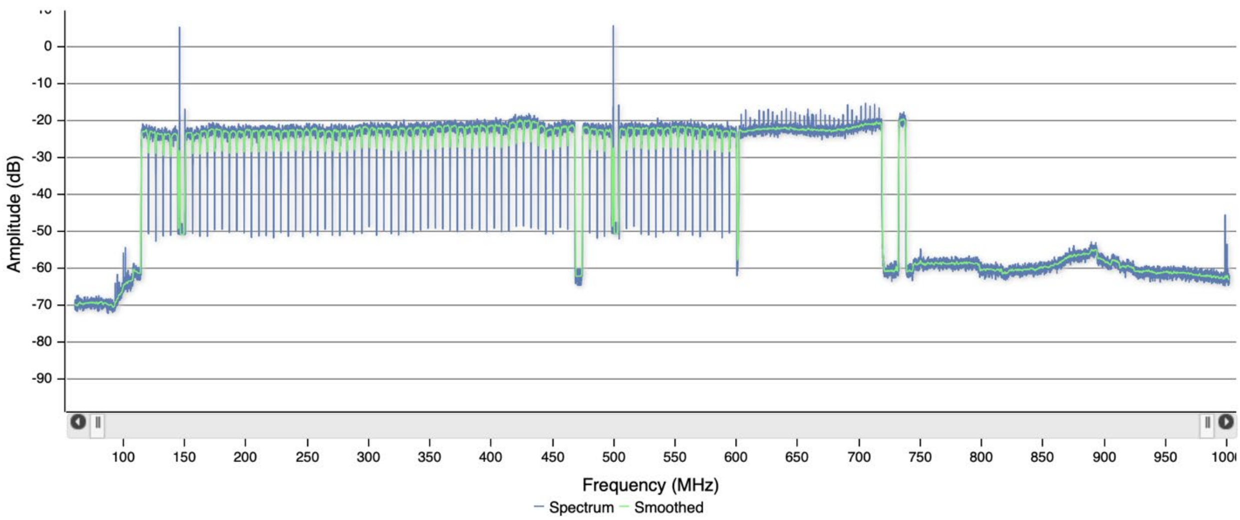


Figure 6 - Flat frequency response after faceplate replacement

(Courtesy of James Medlock, Akleza)

3.1.2. Water Damaged MoCA Filter

Virtually any passive or active network element can become subject to water migration. In some cases, the water can indirectly affect the network elements, resulting in unexpected impedance mismatches. The following example shows an in-line MoCA point-of-entry filter located at the ground block. Like many other types of filters, these passive devices are sealed against water ingress. However, when the drop cable jacket is compromised, the water can easily migrate along the center conductor or dielectric, where there is no water barrier. In the example shown in Figure 7, the filter became filled with water, froze, and expanded, causing the press-fit housing to become separated. The entire assembly was recovered from the field including the drop cable, filter, and ground block. Upon inspection, the Series 6 drop cable was damaged near the tap-side fitting (Figure 8) which is highly consistent with rodent chew marks, commonly seen on drop cables (Figure 9). In this case, there was no water immediately present at either connector interface. However, when a vacuum was applied to one end, the water quickly migrated and became evident at the connector (Figure 10).

The condition and integrity of the outer jacket is critically important to protect the cable plant from water ingress. While evaluating several damaged filters, water ingress and freezing could readily be attributed as the cause. In each example, the water ingress point could be located. Figure 11 shows more examples of typical jacket damage.

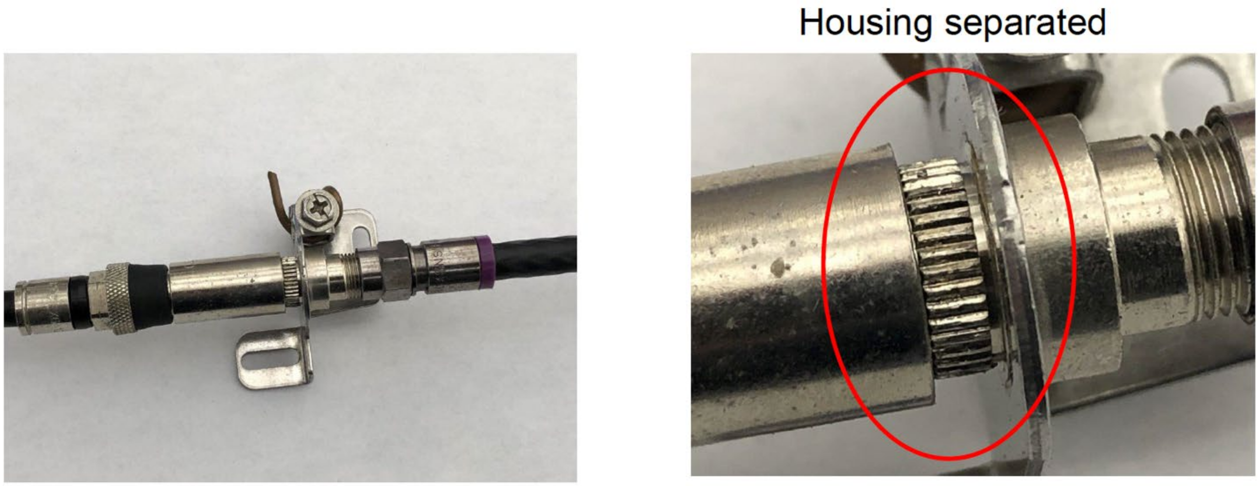


Figure 7 - MoCA filter housing separation

(Courtesy of Skip Palinkas, PPC)

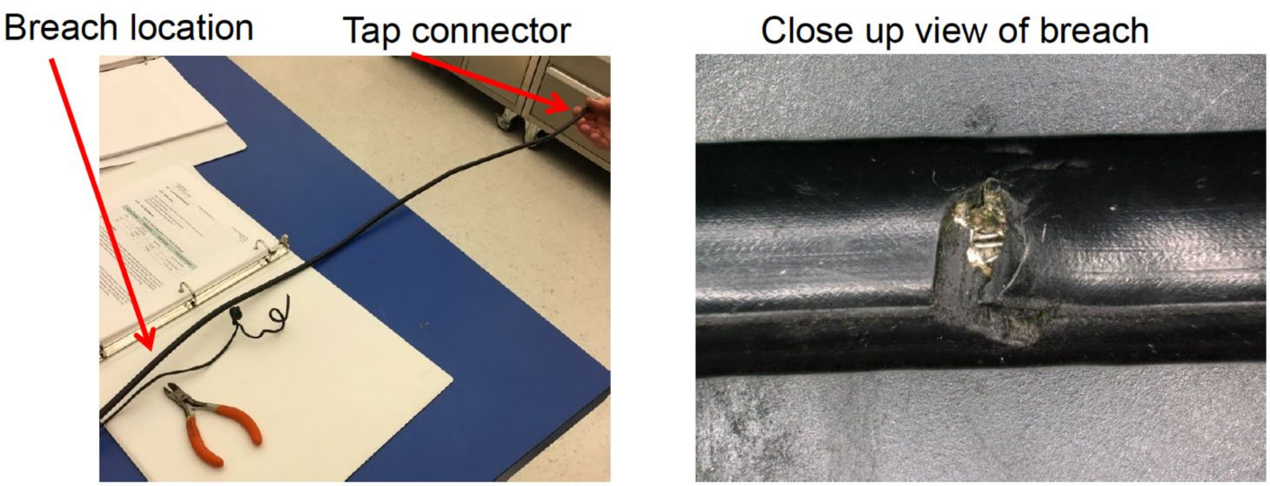


Figure 8 - Coaxial jacket breach near tap-side connector

(Courtesy of Skip Palinkas, PPC)

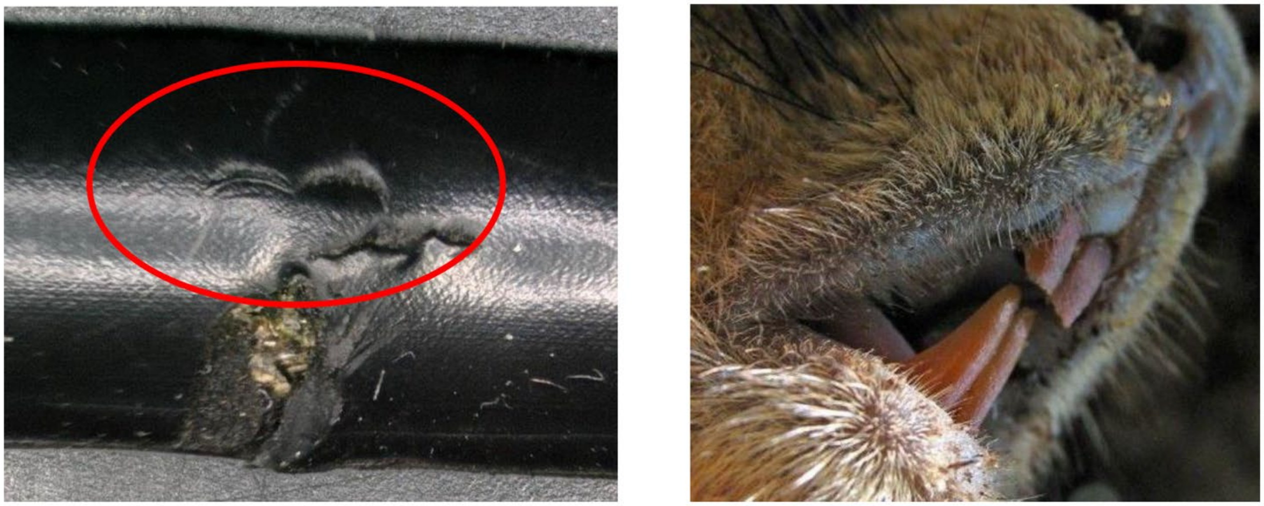


Figure 9 - Jacket breach compared with rodent teeth

(Courtesy of Skip Palinkas, PPC)

Connector removed from MoCA GB

Same connector after a vacuum pulled. Demonstrates drop is saturated

Figure 10 - Water visible after vacuum is applied

(Courtesy of Skip Palinkas, PPC)

Squirrel chew Elongated cut

Figure 11 - Rodent chew compared to elongated cut, common coaxial damages

(Courtesy of Skip Palinkas, PPC)

3.2. Test Results

A number of field trials were conducted in 2020 resulting in a large number of cable samples recovered from the field. In one trial, over 100 drop cables were located and replaced, providing a substantial sample group. Other control groups of bad drops were also brought in from the field. In the latter group, the damaged drops were not necessarily associated with water.

In the example, Figure 12 shows the frequency response of a water-soaked drop cable (bottom) compared with the same type and length of new, unimpaired cable (top). Pockets of severe attenuation can be observed.

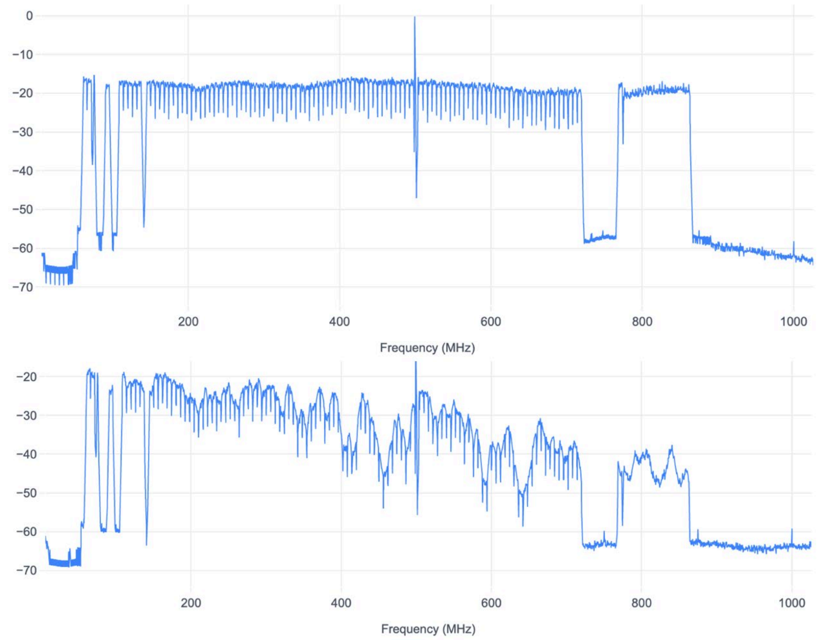


Figure 12 - New drop cable (top) compared to water-soaked cable (bottom)

These two cables were analyzed with test equipment including a speed test which closely approximates the experience a customer would have. A number of these tests were run and Figure 13 shows a typical result. The top value of 1262.7 Mbps download speed is consistently achieved using a new 95-foot RG6 drop cable. Then, when using the same type and length of cable with water damage, a speed of 179.3 Mbps is achieved. This is significantly below the provisioned speed of 1200 Mbps, delivering only 14% of the provisioned performance.

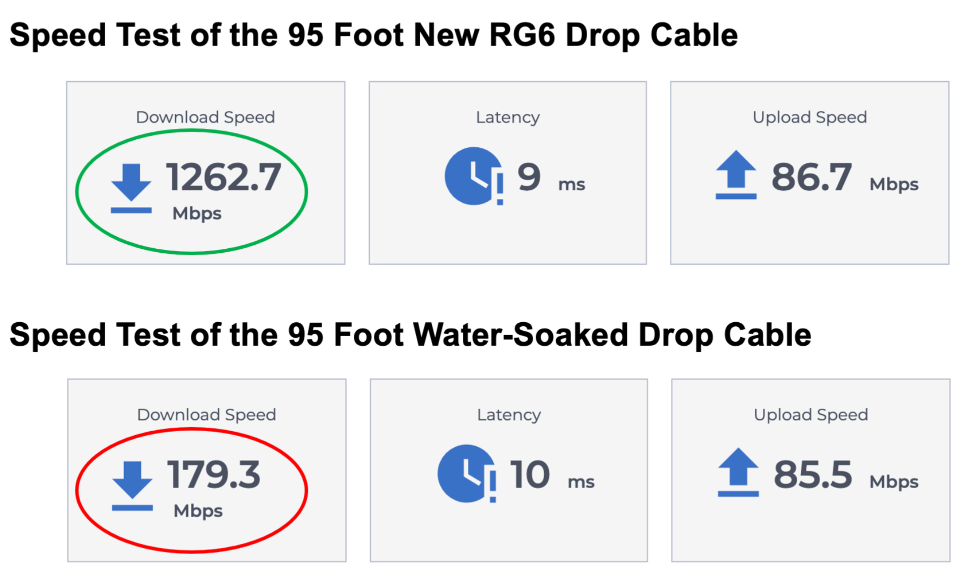


Figure 13 - Speed test comparison of new vs. damaged drop cable

To examine the influence of temperature, the same damaged cable was frozen (Figure 14) at -10 degrees Fahrenheit. After freezing, the frequency response was measured (Figure 15) and the attenuation greatly improved, having well over 25 dB improvement at certain frequencies.

At the same time, speed tests were run, and the results are show in Figure 16. When the damaged cable is frozen, the speed test results improved dramatically. A speed of 1078.4 Mbps was achieved, reaching nearly the same speed of a brand-new cable. Then, within minutes, the cable thawed and was retested at 68 degrees Fahrenheit. When the frozen water returned to a liquid state, diminished speeds returned. In this example, a paltry 70.9 Mbps was the peak download speed.

Figure 14 - Freezing the water-soaked drop cable

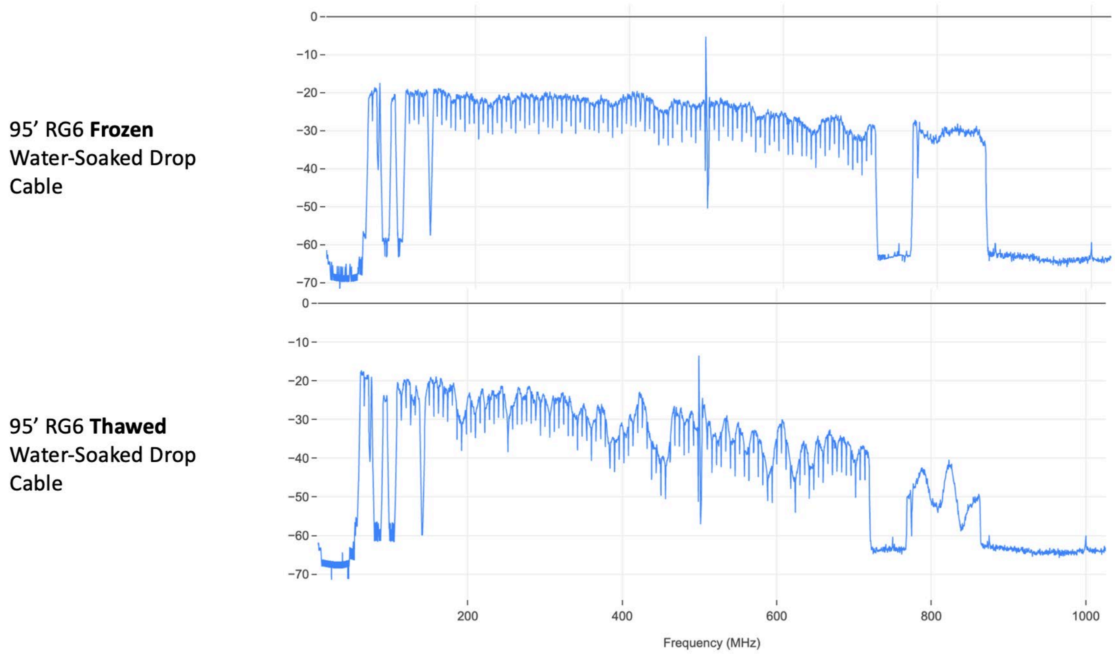


Figure 15 - Frozen (top) compared to thawed (bottom) frequency response

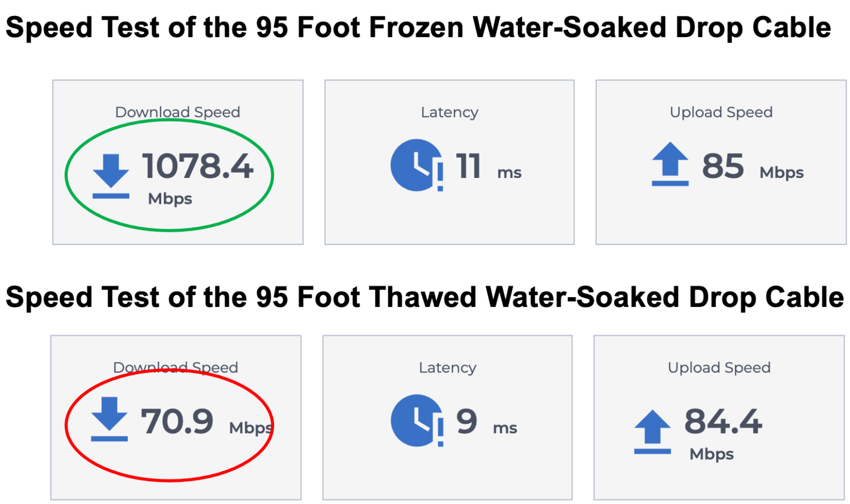


Figure 16 - Frozen (top) compared to thawed (bottom) speed test

4. Customer Impact

4.1. About Customer Experience

As previously discussed, water-soaked cables are a regular occurrence in most cable systems. Regardless of underground or overhead construction, cables can become damaged or otherwise deteriorate, allowing water to ingress and eventually migrate through the length of cable. Depending on the cable's exposure to the elements, the impact on the customer experience can be highly variable.

4.2. Customer Experience – A Typical Example

In the presence of water damage, it's common to hear from our customers that their service was poor and unreliable. In the following example, FBC was used to identify an individual subscriber drop that had water damage, specifically by the unique signature in the displayed frequency response. As Figure 17 shows, the response has a non-periodic wave shape, and attenuation increases dramatically at higher frequencies. Remote polling of the modem showed that most of the downstream SC-QAM signals had poor performance, as shown in Figure 18. The upstream was relatively unaffected.

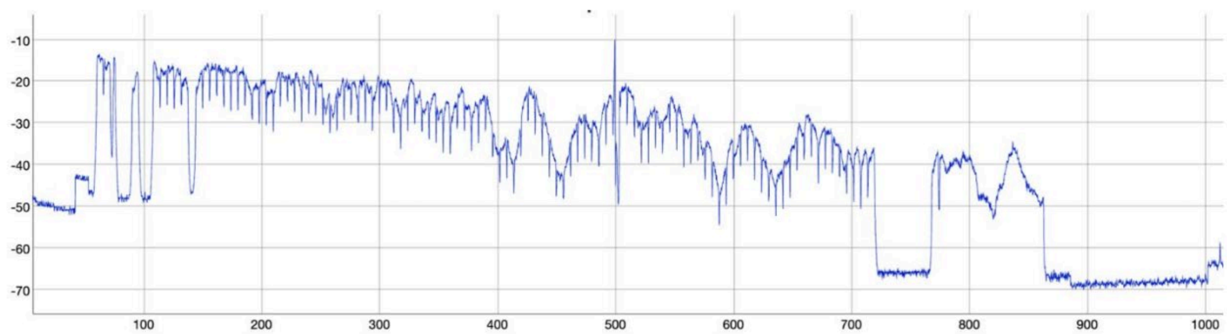


Figure 17 - Water damaged cable frequency response, prior to repair

Note the non-periodic wave shape in the FBC response in Figure 17 and the higher attenuation at higher frequencies. This example occurred when abrasion damaged the cable's jacket, allowing water to enter the cable.

Figure 18 - Impaired downstream SC-QAM power and RxMER levels, per channel

As seen in Figure 18, most of the downstream SC-QAM signals have low signal level and degraded RxMER, indicated in red shaded boxes. The upstream was relatively unaffected.

Technicians went to the subscriber location and were able to find and fix the problem without having to enter the premises. Figure 19 shows the coax jacket, which had been damaged by abrasion from the electrical service drop. The damaged coax jacket allowed water to enter the cable and travel inside of the cable all the way to the ground block. Figure 20 shows water coming out of the connector at the ground block end of the drop.

Figure 19 - Damaged coax jacket where water was able to enter the cable

Figure 20 - Water coming out of the end of the connector at the ground block

The fix was to replace the subscriber drop from the tap to the ground block. Figure 21 shows the FBC screen shot after the new drop was installed, and Figure 22 the post-repair SC-QAM performance.

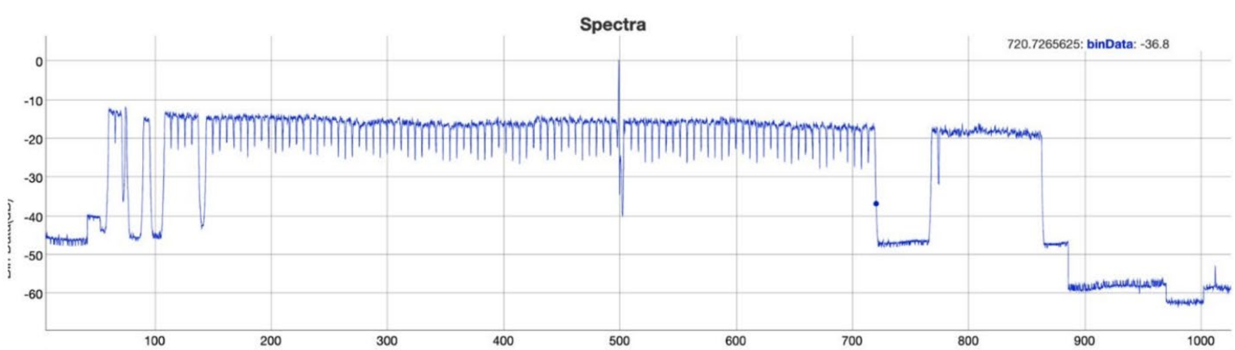


Figure 21 - FBC response after drop cable was replaced from the tap to the ground block

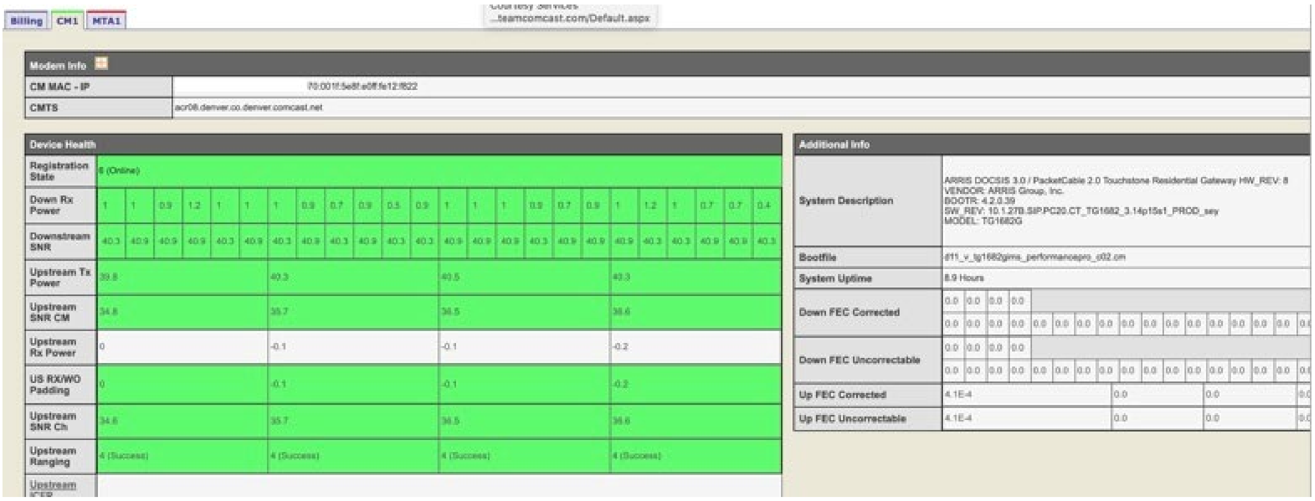


Figure 22 - 40+ dB RxMER, signal performance after drop cable replacement

4.1. Environmental Influence

The impact of temperature and thermal influence on cable networks is well-known. When the cable plant is structurally intact, the system is designed to cope with hot and cold temperatures. However, when the characteristic impedance is compromised, things can become predictably unpredictable.

4.2. Severity Assesment

Fortunately, as illustrated in Figure 23, our fundamental DOCSIS signal quality measurements are excellent for determining the customer impact. The water causes a directly observable degradation in downstream signal power, which can result in degraded receive modulation error ratio (RxMER) and ultimately poor, unreliable performance. Figure 23 enumerates the basic order for conducting a customer impact and severity assessment.

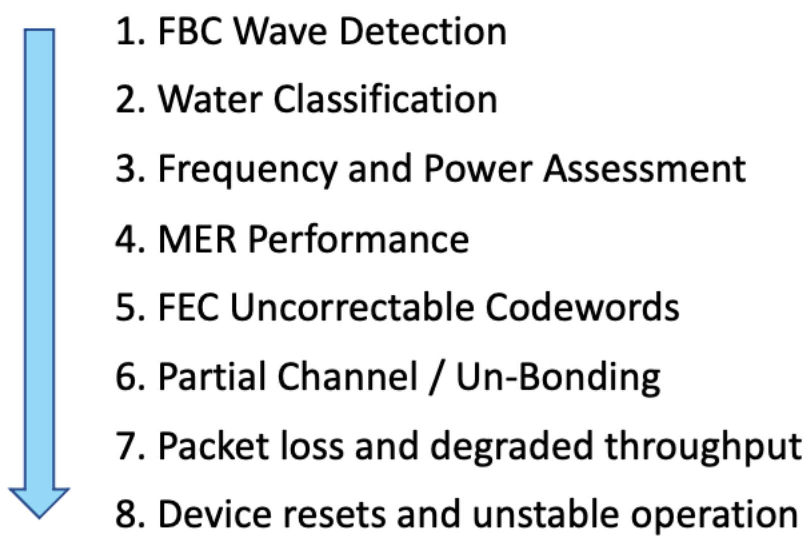


Figure 23 - Severity assessment

Beginning from step 3 in Figure 23, it's common for operator tools to provide some if not all the information. It's fair to say that operators have already been dealing with the outcome of water-soaked cables. Unfortunately, lacking the detection and classification of water damage, the repairs can be inconsistent and often-times, unpredictable. And when the technician has some information about the likely cause of the problem, knowing what to look for is easier so troubleshooting can be faster, and repairs are more likely effective.

4.3. Proactive Repairs

By adding steps 1 and 2 in Figure 23, operators can proactively identify and attribute water damage as the cause. One of the common effects of water damaged cables is a progressive decay of service quality. This is influenced by a number of factors including the amount of moisture, freezing, thawing, heating and cooling. These environmental influences contribute to water migration and accumulation. In some circumstances, these damaged cables can be detected, located and repaired prior to affecting the customer's service.

5. Water Wave Detection Methods

This section covers the methods defined for automatically differentiating between impedance mismatch-related standing waves and water in a coax cable. When it was discovered that there were visually discernable differences between the two impairment types, work began to algorithmically differentiate between the two impairment types. With a few known results to start with, we have tested these methods enough to develop them. After applying the methods to known test results, one known wet drop was added to the PNM test rack at CableLabs and further confirmed after time, after some drying of the cable, too.

5.1. Generalities

Figure 24 shows a typical standing wave in downstream spectrum capture data on the top, while Figure 25 shows the same for a water-soaked cable. The second plot in each figure shows the respective spectrum data after inverse Fourier transform (IFFT) filtered autocorrelation time domain values, and the last graphs in each are cumulative distribution functions (CDFs) of the time domain values obtained by ordering the values after the IFFT from largest to smallest and taking the cumulative values for each observation. Note the differences between the standing wave and water wave plots. First, the waves in the spectrum data are scalloped and repeating in the standing wave case (standing), but do not follow closely any repeating pattern in the water-soaked cable case (wet). Looking at the transformed data in the middle plots of each figure, the standing case appears to have a strong peak, whereas the wet case is more spread out. Translating these data into CDF plots at the bottom of each figure, we see that the standing case has an initial spike and then a more gradual curve up, whereas the wet case starts lower and has a steeper initial climb.

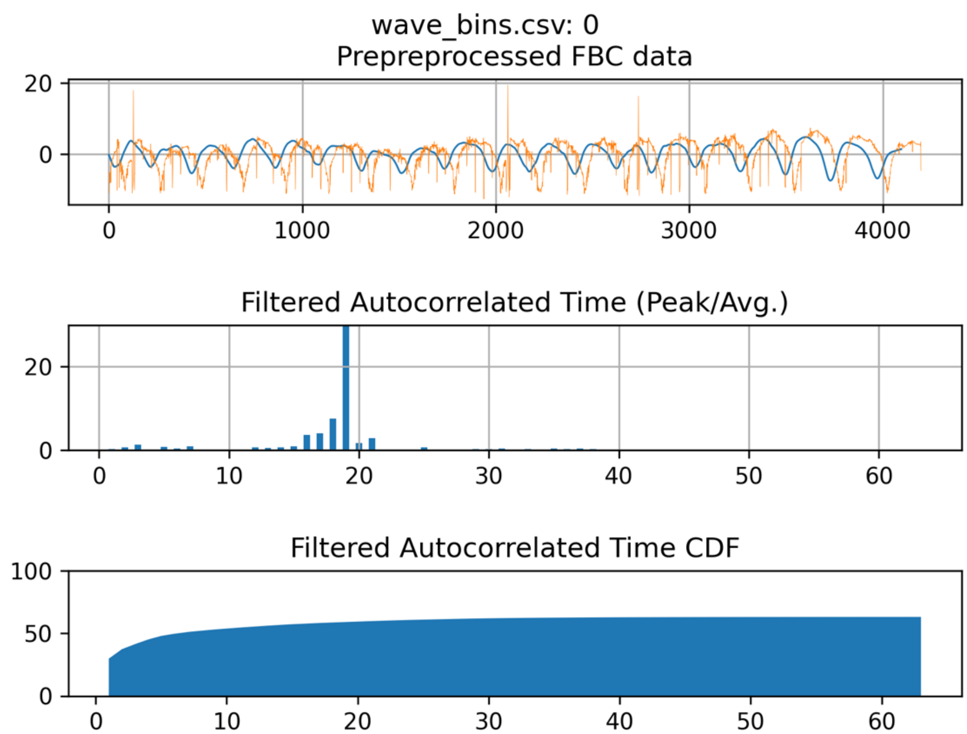


Figure 24 - Standing wave spectrum capture plot, IFFT transformed time domain plot of that same spectrum data, and a CDF of the time domain data

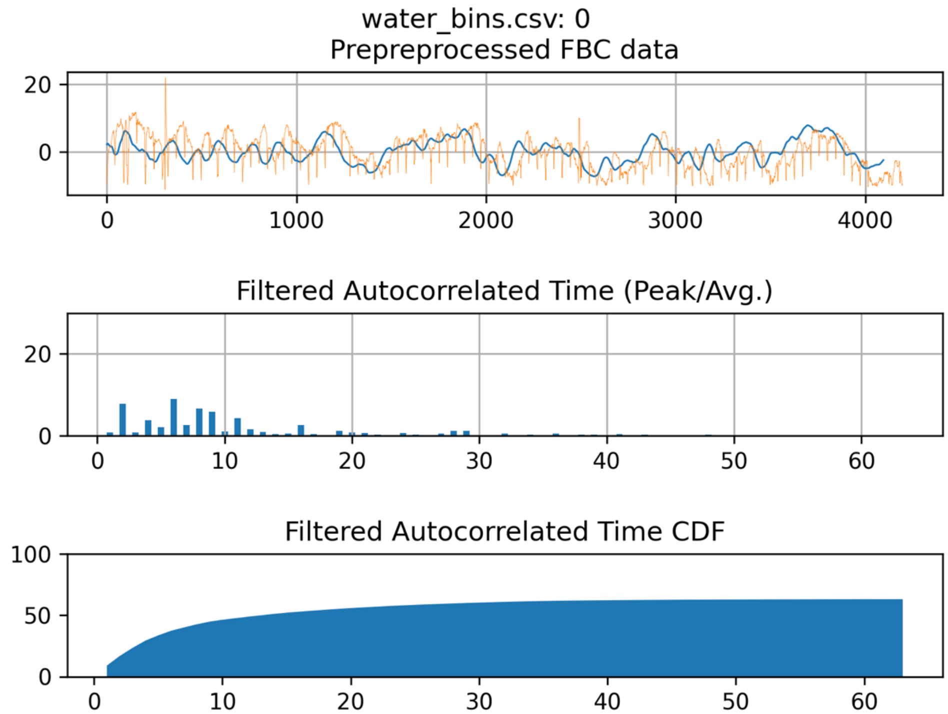


Figure 25 - Water wave spectrum capture plot, IFFT transformed time domain plot of that same spectrum data, and a CDF of the time domain data

5.2. Test 1: Comparisons of a known wet drop and a like section of drop cable.

We obtained a drop from the field which we could visually confirm the existence of water in the drop. We then created a new drop using the same cable length and type for comparison in the tests that follow.

For another indication of the existence of water in a coax cable, see the S_{12} measurements for a normal unimpaired section of coaxial cable (Figure 26) versus the same type of cable that has been affected by water (Figure 27). Note the loss as a function of frequency is rather smooth in an unimpaired cable, but it is not smooth at all in the case of a wet cable. For a treatment of S-parameters including S_{12}, see the PNM point of view document on full duplex DOCSIS® or Ron Hranac's *Broadband Library* article on the subject (https://broadbandlibrary.com/a-quick-look-at-s-parameters/).

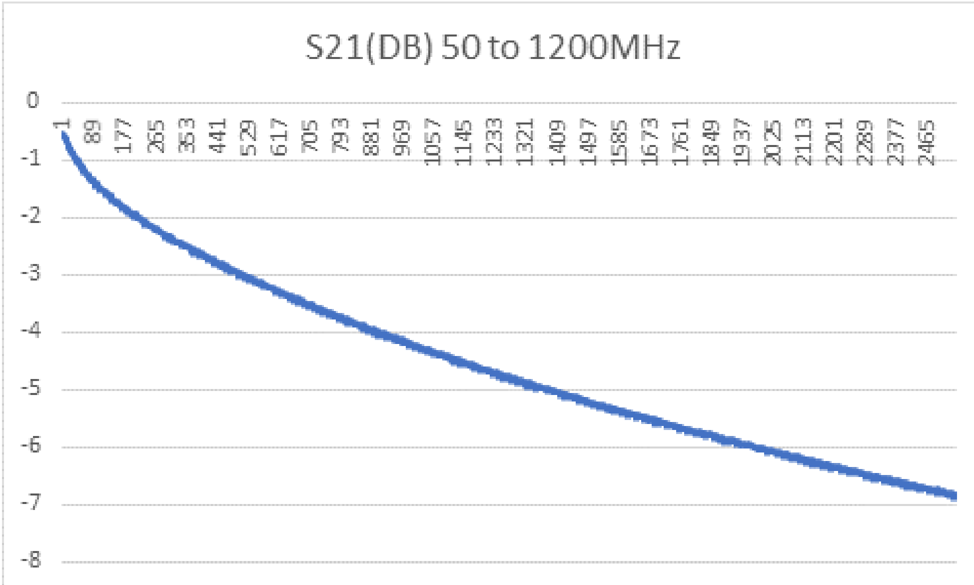


Figure 26 - S_{21} for a normal, unimpaired drop

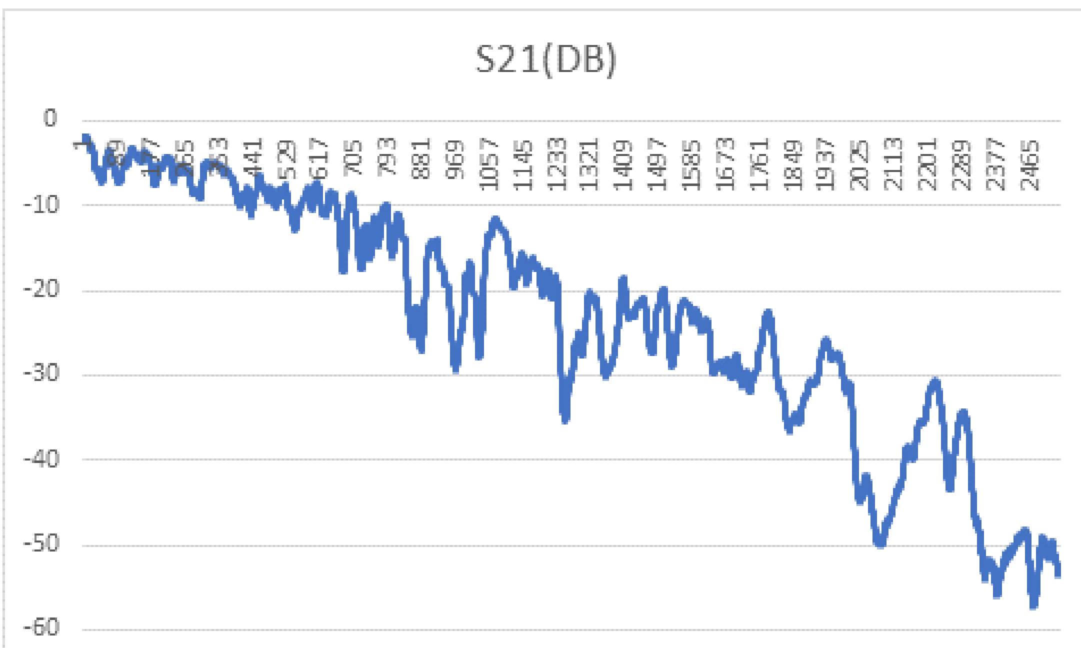


Figure 27 - S_{21} for a water-soaked drop

Next, we examine the group delay of the wet cable, as shown in Figure 28. Note that the group delay is uneven to a small degree over the measurable frequencies, and then at about 1500 MHz measurement isn't possible so the plot shows much higher variability. Ignoring the portion of the plot that is noise and not measurable above 1500 MHz, we see that group delay variation appears in wet cables.

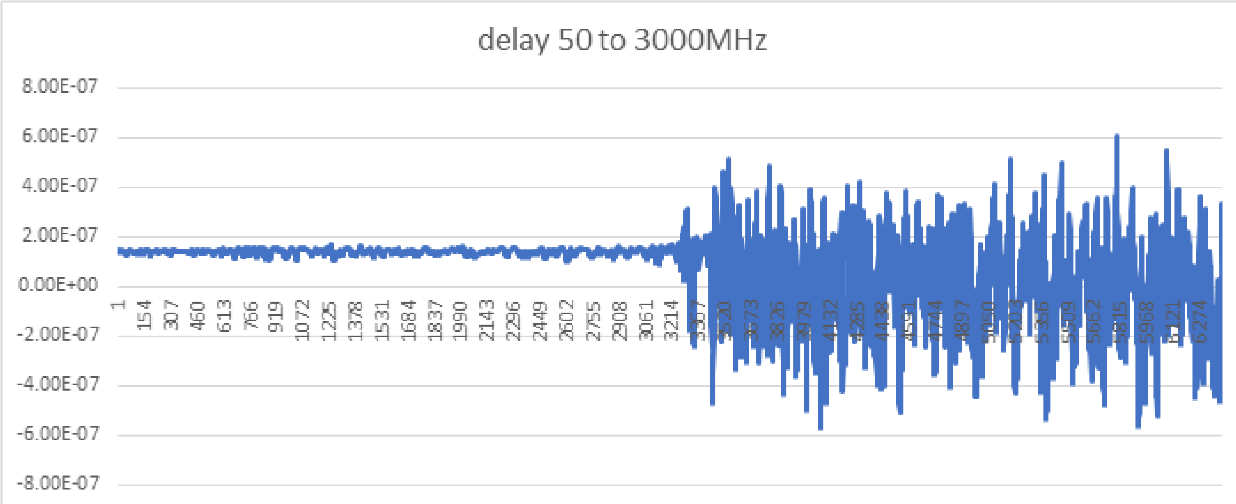


Figure 28 - Group delay for a water-soaked cable

Next, we apply a time domain reflectometer (TDR) to a pair of cables, one wet (WWI cable) and the other in good health (100 ft Series 6), both the same type and length of cable. Here we display the S_{11} and S_{22} values which are reflection coefficients. We see that more energy is reflected in the wet cable compared to the dry cable. Note that we aren't claiming that the entire length of the wet cable is filled with water; we have no way to measure how much of the cable is water soaked and to what degree. We are only showing that some amount of water in the cable will appear differently in reflection measurements (S_{11} and S_{22}).

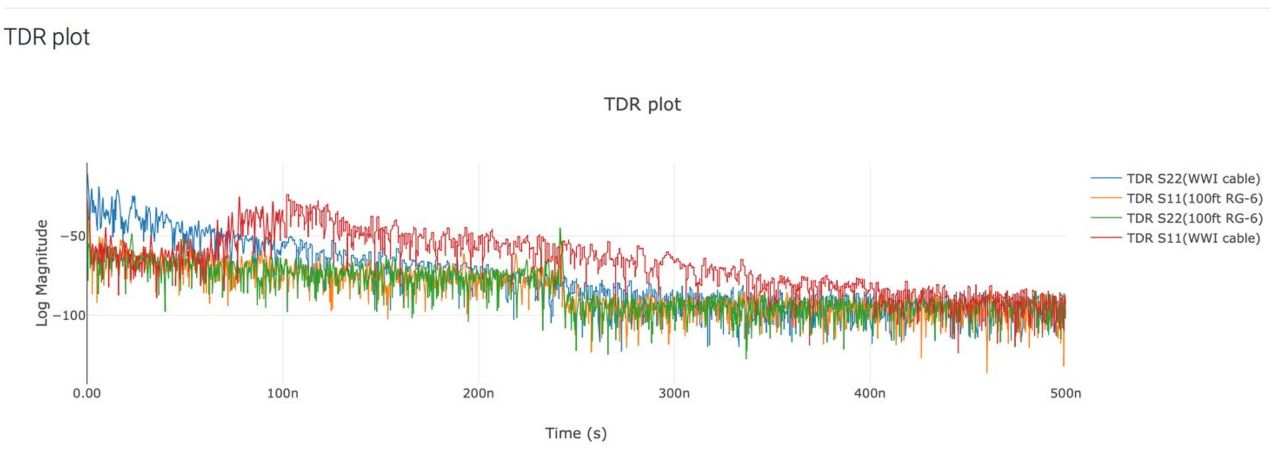


Figure 29 - S_{11} and S_{22} measurements of wet (WWI cable) and dry cable, both 100 feet of Series 6 cable.

Next, we compare the same two cables' S_{11} group delay values. Note again that the wet cable shows variability over the measurable frequencies before about 1.5 GHz, and lots of noise over the higher frequencies that are not reliably measurable. But the unimpaired cable shows nearly flat across the entire plot, at both lower and higher frequencies. Clearly, wet cable has reflective properties, and impacts group delay as well.

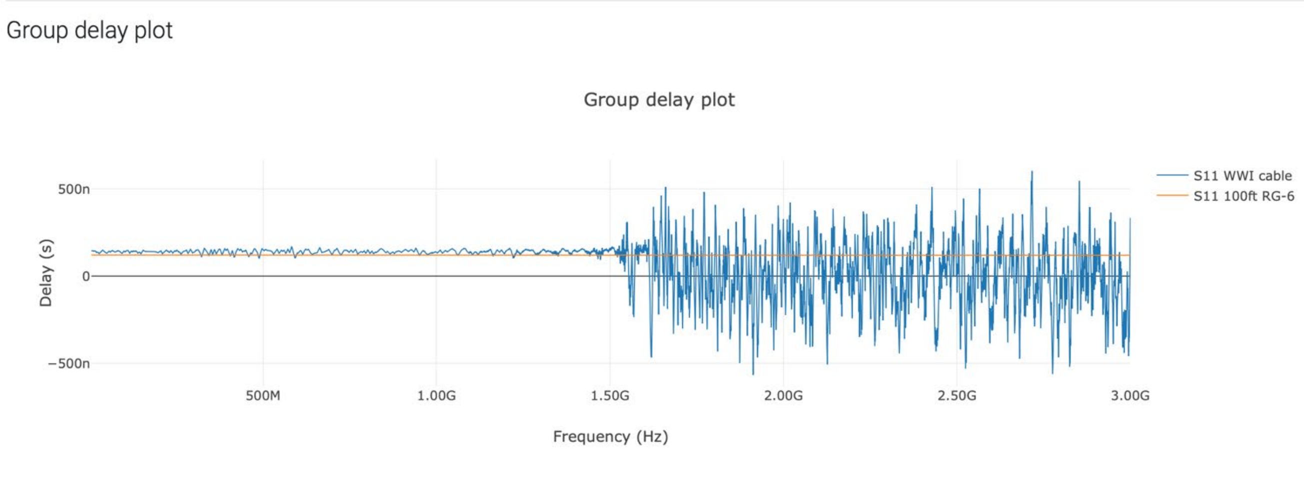


Figure 30 - Group delay plot of S_{11} values for a water-soaked cable (WWI cable) and a clean, unimpaired, dry cable, both 100 feet of Series 6 cable

Looking at the magnitude S-parameter values for these two cables, shown in Figure 29, we see several differences.

- Comparing S_{11} values, the wet cable's values (blue) are higher and slightly more variable than the dry cable's (orange).
- Comparing S_{12} values, the wet cable's values (green) are highly variable and are lower values than the very stable and higher values for the dry cable (straight red line).
- Comparing S_{21} values, the wet cable's values (purple) are again highly variable and are lower values than the very stable and higher values for the dry cable (straight brown line).
- Comparing the S_{22} values, the wet cable's values (pink) are higher and a bit less variable than the values for the dry cable (grey).

While any of the S-parameters can be used to differentiate a wet cable from a normal dry cable, S_{12} and S_{21} appear to show the difference most clearly.

Note: We have not tested and shown a cable with a standing wave for comparison. A follow up step would be to include other types of cable impairments to see if S-parameters can be used to differentiate between different types of impairments. But because the S-parameters can technically define whether a cable is impaired or not, the exercise would be only to determine if S-parameters can be used to differentiate between different types of impairments.

Our primary concern with this test is to find data we can utilize to differentiate between an impedance mismatch-related standing wave and a wet cable. Both are impaired, but a wet cable may be more difficult to spot visually in the field, yet likely isolated to a small span of hard line or a single drop and may be easy to isolate using FBC in CMs.

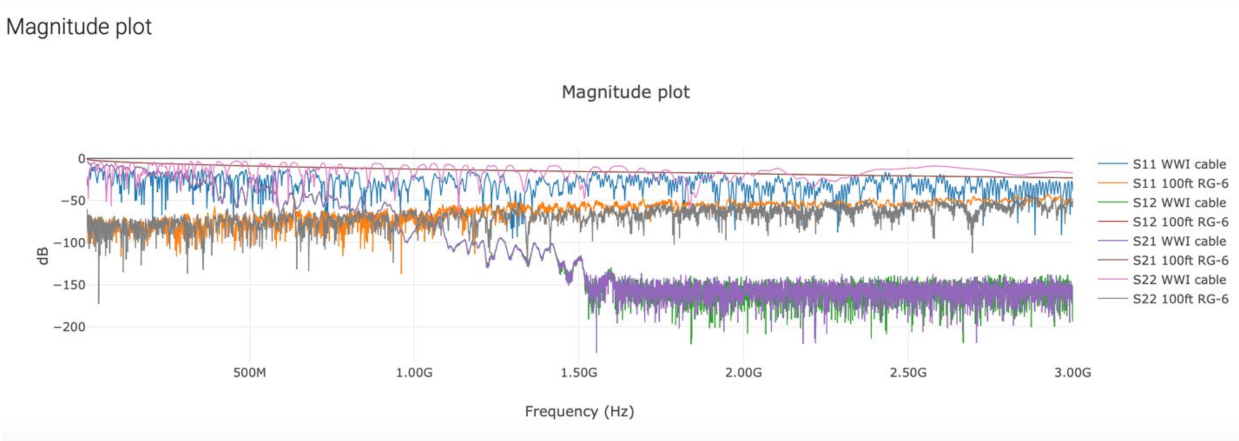


Figure 31 - S-parameters for a wet cable (WWI cable) and a dry, unimpaired cable of the same length and type: 100 feet of Series 6 cable

5.3. Methods for differentiating water from standing waves in coax

The previous test results suggest a few competing methods for determining whether a coaxial cable has been impaired by water intrusion versus is damaged in a way to cause a standing wave. In this paper, we show three promising methods.

We outline two early methods here, and show evidence of their utility, with the expectation that future tests will allow us to compare the effectiveness of these methods and perhaps develop improved methods. Both methods rely on spectrum data obtainable from the CM but can be applied to spectrum data from other sources. An advantage of these simple methods is that they rely on common modem spectrum capture data, and complex data. But we intend to research other methods and data sources for comparison and to improve the reliability of our methods. The intent of these two methods is to identify impairments that can be quickly found and repaired with a clear net positive impact on service and plant health.

Both methods explained here rely on removal of spikes and other noise in the data through smoothing methods, and then the samples are normalized for processing.

A third method is explained here as well, which takes a TDR-like approach and applies a simple threshold, which is consistent with other methods in use, and will be easy for technicians to follow.

5.4. Tom's IFFT method

CableLabs' Tom Williams suggested a simple IFFT of the spectrum data, then to manually look for the clear difference in the time domain data. Group delay in the wet cable should reveal more energy later. Tom's method is essentially as follows.

1. Take a spectrum response, then filter, flatten, and interpolate to remove high level responses such as pilot signals, and low-level responses such as unused spectrum.
2. Apply an IFFT to produce an impulse response to look for dispersion.
    a. If one or two narrow lines are found, this indicates a standing wave.
    b. If the time response is distributed beyond one or two lines, water in the cable is indicated.

3. To improve detection, apply autocorrelation to the time response data. Measure the impulse response coefficients relative to the DC term, remove the two largest coefficients, and remeasure the coefficients. Search for a small drop from these two coefficients to the third as an indicator of water.
4. Search for a downward tilt in the spectrum plot, from low frequencies to higher frequencies. If this tilt is not intended in the plant design (which should be very rare), this is another indication of water in the line.

Tom further tested his method on several suspected CMs whose data were obtained from the field but not all confirmed as standing wave versus wet. Using the suspected impairment categories, he plotted the tilt and an error ratio improvement relative to DC, then drew a line between the categories to form a function that can serve as a threshold for differentiating the two impairment types. The method is updated then as follows.

1. Remove tilt from spectral response. Record the tilt.
2. Perform an IFFT to get time domain data.
3. Select time samples <65 to eliminate the tallest wave response.
4. Record error ratio improvement relative to DC term.

Figure 32 shows a plot of the resulting tilt and ratio statistics from 10 standing waves (as seen in the spectrum data manually) and 10 wet waves (also as seen in the spectrum data).

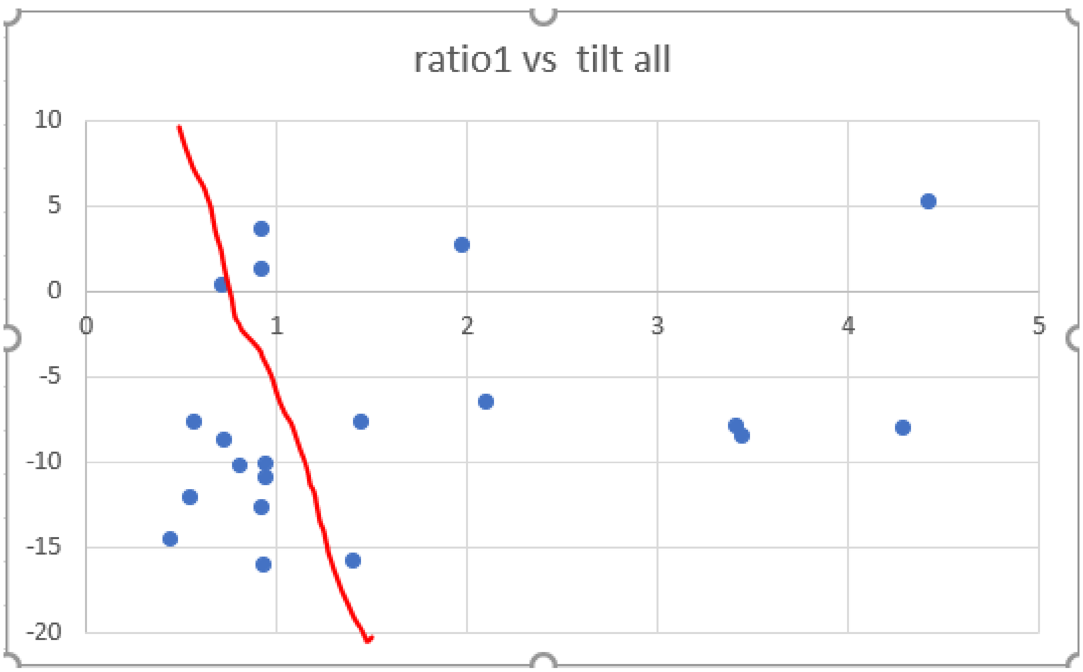


Figure 32 - Error ratio versus tilt, showing a red line that differentiates between a wet cable (left and below) versus a cable with a standing wave (above and right)

Because these 20 spectrum captures are from CMs that have not been confirmed to have standing waves versus water waves, we can only say that they were impaired, and that the two impairment types were visually clustered. Further, these 20 results were picked from a much larger pool of CM responses for their obvious impairments and strong visual differences in the two types of impairment patterns (standing versus wet).

To be certain of the effectiveness of this method, more field data must be collected, and confirmation of the cause should be conducted if the difference is important.

5.5. Jason & Jay's method

CableLabs' Jason Rupe and Jay Zhu, purposely working independently from Tom Williams to come up with a different method, developed a method very similar to Tom's method and extended it to better enable computer programs to differentiate between the two impairment types, relying on proven machine learning and statistical methods to identify that the spectrum data shows an impairment. Once an impairment is discovered to exist, we want to determine whether it is a wet cable or a standing wave primarily.

This method extends off the first by calculating a CDF, then fitting a curve to the resulting data, and using the resulting parameters to differentiate between a standing wave and a water wave. Recall Figure 24 and Figure 25 which showed the CDFs and the initial jump in a standing wave versus the slower climb of the water wave data. By fitting a function to the CDF, we obtain parameters that describe the desired CDF pattern which can then be mathematically compared to rules that will be statistically determined later from field data and can be initially determined using the same data used in Tom's method. The method steps are as follows. This procedure picks up after the spectrum data are cleaned, and an IFFT is performed to obtain the time domain data, which are used in the procedure.

1. In this step, we preprocess the data for additional clean up, and apply Tom's method to get the autocorrelated magnitude values.
2. Calculate the CDF from the time domain data. This requires taking the IFFT results from the spectrum data, in the time domain, and sorting from largest to smallest, then calculating the cumulative of the current and all previous observations for each observation.
3. After calculating the CDF, we fit an exponential curve of the form $a*e^{(-b*x)}+c$ and keep the three parameters.

The parameters of the curve fit are then used to characterize the captured spectrum data from each CM. In the figures that follow, we show a few plots of data from CMs, some with standing waves and others with water waves. Figure 33 is a set of plots from the water impaired drop obtained from the field and then placed in the PNM lab at CableLabs. The data were captured months after placing the drop cable in the lab, and after some drying has taken place. Note that the spectrum plot at the top left almost shows a repeating scalloped pattern, and the filtered autocorrelated time domain values show much energy in a narrow area. This cable may appear almost like a standing wave. This result suggests that a cable that cycles between being heavily water intruded and drying out some may actually look like a standing wave at times. Collecting data over time might confirm the issue, but a CM with this severe of an issue, with neighbors who indicate no issue, should be quick to repair with a drop replacement, regardless of the cause.

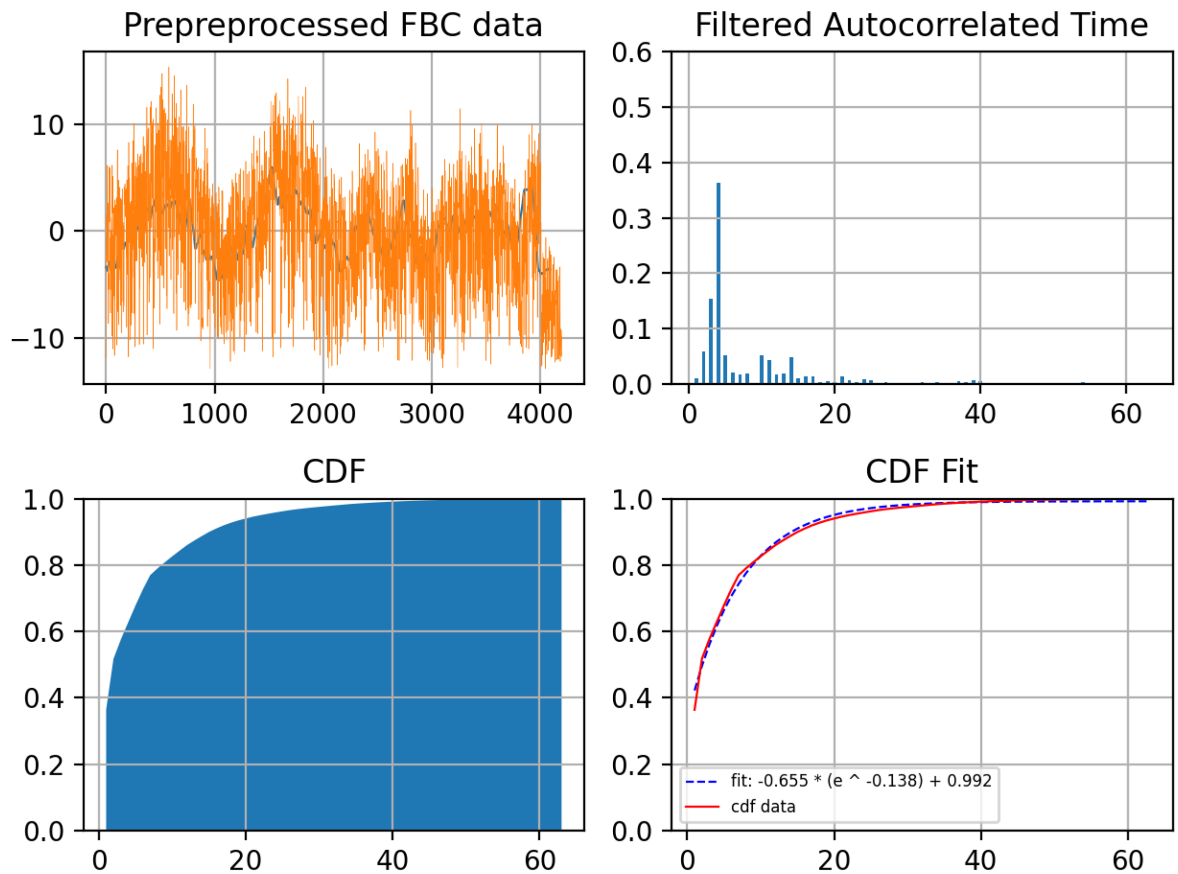
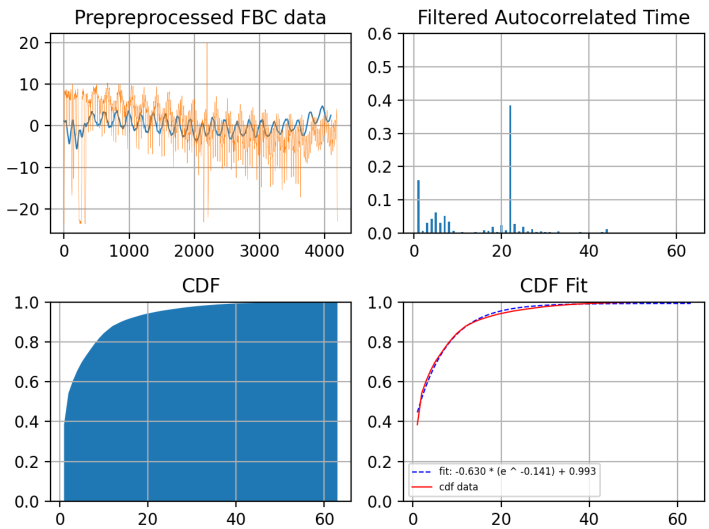
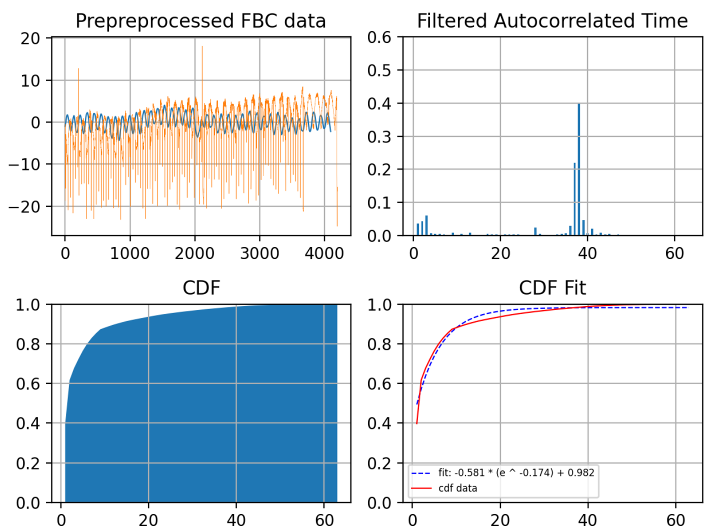


Figure 33 - A confirmed wet drop from the field which has been installed in the PNM lab at CableLabs, and the CM on the end of the drop used to gather spectrum data then processed with the CDF curve fitting method

Figure 34, and Figure 35 show a few CMs with standing waves, and water waves respectively, all sampled from the same 10 used in Figure 33 of Tom's method. Note that, as expected, the standing waves show a sharper CDF curve than the water wave CMs do. While subtle, we expect that the CDF parameters will show this difference and allow us to create, through a large sample of confirmed cable sections, a statistical model that can, based on the parameters of the fit, assign a likelihood of water intrusion versus a standing wave in the cable.


Prepreprocessed FBC data
Filtered Autocorrelated Time
CDF
CDF Fit
fit: -0.630 * (e ^ -0.141) + 0.993
cdf data


Prepreprocessed FBC data
Filtered Autocorrelated Time
CDF
CDF Fit
fit: -0.581 * (e ^ -0.174) + 0.982
cdf data

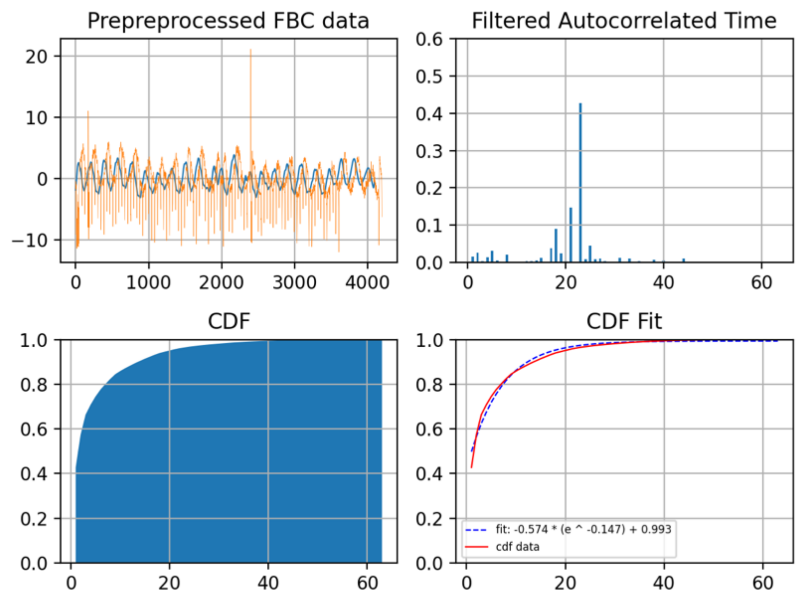


Figure 34 - Three selected suspected CMs with apparent standing waves

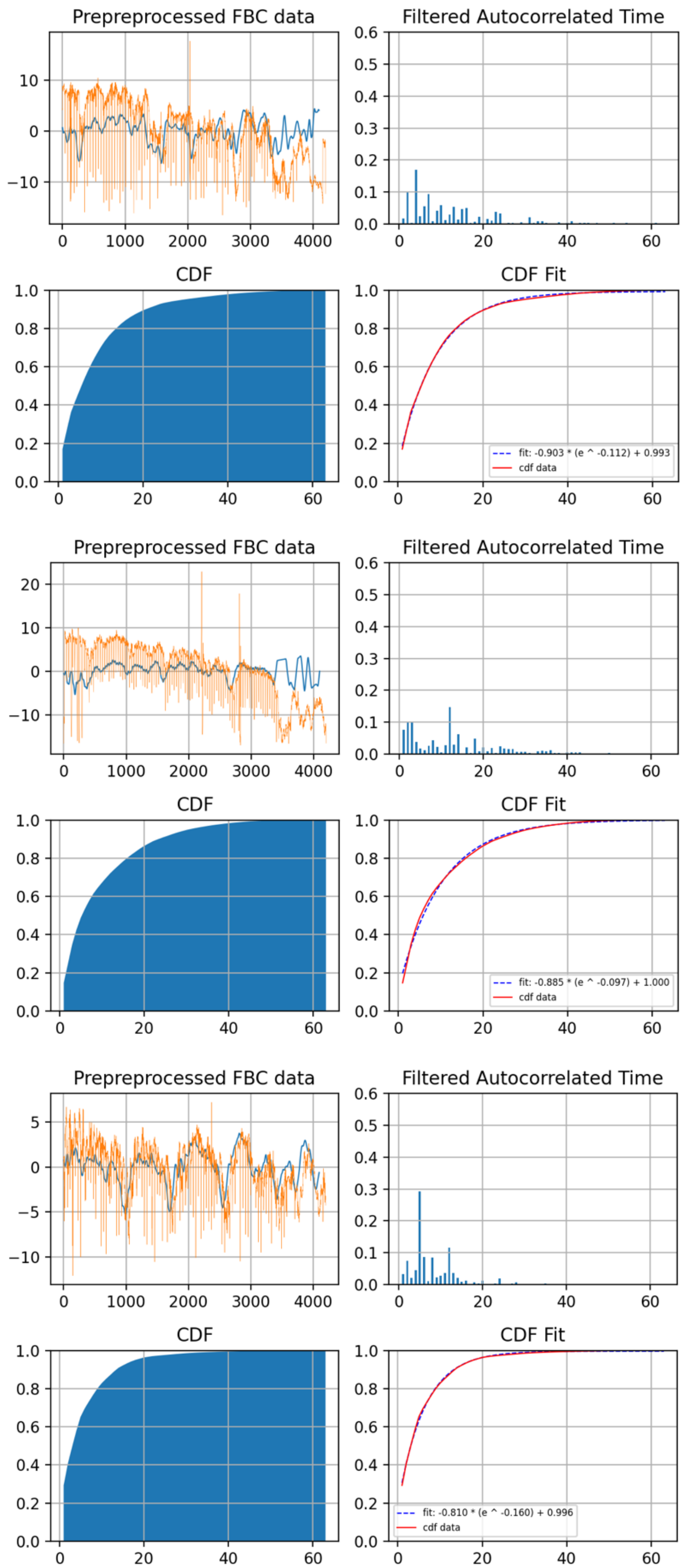


Figure 35 - Three selected suspected CMs with apparent water waves

Extracting the three fit parameters from each of the 20 CMs (10 each believed to have standing waves or water waves), plotting these in 3D in Figure 36, and coloring the point for each CM by the believed class of impairment each has, we see a clear pattern again. Note we show the 3D plot twice in the figure, from different angles, to better show the delineation.

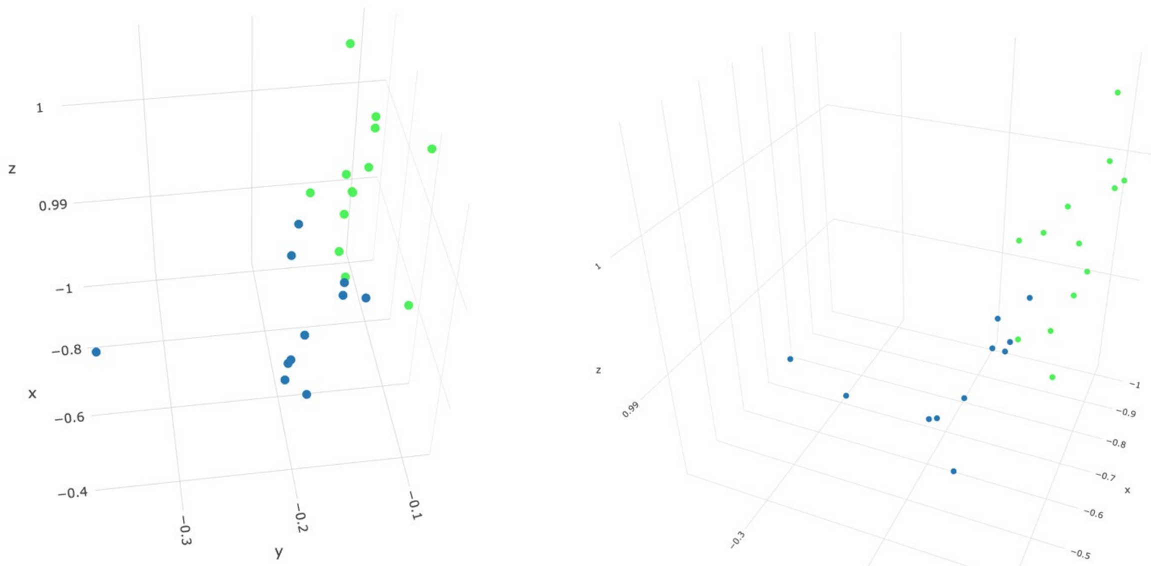


Figure 36 - Curve Fit Plot of Wave Parameters

Figure 36 is a plot, from two perspectives of the three parameters from curve fitting of the 10 CMs with standing waves (blue) and 10 CMs with apparent water waves (green); X=a, Y=b, and Z=c, with X, Y, Z being the plotted values for the parameters a, b, c in the curve fit.
Note that the CMs with suspected water waves tend to have higher (less negative) Y=b values, higher z=c values, and often smaller (more negative) x=a values than those labeled to have standing waves. This pattern can also be seen in the data shown in Table 1, from these same 20 CM spectrum captures (one from each of 20 CMs identified as having either a standing wave or a water wave in the spectrum data) plotted in Figure 33.

Table 1, exponential function fit parameters from the CDFs of time domain data obtained though IFFT method applied to the spectrum capture data from 20 separate CMs, selected from a large group of field data as indicating an impairment, 10 with suspected water waves, and 10 with standing waves. Fitting function: a * e ^ (-b * x) + c.

Table 1 – Exponential function fit of 20 CMs

a	*b*	*c*	*Type*
-0.33276052	0.12582213	0.99626715	Wave
-0.62065159	0.15781587	0.99200869	Wave
-0.60244084	0.17260292	0.9840218	Wave
-0.69048994	0.12123575	0.9928308	Wave
-0.33739765	0.11461487	0.99332933	Wave
-0.73274074	0.3368255	0.98163125	Wave
-0.41528807	0.1360504	0.99606652	Wave
-0.66520054	0.1371799	0.99343827	Wave
-0.60399443	0.16658992	0.98946338	Wave
-0.66897829	0.15190012	0.99240217	Wave
-0.89719314	0.09721336	1.00034371	Water
-0.96202471	0.1512644	0.98994818	Water
-0.86697703	0.12554029	0.99425639	Water
-0.74403271	0.14132146	0.99422719	Water
-0.91005527	0.09920093	1.00122611	Water
-0.78745142	0.09696355	1.00375195	Water
-0.82397893	0.10764474	0.99936019	Water
-0.87474122	0.1210256	0.9909223	Water
-0.9056323	0.09884677	1.00366479	Water
-0.61743961	0.09148825	0.99392027	Water

5.6. Larry's Method

One of most common methods for field technicians to validate the presence of water is by use of a time domain reflectometer (TDR). It is common for a TDR to transmit a fixed-width impulse and capture the reflected response, or echo. The response can be analyzed, in conjunction with the known parameters of the cable (Appendix A) and typically display the fault distance(s). In the case of water reflections, the time domain impulse response shows a distinctive signature compared to a singular point of damage.

By using the full spectrum amplitude bins with some additional processing, the functionality of the TDR can be approximated. Figure 37 shows 3 FBC traces, the top is unimpaired, middle is water damage and bottom are a typical amplitude ripple caused by a standing wave.

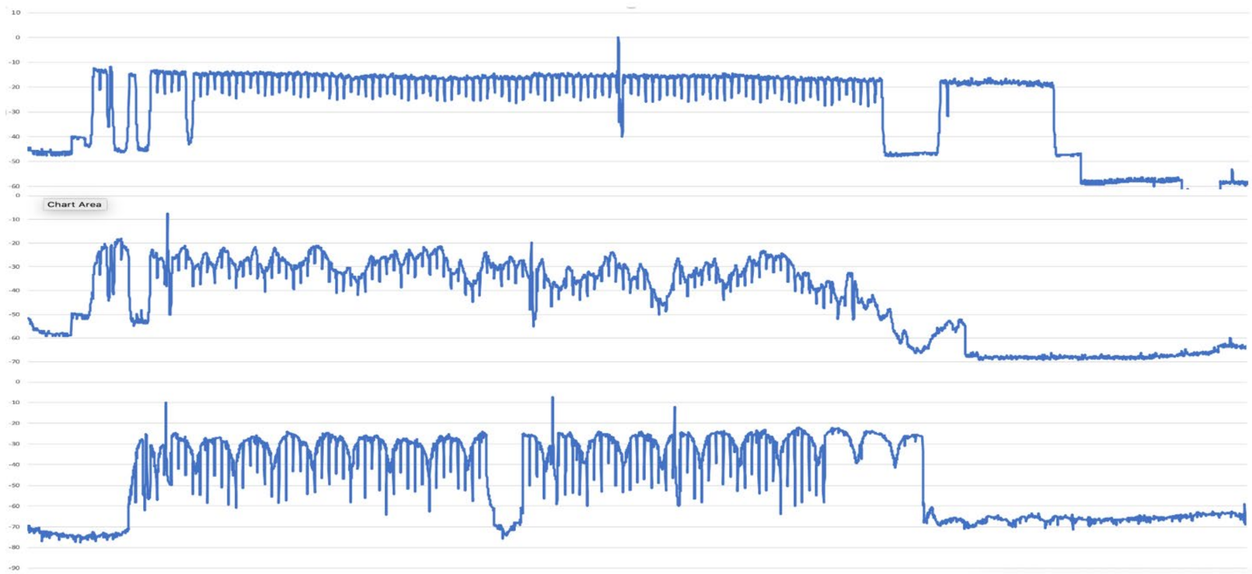


Figure 37 - FBC samples compared, unimpaired (top), water damage (middle), standing wave with amplitude ripple (bottom)

A bit of pre-processing the amplitude bins produces an improved result. The next step illustrated in Figure 38 demonstrates the frequency spectrum with guard band and vacant spectrum being interpolated, or "filled in." In these examples, a simple linear interpolation is done between the SC-QAM and OFDM channel alpha region. This is done to minimize the effect of unoccupied spectrum that would otherwise result as noise in the result. Figure 38 shows unimpaired, water damage and amplitude ripple (top to bottom), after interpolation between the known signal energy.

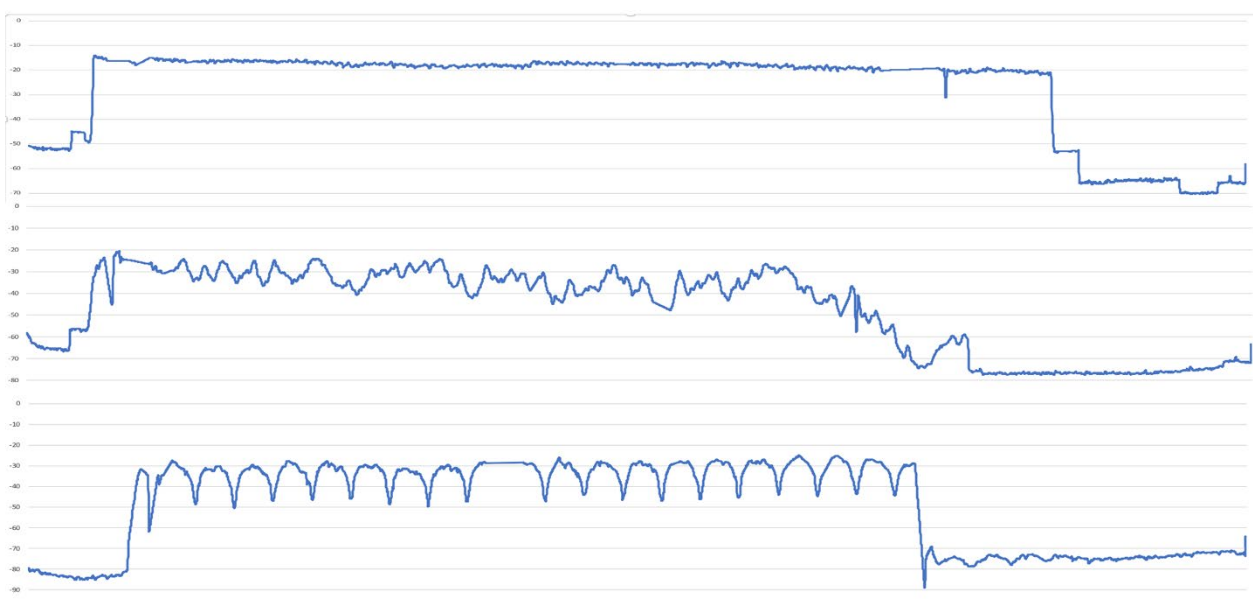


Figure 38 - Interpolated FBC samples with guard bands and vacant spectrum "filled"

After interpolation, the unoccupied spectrum can be cropped, leaving a contiguous block of signal energy, removing any remaining noise floor spectrum. Figure 39 shows the center 4096 bins after removing the other bins. Again, similar to Figure 37 and Figure 38, the top trace is unimpaired, center contains water and bottom is an amplitude ripple caused by a standing wave.

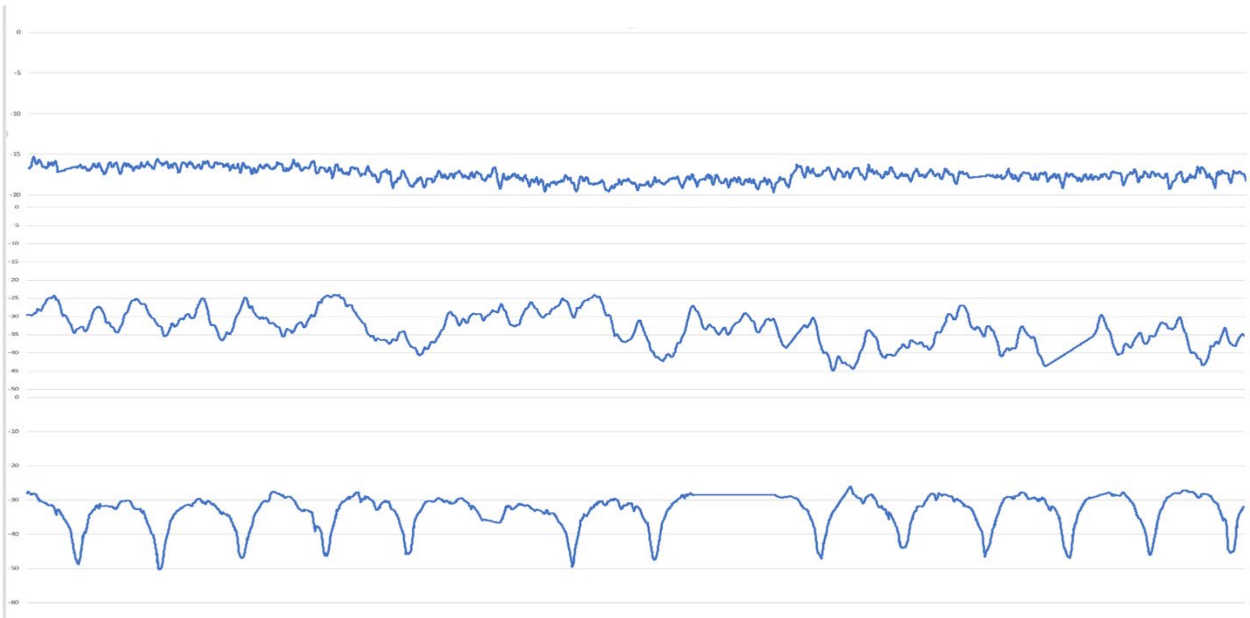


Figure 39 - Samples are cropped to 4096 bins of occupied spectrum

After some pre-processing, the amplitude bins can now be projected to the complex plane, using digital signal processing (DSP). The intent is to perform a Fourier transform to render a time domain impulse response, like the previously discussed TDR. However, the full band capture bins are represented as logarithmic magnitude, meaning the in-phase and quadrature (I&Q) have already been summed and squared. While it is impossible to recover the actual I&Q values, minimum phase assumptions are sufficient derive a reasonable impulse response. This is achieved by instantiating a complex number with zero phase component, uniformly for each bin. Then using an IFFT, the impulse response is obtained (Figure 40). Notice that the top unimpaired trace shows no echo, center trace shows energy spreading and bottom has a singular echo response.

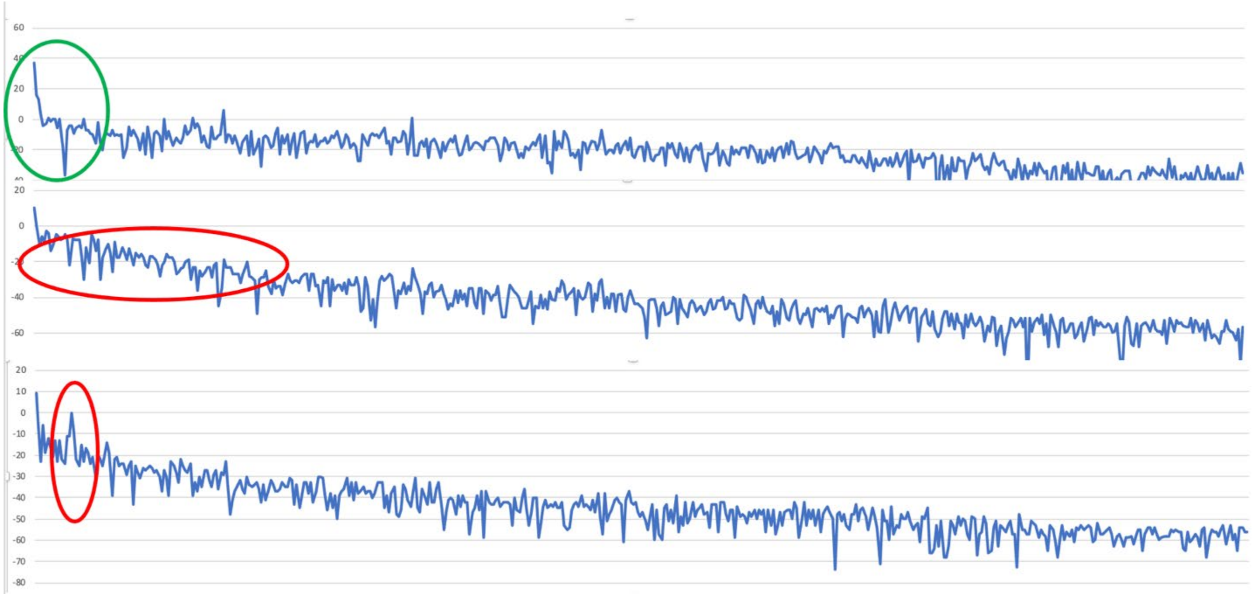


Figure 40 - Log magnitude bins are converted to time domain using zero-stuffed IFFT technique, using minimum phase assumptions

Finally, when multiple time domain impulse responses are overlayed in Figure 41, the spreading becomes more obvious. The red line indicates a threshold that correctly distinguishes between water and amplitude ripple on 100% of the examples provided.

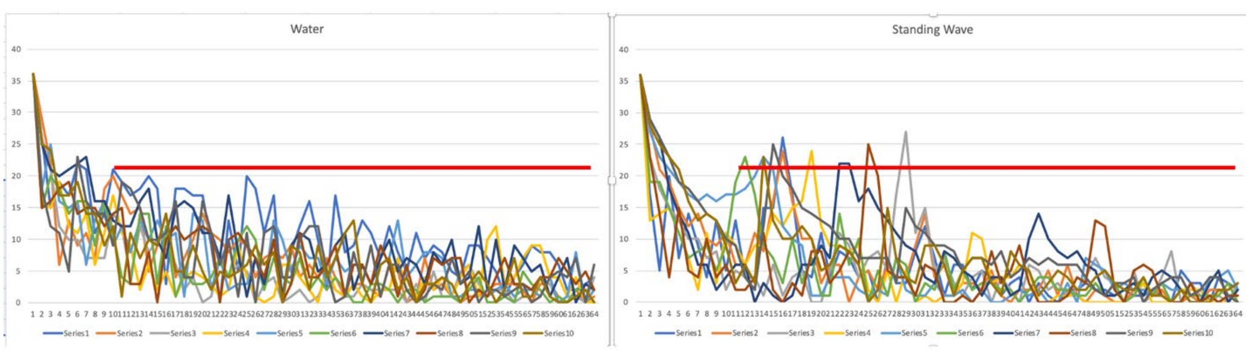


Figure 41 - Time domain spreading in water (left), and peak threshold detection (right)

6. Operational Practice Consideratons

Of the samples recovered in the field trials, virtually all the water damage could have been avoided. There are a number of recommendations discussed below to help reduce the occurrence of water damage.

6.1. Materials Selection

When installing the drop system, consideration of the cable and components are key in the performance and life expectancy of the system along with the methods and practices used for installing it. Our focus for this section will be on how to maintain a weather tight drop cable network.

Let's begin with material selection. When selecting RF cable ANSI/ SCTE 74 2011 Specification for Braided 75 Ohm Flexible RF Coaxial Drop Cable can provide the information needed to ensure that you select the correct cable for the proper use and purpose. Two of the key components of the standard will be jacket construction, designed for either aerial or underground and flooding compound for both aerial and underground cables. Before we get too far, we should discuss flooding compound. Flooding compound in both aerial and underground cable is meant to help preserve against rapid degradation due to corrosion only. It is not intended as a self-repair component and therefore any damage to the jacket of aerial or underground cable should be replaced.

Connectors used should be of the 360-degree compression style with integrated weather seals to limit water migration. The other component that we need to maintain a weather tight, moisture-proof drop cable network would be weather seals for RF port connections. These port seals may be integrated as part of the connector or a separate piece. In either case it is important that we are using the proper seals whenever the connection may be exposed to outside elements or fluctuations in temperature or areas of high moisture such as basements, garages, crawl spaces, pedestals, lock boxes, house boxes etc.

6.2. Installation Practices

Now that we have the materials let us look at how to install them to ensure the integrity of the drop system for years to come. The points that we will cover are those specific to the weatherproofing of the drop system and is not meant to reflect all considerations when installing the drop system.

When preparing the cable for installation we need to be careful with the tools we use and how we use them as damage to the jacket can easily happen. Let's start with proper fitting, preparation, and installation. Using the correct prep tool for the cable size and fitting style as well as ensuring that the tool is sharp will ensure a good fit between the connector and the cable being used. Next is the compression of the connector. For this to be successful we need to be sure we are utilizing the correct compression tool for the fitting being used and that it is in good working condition. A visual inspection of the compression shall be made to ensure that there is a complete and even compression of the fitting to the cable.
RF Port seals, when installing the seal, we need to ensure that the seal extends past the threads of the RF port and contacts the smooth portion of the barrel connection. If the seal is not integrated with the connector the seal should be installed so that the leading edge of the connector is in direct contact with the seal. The seal does not need to be compressed between the connector and the body of the component of the barrel connector to be properly installed.

Regarding the cable itself there are several practices we need to consider as well. Water will follow the route of the cable, riding the exterior jacket looking for a point of entry and/or flowing on the interior of the cable. Therefore, we utilize the practice of installing drip loops along the pathway of the cable to provide a means to displace the exterior water. Drip loops should also be utilized to ensure that any connections or drop components are always higher than the lowest point of the cable. Utilizing gravity to keep all moisture away from connections and components.

Care must be taken on how we attach the cable and methods used for attachment so that the jacket is not damaged. Attachments such as clips and hangers should not have hard or sharp edges that could damage the jacket during installation. In addition, care must be taken during installation as a slip of a tool or improper use can also result in damage to the jacket of the cable.

Something as basic as removing the messenger from aerial cable, if done incorrectly, can also lead to damage of the jacket. By utilizing the vertical pull method, not the horizontal "wishbone" method, the jacket will remain intact during the removal process. Extra care must be taken when preparing a mid-span drop so as not to damage the jacket during messenger wire separation.

When installing aerial cable, the pathway of the cable should be such that the cable does not come in contact with objects that could wear against the jacket and compromise the integrity over time. If such contact cannot be avoided, the use of a protective barrier such as tree guard should be used. With underground cable the best way to protect the jacket is the use of conduit. This would protect the jacket from hard sharp objects below the surface that may damage the jacket, provide a means of protection if there is any digging in the area and finally protect the cable at the critical points where it enters or leaves the ground. If conduit is not used to protect the complete path of the underground cable, then it is a must to protect the cable at the points where it enters and exits the ground. This can be done by using smaller sections of conduit or U Guard. This protection should extend 8 inches below the ground and should extend to at least 3-4 feet above ground.

6.3. Inspection for Damage

We should always be performing a visual and tactile inspection of the cable. We need to be on the lookout for cable that does not look or feel right and completing a further inspection based on these observations. All knicks or cuts in the cable jacket can and in time will permit a pathway for water intrusion and therefore must be dealt with. Remember flooding compound is not meant to be a self-repair method. Whenever you see physical signs that water has entered the cable, this may be corrosion, discolored center conductor or moisture, the cable and / or components must be considered compromised and correctly remedied.

6.4. Repair vs Replace

Replacing the damaged section of the drop system should be the preferred method. By repairing or splicing of the damaged section we cannot be sure that there is not still the presence of moisture that will continue to degrade the cable.

6.5. Cable Handling and Storage

How we store the cable prior to use can also have a significant impact on its performance as well. If possible, all cable should be stored inside of the vehicle prior to use. If this is not possible care must be taken to properly protect the cut end of the cable from taking on moisture as it is exposed to the environment. The cable should also be protected from unintended damage from other items that may be stored around it.

7. Future

Water entering our cables is a common problem with unpredictable impacts to our customers. However, rain being the most common cause is somewhat predictable using national or local weather data. We can imagine a future opportunity to get ahead of water related problems by proactively repairing damaged cables in advance of rainy seasons with prolonged precipitation. In addition to weather, other causes such as sprinkler systems can have predictable periodicity and should also be considered.

Another important observation about this type of impairment is that it affects high-frequency spectrum, worse than low-frequency spectrum. This could influence an operators DOCSIS evolution strategy and how to prioritize cable replacements. For example, if considering using RF spectrum above 1.2 GHz, and operator might decide to increase the priority of replacing these damaged cables.

8. Conclusions

Proactive network maintenance has come a long way in the past 11 plus years but has more valuable but hard work ahead.

As CableLabs focused on achieving accurate impairment detection using PNM, SCTE has been developing operational practices that help operators make PNM actionable and affordable. Partnering with Comcast, over 100 water-damaged subscriber drop cables were recovered from the field. The cable samples were then sent to Comcast's Physical and Environmental lab for testing and characterization of the cables' physical condition and RF parameters. The result of this effort is a new, comprehensive understanding of how water, rain, and freezing impact our networks' coaxial cables.

Using spectrum captures from CMs in the field, we created approaches for differentiating water waves from standing waves (amplitude ripple). The unique frequency response signature created by water in a subscriber drop cable provides an easy way to quickly identify affected drops remotely, without a truck roll. Once a water-damaged drop has been identified, a technician can be dispatched to replace it. The result is a new PNM tool, and more efficient field practices to come.

A strong standing wave as well as a strong water wave both can have significant impact on a customer's service, so both must be addressed. But knowing the difference is important. While on the surface it may seem that knowing the difference between a standing wave versus a water wave in the coax plant is a secondary concern, the difference has at least two key important values.

1. Knowing that the impairment is a water wave versus a standing wave tells the technician what to look for, and where to look for it. A drop affected by water can quickly be replaced once identified. Water-damaged passives can as well, and technicians can look for corrosion, water, nicks in cable, and other plant failure modes that are the causes for the water wave indicated. In contrast, an echo cavity that creates a standing wave may be harder to find and will be indicated by different failure modes in the cable plant.

2. Water in the cable plant can get worse with time. Therefore, early detection is an opportunity to be truly proactive. Removing the problem before it impacts service is best. And if you can identify and remove the problem before it worsens, even better. Early detection affords the opportunity to remove a small problem from the network before severe damage in amplifiers, taps, and other components happens. A quick fix early avoids a lengthy, more costly fix later.

We presented three methods in this paper for finding water in drops using RF spectrum data. We intend to collect validated field data and perform a comparison of the methods in the future, and report on the benchmarking results in an update of the Primer for PNM Best Practices document published by the PNM working group at CableLabs, and expect to reflect the best methods in a future SCTE NOS Working Group 7 field practice. Work is underway now to develop a PNM benchmarking tool for general comparison of PNM methods, allowing us to provide a benchmarking data set to certify and test any packaged PNM algorithm, starting with these water wave methods. A test report will be the output, based on the number of false positives, false negatives, and potential severity weighting of the results. Once demonstrating the value in this use case, we expect to offer the same benchmarking approach for other PNM methods.

This work was the result of continuous improvement in how the industry develops and uses PNM. Working closely among operators, vendors, CableLabs, and SCTE, we were able to shift to a DevOps approach to PNM, with continuous cycling between the operations in the field with research and development. While simultaneously collecting experience and validating ideas in the field, the tools were developed in software, using the PNM test methods available, to create this new tool for improving network quality and customer services.

We intend take this work further to align the causes with various cable types, ages, and other factors to determine whether certain cable types in certain environments or use cases are better than others, and what this means for future cable plant deployments, maintenance, and the useful lifetime of coax cable plant.

9. Appendix

9.1. Characteristics of coaxial cable

Coaxial cable is a two-conductor transmission line. One of the conductors is called an inner or center conductor and is "…surrounded by a concentric conducting shield, with the two separated by a dielectric (insulating material); many coaxial cables also have a protective outer sheath or jacket. The term 'coaxial' refers to the inner conductor and the outer shield sharing a geometric axis."[1] See Figure 42.

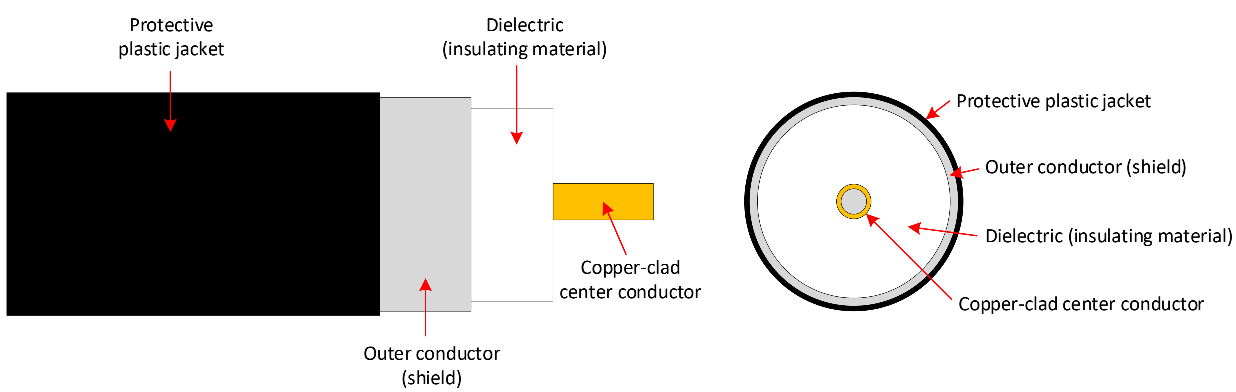


Figure 42 - Coaxial cable side view (left) and end view cross-section (right)

There are two major types of coaxial cable found in cable networks. One type is known as hardline cable and is used in the distribution plant that is attached to utility poles or buried underground. The center conductor is typically copper-clad aluminum (but can be solid copper in some applications), and the shield an aluminum alloy. The name comes from the semi-flexible solid tube-like outer conductor (shield). Hardline cables distribute RF signals throughout the community being served by the cable operator, and in many cases also carry 60 volts to 90 volts AC to power nodes and amplifiers. Figure 43 shows two examples of hardline coaxial cable.

[1] From Wikipedia: https://en.wikipedia.org/wiki/Coaxial_cable

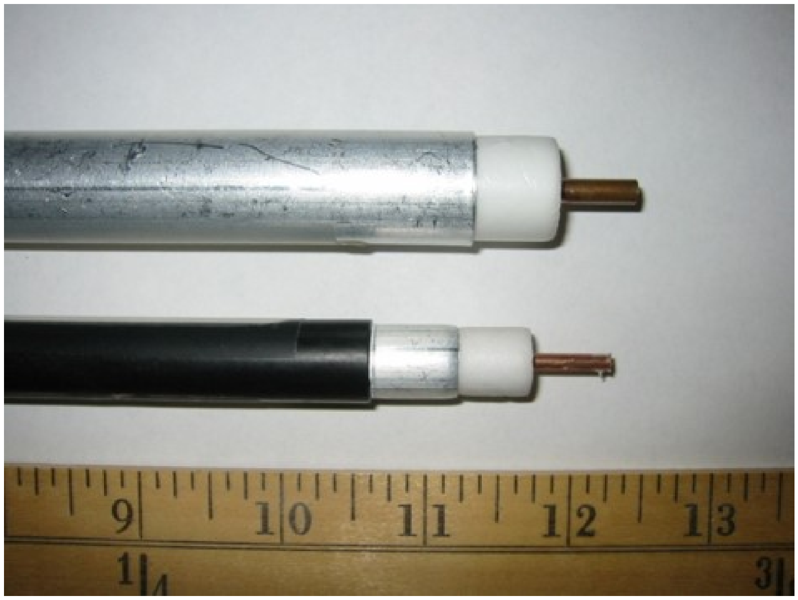


Figure 43 - Examples of hardline coaxial cable: unjacketed 0.750 inch diameter (top) and jacketed 0.500 inch diameter (bottom)

The second type is a smaller diameter, flexible coaxial cable used for the subscriber drop, which is that part of a cable network between the hardline distribution plant and the customer premises equipment inside the home. The center conductor is typically copper-clad steel, and the shield a combination of Mylar-backed aluminum tape and braid. See Figure 44.

Figure 44 - Series 6 coaxial cable with the end prepped for installation of a connector

In both hardline and subscriber drop cables used in cable networks, the dielectric is a closed-cell gas-injected foam. The protective jacket can be polyvinyl chloride (PVC) or polyethylene (PE) plastic, depending on application.

The following summarizes some of the electrical characteristics of coaxial cable. When any of these parameters deviates from desired nominal values, the performance of the coaxial cable and the cable network can degrade.

9.1.1. Impedance

Generally speaking, *impedance* is the combined opposition to current in a component, circuit, device, or transmission line that contains both resistance and reactance. Impedance is represented by the symbol Z and is expressed in ohms. Impedance is further defined as the frequency domain ratio of voltage to current, $Z = E/I$. Impedance in an alternating current circuit, including RF, is a complex value and includes both resistance (the real part of complex impedance) and reactance (the imaginary part of complex impedance) – that is, both magnitude and phase. Impedance can be thought of as a way to describe the concept of AC resistance.

The *characteristic impedance*, Z_0, of coaxial cable is expressed in ohms, and is related to the outside diameter D of the inner or center conductor, the inside diameter d of the outer conductor or shield, and the dielectric constant ϵ (relative permittivity) of the insulating material (dielectric) separating the two conductors. Cable networks use coaxial cables with a nominal characteristic impedance of 75 ohms. As long as the characteristic impedance of the signal source, coaxial cable transmission line, and load or termination to which the cable is connected is the same (that is, 75 ohms), essentially all RF power from the source is delivered to the termination or load, except that which is lost to attenuation.

The following formula can be used to calculate the characteristic impedance of coaxial cable.

$$Z_0 = \frac{138}{\sqrt{\epsilon}} log_{10} \frac{D}{d}$$

where
Z_0 is the cable's characteristic impedance in ohms
ϵ is the dielectric constant of the insulating dielectric material
log is base 10 logarithm
D is the inner diameter of the shield
d is the outer diameter of the center conductor

The calculated characteristic impedance of 0.500 diameter hardline coaxial cable, assuming a dielectric constant of 1.32, a shield inner diameter of 0.452 inch, and a center conductor outer diameter of 0.109 inch, is 74.2 ohms. Anything that affects the cable's dielectric constant and/or the ratio D/d will change the impedance. Figure 45 illustrates the D/d relationship in coaxial cable. Figure 46 shows coaxial cable that has a kinked shield, resulting in a different D/d ratio, which in this case would cause the impedance at the point of damage to be reduced from what it is in the rest of the cable.

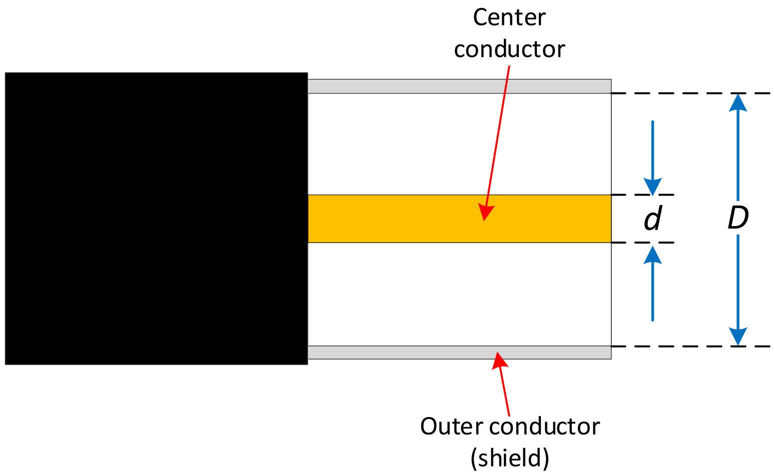


Figure 45 - Illustration of the D/d relationship in coaxial cable

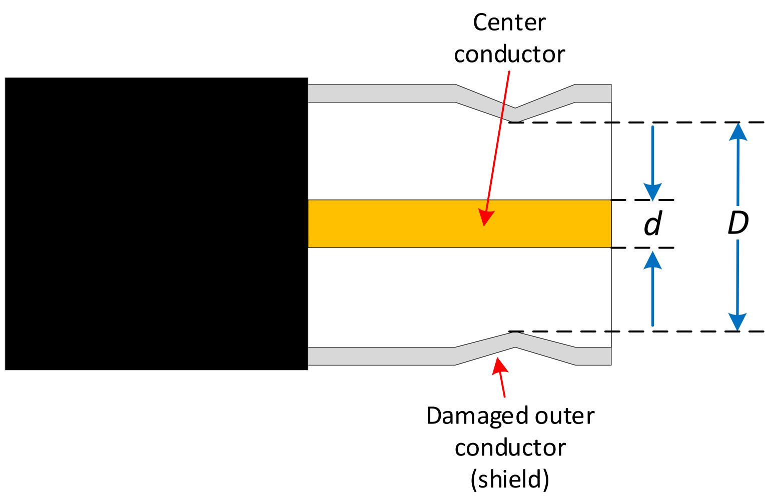


Figure 46 - Damage to the shield in this example changes the D/d relationship, resulting in a change of impedance at the point of damage relative to the rest of the cable

9.1.2. Attenuation

Attenuation (also called loss) is a decrease in the power of a signal or signals, usually measured in decibels. Expressed mathematically, $\alpha_{dB} = 10log_{10}(P_{in}/P_{out})$, where α_{dB} is attenuation in decibels, P_{in} is input power in watts, P_{out} is output power in watts, and $P_{out} < P_{in}$. When signal power is stated in dBmV, $\alpha_{dB} = P_{in}(dBmV) - P_{out}(dBmV)$.

According to *Modern Cable Television Technology, 2nd Ed.*,

> Signal loss (attenuation) through coaxial cable can occur through any of four principal means:
>
> - Radiation out of the cable due to imperfect shielding

- Resistive losses in the cable conductors
- Signal absorption in the dielectric of the cable
- Signal reflection due to mismatches between the cable and terminations or along the cable due to nonuniform impedance

Assuming signal leakage (radiation) from the cable is negligible and there are no significant impedance mismatches, resistive losses in the metallic conductors are the dominant contributor to attenuation, followed by signal absorption in the dielectric.[2] Coaxial cable attenuation is greater at higher frequencies than at lower frequencies, as shown in Figure 47.

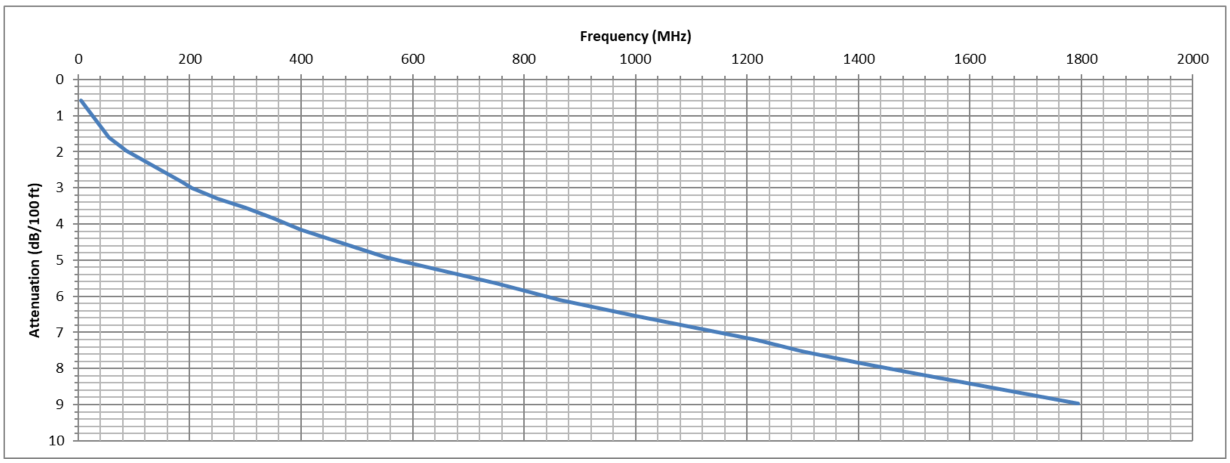


Figure 47 - Plot of typical attenuation in dB/100 feet for Series 6 subscriber drop cable, from 5 MHz to 1794 MHz

Coaxial cable attenuation in decibels changes about 1% per 10 °F temperature change (as the temperature increases, attenuation increases; as the temperature decreases, attenuation decreases).

For more information, see "Coaxial Cable Attenuation" in the Summer 2021 issue of *Broadband Library*.[3]

9.1.3. Dielectric constant

Dielectric constant is a parameter that applies to the dielectric in coaxial cable, and typically refers to relative permittivity.[4] Dielectric constant is related to coaxial cable's velocity factor using the following formula:

$$\epsilon = \frac{1}{VF^2}$$

[2] Note: An increase in the dielectric constant means a lower velocity factor, which increases signal absorption in the dielectric, and increases attenuation for a given size and impedance coaxial cable.
[3] https://broadbandlibrary.com/coaxial-cable-attenuation/
[4] This usage is considered obsolete by some standards bodies in favor of *relative static permittivity*.

where
ϵ is dielectric constant (relative permittivity)
VF is velocity factor

For example, the dielectric constant of hardline coaxial cable with $VF = 0.87$ is about 1.32. As mentioned previously, anything that changes the dielectric constant will change coaxial cable's impedance (and its attenuation).

9.1.4. Velocity factor

Velocity factor is the ratio – in decimal form – of the velocity of an electromagnetic signal propagating through coaxial cable to the speed of light in a vacuum. A common VF for hardline coaxial cable is 0.87, and for drop cable is 0.85. Mathematically,

$$VF = \frac{c}{c_0}$$

where
VF is velocity factor
c is the velocity of the electromagnetic signal traveling through coaxial cable
c_0 is the speed of light in a vacuum,[5] in the same units as c

Another formula for velocity factor is

$$VF = \frac{1}{\sqrt{\epsilon}}$$

where
VF is velocity factor
ϵ is the dielectric constant.

9.1.5. Velocity of propagation

Velocity of propagation (VoP) is velocity factor expressed as a percentage. For example, a VF of 0.87 equals a VoP of 87%. The latter means that RF signals propagating through the coaxial cable have a velocity that is 87% of the speed of light in a vacuum.

9.1.6. Return loss

When the impedance of a load or termination equals the characteristic impedance of the transmission line connected to that load, an incident wave is completely absorbed by the load. In the real world, there are no perfectly reflectionless loads, which means impedance mismatches exist. Impedance mismatches cause reflections. Reflected waves interact with incident waves to produce a distribution of fields in the transmission line known as standing waves. The presence of standing waves in coaxial cable can cause

[5] According to the National Institute of Standards and Technology, c_0 is 299,792,458 meters per second.

amplitude ripple in the frequency domain.[6] There are several ways to characterize the severity of impedance mismatches, among them is *return loss* (R).

Return loss (which is not the same thing as attenuation in the return or upstream spectrum of a cable network) is the ratio, in decibels, of the power incident ($P_{incident}$) upon an impedance discontinuity to the power reflected ($P_{reflected}$) from the impedance discontinuity. Note: When $P_{reflected} < P_{incident}$, return loss is a positive number.

Return loss is used to characterize network components such as active and passive devices, connectors, customer premises equipment, etc. Return loss has sometimes been used to characterize coaxial cable, although structural return loss is far more commonly used. The following is one formula that can be used to calculate return loss:

$$R = -20log_{10}\left(\left|\frac{Z_{device} - Z_0}{Z_{device} + Z_0}\right|\right)$$

where
R is return loss in decibels
log is base 10 logarithm
Z_{device} is the complex characteristic impedance of a device, in ohms
Z_0 is 75 ohms for cable networks

Hardline coaxial cable used in cable networks is typically specified to have a characteristic impedance of 75 ohms ±2 ohms, so the calculated return loss would be at least as good as about 37.4 dB.

9.1.7. Structural return loss

As mentioned in the previous section, return loss is one way to characterize the severity of impedance mismatches, especially in active and passive devices, connectors, and other components used in cable networks. *Structural return loss* (SRL) has been used for decades for coaxial cable, in large part because SRL deals with return loss at specific frequencies caused by evenly-spaced repetitive impedance discontinuities arising during the manufacturing process.[7] The following is from Technical Note 1069, "Testing CATV Cable to 1 GHz," published by Times Fiber Communications, Inc., in April 1999:

> As coaxial cable is manufactured, a number of variables can cause the impedance to change. Recall, the cable's impedance is a function of the cable's physical properties (conductor diameters, insulation's dielectric constant), and if any of these properties change, the impedance will change. For example, the dielectric material is extruded over the center conductor during the manufacturing process. As the dielectric is extruded, its diameter or dielectric constant can change and cause the impedance to change. This impedance change is extremely small and difficult to measure. If only one of these impedance changes occurs in the cable or if they occur at random intervals, the return loss will be good; but due to manufacturing processes, there may be many evenly spaced

[6] The term *standing wave* is often used to describe *amplitude ripple*, although technically speaking amplitude ripple is not the same thing as a standing wave.
[7] Pulley diameter and spacing, non-uniformity of line speed through extruders, vibrations, and other factors contribute to the creation of periodically-spaced, almost microscopic physical dimension variations in the center conductor, dielectric, and shield during the manufacture of coaxial cable.

> impedance changes and return loss problems will arise. Reflections from these evenly spaced impedance changes add together at a frequency corresponding to a half wavelength spacing. Although each impedance change may be very small, when they all add together, they cause a return loss "spike." These spikes can be narrower than 200 kHz. The return loss from these impedance changes is called the structural return loss because the impedance variations are due to structural nonuniformities in the cable.

In the past, a broadband sweep generator in conjunction with a variable bridge and variable termination were used for coaxial cable SRL measurements. As the operating bandwidth of cable networks increased beyond about 600 MHz, the aforementioned method could no longer provide accurate results. New measurement techniques were developed, based on the use of a fixed bridge, network analyzer, a set of calibration standards, and calculations to determine the SRL. A test procedure is described in the standard ANSI/SCTE 03 2016 Test Method for Coaxial Cable Structural Return Loss. The following is an excerpt from ANSI/SCTE 03.

> The purpose of this procedure is to provide instructions to measure cable structural return loss (SRL). The cable impedance as a function of frequency is calculated from a vector (magnitude and phase) return loss. The average of this impedance across the desired frequency range is the "cable reference impedance." The structural return loss is calculated from the cable impedance as a function of frequency and the cable reference impedance. This may be automated, but requires a vector network analyzer, and may be subject to errors due to the cable connection.

Figure *48* shows an example of a measurement of average impedance for a reel of coaxial cable. The top trace is the measurement from one end of the reel of cable, and the bottom trace is from the other end. Figure *49* shows a measurement of the same reel of cable's vector return loss from both ends of the reel.

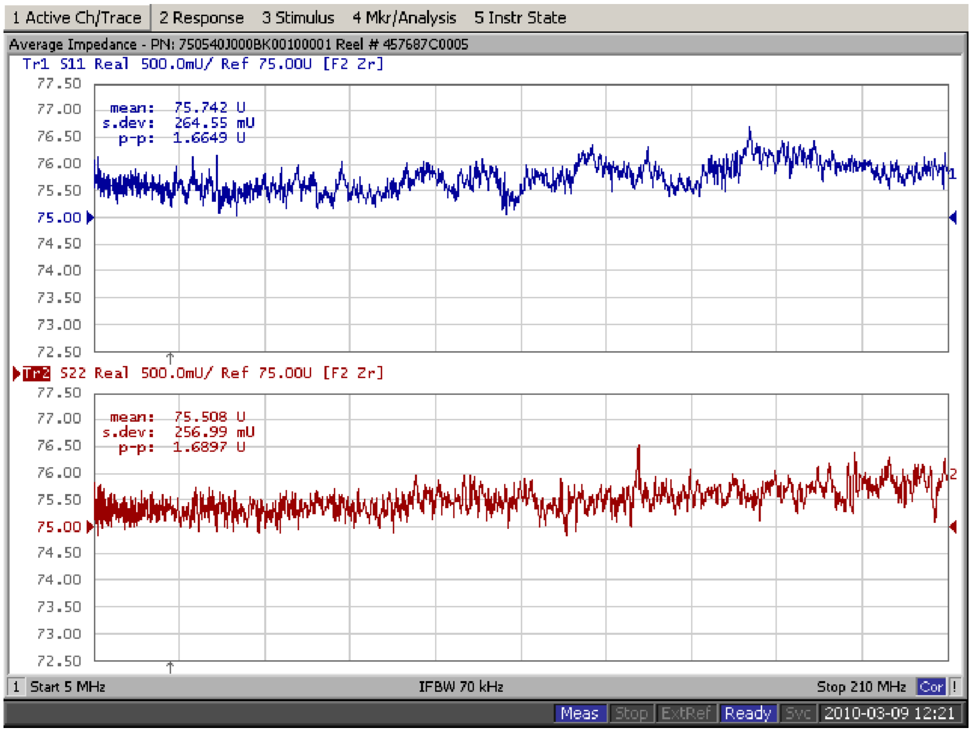


Figure 48 - Example measurement of the average impedance of a reel of coaxial cable, using the method described in ANSI/SCTE 03 2016. (Screen shot courtesy of Amphenol Broadband Solutions.)

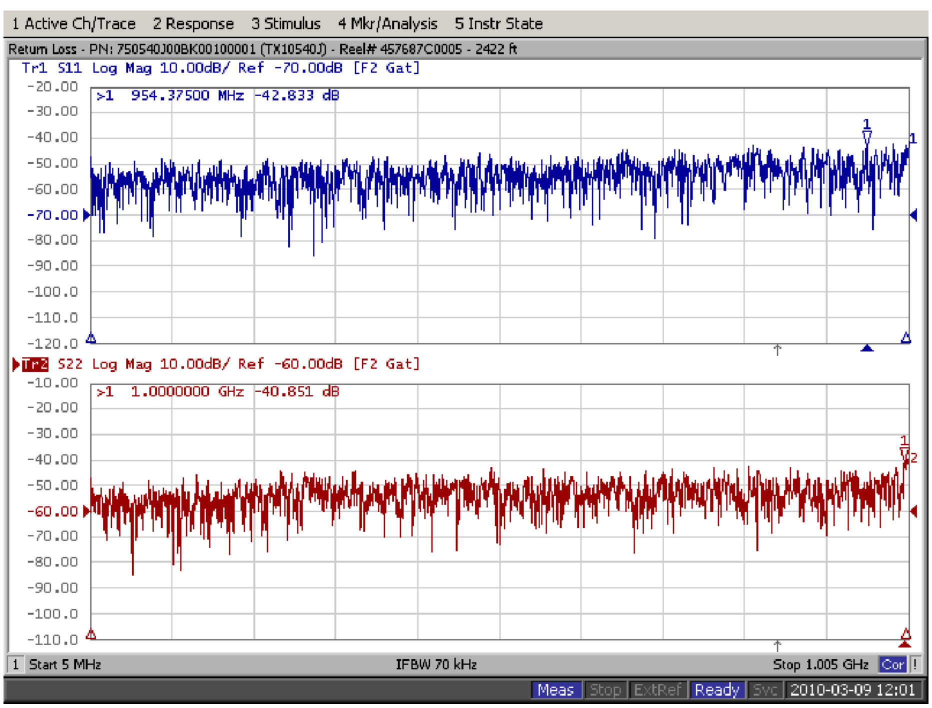


Figure 49 - Measurement of return loss of the same reel of cable in the previous figure. (Screen shot courtesy of Amphenol Broadband Solutions.)

Figure 50 shows the calculation of SRL from the parameters in Figure 48 and Figure 49.

Return Loss to SRL Conversion
per ANSI / SCTE 03 2008
prepared by Tim Cooke

Sample Identification: 750540J000BK00100001 (gated) Reel #: 457687C0005
Footage: 2422 ft

Cable Impedance $Z_o := 75$

	Top		Bottom
Top	$Z_{avg_1} := 75.742$	**Bottom**	$Z_{avg_2} := 75.508$
Top	$RL_1 := -42.833$	**Bottom**	$RL_2 := -40.851$

$$\Gamma\omega_1 := 10^{\frac{RL_1}{20}} \qquad \Gamma\omega_2 := 10^{\frac{RL_2}{20}}$$

$$\Gamma\omega_1 = 7.217 \times 10^{-3} \qquad \Gamma\omega_2 = 9.067 \times 10^{-3}$$

$$Z_{cable_1} := Z_o \cdot \frac{1 + \Gamma\omega_1}{1 - \Gamma\omega_1} \qquad Z_{cable_2} := Z_o \cdot \frac{1 + \Gamma\omega_2}{1 - \Gamma\omega_2}$$

$$Z_{cable_1} = 76.09 \qquad Z_{cable_2} = 76.372$$

$$\Gamma_{srl_1} := \frac{Z_{cable_1} - Z_{avg_1}}{Z_{cable_1} + Z_{avg_1}} \qquad \Gamma_{srl_2} := \frac{Z_{cable_2} - Z_{avg_2}}{Z_{cable_2} + Z_{avg_2}}$$

$$\Gamma_{srl_1} = 2.295 \times 10^{-3} \qquad \Gamma_{srl_2} = 5.692 \times 10^{-3}$$

$$\rho_{srl_1} := \left|\Gamma_{srl_1}\right| \qquad \rho_{srl_2} := \left|\Gamma_{srl_2}\right|$$

$$SRL_1 := 20 \cdot \log\left(\rho_{srl_1}\right) \qquad SRL_2 := 20 \cdot \log\left(\rho_{srl_2}\right)$$

	Top SRL	Bottom SRL
Worst Case SRL	$SRL_1 = -52.786$	$SRL_2 = -44.895$

Figure 50 - Calculated worst case SRL for the reel of cable discussed in this section. (Courtesy of Amphenol Broadband Solutions.)

9.1.8. DC loop resistance

Loop resistance – more accurately, DC loop resistance – is a parameter usually specified in ohms per 1,000 feet, and is important for cable network powering purposes. Typical published DC resistance values for 1,000 ft. of 0.500 hardline cable are 1.35 Ω for the center conductor (measured end-to-end), 0.37 Ω for the shield (also measured end-to-end), and 1.72 Ω for the loop resistance. For loop resistance, imagine shorting one end of a 1,000 ft. length of cable, and measuring the DC resistance between the center conductor and shield from the other end.

What's important here is that the resistance values are at DC – the resistance one would measure with a conventional ohmmeter – and not at the frequencies of the RF traveling through the coaxial cable. Direct current travels through the entire cross section of a conductor. Alternating current, which includes RF, travels on and near the surface of a conductor, a phenomenon known as skin effect.

Abbreviations

AC	alternating current
ANSI	American National Standards Institute
CDF	cumulative distribution function
CM	cable modem
dB	decibel
dBmV	decibel millivolt
DC	direct current
DOCSIS	Data-Over-Cable Service Interface Specifications
DSP	digital signal processing
FBC	full band capture
FDX	full duplex [DOCSIS]
ft.	foot or feet
GHz	gigahertz
I	in-phase
IFFT	inverse fast Fourier transform
kHz	kilohertz
log	logarithm
LTE	long term evolution
MHz	megahertz
MoCA	Multimedia over Coax Alliance
OFDM	orthogonal frequency division multiplexing
PE	polyethylene
PNM	proactive network maintenance
PVC	polyvinyl chloride
Q	quadrature
R	return loss
RF	radio frequency
RxMER	receive modulation error ratio
SC-QAM	single carrier quadrature amplitude modulation
SCTE	Society of Cable Telecommunications Engineers
SID	spectral impairment detection
SRL	structural return loss

TDR	time domain reflectometer
VF	velocity factor
VoP	velocity of propagation

Bibliography & References

- Data-Over-Cable Service Interface Specifications DOCSIS 3.0 Operations Support System Interface Specification CM-SP-OSSIv3.0-I20-121113 (Cable Television Laboratories) [Note: Full band capture was first introduced in this version of the OSSI specification]
- Primer for PNM Best Practices in HFC Networks (DOCSIS® 3.1), CM-GL-PNM-3.1-V02-210114
- Hranac, R., et al, "Full Band Capture Revisited" SCTE Cable-Tec Expo 2020
- Hranac, R., "A Quick Look at S-Parameters" *Broadband Library*, Winter 2019 (https://broadbandlibrary.com/a-quick-look-at-s-parameters/)
- Hranac, R., "Coaxial Cable Attenuation," *Broadband Library*, Summer 2021 (https://broadbandlibrary.com/coaxial-cable-attenuation/)
- National Institute of Standards and Technology, speed of light (https://www.nist.gov/si-redefinition/meet-constants)
- Technical Note / 1069 "Testing CATV Cable To 1 GHz," Times Fiber Communications, Inc., April 1999