Improving Operational Intelligence for Maintaining Cable Networks

A Technical Paper prepared for SCTE by

Mike Spaulding
Vice President, Plant Maintenance
Comcast Corporation
1701 John F Kennedy Blvd Philadelphia, PA 19103
303-917-4003
Michael_Spaulding@cable.comcast.com

Larry Wolcott
Engineering Fellow
Comcast Corporation
183 Inverness Drive West, Englewood, CO 80122
303-726-1596
Larry_Wolcott@cable.comcast.com

Jason Rupe
Principal Architect
CableLabs
858 Coal Creek Cir, Louisville, CO 80027
303-661-3332
j.rupe@cablelabs.com

Table of Contents

Title **Page Number**

List of Figures

Title **Page Number**

1. Introduction

Cable operators have vast amounts of network performance data available to detect and measure defects within the cable plant. Transforming this data into actionable intelligence can be a daunting task, especially having many existing systems and process already in place.

Failure Mode, Effects, and Criticality Analysis (FMECA) was first developed in the 1940s (Summy) and is now widely used in industries including aerospace, automotive, and electronics. The role of FMECA is to identify potential problems that may occur in a system or component, define how to detect the failures, and measure the effect. This analysis provides a consistent way to measure the criticality of common network failures and help prioritize repair efforts.

Authors Spaulding, Rupe, and Wolcott will present the jointly developed progress of the CableLabs and SCTE working groups for Proactive Network Maintenance (PNM), with an operator's perspective from the field. This paper will demonstrate how FMECA can be used to improve customer experience, reduce trouble calls, and increase operational efficiency.

2. Failure Mode Effects and Criticality Assesment (FMECA)

2.1. Background

FMECA is a highly detailed, disciplined process for understanding the impact and mitigation value of critical failure modes. Related to FMEA which is a similar analysis without the criticality component present in the analysis. This process has been around for several decades most notably used in the aerospace industry. The process was used in the aerospace industry to understand the needs for redundancy based on identified critical failures. In other industries such as healthcare, this same FMECA model has been used to identify high risk processes. In an American Society for health care Risk Management (ASHRM) White Paper, the FMECA process is described as "proactive examination of what could go wrong and the opportunity to fix it before it fails."(Summy)

FMECA has been the underpinning of the pattern detection work in the PNM working group. Identifying failure modes based on distinguishable patterns has been one of the most widely used applications of FMECA within our industry. According to co-author Jason Rupe FMECA is defined as "identifying a system and determining if it performs as designed." (Spaulding and Rupe) He further explained that if you are looking at a power network and a fuse blew, did the fuse do what it was designed to do? Yes. The question then becomes what failed leading to the fuse blowing and how do we prevent it. FMECA takes us through the process of understand the *effects, criticality, probability, and decay*. These pieces of information allow us to understand the value and timing of mitigation.

2.2. Definition

2.2.1. Failure Mode

Identifying a condition that signifies an abnormal operation of a system or component in a network, system, or process. These conditions can take the form of a process within a system that no longer meets the requirements of the desired outcome. In a hardware application, failure modes would indicate when components are no longer working as designed. The failure mode itself does not represent severity just the abnormal operation or outcome.

2.2.2. Effects

The meaning of effect in this document will be any empirical measurement of system performance. In Data-Over-Cable Service Interface Specifications (DOCSIS) systems, there are a number of measurements available including registration state, packet loss, latency, forward error correction (FEC), modulation error ratio (MER) and others. Each of the failure modes typically have gradient errors that can be detected, depending on the severity and capacity available for mitigation. For this reason, each failure mode can have discrete effects measurements.

2.2.3. Criticality

In FMECA, criticality assessment may be qualitative or quantitative. For qualitative assessment, a mishap probability code or number is assigned and entered on the matrix. For quantitative measurements, ratios may be applied. This can be useful in network analysis to scale problem severity with the number of nodes effected.

2.2.4. Probability

While not called out in FMECA, the probability of a failure mode is an important consideration when deciding what to do about it. Highly likely failure modes with high criticality should be aggressively mitigated through operations. These are the drivers of cost, friction, and many undesirable outcomes. But even high probability and lower criticality failure modes deserve attention, so they can be properly addressed through fault management, mitigation, and repair measures. On the other hand, highly critical failure modes must be addressed when they happen, no matter how unlikely.

2.2.5. Causality and Decay

Causality, describing degradation or decay, is key to how we can use this in our PNM efforts. In today's environment, we have become experts in identifying faults once an impairment starts to impact DOCSIS performance. We detect the impact of a failure mode through corrected and uncorrected packet errors, unbonded channels, etc. When these effects meet certain thresholds, we dispatch technicians to fix the network failure (DM, or demand maintenance). As we move the thresholds on these metrics further from severity, we are getting ahead of the most severe customer impacts (PM, or preventative and proactive maintenance).

2.3. Application

FMECA is a methodology and process, rather than an application. However, the elements of FMECA map nicely to our cable domain which can easily be implemented as practical applications. In this section, we will decompose the elements of FMECA including cable-specific adaptations and demonstrate how it can apply to real cable systems. Figure 1 shows an example of the FMECA process.

After defining the components of FMECA we will further consider how to operationalize it with data which is readily available to cable operators. Using the model below we combine the components together to determine a priority of events based on decay and criticality. Assigning severity rankings based on criticality and decay rate drives prioritization of how we should address the problems.

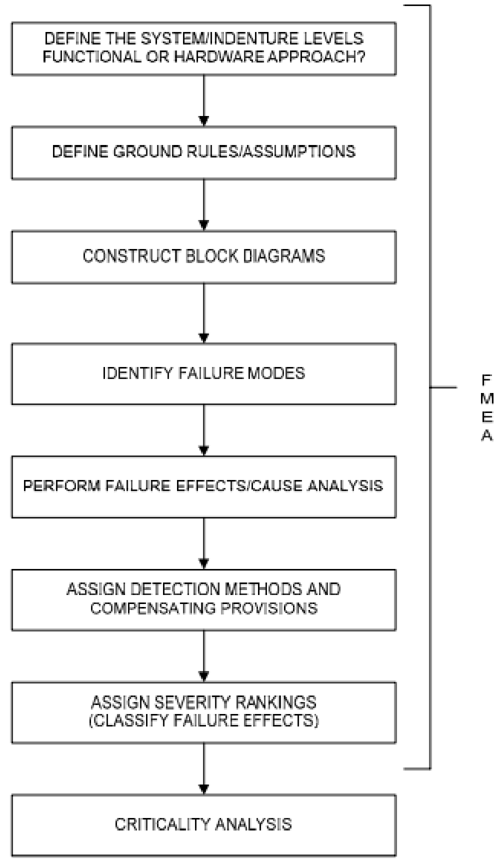

Figure 1 - Failure modes, effects and criticality analysis - United States Army

2.3.1. (FM - Failure Mode) Event Management

The most fundamental aspect of FMECA is identification of failure modes, or the places and reasons that components and/or systems can break. This might seem intuitive but many of our fault management systems have evolved based on symptomology, not necessarily specific cause-and-effect. For example, cable operators might have some form of network monitoring based on packet loss or FEC performance. However, these systems often lack in effective root cause analysis, delegating the troubleshooting process to technicians in the field or operations centers. Figure 2 shows an example of this symptomology-based event management, where potentially hundreds of individual errors are presented to technicians. Those technicians are then subject to analyze and repair based on their individual experience and training. Figure 3 shows this same system failure, modeled in FMECA which provides a root cause analysis, pointing the technician to the exact system component failure, including common repair recommendations. In this example, an amplifier module was experiencing a common form of failure associated to ground plane corrosion. The result was hundreds of symptomatic events which were difficult to interpret and repair efficiently.

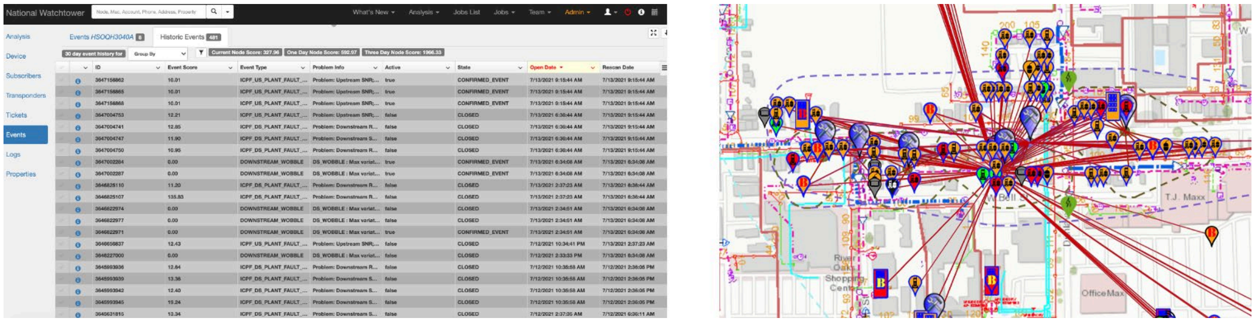

Figure 2 – Example of symptomology-based event management

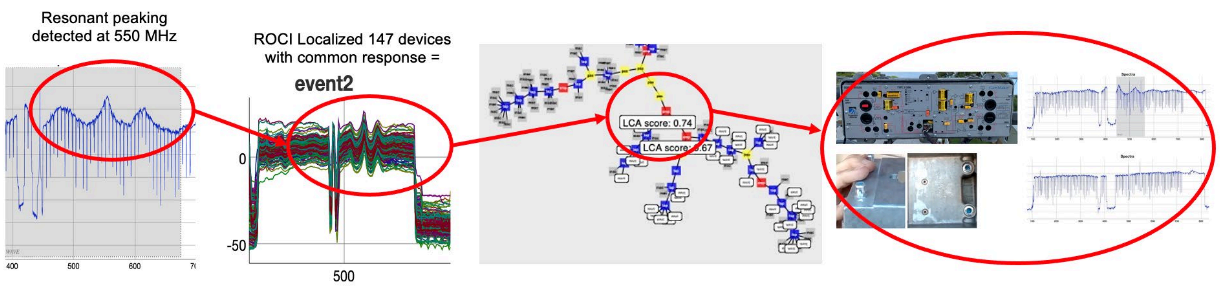

Figure 3 – Example of FMECA-based event management

2.3.2. *(E - Effect) Localization and Service Impact*

The first cable-specific adaptation is to determine the effect, which has additional complexity over some other component-based systems. In cable networks, HFC plant can be thought of (although not entirely correct) as a large, shielded antenna. The cable segments are largely passive with bidirectionality achieved with diplex filters. The performance sensors of our cable networks are typically at the transmitters and receivers (cable modems and CMTS) and often lack knowledge of the component chain between them, such as drops, taps, feeders, splitters, couplers and amplifiers. Because any one of these could be the point of failure, additional localization is usually required. In our example, a graph topology database and radio frequency (RF) signature analysis will be used to help provide fault location. Once the fault is localized, the tree-and-branch nature of hybrid fiber-coaxial (HFC) networks facilitates the cascading effect of service impact analysis (Figure 4).

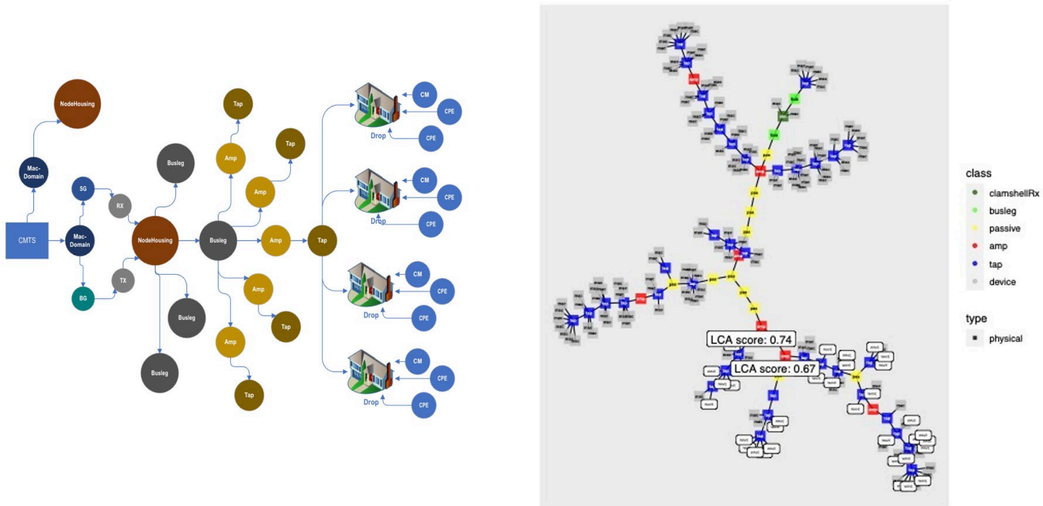

Figure 4 – HFC Network topology represented as a graph model

Going beyond empirical measurements, we can also try to understand the subjective aspects of impaired service. For cable access network services, any friction incumbering the use of the service is an undesirable effect. For a user, friction builds up over time, but memory is not forever. If over a short period of time a customer experiences a lot of friction, their impression of the reliability of a service is damaged. If the friction to switch providers becomes lower, they may become a lost customer.

For network capacity, any signal impairment is an undesirable effect. But clearly, a complete loss of all services is a more significant effect than say noise or signal attenuation in a few frequencies which can be addressed through DOCSIS resiliency mechanisms, or an application that won't authenticate properly to work as intended. But some effects are early indicators of more significant issues to come.
If any undesirable effect becomes significant, then it may rise in criticality.

2.3.3. (C - Criticality) Severity and Decay

The challenge in today's operating environment is showing the business benefit as we push to become more proactive. We look for optimization in initiatives on the basis of trouble call reduction and call-in rates; but what happens when you fix the network before the truck roll and before the calls? That is where modeling the causality as degradation or decay and adding that information to the methodology helps us to create the business and customer value. Through observation, we can determine the rate at which a particular failure mode will decay before it fails and creates the need for demand maintenance. By measuring the severity of degradation or decay, we can predict the point of failure and repair the failed component before the first call. This modeling doesn't work without a component of timing which is given through decay. With the decay timing we can then assign the value of fixing certain failure modes before they impact customers, which eventually generate the truck rolls or calls we've traditionally used to determine customer impact.

In DOCSIS access networks, there are a number of resiliency capabilities that help protect our services from network failures. A failure mode and its effects become critical if the effect becomes significant. That significance can be determined in a number of ways. But in systems and networks, significance is often estimated through a combination of the number of users impacted, the duration of the impact, and the severity of the impact from the effect. Complete loss of service is the most severe, whereas an impairment that does not impact service is likely very low in severity from an end user perspective but may rise in importance if it signals an opportunity as it serves as an indicator of other issues. For example, an outage for an entire node is critical because it impacts all services (S=max) for a large number of customers (N>>1); thus, there is strong incentive to return customers to service immediately, to reduce the outage duration (T). Criticality in this case could be estimated as S*N*T. On the other hand, a damaged drop is much less critical because it impacts a single customer (N=1) and may partially impact their services at worst case (S<<max); so, there is much less urgency with repair in these cases, thanks in part to the resiliency of DOCSIS.

Note that we don't need precise models to predict what will happen and when. It is often good enough just to recognize we found an opportunity to improve operational efficiency and delight customers.

2.3.4. (A - Analysis) Benefit Analysis

One of the outcomes of the FMECA analysis is to provide improved operational intelligence that helps transition from reactive to proactive network repairs. By modeling the number of faults with their severity and decay (Figure 5), the outcomes can projected in new ways, such as network reliability (Figure 6).

Failure Subsystem	Failure Mode	Occurrence	Severity	Duration Days	Decay Rate	Decay Days	Criticality Model	Number of Subs
Home	Wiring	1	0.1	1	0.3	30	-20.00	1
Drop	Cut	1	1	1		60	40.00	1
Drop	Other Damage	1	0.3	0.5	0.025	180	-165.00	1
Drop	Water Damage	1	0.25	0.25	0.083	60	-53.75	1
Drop	Ingress - Customer	1	0.9	0.25		0	22.50	1
Drop	Ingress - Hot Drop	1	0.9	0.25		0	22.50	1
Tap	Dameged / Other	1	0.05	1		0	20.00	4
Tap	Damaged / Water	1	0.2	0.5		0	40.00	4
Feeder	Cut	1	1	1		0	1200.00	12
Feeder	Cracked	1	0.25	0.05		0	15.00	12
Feeder	Water Damage	1	0.6	0.3		0	216.00	12
Amplifier	Power Failure	1	1	1		0	2500.00	25
Amplifier	Grounding Fault	0.05	0.25	0.25		0	7.81	25
Amplifier	Failing Module	0.1	1	0.1		0	25.00	25
Hardline	Cut	1	1	1		0	5000.00	50
Hardline	Damaged	0.2	0.25	0.2		0	50.00	50
Hardline	Shielding Separation	1	0.25	1		0	1250.00	50
Sm Node	Power Failure	1	1	1		0	15000.00	150
Med Node	Power Failure	1	1	1		0	30000.00	300
Large Node	Power Failure	1	1	1		0	60000.00	600
Headend	ACP (Channel Alignment)	1	0.025	1		0	12500.00	5000

Figure 5 – Example of benefit FMECA input, including failures, incedents and criticality

Probabilty of Repair	Repair Disruption Mins	Benefit of Cost (BCR)	Benefits of TCs	Benefit of Churn	Benefit of Reliability
0.30	60.00	-0.09	-0.20	-0.01	-20.00
1.00	0.01	0.19	0.40	0.01	40.00
0.90	0.05	-0.74	-1.65	-0.04	-165.00
0.70	0.05	-0.22	-0.54	0.00	-53.75
0.70	0.05	0.09	0.23	0.00	22.50
0.70	0.05	0.09	0.23	0.01	22.50
0.95	0.05	0.29	0.80	0.02	80.00
0.75	0.25	0.27	1.60	0.04	160.00
1.00	0.01	22.15	144.00	3.60	14400.00
1.00	0.01	0.24	1.80	0.05	180.00
1.00	0.01	3.46	25.92	0.65	2592.00
0.50	0.01	83.33	625.00	15.63	62500.00
0.50	0.01	0.26	1.95	0.05	195.31
0.50	0.01	0.83	6.25	0.16	625.00
1.00	0.01	277.78	2500.00	62.50	250000.00
0.70	0.01	2.31	25.00	0.63	2500.00
0.70	0.01	57.87	625.00	15.63	62500.00
0.70	0.01	2083.33	22500.00	562.50	2250000.00
0.70	0.01	8333.33	90000.00	2250.00	9000000.00
0.70	0.01	33333.33	360000.00	9000.00	36000000.00
0.70	0.01	181159.42	625000.00	15625.00	62500000.00

Figure 6 – Example of benefit FMECA output, icluding network reliability

2.3.5. Feedback Loop

This is not described in FMECA systems and methodologies but is important to maintain a modern machine learning (ML) and artificial intelligence (AI) based system. As our cable access networks continue to evolve, the management systems need to become more adaptive. Especially as these systems become more reliant on ML and AI systems, the models need feedback to improve. By providing feedback to the system, they may continue to improve and adapt (Figure 7).

1. Failure mode detection using ML and AI pattern matching
2. FMECA knowledgebase provides repair recommendations to technician
3. Technician makes informed repairs, reducing the analysis time
4. System automatically validates repair and potentially solicits feedback
5. Pattern matching models and recommendations adapt

Ultimately, as the systems continue to adapt and improve, gains in repair times and network reliability become realized.

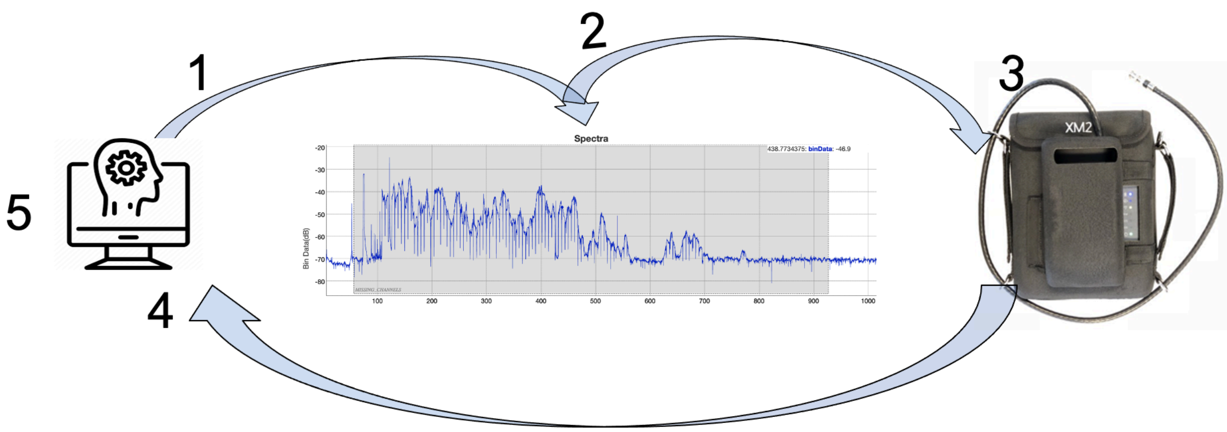

Figure 7 – Closed loop detection, reccomendation and repair validation

3. Use Cases

In both the CableLabs and SCTE Network Operations Subcommittee working groups for PNM, a number of failure modes have been identified and documented. The following Figure 8 shows examples of these documented downstream RF failure modes; these failure modes to RF transmission are often referred to as impairments or faults, to differentiate from the network failure mode which causes the RF failure modes. The working groups are continuing to make progress in this area including understanding and troubleshooting upstream RF impairments and developing a repair matrix. Additional examples of this upcoming work can be seen in Figure 9.

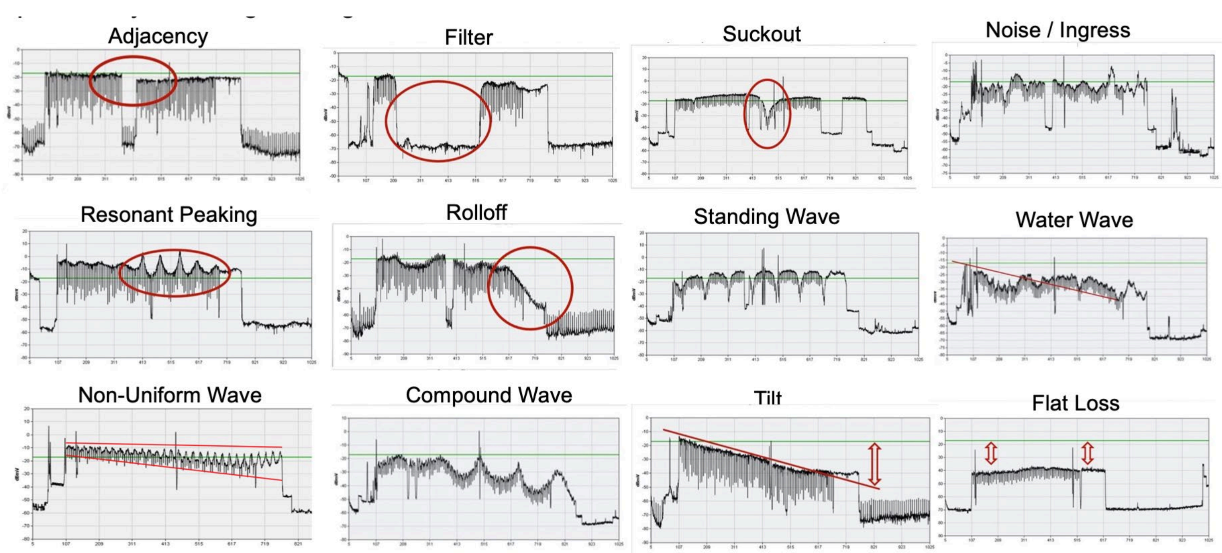

Figure 8 – Downstream RF failure mode examples from SCTE Industry Reference 208

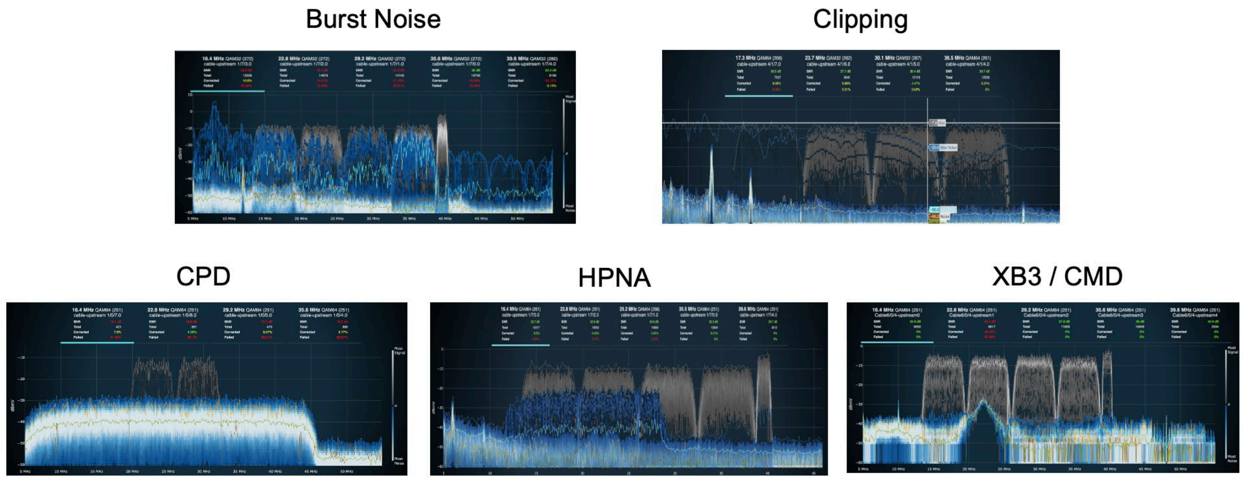

Figure 9 – Upstream RF failure mode examples from upcoming SCTE Industry Reference

3.1. Water Damaged Cables

In the previous material, we reviewed the fundamentals of FMECA and how the process could be adapted to work in a cable access network. In this section, we will apply what we've learned to a specific use case which has been a recurring theme in recent SCTE PNM working groups: water damaged cables.

3.1.1. Specification

The first step in our water damaged cable use case is to define the system and failure mode. Our implementation will rely on recent PNM advancements which allow cable operators to accurately detect, and measure cable failure associated to water ingress. This failure mode has been well documented and specified in previously published SCTE material, found in the bibliography.

3.1.2. Detection

Impairments in DOCSIS RF are easy to detect, but that is only the first step in efficient maintenance. A simple spectrum capture or RxMER per subcarrier plot will reveal an impairment in the signal, and the signature of the impairment indicates the type of fault. These and additional PNM tests and queries help us measure the impact on the RF signal, which we can translate to impact on service through a model.

Detection of the impairment and identifying its type allows us to do something about it and know how important it is to address the fault. Each fault type can behave differently over time, as it is exposed to elements such as heat, dryness, water, ice, and cold.

There have been many different methods devised for identifying one type of impairment from another, such as the CableLabs Spectrum Impairment Detection, or the CableLabs Anomaly Detector. (See [Zhu, Sundaresan, Rupe] for details on the machine learning based Anomaly Detector available for use by CableLabs members.) These methods all essentially match patterns in bin data, which are indicators of the fault type.

As explained in an Expo paper from 2021 [Fox, et. al.], water damaged cables are indicated from spectrum data with a signature of a few factors: a random (aperiodic) pattern of fluctuating attenuation over frequency bins, and often a general trend of more attenuation toward higher frequencies. As a result, a pattern matching solution can be used to identify water in cables. As described in the paper mentioned here, a two phased approach works well: identify a standing wave, which is indicated by highly variable attenuation over frequency bins, and then use a secondary test that separates standing waves (which are periodic) from water waves (which are aperiodic).

Possible approaches, some described in that paper, include transforming the data further to find how periodic the variability may be, or calculating and removing any slope in the bin data. For example, taking the bin data, calculating and removing the slope trend from the data, and then using an FFT to transform the bin data into a new frequency domain to find the frequencies that might describe the variability in bin signal levels; a single strong frequency would indicate a standing wave, whereas several nearly equally strong frequencies would indicate water is the culprit.

We have also learned that water in a coax cable causes variability in the phase of the signal as well. With the ability to capture complex (I,Q) bin data, we can further confirm the presence of water in the cable.

All this information helps us localize too, as we'll explain next.

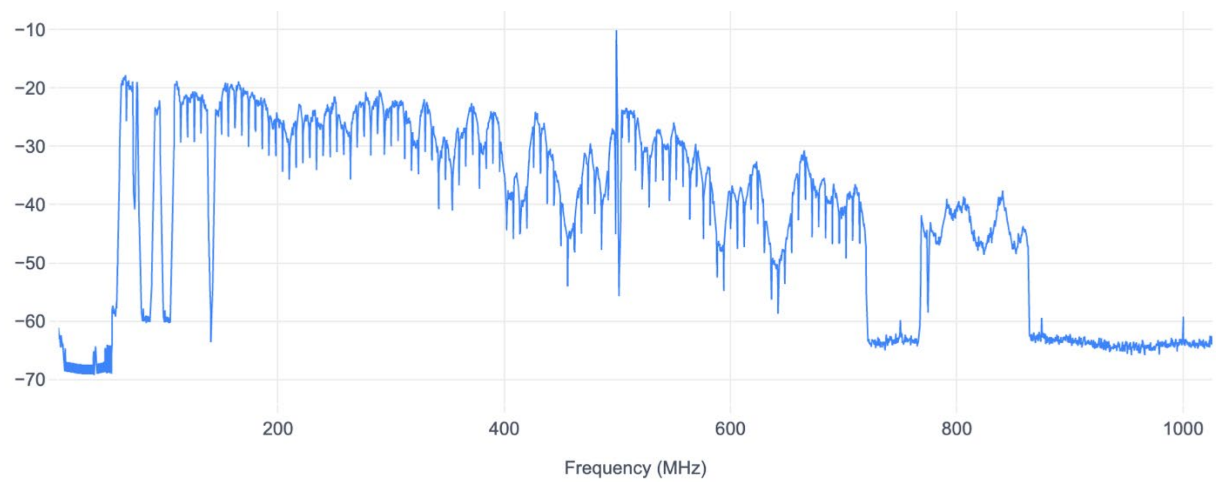

Figure 10 – Water impaired frequency response

3.1.3. Localization

As previously discussed in Section 2.3.2, localization is conducted through a cable-specific adaption to the FMECA model. Because of the tree-and-branch structure of our HFC networks, additional topology or location information is required to determine the effects. Fortunately, water-soaked cable localization is straightforward. Cables with water ingress are almost always outside, so that limits the localization to the drop network (Figure 11) or distribution cable such as feeders and trunk. The simplest, most effect method is to determine if the water signature is isolated to a single location, or multiple. There are a number of basic pattern-matching routines that can accommodate this type of localization. There are some examples where incorrect localization can occur with this method, but these should be considered edge-cases.

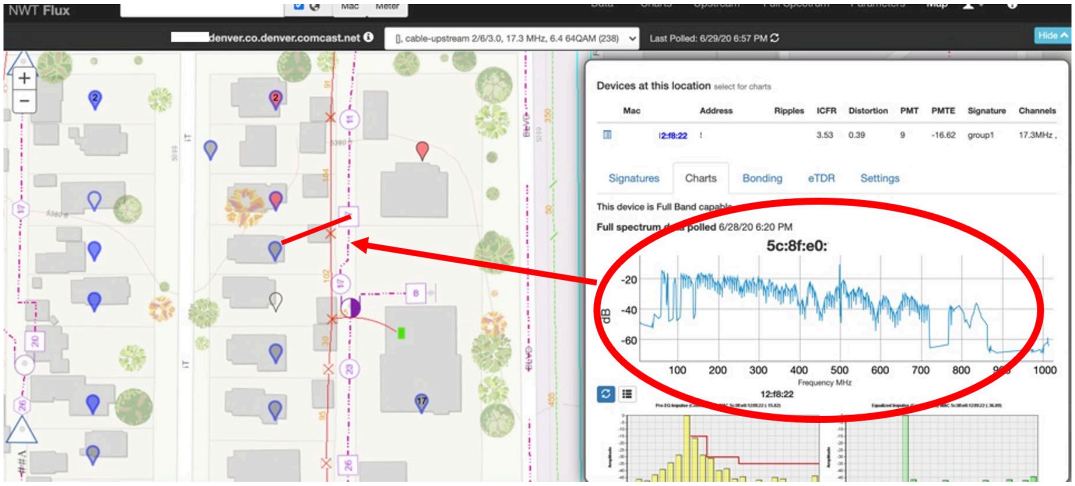

Figure 11 – Water signature localized to a single location indicating damaged drop cable

3.1.4. Criticality

One of the most intriguing aspects of our water damaged cable use case is that it has a predictable decay model. In the case of RG drop cables, the water damage always gets worse with little-to-no improvement over time, other than the transient effects of temperature. In the case of water-soaked RG6 drop cable, water can migrate or drain, but mostly it pools within the dielectric. Once the dielectric has been compromised, a chain of decay becomes inevitable. Figure 12 illustrates this degradation process.

As we explained earlier, the criticality of an impairment is estimated by the number of customers impacted, the severity of the impact (in terms of impacted services, potential service impacts, etc.), and the duration of the impact. While DOCSIS provides strong resiliency in RF signals, severity is estimated proactively in terms of potential impact to service. The potential impact is estimated through a model describing the degradation or decay path that the wet cable will take if left to degrade.

Again, see Figure 12, which describes the degradation path of a coax cable, such as an exposed drop. At first, the cable is protected from the elements. After time, that protection weakens, and the elements can begin to enter the shield. After more time, water gains access to the braiding of the shield, and fills the gaps between the wires. After some amount of freezing and thawing, the insulation begins to fail, and the distance between the shield and center conductor can change, leading to changes in the dielectric constant and multiple impedance changes. After more time, the water can get to the center conductor, and corrosion can occur throughout this degradation process. As this degradation progresses, PNM telemetry can indicate worsening degradation by showing a stronger water signature in the bin data.

Field observation and testing of recovered cables provides various snapshots of this degradation path, so we know it happens, and we can compare the impairment patterns to the failure modes found in the field to align our telemetry to the likely network failure modes. All this allows us to know that PNM is meeting its intent.

With additional work, we could develop prediction models to estimate the time to the next level of failure. But we already know enough. Once we find a failure mode, and we can estimate its severity in the future, we can determine its criticality, and therefore know the problem is worth addressing well before the cost of failure is inflicted.

Through PNM, we delight customers and save on operations costs. With water-soaked cables, the motivation is clear, as is the link from impairment to fault to failure.

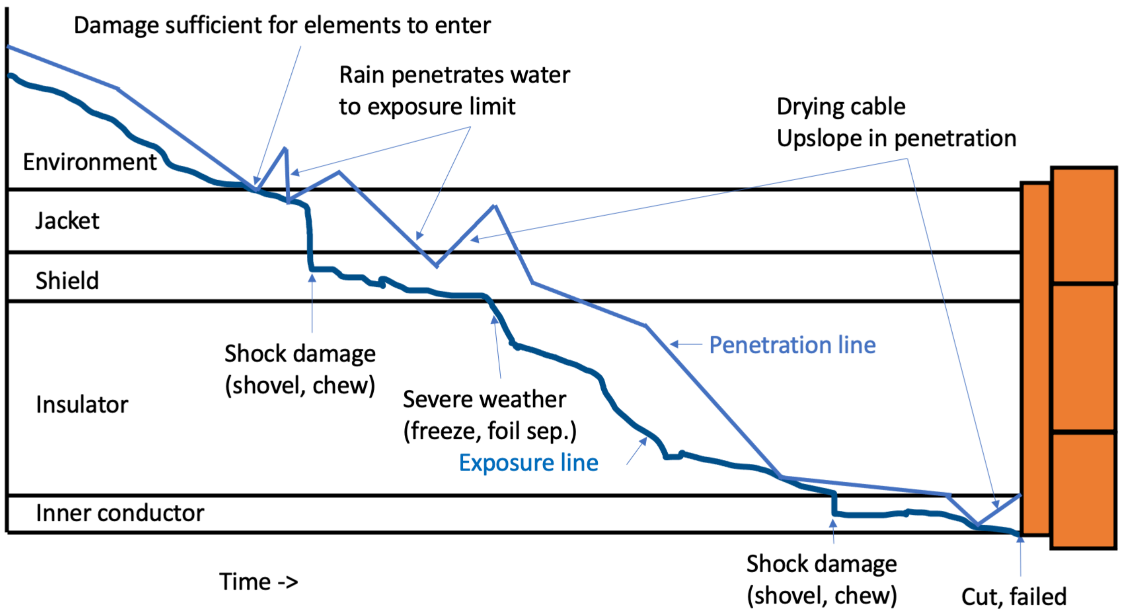

Figure 12 - Example degradation of cable with exposure and water penetration

3.1.5. Effects

Empirical performance measurements can often be a good lead indicator of experience, which is subjective. In early field trials of our water detection, the effects were easily validated with before-and-after signal analysis (Figure 13). While the criticality model discussed in section 3.1.4 is a work-in-progress, and we intend to identify other degradation patterns to extend our knowledge, the merits of fixing these types of problems are agreeable. Starting with the worst problems first is obvious, and eventually we'll get ahead of the critical failures.

"We ran on this high-variance water in cable address over the weekend. The customer is internet only for the past 4 years and no trouble calls in history. This customer's service has definitely been suffering."

Tech Notes

- Yes, the recommended fix was correct
- Drop had had water damage for a very long time. Corrosion on center conductor and powder when fitting cut off.
- Drop had quite a bit of age to it, and I can tell it had come down and been driven over multiple times in the past. A lot of flattened sections along the line.
- Also, there was a return noise filter at tap for noise.
- Customer had, for quite some time, many intermittent issues with service dropping out for long periods of time.
- Home performance test was failing and is now passing.

- We contacted customer to make arrangements for access.

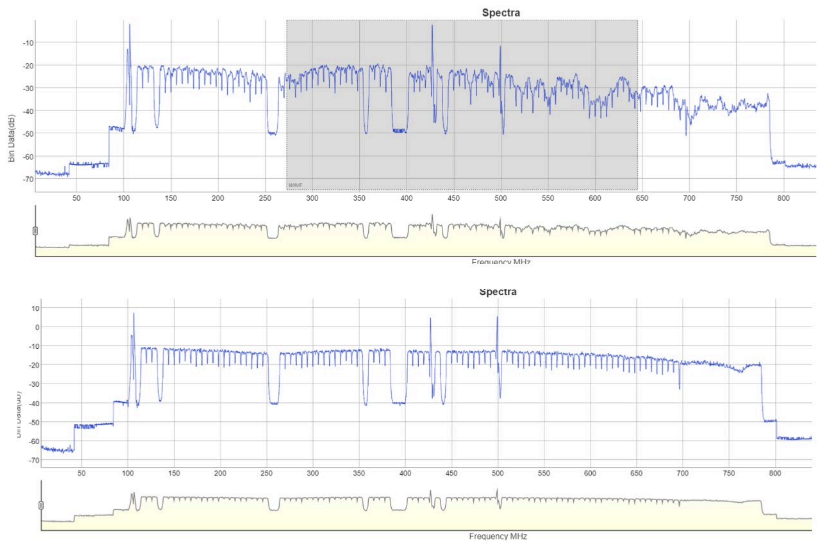

Figure 13 – Field trial, water wave before and after repair

3.1.6. Benefits

In the water damaged cable field trials, the benefits have been modeled to help provide a way to quantify and rationalize the value of proactive vs. reactive repairs. To support the field trial, a year's worth of drop replacements were analyzed. The analysis yielded interesting results in the repair time of typical drop replacement activity.

On average, by removing the need to troubleshoot and diagnose, repairing these water damaged drop cables resulted in 1 hour of improved operational efficiency. When multiplied by the number of instances, the operational benefits are compelling. However, there are additional benefits that are realized:

- Our proactivity delights our customers rather than forcing them to call us
- Improves network reliability in a measurable way
- Removes friction from customers that may be silent, but unhappy with their service

4. Conclusion

Most cable operators have network monitoring and management systems including PNM. In many cases, we've become excellent stewards of our network performance and aim to provide the best possible customer experience. FMECA provides an easy to understand and intuitive methodology for maintaining a consistent knowledgebase of failure modes, severity assessment, and repair prioritization.

By extending FMECA with DOCSIS PNM, we have access to network telemetry which can indicate an impairment. The impairment signature indicates the type of fault in the RF signal, which we can link back to a network failure of a particular type. We trace impairment to fault to failure mode in the network, and that helps us know what to look for and where, and what to do to fix it. When coupled with cable's PNM, FMECA helps us transition from "find failure and fix it" to "anticipate failure and prevent it".

Abbreviations

AI	artificial intelligence
ASHRM	American Society for health care Risk Management
CM	cable modem
CMTS	cable modem termination system
dB	decibel
DM	demand maintenance
DOCSIS	Data-Over-Cable Service Interface Specifications
FEC	forward error correction
FFT	fast Fourier transformation
FMECA	failure mode, effects and criticality analysis
HFC	hybrid fiber-coaxial
IQ	in-phase and quadrature
MER	modulation error ratio
ML	machine learning
N	number of occurrences
PNM	preventative and proactive maintenance
PM	proactive network maintenance
RF	radio frequency
RG	residential grade
S	services
SCTE	Society of Cable Telecommunications Engineers
T	time

Bibliography & References

"Proactive Network Maintenance Using Fast, Accurate Anomaly Localization and Classification on 1-D Data Series." *IEEE Xplore*. Web. 12 Aug. 2022.

SCHOOMAKER, PETER J. "Failure Modes, Effects and Criticality Analysis ... - United States Army." United States Secretary of the Army. Web. 12 Aug. 2022.

Summy, Elizabeth. *W H I T E P A P E R White Paper - ASHRM*. American Hospital Association, https://www.ashrm.org/sites/default/files/ashrm/FMEAwhitepaper.pdf.

Rupe, Jason. "Interview on Failure Mode Analysis." Online interview. 1 June 2022.