What Gets Measured Gets Done / What Gets Analyzed Gets Transformed

Analytics for a Wider/Deeper Network View

A Technical Paper prepared for SCTE•ISBE by

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Introduction

With the acceleration of technology in homes comes a corresponding increase in the number of switching power supplies potentially impacting the upstream plant. More and more in-home electronics devices -- Internet-connected appliances, battery chargers, LED lights, video set-top boxes (STBs), broadband gateways and cable modems -- come with switching power supplies inside of them, which contribute to an age-old issue known as Common Mode Disturbance, or CMD.

This is happening coincident with the industrial shift away from traditional centralized architectures to distributed architectures. Distributed Access Architectures (DAA) are on the rise because of a growing need to fulfill newer needs, such as low-latency and high-speed applications. Yet the traditionally persistent issue that is Common Mode Disturbance (CMD) continues to impact networks in negative ways. While tools have improved dramatically in the last few years in addressing such pesky problems as CMD, it continues nonetheless to impact even the more modern fiber deeper and distributed networks.

Specifically, the rise of CMD noise, in part trigged by the explosion of Internet-connected CPE in our customers' homes, catalyzed within Comcast an impairment identification and mitigation framework described in this paper. The "identification" portion of the framework is informed by machine-level telemetry data, to better measure the impairment; and the mitigation portion of the framework is enabled by advanced data analysis. (Hence the title, "what gets measured gets done; what gets analyzed gets transformed.")

Our intent is to provide new insights into age-old problems, as well as a framework for analyzing old and new problems alike. New, machine-informed ways of looking at the traditional time and frequency domains of RF information can help to create a "Taxonomy of RF Impairments" – a first in the industry (to our knowledge), which has developed as a playbook to tackle impairments. This work will ultimately lead the industry toward an effective use of cable assets and aid in the creation of a more elastic, low latency network.

Overview

Comcast has initiated a suite of projects to address some of the systemic operational challenges related to the evolving Hybrid-Fiber-Coaxial (HFC) and optical networks by applying some new advanced technologies, and by innovating on our existing platforms. Several examples are highlighted in this paper, including mitigating switching power supply noise and new data analytics. The first, RF ingress mitigation, is described in detail below. The opportunity development process is described in Figure 1, with four discovery and solution development stages that feed the solution development and deployment funnel, as shown in Table 1.

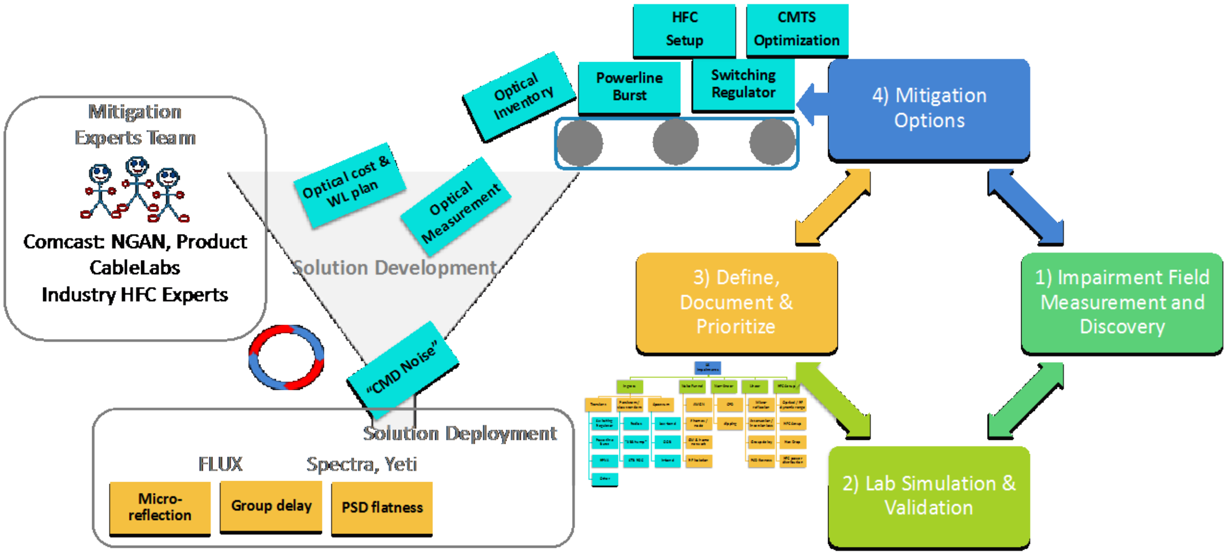

Figure 1 - Opportunity development process

Table 1 - Opportunity development work streams

Stage	Description
Impairment Field Measurement and Discovery	Opportunities to improve operational efficiency are discovered doing field measurements using lab grade Test and Measurement (T&M) equipment and leveraging Comcast's PNM and other OSS tools. Currently a field measurement campaign is ongoing to identify the root cause of the most impactful challenges to the access network that are causing operational expense and impacting customer experience.
Lab Simulation & Validation	Once these challenges are discovered in the field, they are evaluated in-depth in the lab to characterize the specifics and test different scenarios, to understand the impact and opportunity for improvement.
Define, Document & Prioritize	After the challenges are characterized in detail in the lab, they are documented and prioritized for the design of mitigation approaches. These details are added to a growing taxonomy of HFC impairments, with comprehensive descriptions characterizing the impairment. As the taxonomy grows, we plan to continually update the industry with additional descriptions for CMD and other noise.
Mitigation Option & Solution Development	For each of the prioritized challenges, we developed a set of options to mitigate or reduce the impact. One of the mitigation options detailed in this paper relates to CMD Noise. Other options under development for CMD noise issues range from customer communication channels to new self-install-kit (SIK) connectors to new low-cost HW that can block the noise from getting into the network. Once the mitigation options are prioritized, solution design is completed.
Deployment	Deployment of the solutions include field trials to evaluate both network performance metrics, such as Modulation Error Ration (MER), uncorrectable codeword error ratio (CER) and packet loss, and operational business metrics such as call-in rates (CIR), tickets, and truck rolls. Based on the efficacy of the solution, it can be deployed across the network.

In recent years Comcast has developed some very effective operational tools described in other SCTE publications.[1] This paper describes another such development and approach, focused on a growing HFC impairment, with an opportunity to improve the customer experience and operations. In essence, a new take on operationally-hardening a mature technology. Future focus areas, as shown in Figure 1 include additional advanced data analytics and optical measurement solutions.

1. Common Mode Disturbance

1.1. Field Measurement

With the acceleration of technology in homes there is an increasing number of switching power supplies. Switching power supplies are increasing with the growth of home electronics, Internet-connected appliances, battery chargers, LED lighting, video set-top-boxes (STBs), broadband gateways and cable modems (CMs), among many other uses. These power supplies convert AC line power to different DC voltage levels required for the consumer electronics circuits, through methods such as switching the current into a capacitor whose voltage is monitored and controls the frequency of the switch. One example power supply circuit is shown in Figure 2.[2]

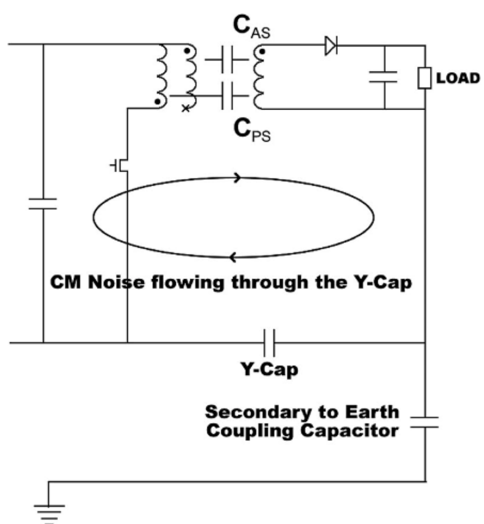

Figure 2 - Example switching power supply circuit[2]

The initial in-rush current when charging the capacitor may result in a noise current spike onto the ground of the device. This noise is referred to as Common Mode Disturbance (CMD) by power supply engineers. Because the coaxial cable's outer conductor is grounded, it can become a path for the noise

[1] L. Wolcott, J. Heslip, B. Thomas, R. Gonsalves; A Comprehensive Case Study of Proactive Network Maintenance, SCTE TEC EXPO 2016

[2] Y. P. Chan, B. M. H. Pong, N. K. Poon and J. C. P. Liu, "Common-mode noise cancellation in switching-mode power supplies using an equipotential transformer modeling technique", IEEE Tran. Electromagn. Compat., vol. 54, no. 3, pp. 594-602, 2012

current. When there is an imbalance in the coaxial transmission path, the common mode noise current converts to differential mode current.[3]

Examples of imbalance in the coaxial transmission path include loose connectors with poor ground continuity, shield break on a cable, bending[4] (kinks) in the coaxial cable, and impedance mismatches. When an imbalance occurs, mode conversion occurs. In other words, the common mode noise from that home will couple into the cables that funnel data from all the other homes in that serving area, to the Cable Modem Termination System (CMTS), thus impacting the performance for all devices on the upstream signal path. Characterizing this type of noise, to ensure equipment attached to a cable network does not negatively contribute to the HFC noise levels, has been standardized as part of the SCTE 249 IPS standard based on a coupling- decoupling network.[5]

One example of CMD noise coupling into the HFC through a loose coaxial connector on a CM is shown in Figure 3, along with the same noise measured per the SCTE 249 test method. Another similar picture of the noise, as seen by a spectrum analyzer with min and max hold located near the CMTS, is also shown in Figure 3, with the noise coupling into the network at an impactful level underneath the 23.7 MHz carrier. Note that both pictures show the peak of the noise power between 20 and 25 MHz -- with impact into a lower DOCSIS 3.1 upstream carrier centered at 17 MHz typically placed below the 23 MHz Carrier.

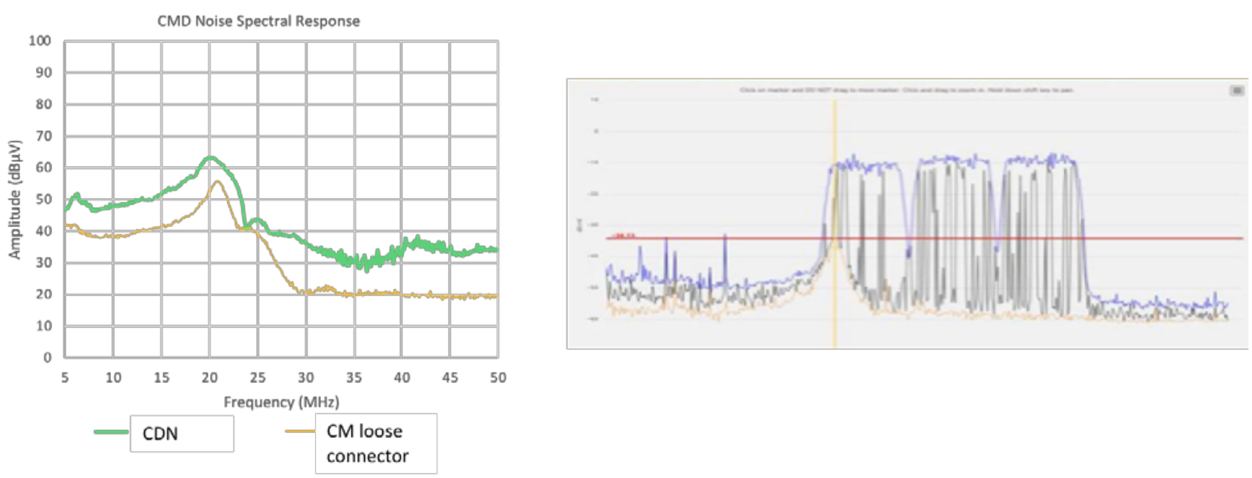

Figure 3 - Coupling decoupling network vs. CM with loose connector, on an HFC network with max-hold spectrum analysis.

1.2. Lab Simulation

Upon laboratory investigation, this noise signature appears to be highly impactful to the DOCSIS signals, from the perspective of a spectrum analyzer on max hold or the SCTE standard CDN. In fact, it can create service-impacting DOCSIS codeword errors, resulting in packet loss. A deeper lab perspective was

[3] A. Axelrod, K. Povolotski, and S. Nir, "Experimental study of DM to CM conversion in elements of data communication links," in Proc. Int. Eur. Electromagn. Compat. Symp., Sorrento, Italy, Sep. 2002, pp. 435–440.
[4] Xinglong Wu, Flavia Grassi, Sergio A. Pignari, Paolo Manfredi, Dries Vande Ginste, "Circuit interpretation and perturbative analysis of differential-to-common mode conversion due to bend discontinuities", Electrical Design of Advanced Packaging and Systems Symposium (EDAPS) 2017 IEEE, pp. 1-3, 2017.

[5] SCTE IPS TP 228 expected to become SCTE 249 standard before SCTE TEC Expo

obtained, beyond field measurement, by characterizing the signal with a Vector Signal Analyzer -- a high-speed sampling scope for signal analysis. While this noise appears to be intractable and a potentially significant customer experience detractor in the frequency-domain, mitigation opportunities become even more pronounced in the time-domain. CMD noise, viewed in the time-domain, is shown in Figure 4.

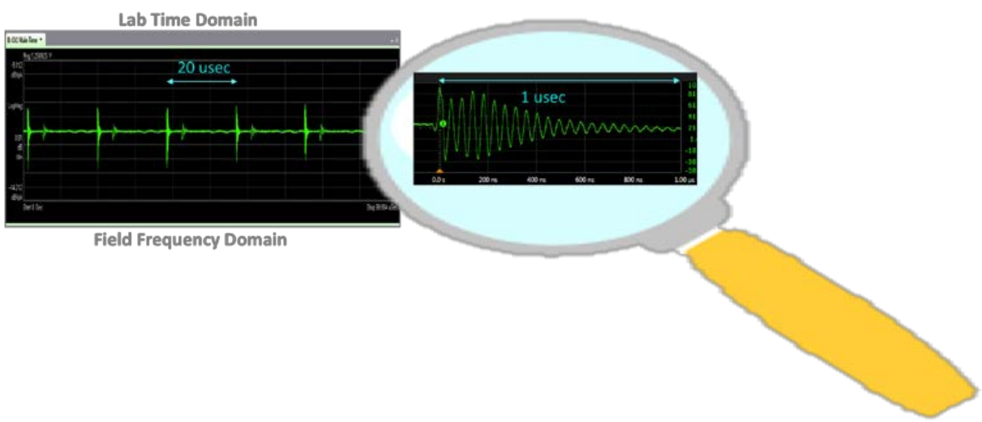

Figure 4 - CMD noise time-domain analysis

The CMD noise is actually a very periodic burst noise. The burst rate depends on the frequency of operation of the switching power supply, typically 50 to 75 kHz or a period of 14 to 20 usec. Other switching regulators have been seen up to a 200 kHz switching rate. When the in-rush current of the regulator spikes, the duration of the noise burst is only about 1 usec, or less than 10% of the time. Measured across a variety of make and models of Consumer Premise Equipment (CPE) and power supplies, the time-domain shows a very tight bound of period and duration across the equipment.

1.3. Mitigation Design

The Reed-Solomon (RS) method of forward error correction (FEC) used in the DOCSIS 3.0 upstream signal path reaches a rate of diminishing return with the amount of overhead vs. error correction performance with respect to Additive White Gaussian Noise (AWGN) or time-invariant noise. That said, Reed-Solomon encoding is a great coding scheme for dealing with transient noise sources, especially with the support of an interleaver. From a spectrum analyzer perspective, the noise appears to be time-invariant and very difficult to mitigate without sending a truck to a customer’s house. From a time-domain perspective, it falls into the area where D3.0’s error correction can have its maximum benefit.

Without going through detailed modeling, Figure 5 visualizes the concept. Based on a default D3.0 burst profile configuration that had been used on the network, a new, D3.0 burst profile was designed to eliminate the packet loss caused by the CMD noise. The CMD noise, at a 14 to 20 usec period, will impact every single codeword. In fact, one of the key metrics used in operations to identify when CMD noise is coupled into the network is a very high rate of correctable codeword error ratio (CCER) because it is causing errors to every codeword if it is coupled in at a high level.

If each time the bust of noise hits a codeword, and it is at a high enough power level to cause an error, it will error four RS symbols for the given modulation and symbol rate (64 QAM, 6.4 MHz) in the example. At the current 20 usec period, this burst can hit the short data grant three times and the long data grant five times with the default configuration. In the default configuration, only three bursts can be fixed in the short data grant, and four bursts can be fixed in the long data grant. As a result, the performance is variable for short packets and very bad for long packets or concatenated data bursts. By restructuring the short and long data grant, the short data grant codeword can fix more than three bursts, and the long data grant can fix four bursts. The long data grant is re-defined so that only four noise bursts can impact the codeword, based on the time-domain characteristics of the CMD noise. Similarly, the Unsolicited Grant Service (UGS) data grant can be re-defined to eliminate the packet loss caused by CMD to the voice packets. If there are multiple sources of CMD noise, a similar analysis and modulation profile can be developed to manage the uncorrelated noise sources. Additionally, applying a D3.0 block interleaver can add additional margin when there are multiple CMD sources, which are uncorrelated in timing with each other and the data traffic and codewords.

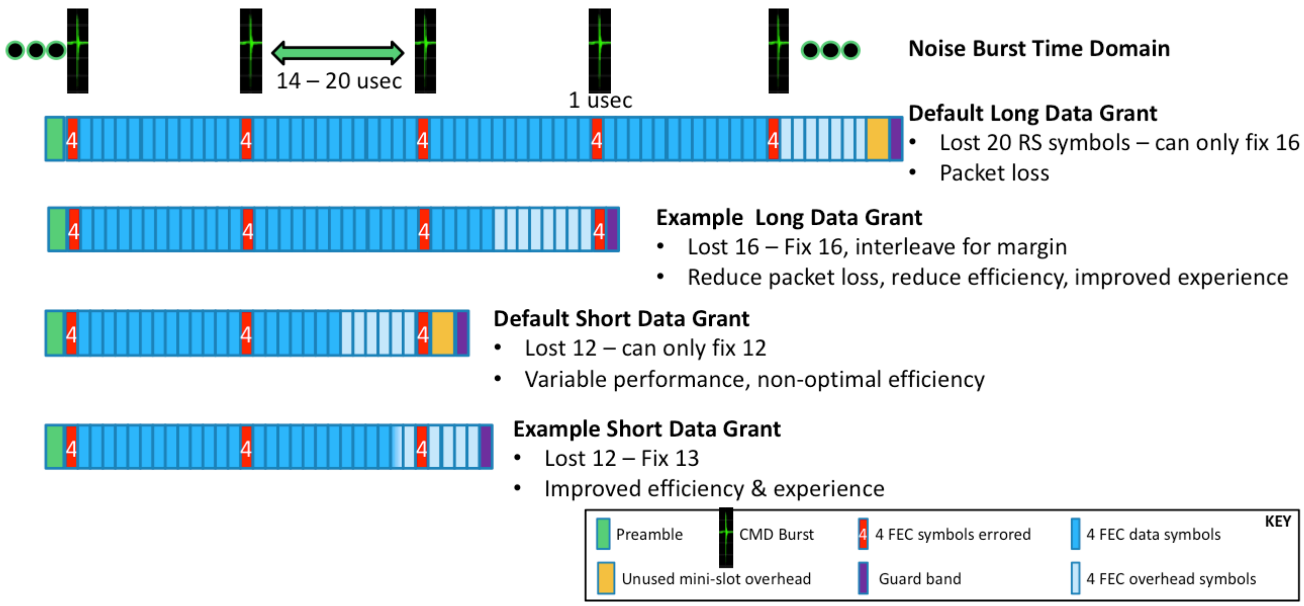

Figure 5 - Example DOCSIS modulation profile design with transient noise

When adjusting modulation profiles and D3.0 US channel parameters, it's important for all the configuration "knobs" to be set compatibly and collectively. By also adjusting the symbol rate, max bust size for the short data grant, preamble length, and guard time, the overall efficiency across packet sizes can be improved. When these techniques are applied to the lower two channels, most impacted by CMD noise, the result is increased robustness. Applying more efficient lower overhead FEC to the upper two channels can improve capacity and efficiency. The overall capacity of all four bonded channels can be maintained while mitigating the impact of the noise on the user experience as shown in Figure 6.

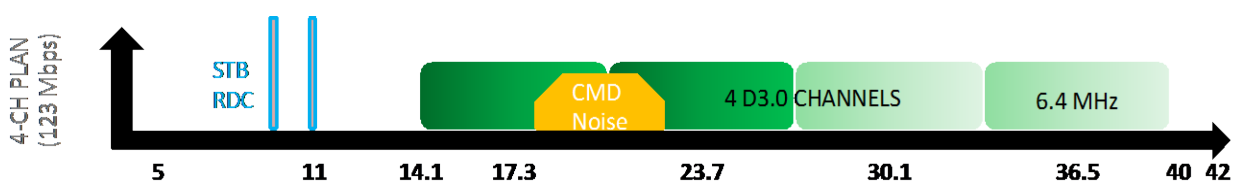

Figure 6 - Balancing robustness vs. efficiency to maintain total bonded capacity

The overall efficiency for each channel can be modeled based on the packet size or concatenated transmission burst, as shown in Figure 7.

- Because of default modulation profile inefficiencies for small packets, the example improves data efficiency by ~5% across all channels.
- Efficiency is reduced by ~4% for larger packets across all channels
- Efficiency is reduced by ~8% for Channels 1 and 2 in lower spectrum
- Speeds are improved by fewer TCP slow starts and re-transmissions, as shown in next section

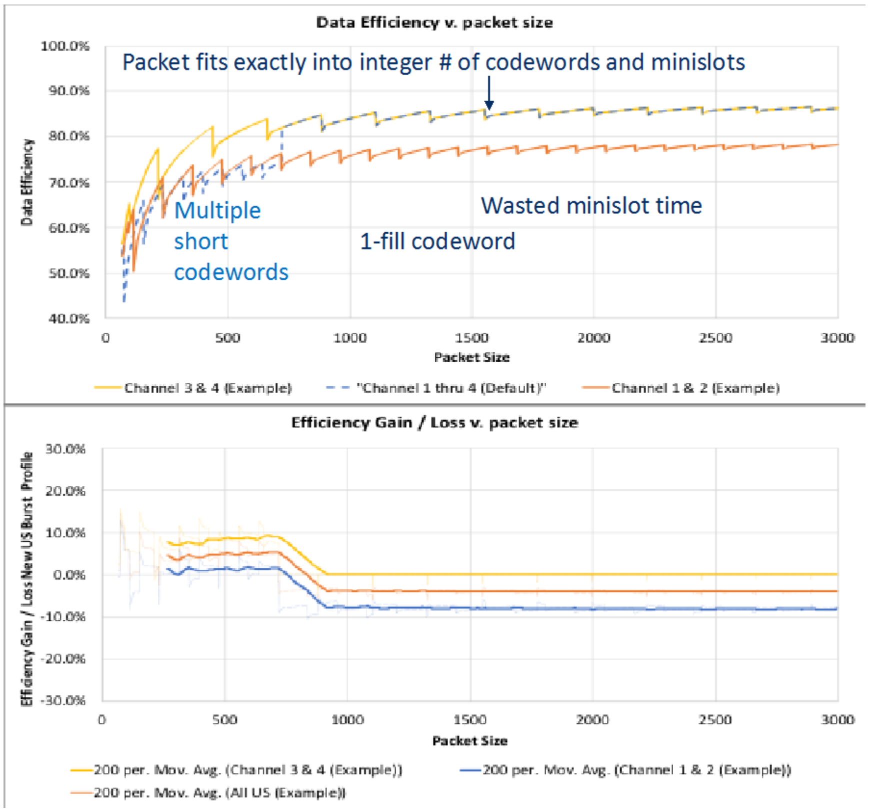

Figure 7 - Modulation Profile Efficiency per burst size model

1.3.1. Lab Test of Mitigation Modulation Profiles

These example configurations were tested in the lab to determine if the D3.0 FEC design could improve the customer experience. The new modulation profiles were tested with both TCP and UDP traffic while measuring the loss from the traffic generator. The level of CMD noise coupled into the upstream was increased until a significant impairment was caused, and then the new profile was applied to test the improvement in customer experience. Figure 8 and Figure 9 show the improvement in customer experience for TCP traffic. As the CMD is added, it impacts the bottom two channels, and the throughput of the network dropped in half as the upstream packet loss was increased for the two lower channels. As the new profiles are configured, the upstream and downstream throughput improves back to levels equivalent to no impairment, even though the noise is still in the channel. Because the TCP performance in the downstream is also impacted by the packet loss in the upstream, the downstream performance is also impacted by the upstream CMD noise, and improved by the new profile. The packet loss is reduced to a level that is no longer impactful to the customer experience for both one and two uncorrelated CMD interference sources.

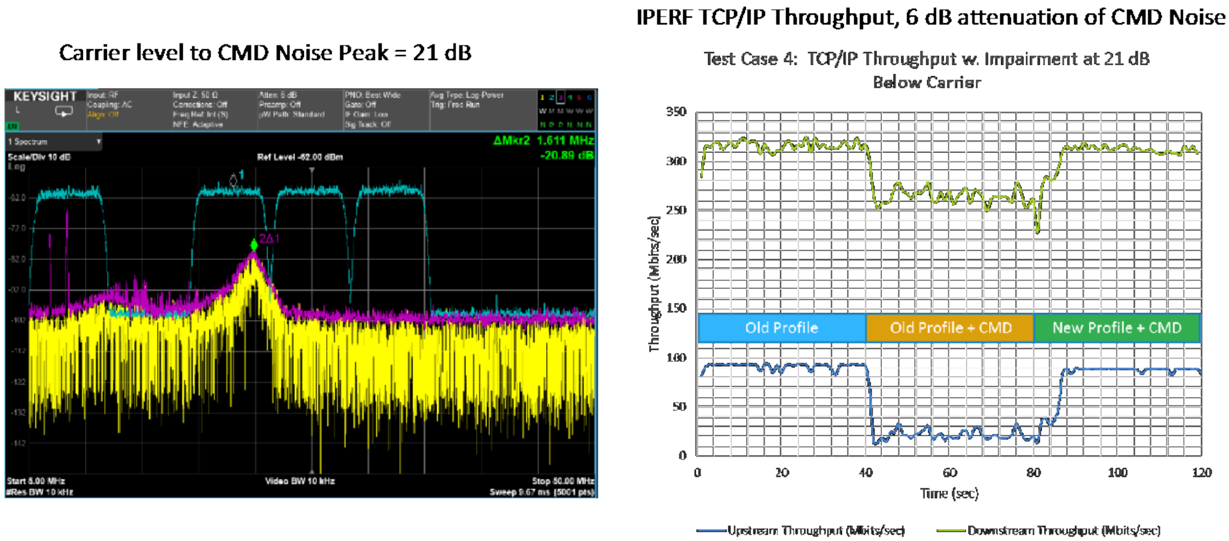

Figure 8 - 1 CMD interference source, throughput improvement in upstream and downstream

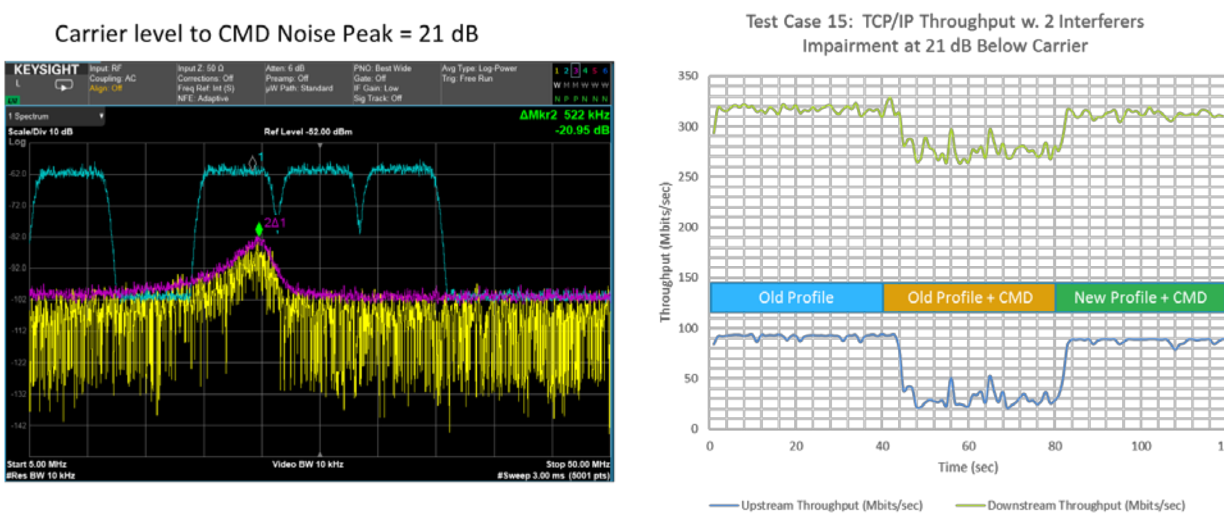

Figure 9 - 2 CMD interference sources, throughput improvement in upstream and downstream

Figure 10 shows the CER, CCER and UDP Packet Loss. Because the CMD noise is hitting every codeword, there is a high level of CCER, but many codewords are uncorrectable and causing packet loss. After applying the new modulation profile, the CER drops to an acceptably low level, reducing the packet loss. The CCER increases because all the errors are now being corrected, which reduces the packet loss and improves the customer experience.

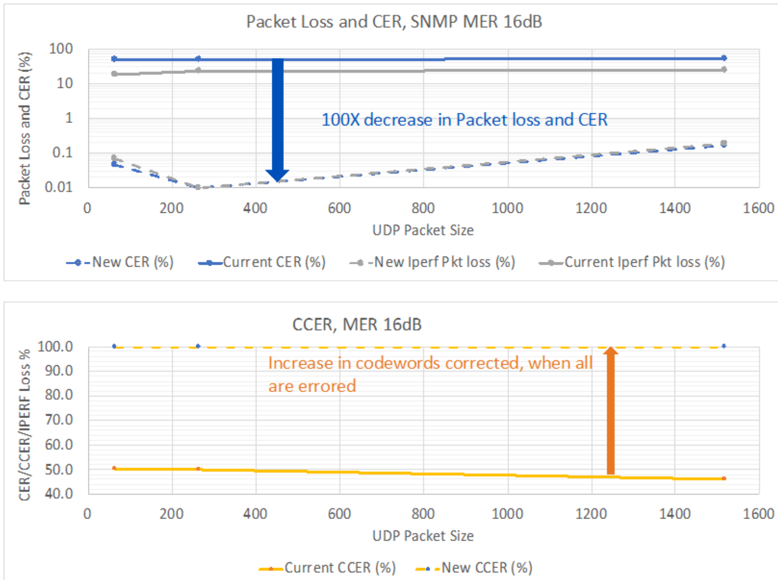

Figure 10 - Packet Loss, CER and CCER for UDP packets for default and new modulation profile

While CCER is generally considered “a bad thing,” because it means there is noise present in the network and causing errors, it is also a good thing if it means fewer uncorrectable errors are occurring, as in this example. The CER has been converted to CCER and has reduced the packet loss, thus improving the customer experience.

1.4. Field Test and Deployment Results

These new configurations were tested in the field against a population of nodes that were exhibiting interference from CMD noise. Codeword errors were tracked across all the CMTS upstream channels for a population of CMTSs that had the configuration changed. For each five-minute time sample, the CER was classified as not degraded, degraded or severely degraded. These samples were then plotted and accumulated to understand the impact of the new modulation profile design. A similar population of CMTSs acted as experimental control and did not have the configuration changes applied over the same period of time. During the test the CNR of the channels for the configured and control population was also tracked to identify any changing network conditions that would differ between the groups. Before and after comparisons and comparisons between the experimental and control population were completed. The results were the following:

- CER Degradedness was reduced by 20% across all configured US interfaces vs. 12% experimental control
- CER degradedness for the most impacted CMD interfaces (23 MHz) was reduced 20% vs. 8.6% experimental control

Many examples were identified of improved CER, as shown in Figure 12. In these figures, after the new modulation profile configuration was changed, the CER was reduced to acceptable levels. The CCER is still showed that significant errors were occurring, and that the noise was still present in the network -- but because the errors had been corrected by the FEC, the customer experience was improved. This CCER dynamic is useful because it indicates there is still a noise source on the network that can be fixed to improve performance, but the customer experience has been much improved -- enabling network engineers to address the problems disaffecting the customer experience first.

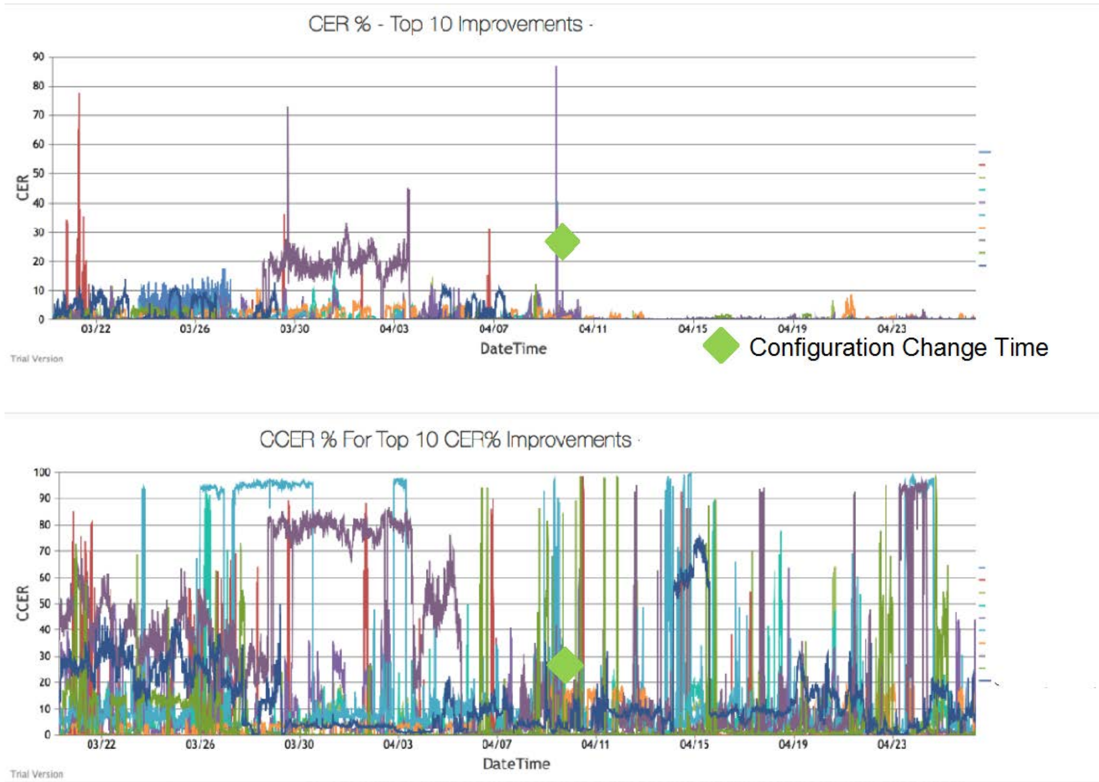

Figure 11 - CER and CCER before and after modulation profile configuration change

A simplified example is shown in Figure 12 for one of the channels where the errors are seen to be happening regularly before the change, both corrected and uncorrectable. A time frame of continuing errors over several days was occurring during the configuration change window. Even though the noise remained in the network, causing errors, the errors were all being corrected after the new profile was deployed. When the noise spikes re-occurred in the future, the CER was maintained at a low level sufficient for improved customer experience.

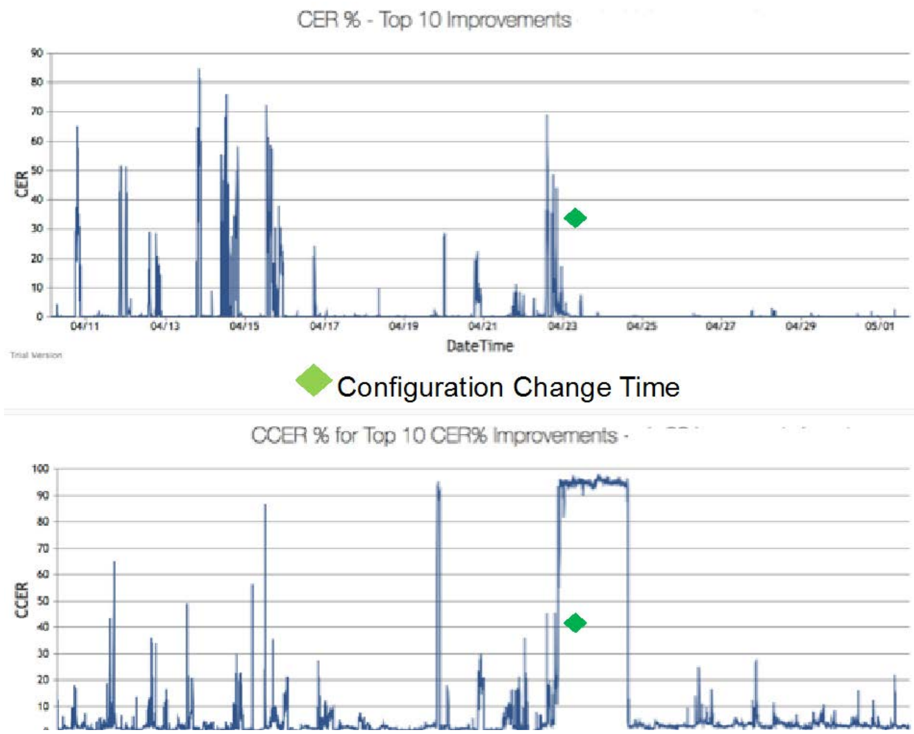

Figure 12 - Single Interface example where configuration was modified in the middle of a CMD noise event over several days

2. Data Analytics

Over the last many years, MSOs have made a quantum leap in securing real-time data about the state of their networks. Some of the data is derived from the CMTS; other data is from the CPE and CMs; yet other data comes from specialized equipment that tracks noise and other effects throughout the system. These are unofficially known as the “Sources of Truth” (SOT) for MSO analytics teams. This data is then analyzed, curated and made available to multiple teams within the organization to seek incremental improvements to the customer experience.

Within Comcast, these sets of real time telemetry data are collected and presented via several SOTs. These data sets are analyzed using advanced analytic tools and dashboards set up to test various Proofs of Concepts (POC) before rolling them out system wide as analytics tools.

The goal of the data analytics effort has been to leverage available SOTs, drill down to the MAC address level and create associations that help network engineers to understand pervasive noise impairments, necessarily separating them from transient hits that mar service, but are hard to pin down. In addition to understanding network impairments, analytics can be used to optimize network configurations and HFC physical setup metrics.

Nodes could be classified as Green, Yellow or Red in proportion to customers affected over a period of time. Such classification, based on multiple internal constructs, enables a common focus for setting up priorities. Notice that the red nodes may be so designated because of a car colliding with the telephone pole, thus taking out service -- or because of excessive transient ingress coming in and marring the customer experience.

Figure 13 is a snap shot of a Green node with three upstream (US) channels. The graph on the left is the distribution of CM TX level, and the graph on the right shows SNR distribution across the CPEs for the same three RF US channels. While this is a popular way of constructing analysis, it does not show the full story.

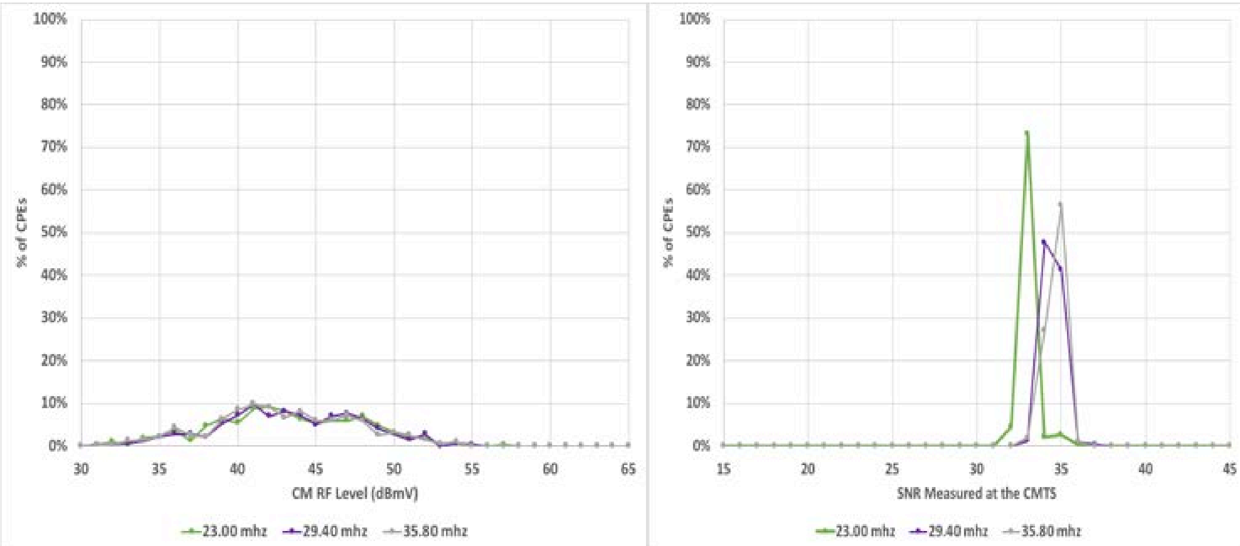

Figure 13 - Green node with 3 upstream channels

Figure 14 combines both of the above representations and shows the RF transmit level vs. SNR values, in one spot. This enables us to see that this Green node has a tight distribution of SNR across the RF levels (as expected) and points to a well-behaved node deserving of its Green designation.

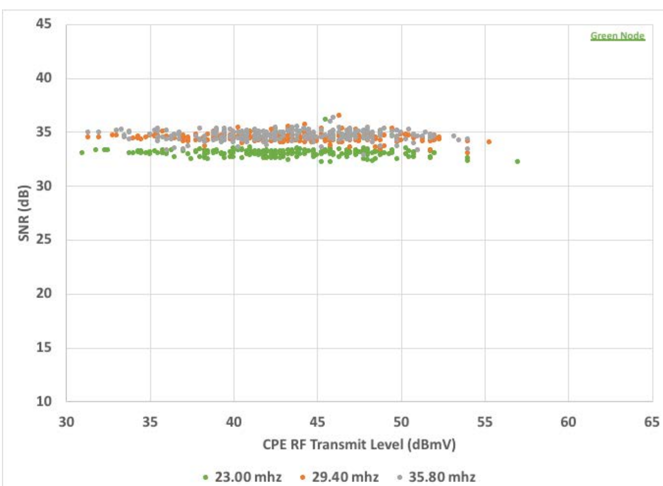

Figure 14 - Green node 3 channel SNR and TX correlation

A Yellow node, on the other hand, has a slightly wider distribution on the SNR metric, which is also reflected in the scatter plot, as shown in Figure 15.

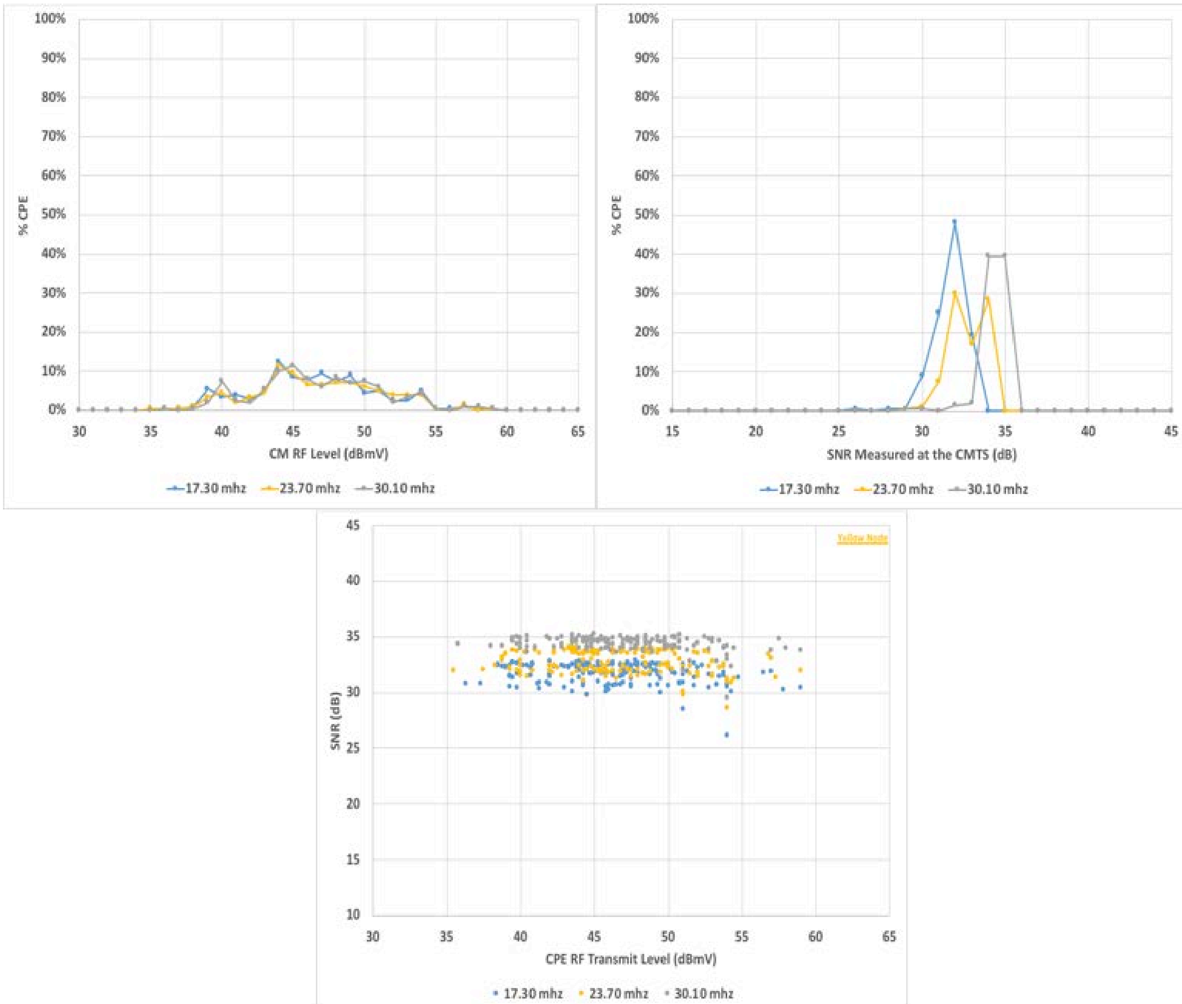

Figure 15 - Yellow Node with 3 US channels CM TX Power and SNR

A persistently wide distribution of SNR could be an indication of transient effects, which we will be able to more clearly in the next set of figures that represent a Red node. In Figure 16 the SNR is very widespread and one of the channels has a very poor SNR value, possibly impacting reliable transfer of information. A loss of code-word-errors is especially problematic for TCP/IP throughput, and is likely to impact customer experience negatively.

A look at the scatter plot indicates how profound and widespread this effect is, and gives us an indication of amounts of ingress in the system. The specific impairments on this node include the impact of the CMD discussed earlier.

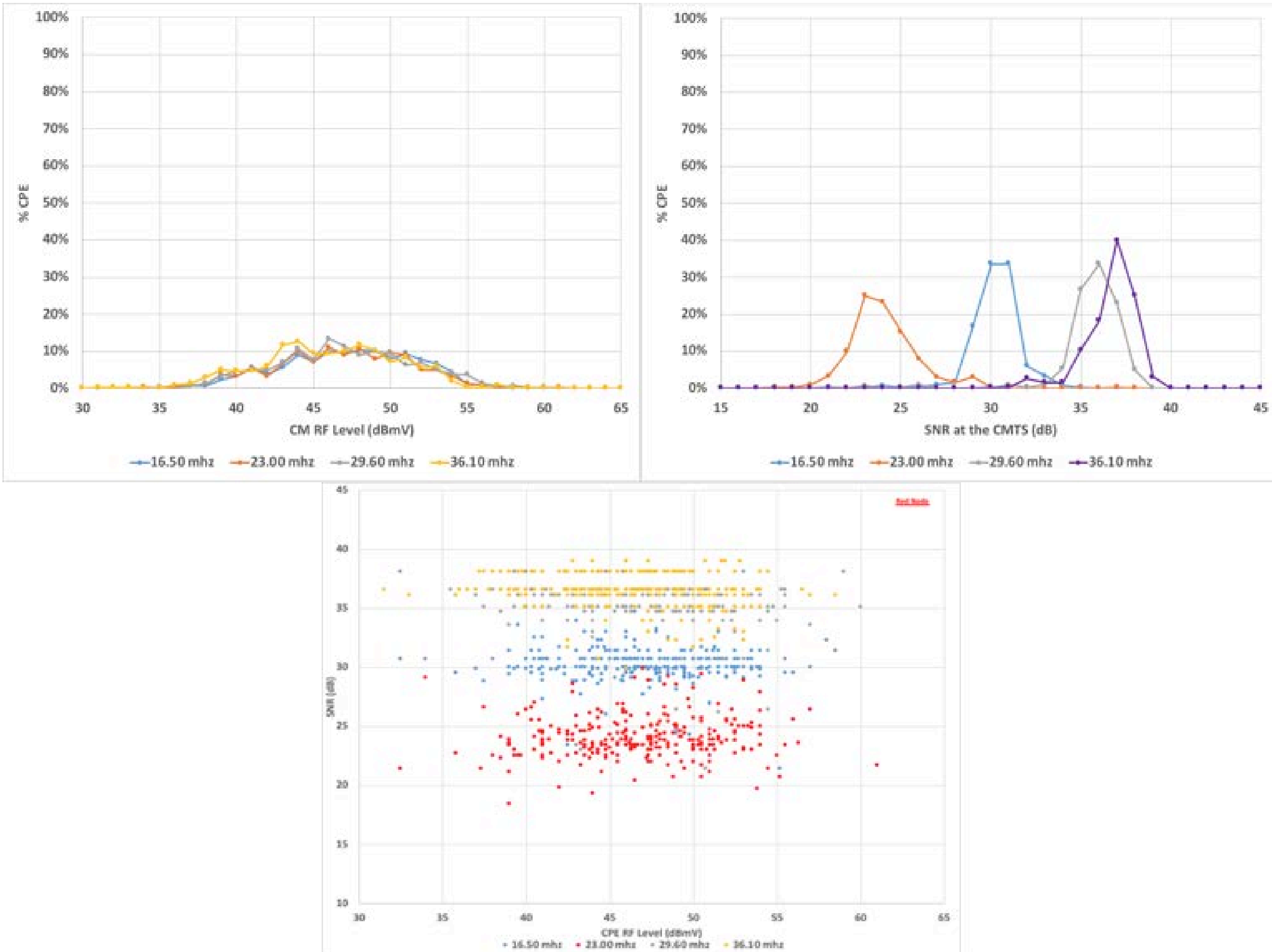

Figure 16 - Red node with 4 US channels CM TX Power and SNR

While the above analysis above is just a snapshot and has taken just three nodes into account, Comcast supports analytics for hundreds of thousands of nodes in continuous operation, spread over three divisions that pass 55M households (HHP). The challenge is to take this analysis, add additional metrics and scale it on dashboards.

2.1. Leading and Lagging Indicators

Customer experience, while vital, is a lagging indicator for our network. Rather than risk customer experience, it is important to gather sufficient metrics to understand some leading indicators, and use those to improve the customer experience before it degrades.

A preliminary form of data analysis could acquire the sets of data from multiple SOTs and arrange them so that the inter-relationships between multiple parameters is easier to project. A cross correlation matrix can be constructed as shown below in Figure 17.

US						
CM Tx	dBmV	Mean/Max/Min/SD		f1, f2, f3, f4	For each MAC address	
CM RX	dBmV	Mean/Max/Min/SD		f1, f2, f3, f4	For each MAC address	
CM MER	dB	Mean/Max/Min/SD		f1, f2, f3, f4	For each MAC address	
CM cCER	%	Mean/Max/Min/SD		f1, f2, f3, f4	For each MAC address	
CM ucCER	%	Mean/Max/Min/SD		f1, f2, f3, f4	For each MAC address	
DS						
CM MER	dB	Mean/Max/Min/SD		f1 .... fn	For each MAC address	
CM RF level	dBmV	Mean/Max/Min/SD		f1 .... fn	For each MAC address	
Mean/Max/Min/SD for each f1, f2, f3, f4 US and f1 ... fn DS across all the MACs in the Node						
Cross Correlation Matrix						
	CM Tx	CM RX	CM MER	CM cCER	CM ucCER	
CM Tx		%	%	%	%	
CM RX			%	%	%	
CM MER				%	%	
CM cCER					%	
CM ucCER						

Figure 17 - Network performance cross-correlation matrix

For example, in the above set that can be measured continuously in real time or at least several times a day, a smaller standard deviation (SD) for all the parameters across the day, or of the SD across the multiple devices, would mean a tighter control of the network. However, a tighter control of one parameter, with a relatively higher variance in other parameters would be akin to transients that would then need to be brought under control, all of these being leading indicators of network health.

Of the metrics, the relationship between MER/SNR and the CCER or CER is the most an interesting relationship to help diagnose RF problems. For one thing, acquiring CER data at the resolution of a single MAC address can be difficult to collect, especially at scale. But its relationship to the MER, if tight and well behaved, would give us great confidence of the lack of non-linearities in any part of our system. This fact can be gleaned by a cross-correlation matrix of the kind described above.

Figure 18 illustrates a preliminary example of a dashboard that could track a large number of variables, on a node-by-node basis, drilled down to the MAC addresses along with a correlation matrix:

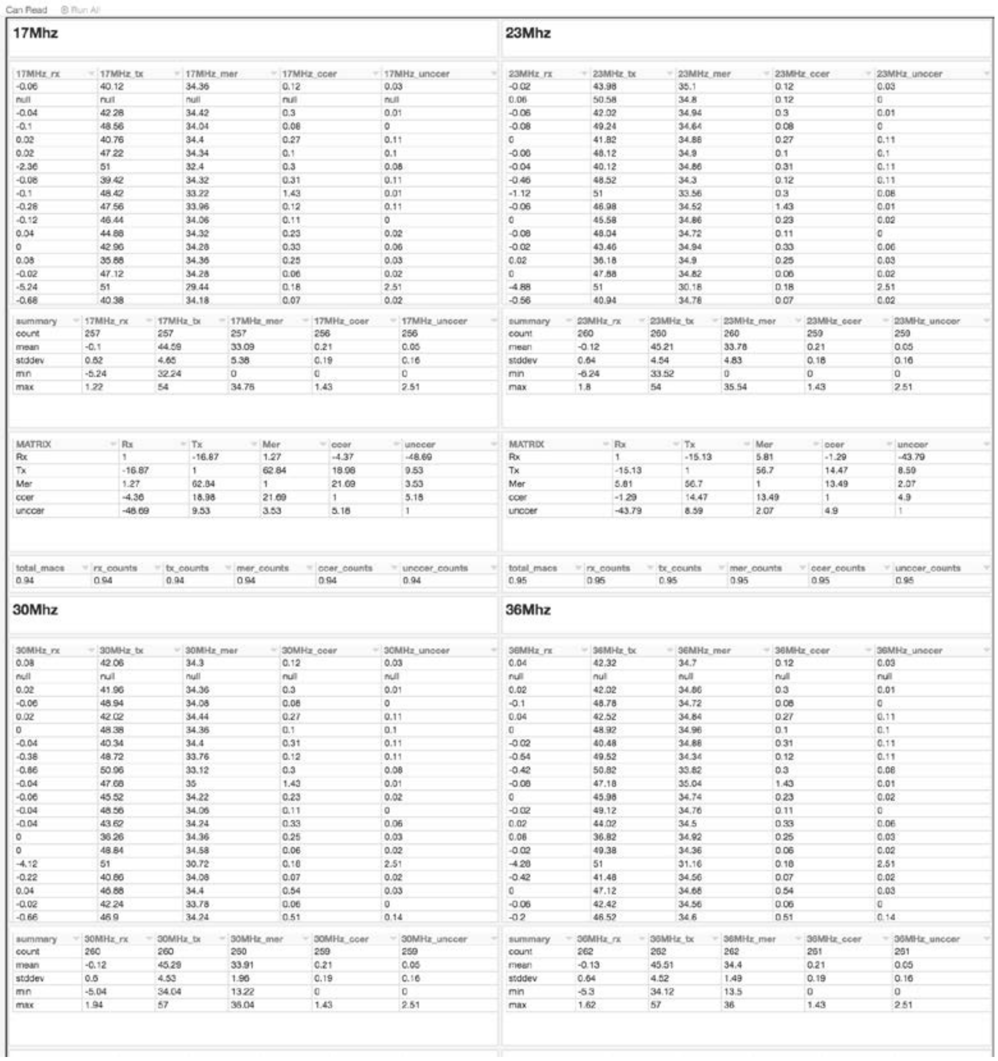

Figure 18 - Cross-correlation matrix dashboard

At the current time, various metrics of the above dashboard are available from different SOTs. An effort that consolidates information from all the diverse SOTs would establish the internal consistency of our data acquisition and also enable visibility of key leading indicators.

Conclusion

The rise of CMD noise, coincident with the rise of switched power supplies in consumer CPE and other in-home electronics, catalyzed the identification and mitigation framework described in this paper. The framework consists of:

1) Identifying operational challenges in the field, finding the root cause and characterizing the noise
2) Applying detailed lab characterizations to effectively understand the options for mitigation, which enabled the design that assuages the impacts on customer experience
3) Documenting and modeling a solution to the CMD challenge
4) Field trialing and deploying the solution and verifying its efficacy

This full cycle example of the CMD mitigation framework demonstrates an opportunity to simultaneously mitigate a network issue and enable better operational efficiencies for plant maintenance. In the example of CMD noise and advanced analytics of CM network data the customer experience was improved with increased operational efficiency.

This paper describes a discovery and development process to identify opportunities to improve network performance, develop solutions and to use data analytics to validate the improvements. This paper demonstrates that … *what gets measured gets done, and what gets analyzed gets transformed.*

Abbreviations

AC	Alternating Current
bps	bits per second
CCER	Correctable Codeword Error Ratio
CDN	Coupling Decoupling Network
CER	Uncorrectable Codeword Error Ratio
CM	Cable Modem
CMD	Common Mode Disturbance
CMTS	Cable Modem Termination System
CPE	Consumer Premise Equipment
dB	Decibel
DC	Direct Current
DOCSIS	Data over Cable Systems Interface Specification
DS	Downstream
FEC	Forward Error Correction
HFC	Hybrid Fiber-Coax
Hz	Hertz
ISBE	International Society of Broadband Experts
IUC	Interval Usage Code
LED	Light Emitting Diode
MAC	Media Access Control
MER	Modulation Error Ratio
MHz	1x10^6 Hz
PoC	Proof of Concept
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
RX	Receive
SCTE	Society of Cable Telecommunications Engineers
SIK	Self-Install-Kit
SNR	Signal to Noise Ratio
SOT	Source of Truth
STB	Set top Box
T&M	Test and Measurement
TCP	Transmission Control Protocol
TX	Transmit
UDP	User Datagram Protocol
UGS	Unsolicited Grant Service
US	Upstream

Bibliography & References

See footnotes