Hybrid Fiber Coaxial (HFC) Spectrum Efficiency and Quality

Systematically Evolving Networks using Profile Management Platform (PMA)

A Technical Paper Prepared for SCTE by

Jay Liew, Advanced Analytics Architect/Charter Communications

Table of Contents

Title **Page Number**

1. Introduction ... 3
2. Analyzing Plant Conditions ... 4
   2.1. Using data to determine network performance ... 4
3. Profile Management Application ... 6
   3.1. Determining gains and losses ... 7
   3.2. Potential gain from a live port ... 8
4. High-split Roll-off ... 9
   4.1. Initial feedback ... 9
   4.2. Utilizing OFDM channel on a high-split deployment ... 11
5. Autonoma Platform ... 11
   5.1. Data Ops ... 12
   5.2. Model Ops ... 13
6. Conclusion ... 15

Abbreviations ... 17

Bibliography & References ... 17

Acknowledgements ... 18

List of Figures

Title **Page Number**

Figure 1 – Med Var plot of Mac Domain A ... 4
Figure 2 – Med Var plot of Mac Domain B ... 4
Figure 3 – LTE impaired cable modem ... 5
Figure 4 – Cable Modem Exhibit 1 ... 7
Figure 5 – SNMP Polling Architecture ... 12
Figure 6 – Modern Streaming Telemetry Data Arthitecture ... 13

List of Tables

Title **Page Number**

Table 1 – DS RxMER to QAM Level Mapping ... 6
Table 2 – Lab Performance of Cable Modems using Flat-Configured Profiles versus Customized Profiles ... 8
Table 3 – Potential Gain/Loss comparison using profiles with non-FEC and FEC adjustment ... 9

1. Introduction

During the COVID-19 Pandemic, the surge of broadband bandwidth utilization grew 16% for downstream (DS) consumption while upstream (US) increased 33% from March to May 2020. The resiliency of the hybrid fiber-coaxial (HFC) network delivered nationwide service as subscriber demand continued to increase. As demand for broadband connectivity services continues to grow, Charter Communications and other multiple service operators (MSOs) must utilize intelligent automation (IA) driven by artificial intelligence (AI) and machine learning (ML) technology to address HFC network capacity growth and issues.

Plant upgrades such as high-split are underway and, eventually, DOCSIS 4.0. To defer the high costs of future enhancements and improve capacity, MSOs can extract maximum capacity from existing plants. They can also use this same solution and approach to augment bandwidth capacity for new deployments and network upgrades.

The HFC network is complex. Every plant is unique and requires customization to address individual plant conditions. Using Charter's network data-driven platforms, we can determine how to design, build, or evolve our network. For example, in-home modem telemetry is necessary to fix impairments in the plant. Telemetry collected from devices in the plant transmits the device's health and reports the condition of the plant.

In this paper, we'll discuss the techniques used to evaluate plant conditions and how Charter's Autonoma is used to repair them. Autonoma is one of Charter's data platforms used to standardize data and software engineering by delivering Charter's network data needs under one program and making all network data and models available companywide. Profile Management Application (PMA) is a use case running on Autonoma that aims to focus on the entire data life cycle, including:

- Streaming and data acquisition capability;
- The ability to analyze data using data engineering for governed analytics data sets with ML capability;
- An automation platform that focuses on closed-loop implementations for various use cases.

We'll also discuss optimizing spectrum usage on plants with ingress and roll-off impairments on high-split deployments.

[1] Analytics from Charter Data Technologies Group.

2. Analyzing Plant Conditions

Telemetry data determines the state of the network and provides information that's not easily detectable. Often, subscribers may not be aware of network impairments. However, the network operator must be aware of impairments in order to fix issues, ensure subscriber quality of experience, and meet subscriber expectations.

Proactive Network Management (PNM) data contains critical telemetry information for cable operators to proactively manage and mitigate plant issues. Receive modulation error ratio (RxMER) data provides the status of a subscriber's home network and describes the condition of a service group.

2.1. Using data to determine network performance

Figure 1 and **Figure 2** are sample snapshots of media access control (MAC) domains from different cable modem termination systems (CMTSes). Each dot represents a single cable modem that represents the associated median RxMER value and the variance for all subcarriers on the orthogonal frequency division multiplexing (OFDM) channel. This methodology allows operators to see the current condition of the network, which they can trend over time.

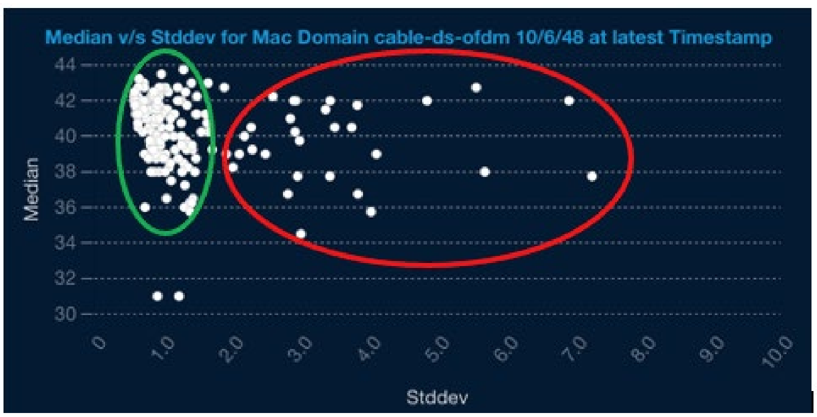

Figure 1 – Med Var plot of Mac Domain A

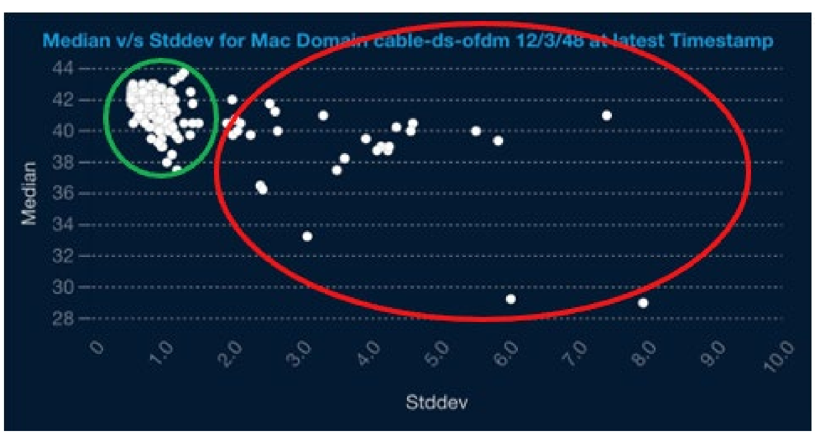

Figure 2 – Med Var plot of Mac Domain B

Using the Med Var plot observations, operators can anticipate a scatter plot pattern to be created from OFDM channels operating in the Long Term Evolution (LTE) frequencies. The OFDM channels shown in the above samples range from approximately 680 MHz to 772 MHz.

Note: This pattern is only identified on plants running on LTE interfered OFDM spectrum and may not apply to other kinds of impairment such as high-split roll-off.

The clusters in the top-left green circles in **Figures 1 and 2** denote healthy cable modems with high median RxMER and low variance. The cable modem on the bottom right denotes unhealthy cable modems that are most likely in partial service.

As the level of variance increases, the severity of impairment increases, as represented by the clusters in the red circles. Our analysis of the RxMER variance for CMs allowed us to classify the modems to a degree of impairment.

Below are our field data observations:

- Standard deviation of <1.0 dB represents cable modems with very consistent RxMER values across the channel. Cable modems lock on the highest-profile signal quality supports.
- Standard deviation of >1.0 dB and <3.0 dB represents cable modems with moderately inconsistent RxMER values across the channel. Cable modems may not be able to lock on the highest profiles.
- Standard deviation of >3.0 dB and <5.0 dB represent cable modems with highly inconsistent RxMER values across the channel. Cable modems may not be able to lock onto more than one profile.
- Standard deviation of >5.0 dB represents cable modems with extremely high inconsistent RxMER values across the channel. Cable modems will not be able to lock onto more than one profile. In many instances, cable modems will exhibit partial-service characteristics.

Most impairments from the data (680 MHz-772 MHz) are LTE-related, as portrayed in **Figure 3**. Using the RxMER data, we correlated the profile posture of cable modems from the Mac Domains. We also collected profile postures for each cable modem CMTSes in **Figures 2 and 3**.

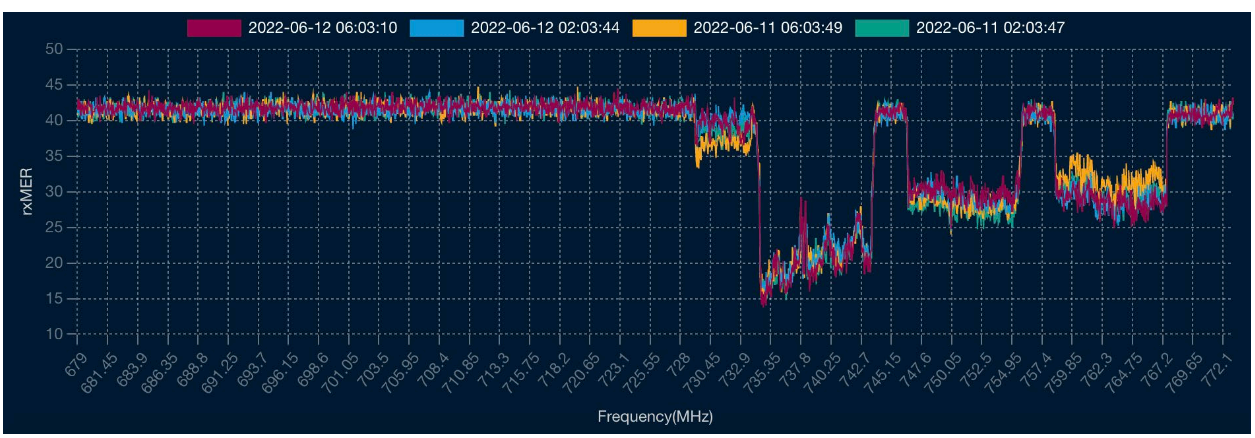

Figure 3 – LTE impaired cable modem

We configured default fixed profiles at 4096 QAM, 1024 QAM, and 256 QAM. Data from live plants indicated the dynamic nature of these profile changes was visible from the hottest to the coolest part of the day, from day to day, season to season.

3. Profile Management Application

Intelligent automation can change the configuration of the CMTS many times a day and should be evaluated to ensure minimal impact on the network. For example, a radio frequency (RF) plant can lose capacity instead of gaining capacity when using PMA profiles without considering Forward Error Correction (FEC).

The PMA software solution optimizes the use of the spectrum by automating the generation of DOCSIS 3.1 profiles and customizing profiles to the condition of the plant. Ultimately, using PMA optimized with FEC data, will enable gains in capacity.

The RxMER and bit-loading thresholds determine the profile a CM runs. The **DS RxMER to QAM Level Mapping** in **Table 1** is specified in the DOCSIS PMA Technical Report, and guides RxMER and bit-loading thresholds.

Table 1 – DS RxMER to QAM Level Mapping

Constellation / Bit loading	CNR / MER (dB)
16 QAM	15.0
64 QAM	21.0
128 QAM	24.0
256 QAM	27.0
512 QAM	30.5
1024 QAM	34.0
2048 QAM	37.0
4096 QAM	41.0
8192 QAM	46.0
1634 QAM	52.0

Using lab tests and data from Charter's network, we concluded that low-density parity check (LDPC) is highly efficient for correcting errors. Moreover, the RxMER thresholds can several dBs below the specification, as shown in Table 1, and continue to work at the highest-available profile (4096 QAM). We performed comprehensive testing in Charter's lab and verified it in production using RxMER readings and the profile posture of those devices in the network.

Figure 6 shows a cable modem with a median of 35.75 dB and a standard deviation of 1.43 dB from the latest RxMER readings. The modem exhibited profile changes from 12 to 10-bit flat profiles during the day, and the other way around in the early morning hours. The graphic also shows that LDPC can correct error packets even if the variance of the signal quality is moderate, with parts of the channel dipping below the 35.0 dB threshold.

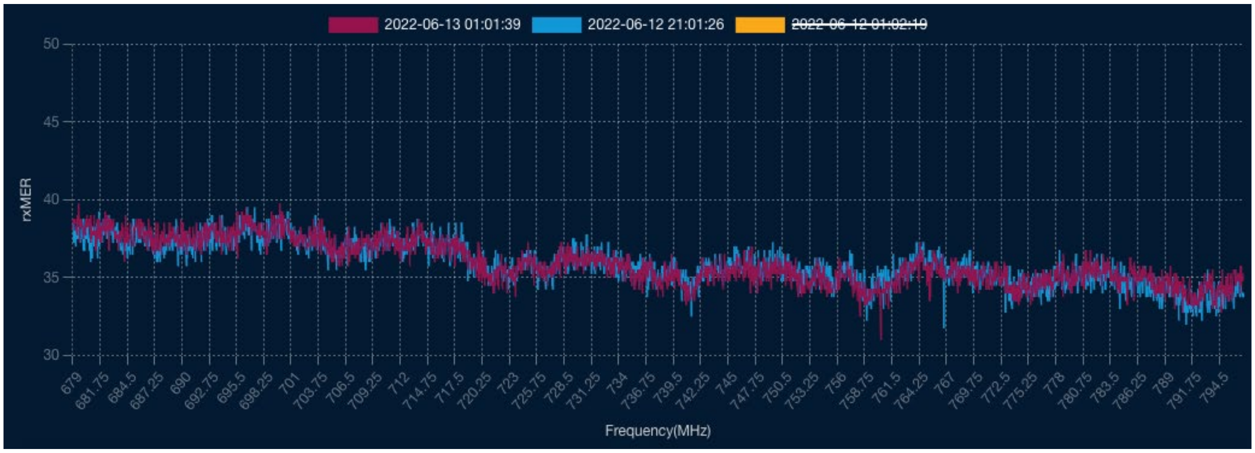

Figure 4 – Cable Modem Exhibit 1

The use of FEC to baseline RxMER relative to QAM Level Mapping is critical to maximize the gain, by calculating profiles, as aggressive as FEC can handle. Conservative RxMER to QAM Level Mapping can lead to loss of capacity in plants with relatively clean environments.

The data from CMTSes determine that 70-95% of cable modems operate on the highest bit rate of 4096 QAM at any given time. Varying conditions in the plant from day to day and hour by hour cause a disparity in performance. Unless cable modems can operate at higher bit rates, there's no capacity gain for CMs running on the highest bit-modulation available. However, capacity increases on cable modems not running at the highest bit rate.

This evidence leads us to ask the following questions:

- How many modems can be removed from partial service using customized profiles for each service group?
- How much extra capacity can be gained from cable modems not operating on the highest profile?

3.1. Determining gains and losses

We can determine cable modem speed gains and losses using PMA versus flat-configured profiles. Our configuration includes five 6-MHz, 8 bits-per-hertz, Single Carrier QAM (SCQAM) channels, and one 96 MHz-wide OFDM channel.

We injected noise into the channel spectrum on 12 cable modems, running on 12-bit profiles for our experiment. By injecting noise into the channel, we changed the 12 modems operating 12-bit profiles to three partial-service modems and changed nine modems to run on 8-bit profiles. We hypothesized the best speed gains would impact modems with partial service.

As portrayed in **Table 2**, traffic passed through the modems that used the SCQAM and OFDM channels. The impaired modems passed traffic entirely on the SCQAM channel. The PMA-generated profiles increased speed and capacity for impaired modems and modems running on lower fixed-modulation profiles.

Table 2 – Lab Performance of Cable Modems using Flat-Configured Profiles versus Customized Profiles

Cable Modems	Non-impaired		Impaired		Impaired PMA	
	Profiles **	Speed (Mbps)	Profiles **	Speed (Mbps)	Profiles ***	Speed (Mbps)
CM1	0,1,2,3	907	0,1,(2),(3)	665	0,1,2,3	836
CM2	0,1,2,3	907	(CH)0,1,2,3	175	0,(1),(2),3	655
CM3	0,1,2,3	907	0,1,(2),(3)	665	0,1,2,3	836
CM4	0,1,2,3	907	(CH)0,1,2,3	175	0,(1),(2),3	655
CM5	0,1,2,3	908	0,1,(2),(3)	665	0,1,2,3	836
CM6	0,1,2,3	907	0,1,(2),(3)	665	0,(1),2,3	811
CM7	0,1,2,3	907	0,1,(2),(3)	665	0,(1),2,3	811
CM8	0,1,2,3	903	0,1,(2),(3)	665	0,(1),2,3	811
CM9	0,1,2,3	907	(CH)0,1,2,3	175	0,(1),(2),3	655
CM10	0,1,2,3	907	0,1,(2),(3)	665	0,(1),2,3	811
CM11	0,1,2,3	907	0,1,(2),(3)	665	0,1,2,3	836
CM12	0,1,2,3	906	0,1,(2),(3)	665	0,1,2,3	836

** Flat profiles where 0 = 6 bits, 1 = 8 bits, 2 = 10 bits, 3 = 12 bits, CH = impaired

*** Customized profile where 0 = 6.26 bits, 1 = 10.76 bits, 2 = 10.38 bits, 3 = 7.63 bits

NOTE: PMA profiles generated using FEC-adjusted RxMER and bit-loading thresholds

The data also indicated cable modems removed from partial service gained an average of 7.36 bits per hertz across the OFDM channel, a capacity increase of 480 Mbps for partial-service modems. For modems running on 256 QAM, the capacity increased from 8 bits per hertz to profiles utilizing an average of 10.76 bits per hertz and 10.38 bits per hertz, gaining more than 2 bits per hertz with speeds between 146 Mbps and 171 Mbps. This change represents a significant capacity increase for cable modems operating on low-modulation profiles and partial-service modems, thereby increasing modem speed for those cable modems.

3.2. Potential gain from a live port

Actual field experience works differently from what we simulate in the lab. In the field, a more diverse set of impairments of varying degrees require classification and clustering. Using the Mac Domains in **Figure 2** (above), we calculated the gain loss potential, identified cable modems that are impaired.

The CMTS can run on four profiles with a maximum of four segments. We tested two scenarios, one without FEC and one using FEC, optimizing RxMER bit-loading thresholds.

The results are summarized in **Table 3** as follows:

Table 3 – Potential Gain/Loss comparison using profiles with non-FEC and FEC adjustment

Cable Modems (206 total)					
Flat Profile Configuration		Non FEC PMA Profile Configuration		FEC PMA Profile Configuration	
Bit Load (bits per hertz)	# CM	Bit Load (bits per hertz)	# CM	Bit Load (bits per hertz)	# CM
12	182 (88.3 %)	10.4	182 (88.3 %)	12	182 (88.3 %)
10	14 (6.76%)	10.0	2(0.9%)	11.6	8 (3.8%)
8	5 (2.4%)	7.8	18 (8.7%)	10.4	10 (4.8%)
		5.5	4 (1.9%)	7.1	6 (2.9%)
0	5 (2.4%)	0	0	0	0

When calculating PMA without FEC to adjust RxMER bit load mapping, we discovered:

- Capacity loss by 1.6 bits per hertz for CMs operating on the highest profile;
- General loss of total capacity by 14%;
- Partial-service cable modems are taken out of partial service.

When calculating PMA using FEC to adjust RxMER bit load mapping, we discovered:

- Cable modems running on the highest profiles don't lose capacity;
- Partial-service cable modems are taken out of partial service;
- Increased capacity for cable modems that are not on the highest QAM level.

4. High-split Roll-off

The path to 10G is underway. Using trials, we proved the viability of frequency-division duplexing (FDD) DOCSIS 4.0 by demonstrating the ability to deliver multi-gigabit symmetrical service. Network evolution is complex requiring expensive plant hardware configurations and upgrades, necessitating network operators to take the necessary steps to evolve the network.

4.1. Initial feedback

The **Figure 8 – (Lab) Sample Cable Modem from Cluster A** mimics a live field environment consisting of a node with a cascade of five amplifiers (1.2 GHz), with 32 passive taps (1.0 GHz), with 20 devices on five taps. The most salient pattern is the three distinct clusters (A, B, and C). The cable modem data from the RxMER data indicates the roll-off behavior is different between cable modems and can be completely different within each cluster.

A is the best performing cluster, demonstrating moderate impairment with cable modems located on the second and third amplifiers, with four-seven passive devices.

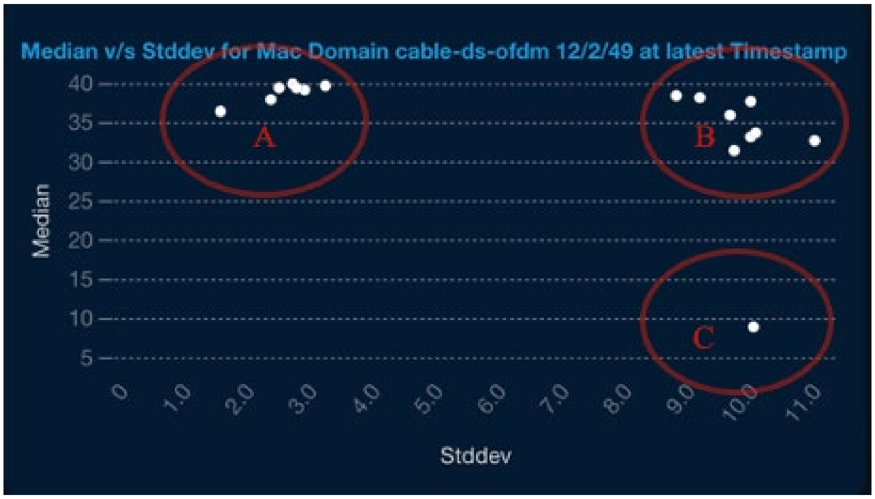

Figure 7 – (Lab) 1.0-1.2 GHz Spectrum Med Var Plot

Figure 8 is a sample cable modem from *Cluster A* in **Figure 7** and demonstrates a usable spectrum through the entire 192 MHz OFDM channel.

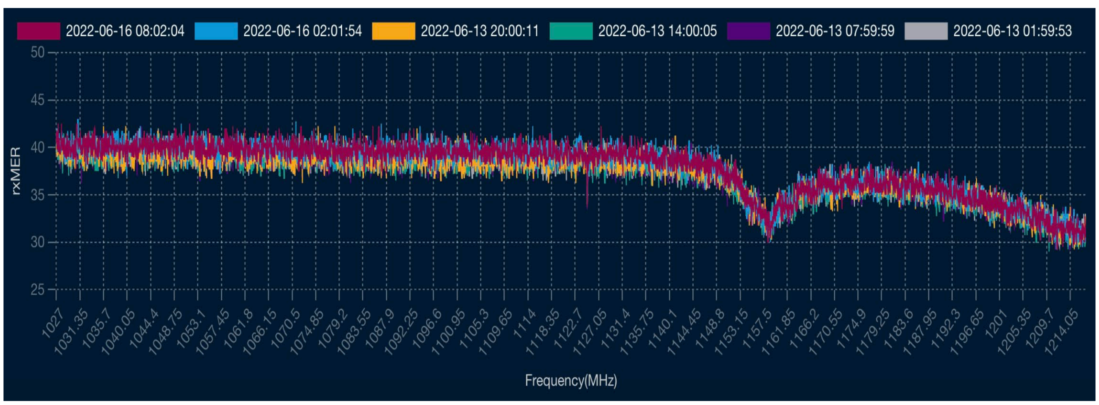

Figure 8 – (Lab) Sample Cable Modem from Cluster A

Cluster B (**Figure 7**) demonstrates extreme impairment with high median RxMER, with cable modems on the fourth amplifier with 11-13 passive devices (shown in **Figure 9**), with usable OFDM spectrum through 1.18 GHz.

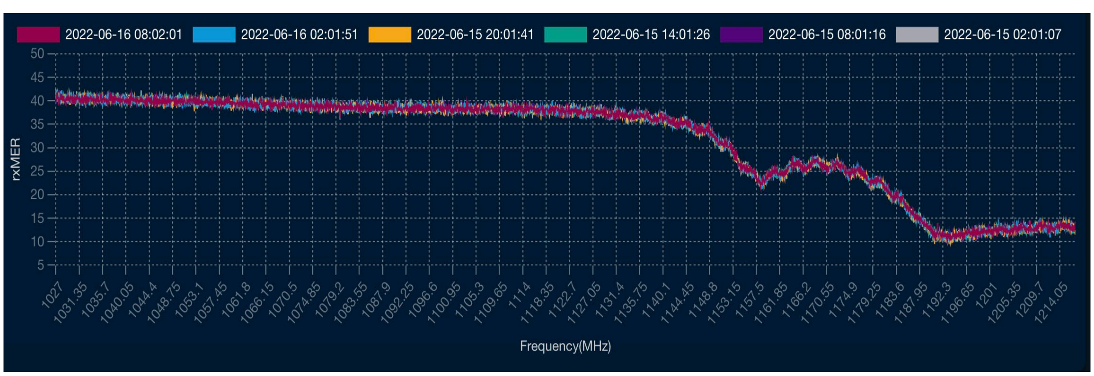

Figure 9 – (Lab) Sample Cable Modem from Cluster B

Cluster C (**Figure 7**) is a single cable modem with extremely low signal quality with extreme impairment as shown in **Figure 10**. The cable modem is on the fifth amplifier with 20 passive devices. Some cable modems deep in the network cannot report OFDM telemetry due to channels in partial service.

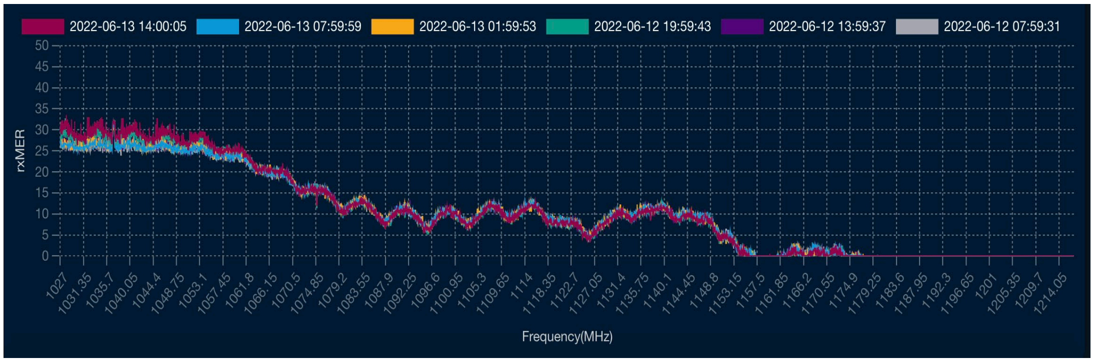

Figure 10 – (Lab) Sample Cable Modem from Cluster C

4.2. Utilizing OFDM channel on a high-split deployment

The signal quality in the Med Var charts and RxMER data from cable modems indicates variability for every modem in the service group. The deployment variance is caused by the roll-off, which is caused by the 1.0 GHz taps. This is a unique situation for how an operator can create a profile that works on the channel without sacrificing spectrum and capacity. Using this analysis, we can systematically develop a roadmap for high-split deployments as follows:

- Flat profiles don't work where the roll-off region renders higher parts of the spectrum unusable for most cable modems.
- PMA profiles must operate at 1.0-1.2 GHz to work with the roll-off region.
- Operators can incrementally upgrade plant components such as taps using PMA profiles.

To mitigate the roll-off region entirely for an OFDM channel running on 1.0-1.2 GHz, replacement of taps in the plant will be required. By using PMA we can defer the initial costs of the deployment. Using the data within our lab, we can learn and derive a systematic plan to upgrade a high-split plant. This will give us the ability to postpone upgrades and reduce the initial costs of deployments, simultaneously boosting capacity until upgrades are necessary.

5. Autonoma Platform

As mentioned earlier, PMA is running on Autonoma, that focuses on Data Ops, by building fast and reliable data pipelines, feeding Model Ops, by turning data into action. As the network continues to evolve, data has become prominent in architecting the modern network. The evolution applies to the physical access network architecture and how we design data and software. It isn't practical for large MSOs like Charter to operate approximately 5,000 CMTSes in a 54 million homes-passed footprint using traditional polling such as Simple Network Management Protocol (SNMP) or command-line interface (CLI).

There is cost associated with supplementing and accommodating polling capability and increasing the number of devices. Demand is extensive for data, since various consumers have differing requirements. It is impossible to control multiple data-polling agents, polling disparate management information bases (MIBs) at disparate frequencies during various times of the day.

5.1. Data Ops

"Growing scale and the increasing use of automation in next-generation enterprise networks require a modern, more efficient approach to network data capture and analytics" – Bo Lane, VP Global Engineering, Kudelsky Security

One of the challenges for operators is how to promptly acquire network data from devices. Two classes of data are required to operate the network:

- **Bulk data**: Telemetry data that is collected at predefined frequencies from all devices on the network;
- **Real-time polling**: Data collected from devices, on an ad-hoc basis, that identifies the devices' conditions at a particular moment.

As the network modernizes, it becomes more complicated to operate, and requires telemetry to operate the network. **Figure 11** is an example of SNMP polling architecture. As the number of devices increase, so does the complexity, and reliability decreases for bulk-data ingestion.

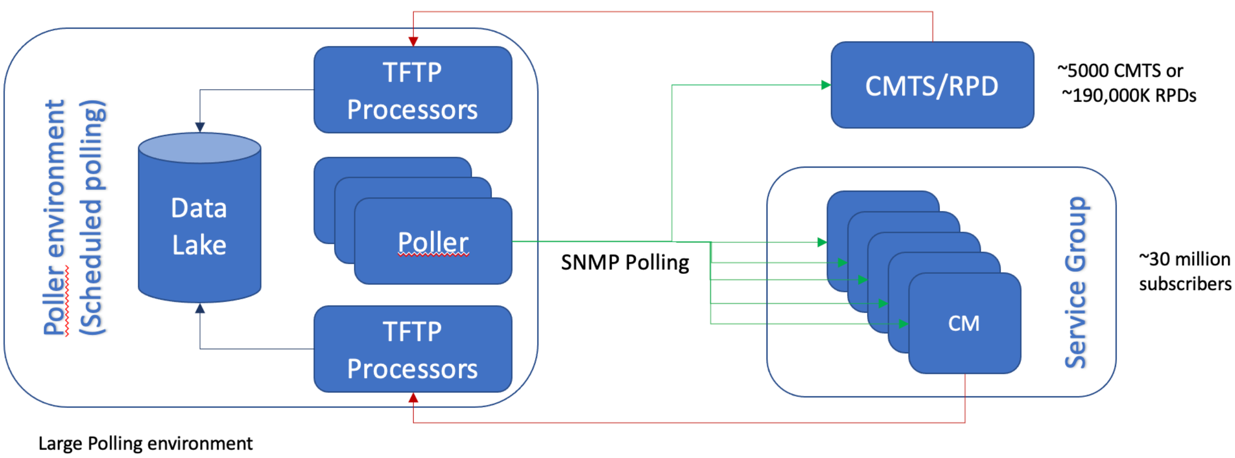

Figure 5 – SNMP Polling Architecture

Alternatives to polling methods like push-based data acquisition are becoming more relevant as real-time data becomes more critical. For example, if the signal quality for a particular channel degrades or experiences latency issues on a specific device, details of the event close to real-time are required. The responsibility to acquire data from remote polling mechanisms shift to the device to provide the telemetry at a granular level.

Figure 12 (below) illustrates a modern data architecture.

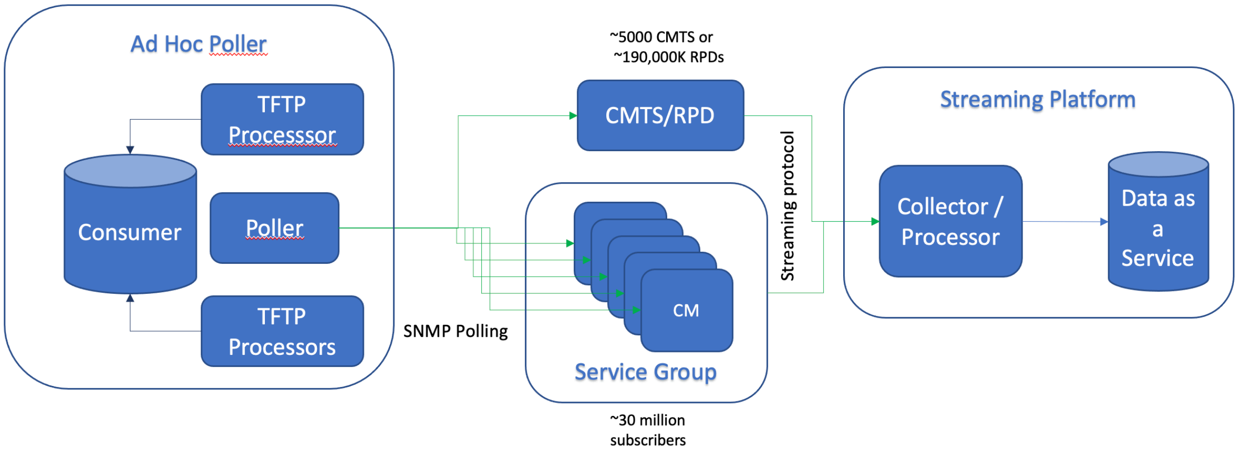

Figure 6 – Modern Streaming Telemetry Data Arthitecture

5.2. Model Ops

The DOCSIS 3.1 PHY specification provides many capabilities to gather telemetry data to conduct PNM. RxMER, a signal-to-noise ratio, is one of the most helpful signals for diagnosing the condition of individual modems on the Charter network. RxMER provides measurements for each subcarrier in the OFDM (downstream) or OFDMA (upstream) channel. We can determine the quality of the signal subscribers receive, including a range of potential impairments that can impact service experience, by analyzing the data's level, shape, and spread.

Some of these impairments, shown in **Figure 13**, include conditions such as:

- **Amplitude Ripple:** Caused by improper network alignment, micro-reflections, or missing end-of-line terminators;
- **Suckout:** Caused by unterminated cable, smashed cable, or repeating divets;
- **LTE Ingress:** Caused by signal leakage (the passage of an outside signal into a coax cable), which can be remediated using Exclusion Bands;
- **Roll-off:** A result of improper balancing, bad amplifiers, or exceeding amplifier specification;
- **Standing Wave:** Can be used to determine the distance to a fault and is the initial premise behind PNM.

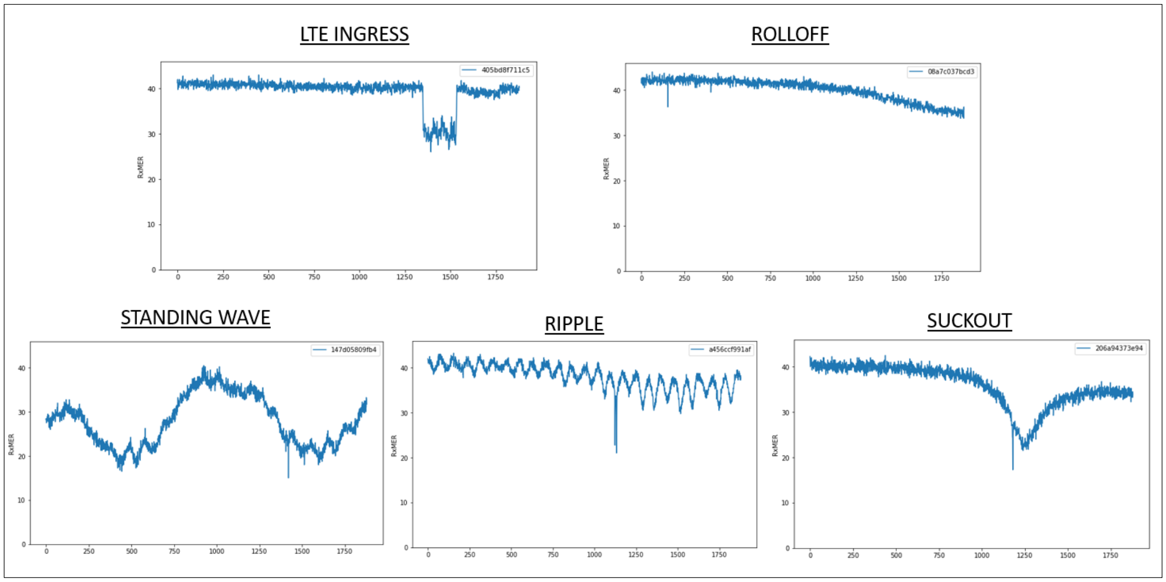

Figure 13 – Impairment Classifications

The classification impairments can identify potential network faults with a known solution. Using the data patterns, we can score and rank-order potential candidates to resolve issues in the field. The challenge is these patterns aren't self-evident, and manually reviewing the available data can be difficult and time-consuming.

We leveraged heuristics and unsupervised learning using AI and ML methods to acquire sufficient sample impairments. Paired with subject-matter-expert consultation, we provided a suitable training set for supervised machine-learning model development.

Using ML, we can monitor data signals 24x7x365, automatically identifying and classifying various impairment types. We can also detect if several modems are displaying the same impairment—a clear indication of an outside plant (OSP) issue—to isolate the impact in homes versus OSPs using clustering and nearest-neighbor modeling, illustrated **Figure 14** (below).

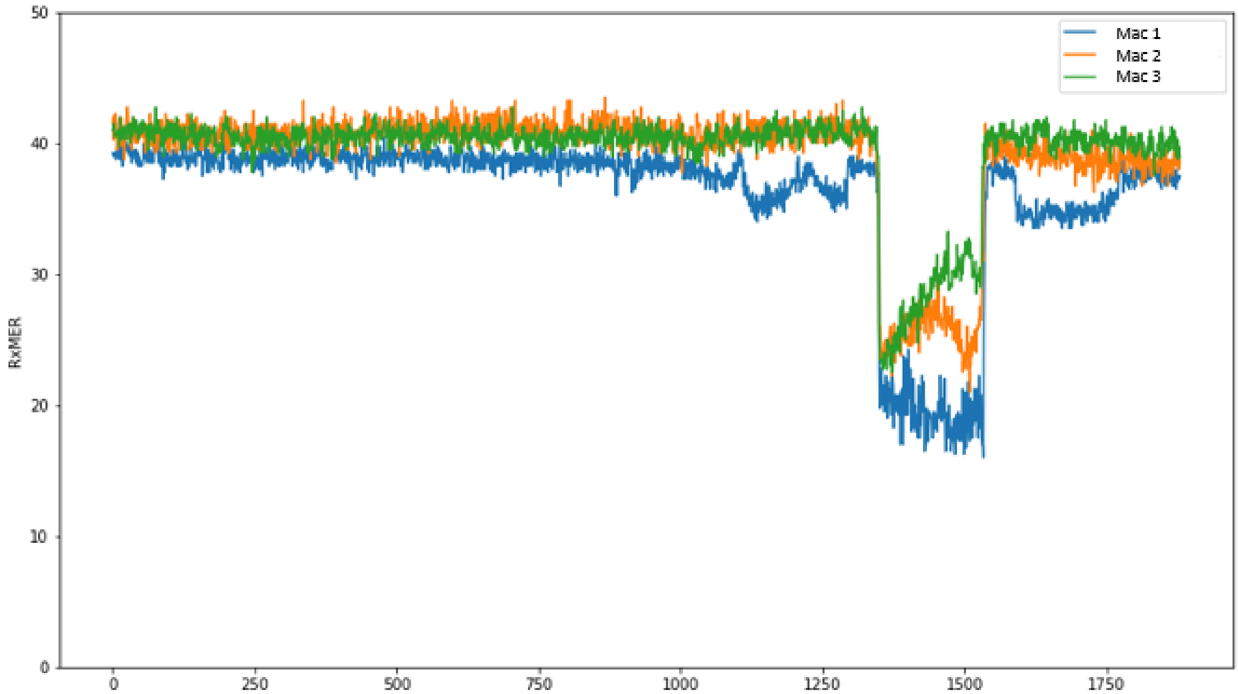

Figure 14 – ML Nearest-neighbor Algorithm Identifying a Cluster of Impairments

6. Conclusion

As the HFC network changes, data is necessary for the evolution of the network. Furthermore, we can use data to determine how and when to make changes to the network.

Software solutions are cost-effective ways to troubleshoot and address impairment issues in the plant. While software solutions may not solve plant issues, they provide time for operators to address issues without immediately sending a technician to a site.

PNM data allows the operator to assess plant conditions in real time by the subscriber, service group, CMTS, and region. We can use various methods to understand a service group. For example, we can learn traits from a collection of devices using clustering. PMA also allows operators to fix impaired cable plants.

We tested plants with LTE Ingress impairments and determined adjustments to the RxMER and QAM-level mappings were required. Our findings are as follows:

- RxMER and QAM-level mappings that are too conservative will result in a capacity loss on the OFDM channel, and FEC is needed to optimize PMA Engine;
- We optimized RxMER and QAM-level mappings for maximum capacity gain;
- Optimizing PMA can gain 30-40% (aggregate capacity) for cable modems not operating on the highest QAM level;
- 3-5% capacity gain for the overall channel;
- We removed cable modems from partial service using PMA;
- Cable modems operated at higher QAM levels when using PMA.

PMA can assist with transitions such as high-split deployments. Our lab-simulated plant indicated a relationship between signal quality, the amplifier, and tap cascades. We based the following assumptions on plants with 1.2 GHz amplifiers working with 1.0 GHz taps, with the cable modem spectrum exhibiting roll-off:

- Fixed modulation profiles don't work on high-split deployments because of spectrum roll-off;
- Dynamic profiles are required to direct spectrum roll-off to utilize a 1.0-1.2 GHz spectrum;
- PMA provides operators the ability to use a 1.0-1.2 GHz spectrum based on the subcarrier RxMER;
- PMA allows operators to strategically execute plant upgrades.

The evolution of modern networks requires ML to process the increasing volume of data and the number of data sets from devices which include:

- Transitioning from pull-based polling methods (e.g., SNMP) for bulk data collection;
- Modernizing bulk data collection using push-based methods, such as gRPC network management interface (gNMI), message queueing telemetry transport (MQTT), Kafka, and other stream-based protocols;
- Only using pull-based polling methods, such as SNMP, for limited, ad-hoc situations.

Machine learning is vital for how networks operate in the future, including:

- Leveraging heuristics and ML to get an adequate number of sample impairments to develop and train models;
- Data-signal monitoring on a 24x7x365 basis to automatically identify and classify various impairment types;
- Clustering classified impairments and using nearest-neighbor modeling to localize impairments.

Abbreviations

AP	Access Point
CLI	Command Line Interface
CM	Cable Modem
CMTS	Cable Modem Termination Service
DS	Downstream
FEC	Forward Error Correction
GHz	Gigahertz
gNMI	gRPC Network Management Interface
gRPC	Google Remote Procedure Call
HFC	Hybrid Fiber Coax
bps	Megabits per second
MHz	Megahertz
MSO	Multiple System Operator
LDPC	Low Density Parity Check
LTE	Long Term Evolution
QAM	Quadrature Amplitude Modulation
OFDM(A)	Orthogonal Frequency Division Multiplexing (Access)
OSP	Outside Plant
PMA	Profile Management Application
PNM	Proactive Network Management
RxMER	Receive Modulation Error Ratio
SCQAM	Single Carrier QAM
SCTE	Society of Cable Telecommunications Engineers
SNMP	Simple Network Management Protocol
SNR	Signal Noise Ratio
US	Upstream

Bibliography & References

Data-Over-Cable Service Interface Specifications Technical Reports. DOCSIS 3.1 Profile Management Application Technical Report. CM-TR-PMA-V01-180530 (May 30, 2018)

Diana Goovaerts, *Charter hits 8.5 Gbps in DOCSIS 4.0 test with Vecima*: Fierce Telecom, January 6, 2022.

John Edwards, *Streaming telemetry challenges SNMP in large, complex networks*: Network World, September 29, 2020.

Acknowledgements

The research and analysis as discussed in this paper would not have been possible without the work of Charter's Network Technology Group and Data Technologies group, including:

Roger Stafford, Principal Engineer, Access Network Architect, Network Technology Group
Vinod Dani, Principal Engineer, Access Network Architect, Network Technology Group
Derik Johnson, Principal Data Scientist, Data Technologies Group
Karl Harrison, Principal Engineer, Access Network Architect, Network Technology Group
Justin Stiles, Principal Engineer, Access Network Architect, Network Technology Group
Diana Linton, Network Engineer, Access Network Architect, Network Technology Group

