Understanding The Challenges of DOCSIS Proactive Network Maintenance

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1. Introduction

DOCSIS® Proactive Network Maintenance (PNM) is crucial for cable operators to enhance network performance and reliability. By monitoring and analyzing data from network devices, PNM can detect issues early, improving service quality and subscriber satisfaction. Despite its benefits, PNM faces challenges that limit its effectiveness.

Developed over a decade ago, PNM reduces maintenance costs and service disruptions. It enables both proactive and efficient reactive repairs, enhancing performance measures and key performance indicators. PNM data supports proactive repair planning, minimizing costs and customer impact, and streamlines reactive repairs by pinpointing faults. Additionally, PNM queries and tests provide insights for continuous improvement in service and network performance. As PNM evolves, its impact on network operations grows, ensuring its importance in cable network operations.

However, operators encounter challenges in implementing and expanding PNM operations. These include data overload, ineffective reporting structures, inefficient processes, and non-standard vendor implementations. Data overload complicates processing and analysis, obscuring actionable insights and hindering timely decision-making. Ineffective reporting structures make it difficult to optimize the network, while inefficient processes delay issue resolution. Non-standard vendor implementations cause interoperability issues.

This paper analyzes these challenges and their impact on network management, using real-world examples and case studies. It offers recommendations and solutions for optimization, helping operators enhance PNM effectiveness and improve network performance and subscriber experience. While non-compliance with PNM telemetry reporting standards is known, this paper focuses on managing the data once it is available. The PNM Working Group (PNM-WG) at CableLabs has been working to define PNM use cases, and this paper addresses how to utilize the data effectively once it is obtained, akin to determining once the dog catches the car, what does the dog do?

2. Current Approaches

Currently in DOCSIS PNM operations, two approaches are typically leveraged. This section will delve into both, illuminating their possibilities and flaws.

2.1. Conventional Approach

Conventional DOCSIS data strategies for PNM focus on pre-emptively identifying and addressing issues to ensure high reliability and performance. Key strategies include threshold-based alerts, where operators set fixed thresholds for metrics like signal levels, signal to noise ratio (SNR), and modulation error ratio (MER), triggering alerts for timely intervention. Trend and historical analysis involves collecting and analyzing data to identify long-term patterns and deviations, allowing operators to spot emerging issues early. Anomaly detection uses statistical methods to identify irregularities, while correlation analysis examines relationships between metrics to pinpoint root causes. Predictive analytics forecast potential problems based on historical trends, enabling scheduled preventive maintenance. Regular audits and preventive maintenance, along with customer experience monitoring, ensure ongoing network health and prioritize maintenance activities based on service quality metrics and customer feedback.

The current approach to DOCSIS® Proactive Network Maintenance (PNM) focuses on a few key strategies to keep the network running smoothly. First, fixed thresholds are set for important metrics like signal levels, signal-to-noise ratio (SNR), and modulation error ratio (MER). When these metrics go outside their set limits, alerts are triggered so operators can address issues before they become serious. Second, by analyzing long-term data, operators can identify patterns and trends, and establish normal performance baselines, which make it easier to spot potential problems early. Lastly, regular audits and scheduled maintenance are conducted to catch and fix issues proactively, helping to prevent unexpected failures. These combined efforts help ensure consistent and reliable network performance.

2.1.1. Flaws and Consequences of the Conventional Approach

The conventional approach to using DOCSIS data for proactive network maintenance has several significant flaws. Fixed thresholds for critical metrics often fail to account for dynamic network conditions, resulting in false positives and negatives that can overwhelm operators with unnecessary alerts and obscure important issues. The vast amount of data generated can lead to data overload, complicating the prioritization of insights and slowing decision-making. Inconsistent data quality, due to factors like noise and interference, further hampers accurate analysis. Additionally, the approach is often reactive, identifying issues only after they impact the network, leading to delayed responses and prolonged disruptions. The need for constant monitoring and manual intervention is resource-intensive, prone to human error, and incurs high operational costs. Scalability is also a challenge, as traditional methods struggle to handle the growing complexity of networks and adapt to new data types and technologies.

2.1.1.1. Known Consequences

The flaws in the conventional approach have several known consequences. Fixed thresholds can lead to false positives and negatives, triggering unnecessary alarms or missing real issues, particularly when network conditions fluctuate. Data overload results in analysis paralysis, where the sheer volume of data slows down decision-making and leads to the potential overlooking of critical signals. Inconsistent data quality can result in inaccurate conclusions, as variability in reporting and issues like noise and interference distort the data. Reactive management leads to delayed identification of issues, prolonging downtime and service degradation. The resource-intensive nature of the approach increases operational costs, and the lack of scalability and adaptability limits the effectiveness of network maintenance as the network grows and evolves.

2.1.1.2. Unintended Consequences

The conventional approach also leads to several unintended consequences. Operations teams can become overloaded with continuous alerts from fixed threshold breaches, leading to alert fatigue and the potential ignoring of critical issues. Excessive focus on monitoring and troubleshooting diverts resources from proactive improvements and innovation. The failure to leverage advanced analytics means missed opportunities for deeper insights and predictive capabilities, and valuable data might be underutilized, leading to missed opportunities for network optimization and enhanced service quality. Finally, delayed issue identification can degrade service quality, negatively impacting customer experience and satisfaction, and misidentification of issues can lead to inefficient resource allocation, such as sending technicians to non-existent problems or overlooking areas that need immediate attention.

2.2. Statistical Analysis Approach

Statistical analysis of DOCSIS data significantly improves network management by tracking key metrics such as signal levels, SNR, MER, error rates, throughput, latency, and packet loss. This approach enables operators to monitor performance, establish baselines, and identify anomalies that trigger alerts when thresholds are breached. Long-term trend analysis helps understand network evolution, plan improvements, and manage peak usage times. Predictive maintenance is enhanced through regression models and time series analysis, which forecast component failures, enabling proactive repairs and reducing downtime. Analyzing network usage data supports capacity planning to meet demand during high-usage periods, while Quality of Service (QoS) optimization detects early signs of service degradation, allowing for efficient resource allocation.

Root cause analysis uses correlation techniques to identify relationships between metrics and pinpoint causes of network issues, leading to targeted interventions. This improves customer experience by prioritizing repairs based on service impact. Regular analysis and reporting ensure regulatory compliance and provide performance insights to stakeholders. Techniques like descriptive statistics, moving averages, regression analysis, and anomaly detection help summarize data, identify trends, predict performance, and detect outliers. Overall, statistical analysis enables proactive DOCSIS network management, ensuring reliability, efficiency, and high service quality. Additionally, by simplifying complex data into actionable insights through steps like data collection, anomaly detection, and predictive modeling, operators can more effectively monitor, predict, and address network issues. Visualization tools like real-time dashboards and heat maps further aid in managing and optimizing network performance.

2.2.1. Flaws with the Statistical Analysis Approach.

Applying statistical analysis to raw DOCSIS data is prone to several inherent flaws due to the complexity of the data, variability in network conditions, and limitations in statistical methods. High variability and noise in the data can lead to false alarms, as temporary fluctuations in signal levels caused by environmental factors or network congestion might be misinterpreted as persistent issues. The lack of contextual understanding means that significant drops in metrics like SNR, which could be due to known maintenance activities or weather-related issues, may be incorrectly flagged as critical problems. Complex interdependencies within DOCSIS networks can lead to misdiagnoses, as statistical correlations may not accurately reflect causation, resulting in inappropriate fixes. Threshold-based triggers may not account for acceptable variations under different network loads, causing unnecessary alerts during peak usage times. Additionally, analyzing small, unrepresentative samples can lead to decisions that do not effectively improve overall network performance. Temporal misalignment in statistical analysis may cause intermittent issues or time-specific problems to be missed, leaving critical issues unresolved and customers dissatisfied.

2.2.2. Inaccuracies and False Positives

Inaccuracies:

- **Misinterpretation of Normal Variability**: Statistical methods might incorrectly flag normal fluctuations in signal levels as significant issues, mistaking regular variability for faults.
- **Aggregation Bias**: Averaging metrics across the network can conceal localized issues, leading to an inaccurate assessment of overall network health.

False Positives:

- **Routine Maintenance**: Maintenance activities may temporarily spike error rates or cause signal drops, which could be wrongly identified as critical network issues by statistical analysis.
- **Environmental Interference**: External factors, such as weather conditions or nearby electronic devices, can temporarily impact network metrics, leading to false alarms if not properly contextualized.

These flaws highlight the potential pitfalls of misusing statistical methods in network analysis.

3. Challenges

This section will provide an overview of the key challenges faced in the implementation of PNM. Despite the proven benefits of PNM, operators encounter significant obstacles that hinder its full potential. By understanding these challenges, we can better appreciate the complexities involved in maintaining and improving network performance, paving the way for targeted solutions and enhancements.

3.1. Data

PNM data is used for more than maintenance, and certainly for more than proactive maintenance. Because this data informs the urgency of repair actions, so that operators can prioritize their work appropriately, it feeds all repair operations, and the decisions that must be made around network operations. Network operators need these data for management reporting, performance monitoring, service assurance, and even planning and engineering. With all these uses, the collected data are joined with other data, then models developed and applied to provide measures of performance and effectiveness, and key performance indicators created from that. The result is a great expansion of the telemetry into multiple forms of the information. All these uses drive operators to collect and store a lot of data, all of which needs to be well organized and feed tools, measures of performance, and key performance indicators, expanding the data burden further.

Operators have mostly chosen to manage PNM data using a common collection framework, much like the solution created by CableLabs, to reduce the burden of data collection on the network. While that addressed one important pain point for operators, it brought efficient delivery of data to the data lake. More data increased the next challenge: organizing these data for use.

Continuous improvement means continuous work to improve and update the automation that feeds these network operations needs. That takes resources: experts in networking and data analysis, data storage, and computation.

3.1.1. Data Overload

Difficulty in Data Filtering
Data overload is a significant challenge in PNM systems due to the vast amounts of data generated from various network devices, such as signal levels and error rates. Operators often struggle to process and analyze these complex data streams, which are collected at different frequencies and intervals from diverse network components. This complexity makes it difficult to filter out irrelevant noise and identify meaningful insights, crucial for PNM. Additionally, real-time analysis of such large data volumes strains computational resources, introducing latency and the risk of errors, such as false positives and negatives, that undermine confidence in the system.

Resource Constraints
PNM systems face significant resource constraints, including the need for substantial computational power to analyze large data volumes in real-time. The introduction of OFDM and OFDMA channels further escalates processing requirements, necessitating scalable computational infrastructure, which can be financially challenging, especially for smaller providers. Moreover, effectively analyzing PNM data requires skilled personnel with expertise in data science, statistics, and network engineering, adding to the resource burden. Budgetary constraints also play a role, as both capital expenditures for infrastructure and ongoing operational expenses, such as maintenance and software licensing fees, can strain operators' finances. Inefficient resource utilization further risks underutilization of expensive assets, leading to inefficiencies and missed opportunities for network optimization.

Impact on Decision Making
The overwhelming volume and complexity of data in PNM systems significantly hinder decision-making for network operators. Identifying critical issues becomes challenging, leading to delays in response times and exacerbating network disruptions, ultimately degrading service quality. Without robust filtering mechanisms, distinguishing actionable intelligence from noise is difficult, complicating the interpretation of data and extraction of meaningful insights. Addressing data overload is essential for improving decision-making and ensuring timely resolution of network issues in PNM operations.

3.1.2. Missing Data

Missing or unavailable data significantly undermines the effectiveness and reliability of a PNM operation. Proactive maintenance relies on comprehensive and accurate data to predict and address potential issues before they affect network performance. When key data is missing, critical aspects of network maintenance are compromised. Incomplete data can lead to inaccurate assessments of network health, misdirecting maintenance efforts and wasting resources. Missing metrics such as signal levels and error rates obscure network performance visibility, leading to undetected issues that can escalate into major disruptions. The absence of historical data hinders trend analysis and anomaly detection, preventing proactive problem identification. Ensuring that all necessary data, such as network topology and geo-location of elements, are complete and up to date is essential for the success of any proactive network maintenance strategy.

These missing data points severely limit the set of algorithms, techniques, and processes available for analysis, leading to several key issues:

- **Incomplete Network Picture**: Without a complete network topology, it becomes difficult to accurately map the network and understand the interconnections and dependencies between various elements.

- **Geographical Challenges**: Lacking geo-location data for network elements can impede the ability to localize issues accurately and efficiently.

- **Customer Connection Details**: Entry point documentation is crucial for understanding where and how customers are connected to the network.

- **Limited Analytical Capabilities**: The absence of critical data restricts the use of advanced algorithms and techniques, such as machine learning models, which rely on comprehensive datasets for training and accuracy.

- **Ineffective Troubleshooting**: Missing data can lead to ineffective troubleshooting and prolonged resolution times, as network operators may have to rely on incomplete information to diagnose and address issues.

3.1.3. Ineffective Reporting

Effective reporting is crucial for PNM operations, as it enables operators to monitor network performance, diagnose issues, and make informed maintenance decisions. Timely and accurate reports offer insights into key performance metrics, helping to identify emerging issues and prioritize resources for proactive maintenance. However, ineffective reporting can delay issue detection, hinder root cause analysis, overlook subtle performance trends, lead to inefficient resource allocation, and complicate performance benchmarking.

One significant challenge in reporting is the lack of actionable insights. While PNM systems generate vast amounts of data on signal levels, error rates, and other metrics, operators may struggle to distill this data into meaningful insights due to its volume and complexity. Poor data visualization further exacerbates this issue, as convoluted presentations can hinder operators' ability to identify trends and anomalies. Additionally, limited customization options in reporting tools may result in reports that do not align with operators' specific needs, leading to the inclusion of irrelevant information.

Inconsistent reporting practices across different teams or departments can also undermine the accuracy and reliability of data, making it difficult to compare performance across various network segments or time periods. Reports that lack historical context may fail to provide insights into long-term performance patterns, potentially missing root causes of issues or future challenges. Finally, insufficient integration with decision-making processes can limit the utility of reports, as reports not integrated with operational workflows may lead to delays or oversights in addressing network issues.

3.1.4. Inadequate Data Comprehension

A lack of proper understanding of DOCSIS data can significantly impair the effectiveness of a PNM operation in several ways:

- Misinterpretation of Metrics: Without a deep understanding of DOCSIS data, operators may misinterpret key metrics such as signal levels, SNR, MER etc. This can lead to incorrect assessments of network health and potentially overlook emerging issues.
- Inaccurate Diagnosis: The inability to accurately interpret DOCSIS data can result in misdiagnosing the root causes of network issues. For example, a problem that appears to be related to signal degradation might actually stem from interference or hardware faults. Incorrect diagnoses can delay effective interventions and prolong service disruptions.
- Delayed Response: Misunderstood data can lead to delays in identifying and responding to network anomalies. Operators may struggle to prioritize issues effectively, causing critical problems to escalate before they are addressed. This can degrade service quality and lead to increased customer dissatisfaction.
- Ineffective Decision-Making: Inaccurate or incomplete data interpretation hampers decision-making processes. Operators may make decisions based on incorrect assumptions or incomplete information, leading to suboptimal maintenance strategies and resource allocation.
- Resource Wastage: A lack of proper understanding can result in inefficient use of resources. For instance, operators might allocate resources to address perceived issues that are not actual problems, while real issues remain unresolved. This not only wastes time and effort but also increases operational costs.
- Failure to Leverage Advanced Techniques: Advanced analytical techniques and predictive maintenance rely on accurate and comprehensive data interpretation. Without a proper understanding of DOCSIS data, operators may be unable to implement these techniques effectively, missing out on opportunities for proactive and predictive maintenance.
- Impact on Customer Experience: Ultimately, a poor understanding of DOCSIS data can lead to a decline in network performance and service quality, negatively impacting customer experience. Increased service disruptions, slower issue resolution, and inconsistent service quality can result in higher customer churn and a damaged reputation for the service provider.

3.2. Hardware/Software Limitations

3.2.1. Non-Standard Vendor Implementation

The CableLabs PNM-WG recently published five use cases meant to address some of the challenges relating to non-standard vendor implementations and lack of reliable data delivery.

- Pre-equalization data for OFDMA - the importance and use of pre-equalization data with OFDMA is an emerging concern so support by vendors is imperative.
- RxMER data for OFDMA - Upstream RxMER per subcarrier at the CM level is necessary for upstream profile management, but also is a very important tool for localizing faults in the network.
- Smart amplifier telemetry - smart amplifiers are being deployed and need to have transponders for control; they are also at important locations in the network that can enable better localization and fault identification if instrumented with PNM tests such as spectrum capture, and ability to separately collect data from network branches.
- Telemetry data transfer - large amounts of data are needed for localizing faults or monitoring the network, and modern methods for streaming or obtaining bulk data are necessary for PNM. This use case explains the value and way the data are used so that vendors know what to support in their systems.
- Upstream triggered spectrum capture data - this capability is most important for troubleshooting in the upstream network. RPHY[1] nodes have really come through with data delivery, but the various triggering modes are still lacking in deployment, so there is work yet to do.

Modern data delivery mechanisms are emerging, and the PNM use cases that use them are now being proven in the field. As a result, operators are beginning to see and take full advantage of PNM in many cases, but not all. There continues to be deployed solutions that can't address the important use cases defined for PNM. As a result, some challenges remain until better alignment around the specifications is achieved.

3.3. Process

Processes within PNM operations play a crucial role in ensuring the effective management, monitoring, and optimization of network performance. These processes encompass various activities, including data collection, analysis, decision-making, and action implementation, aimed at identifying and addressing network issues before they escalate into service disruptions or impact subscriber experience. However, inefficiencies within PNM workflows can impede the effectiveness of these processes, hindering the identification of issues and resource allocation in several ways.

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[1] RPHY - remote-PHY, remote physical layer, RPD - remote PHY device. Defined in CM-SP-R-PHY-I18-231025 [2]

3.3.1. Challenges

3.3.1.1. Data Collection

There are 2 types of data: obtained from CMTS and obtained from CM. Both of them have their own characteristics and challenges. While data obtained from CMs can be "parallelized" (from each modem independently), data from CMTS cannot be due to lack of resources on the CMTS and other implementation specific restrictions.

Data obtained from CMTS is significantly restricted in terms of instant availability as they usually require some queueing mechanisms implemented by PNM applications.

In case of hardware limitations (e.g., USTC[2]) there may be required constant switching between channels and reconfiguration of the hardware. This leads to excessive loads on chassis and less interactive data acquisition.

Inefficient data collection processes may result in delays or gaps in obtaining critical network performance data from CMTS, CMs, or other monitoring devices.

3.3.1.2. Data Analysis

As we are dealing with a large number of collected datasets for use in PNM techniques, manual, or ad-hoc data analysis methods are inefficient, time-consuming and may lead to inconsistent or incomplete analysis, making it challenging to detect performance anomalies or emerging issues accurately. These inefficiencies can delay the identification of network issues and hamper operators' ability to take timely corrective actions.

3.3.1.3. Decision-Making

Inefficient decision-making processes can result from a lack of standardized procedures, unclear roles and responsibilities, or inadequate information sharing among stakeholders. Without clear decision-making frameworks or escalation paths, operators may struggle to prioritize issues effectively, leading to delays in addressing critical network issues or allocating resources to high-priority tasks. Furthermore, decision-making bottlenecks or delays can exacerbate the impact of network issues, increasing the risk of service disruptions or subscriber dissatisfaction.

4. Potential Solutions

This section outlines strategic solutions to address the challenges encountered in DOCSIS® PNM implementation. Through practical recommendations and actionable insights, this section seeks to provide a roadmap for overcoming existing obstacles and achieving sustainable improvements in network maintenance and management.

4.1. Data

The development of performance measures aligned with KPIs, unified for network tools and across technologies, aims to reduce the data archival burden. Purpose-built performance measurements, based on standard telemetry and industry practices, will diminish the need to store extensive amounts of raw network data for multiple months. Robust, well-planned performance measurements will be easier to

[2] USTC - upstream spectrum triggered capture, described in CM-SP-CCAP-OSSIv3.1-I16-190917 [1]

maintain, understand, and utilize effectively, even as operations and technologies evolve. CableLabs, through the Optical Operations and Maintenance Working Group, is spearheading an effort to align KPIs across optical and DOCSIS access technologies, marking a significant first step in this initiative.

4.1.1. Algorithm Optimization

As already established, modern PNM applications are dealing with large amounts of data. Regardless of the CM population, computational power is always a premium resource. To fit into existing computational constraints while processing sheer volumes of collected data, it is essential to use better algorithms.

Possible optimization vectors:

- Design processing algorithms to maximize performance on existing hardware solutions. Developers need to create algorithms which are tailored to the specific function. Some solutions are obvious like use of fast Fourier transform (FFT) instead of slower discrete Fourier transform (DFT), while others might require additional testing and selecting best fit algorithms. e.g. Quick sort is faster in general, while in some cases other algorithms perform better based on input data.
- Process input data to fit into more efficient algorithms: e.g. (i)FFT instead of (i)DFT. This might require adding empty values to fit better algorithms requirements.
- Reduce dataset where it is possible without significant sacrifice of precision and accuracy of computation. In some cases, dimensionality of the data or its size can be reduced depending on specific PNM calculations where data reduction penalty does not affect results of PNM computational algorithms.
- Optimize computational algorithms to utilize hardware accelerations (GPU, TPU etc). Self-hosted (on-premises), private and public clouds offer hardware accelerated solutions. Investing into optimization of computational algorithms to perform better on GPU/TPU offers significant acceleration in efficiency.

4.1.2. Data Prioritization

Establishing clear criteria for prioritizing data based on its relevance and impact on network performance can help operators focus their attention on critical issues and expedite decision-making processes.

4.1.2.1. Identification of Intrinsic Properties:

Operators begin by identifying the intrinsic properties of data that are most indicative of network performance and health. These intrinsic properties may include signal levels, error rates, SNR, modulation profiles, and network traffic patterns. By understanding the fundamental characteristics of data, operators can prioritize information that directly influences network operations and subscriber experience.

4.1.2.2. Assessment of High-Fidelity Measurements:

High-fidelity measurements refer to data points that are collected with high accuracy, precision, and reliability. These measurements provide a granular and detailed view of network conditions, enabling operators to detect subtle changes and anomalies that may signal potential issues. Examples of high-fidelity measurements include real-time spectrum analysis, fine-grained error rate metrics, and precise signal level measurements. See Figure 1.

Intrinsic Characteristic	High-Fidelity Measurement	Definition	Measurement Method
Network Utilization and User Activity	Throughput	Quantifies data transfer rate over the network.	Use tools like Iperf or network monitoring software to measure upstream and downstream throughput.
	Packet Loss Rate	Measures percentage of lost packets during transmission.	Use network monitoring tools to capture and analyze packet loss statistics.
	Latency	Measures time delay between sending a packet and receiving a response.	Conduct ping tests or use specialized latency measurement tools.
	Jitter	Measures variation in packet arrival times.	Use tools that analyze packet arrival times over a period to detect jitter.
Shared Medium and Bandwidth Contention	Signal-to-Noise Ratio (SNR)	Measures signal quality relative to background noise.	Use diagnostic tools on CMTS or cable modems to measure SNR for upstream and downstream channels.
	Error Rate	Quantifies rate of errors in transmitted data packets.	Use diagnostic tools or network monitoring software to capture error statistics (e.g., FEC corrections, uncorrectable errors).
Latency Variability	Latency	Measures time delay between sending a packet and receiving a response.	Conduct ping tests or use specialized latency measurement tools.
Frequency Allocation and Interference	Signal-to-Noise Ratio (SNR)	Measures signal quality relative to background noise.	Use diagnostic tools on CMTS or cable modems to measure SNR for upstream and downstream channels.
Adaptive Modulation	Modulation Error Ratio (MER)	Measures ratio of received signal power to noise and interference error.	Use diagnostic tools on CMTS or cable modems to measure MER for downstream channels.
Dynamic Bandwidth Allocation	Dynamic Bandwidth Allocation Efficiency	Measures effectiveness of bandwidth allocation based on real-time demand.	Analyze traffic patterns and bandwidth allocation logs to assess network adaptation to varying demand levels.
Service Flow Prioritization	Quality of Service (QoS) Metrics	Measures adherence to service level agreements and traffic prioritization.	Use QoS monitoring tools to classify and measure different traffic flows based on priority levels.

Figure 1 - Intrinsic properties and correlated high-fidelity measurements

4.1.2.3. Establishment of Prioritization Criteria:

Operators establish clear criteria for prioritizing data based on its intrinsic properties and high-fidelity measurements. This may involve defining thresholds for each metric to determine acceptable ranges of performance and identifying deviations that warrant further investigation. For example, data indicating significant fluctuations in signal levels or a sudden increase in error rates may be prioritized over less critical metrics. A simple depiction of this prioritization is described in Figure 2.

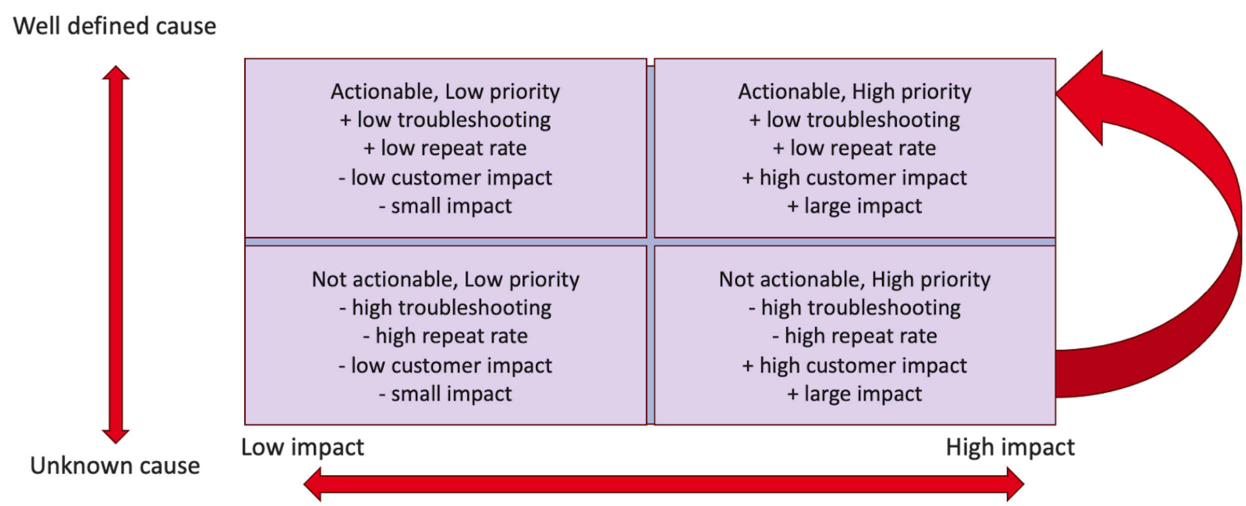


Figure 2 - Prioritization Matrix

Here are some examples:

1. Actionable but low priority - the impairment is well understood to be stable, with low or no customer impact or impact to service, so repair makes little impact. It is also easy to find. As an example, there is an impedance mismatch pair across a span of hard line due to a splice of cable. The splice is well sealed and has not degraded. But keep an eye on it as that could change and the priority could shift upward.

2. Not actionable and low priority - the impairment is not easy to find, very small, and not impacting service. For example, a slightly elevated noise floor might be worth watching closely to see if it increases, but locating it is difficult and the impact is low; if it is also stable, the best course may be to monitor. If it becomes unstable or worse, then it may need to be addressed anyway as it moves to the next category.

3. Not actionable but high priority - the case of a problem difficult to troubleshoot and has a high repeat rate but has large impact to fix and impacts service to a large degree should be addressed anyway, but it is unfortunate the work is not as likely to succeed and will be difficult to do well. For example, a large amount of ingress is difficult to localize and troubleshoot, and may have a high repeat rate, but it impacts a lot of customers and can be severe enough to have a large impact on service. For this reason, it is worth investigating new technologies and techniques to better find the source of the upstream noise. This is a focus of the PNM work at SCTE and CableLabs. We want these to be lifted to the last category.

4. Actionable and high priority - the case of a problem that is easy to troubleshoot and has low repeat rate, meaning it is solved correctly the first time, then it is actionable. But if it is also a high priority, it is an imperative. An example of this is water in the cable plant. These are easy to localize by finding the common set of customers or customers who are impacted, which indicates the location of the fault. The signature of this problem in spectrum capture and RxMER makes it easy to identify as water in the cable or network component. With a high impact to service, it is imperative to fix, and fast.

When it comes to prioritizing PNM work, the behavior of the network matters.

- Stable faults, even if they are taxing to DOCSIS resiliency, can be prioritized by the severity that we can measure such as RxMER or BER values.

- Faults that exhibit variability may actually be more urgent because the variability may become severe enough to impact service intermittently or even severely. This can happen even if the fault has not led to an impact yet. This situation is a clear PNM opportunity and should be prioritized higher than many stable faults.

- Faults that are variable in impact and also exhibit a degrading trend may be even more urgent because they are more likely to lead to impact on service if left unaddressed; if the variability doesn't become an intermittent problem, eventually the trend will degrade service to a point where service is what becomes intermittent. Often these get the highest priority.

To assess these different cases fairly, a risk model can be employed. The probability of a problem appearing over time can be modeled as a function of time, and that can be used to schedule repair to address the faults in a way that minimizes the impact to service.

When it comes to combining various measures of performance for use in a measure of importance to be addressed there are a few ways to handle it.

1. Simple measurement grouping - create a matrix of the measurements and use cases, mark the measurements relevant to each use case, and use to track the experience.

2. Weighted matrix - take the simple measurement grouping and weigh the measurements according to importance on each use case.

3. Model-driven service reliability - create models that depict the impact of various measurements on service reliability use cases.

4. Fuzzy-Utility-Model-driven service reliability - determine the service impact limits on measurements, estimate the utility at degraded levels in a functional way, and feed this into a model that translates the measurements into a service reliability for each use case defined.

Multi-attribute utility theory is a method that helps combine multiple measures of performance for decision making, providing assurance that the components are considered as intended by applying additive and multiplicative models to form the mix. This method can be employed to form a prioritization based on multiple inputs, which is the task operators are faced with.

4.1.2.4. Contextualization of Data:

Data is contextualized based on its relevance to network operations, subscriber impact, and business objectives. Operators consider the broader context in which data is collected, such as geographical location, network topology, and service offerings. For instance, data indicating performance degradation in densely populated areas or affecting critical services may be prioritized over less critical issues with minimal subscriber impact.

4.1.2.5. Real-Time Monitoring and Alerting:

Real-time monitoring and alerting mechanisms are employed to identify and prioritize data that requires immediate attention. High-fidelity measurements are continuously monitored for deviations from normal operating conditions, and alerts are triggered when predefined thresholds are exceeded. This enables operators to respond promptly to time-sensitive issues and minimize their impact on network performance and subscriber experience.

4.1.2.6. Integration of Advanced Analytics:

Advanced analytics techniques, such as machine learning algorithms and predictive analytics, are leveraged to enhance data prioritization capabilities. These techniques analyze historical data patterns, identify trends, and predict future network behavior, enabling automated prioritization of data based on its likelihood of impacting network performance. By integrating advanced analytics, operators can streamline decision-making processes and focus their efforts on addressing the most critical issues more efficiently.

4.1.3. Advanced Analytics Tools

Leveraging advanced analytics tools, such as machine learning algorithms, can automate data analysis processes and facilitate the identification of patterns and anomalies within the data.

4.1.3.1. Machine Learning Algorithms:

Machine learning algorithms are a key component of advanced analytics tools used in PNM. These algorithms can automatically identify patterns, trends, and anomalies within the data without the need for explicit programming. Supervised learning algorithms, such as classification and regression, can be used to predict network issues based on historical data, while unsupervised learning algorithms, such as clustering and anomaly detection, can uncover hidden patterns and outliers within the data.

Multimodal and multi-model machine learning techniques, using PNM and other DOCSIS telemetry data, have been successfully applied to identify and localize various types of impairments and noise in hybrid fiber/coax (HFC) networks. Multimodal machine learning involves processing multiple datasets obtained from different sources, such as CMTS and CMs, in both real-time and historical contexts. The goal is to leverage complementary information to improve the performance of the model and to understand complex scenarios that a single modality cannot fully capture. In contrast, multi-model machine learning involves using multiple machine learning models, with the results of these models combined and correlated to accurately predict complex situations. Both approaches are well-suited to addressing the challenges of noise and impairment localization in HFC networks. Predicting the location and type of an impaired component, such as a corroded tap in an HFC network, as well as its impact in terms of causing noise-related distortion and/or ingress, is much more accurate using these approaches.

4.1.3.2. Predictive Analytics:

Predictive analytics techniques are employed to forecast future network performance and identify potential issues before they occur. By analyzing historical data and identifying trends, predictive models can anticipate network degradation, equipment failures, and service disruptions, enabling operators to proactively address these issues and minimize their impact on subscribers.

4.1.3.3. Anomaly Detection:

Anomaly detection algorithms are used to identify unusual patterns or deviations from normal behavior within the data. These anomalies may indicate potential network issues, such as signal degradation, equipment malfunctions, or security breaches. By automatically flagging anomalies in real-time, operators can prioritize their response efforts and take corrective actions to mitigate the impact on network performance.

4.1.3.4. Root Cause Analysis:

Advanced analytics tools enable operators to perform root cause analysis to identify the underlying factors contributing to network issues. By correlating disparate data sources and analyzing causal relationships, operators can pinpoint the root causes of performance degradation and implement targeted interventions to address these issues at their source.

4.1.3.5. Prescriptive Analytics:

Prescriptive analytics techniques go beyond descriptive and predictive analytics to recommend optimal courses of action to optimize network performance. By leveraging insights derived from historical data and predictive models, prescriptive analytics tools can recommend specific maintenance activities, configuration changes, or network optimizations to improve performance and prevent future issues.

4.1.4. Scalable Infrastructure

Investing in scalable infrastructure can provide operators with the computational resources needed to handle large volumes of data without straining existing systems. On-prem, cloud-based and hybrid solutions are matured enough and widely available.

Scalable PNM applications can be deployed.

- **Virtualization**: Virtualization technologies such as VMware vSphere, Microsoft Hyper-V, and KVM can deploy PNM applications in isolated virtual machines. While virtualization offers benefits such as resource isolation, ease of maintenance and compatibility with legacy applications, it is not a lightweight solution as additional virtualization overhead is required.

- **Containerization**: Containerization offers a lightweight approach for deploying scalable and high availability applications. Containers are essential building blocks for micro-services-oriented infrastructure. Docker, podman, CRI-O are one of the many available containerization solutions. Additionally, Orchestration platforms such as Kubernetes, Docker Swarm and Apache Mesos/Marathon offer automation and ease of deployment, auto-scaling, high availability and rolling updates with minimal interventions. Benefits of containerization: portability, resource efficiency, isolation and security, scalability, and developers' productivity. See Figure 3.

- **Serverless Computing**: Serverless computing platforms such as AWS Lambda, Azure Functions, and Google Cloud Functions offer an alternative approach to deploying and running PNM applications without managing underlying infrastructure. With serverless computing, operators can focus on writing code and defining triggers, letting the platform handle provisioning, scaling, and maintenance automatically.

Benefits of Containerization:

- **Portability**: Containers can run on any infrastructure that supports container runtimes, enabling operators to deploy PNM applications consistently across different environments.
- **Resource Efficiency**: Containers consume fewer resources compared to traditional virtual machines, resulting in higher resource utilization and reduced infrastructure costs.
- **Isolation and Security**: Containers provide lightweight process isolation, reducing the risk of security vulnerabilities and minimizing the impact of potential exploits.
- **Scalability**: Containers are inherently scalable, allowing operators to dynamically scale PNM services up or down based on demand.
- **Developer Productivity**: Containerization simplifies the development and testing process by providing a consistent runtime environment for developers across different platforms.

Figure 3 - Benefits of containerization.

4.1.5. Reporting

1. Establishing a formal Data Governance program

A robust data governance framework plays a pivotal role in ensuring the effectiveness of network health reporting within an organization. Firstly, it institutes data quality assurance measures, setting standards and processes to guarantee the accuracy, reliability, and consistency of the data used for reporting. Secondly, data standardization efforts establish uniform data formats, definitions, and terminology across the organization, promoting consistency and comparability in network health metrics analysis. Thirdly, the framework prioritizes data security and privacy, implementing access controls, encryption protocols, and data masking techniques to safeguard sensitive network health data from unauthorized access or breaches. Additionally, it defines roles, responsibilities, and permissions for data access and sharing within the organization, fostering transparency, accountability, and collaboration among stakeholders. Furthermore, through comprehensive data lifecycle management policies and procedures, the governance structure ensures compliance with regulatory requirements, optimizes storage resources, and minimizes data redundancy and obsolescence. Lastly, the framework fosters a culture of Continuous Improvement, encouraging ongoing monitoring, evaluation, and refinement of reporting processes to enhance accuracy, efficiency, and relevance of network health reports over time. Overall, a well-implemented data governance framework underpins the reliability, integrity, and utility of network health reporting, facilitating informed decision-making and strategic planning within the organization.

2. **Standardized Reporting Frameworks**

Implement standardized reporting frameworks with predefined metrics, formats, and procedures to ensure consistency and comparability across different network segments and time periods. This helps streamline reporting processes and facilitates meaningful comparisons and trend analysis.

3. **Enhanced Data Visualization**

Utilize advanced data visualization techniques and tools to present network performance data in clear, intuitive, and interactive formats. Visualizations such as charts, graphs, and heatmaps can help operators identify trends, anomalies, and performance degradation more effectively, facilitating quicker and more informed decision-making.

4. **Customizable Reporting Templates**

Provide operators with customizable reporting templates that allow them to tailor reports to their specific needs and preferences. This enables operators to focus on KPIs and relevant metrics, avoiding information overload and ensuring reports are concise, relevant, and actionable.

5. **Continuous Improvement and Feedback Loops**

Establish processes for continuous improvement of reporting mechanisms based on feedback from operators, stakeholders, and end-users. Regularly solicit input on reporting needs, preferences, and challenges, and incorporate feedback to refine reporting templates, visualization techniques, and data analysis methods iteratively.

4.2. Hardware/Software Limitations

4.2.1. Non-Standard Vendor Implementations

Non-standard vendor implementations can present significant challenges for maintaining consistency, interoperability, and efficiency in a PNM operation. However, several potential solutions can address these challenges effectively:

1. **Standardization and Compliance Requirements**:

    - Implement industry-wide standards and compliance requirements that vendors must adhere to. Organizations like CableLabs often develop and promote such standards for DOCSIS technology.

    - Encourage vendors to comply with these standards through contractual obligations and certification processes.

2. **Vendor-Agnostic Tools and Platforms**:
    - Develop and deploy vendor-agnostic tools and platforms that can interface with equipment from different vendors seamlessly. This includes using middleware solutions that standardize data formats and protocols across different vendor devices.
    - Implement open-source solutions and APIs that facilitate integration with various vendor systems without relying on proprietary technologies.
3. **Interoperability Testing and Certification**:
    - Conduct rigorous interoperability testing to ensure that equipment from different vendors can work together effectively within the network.
    - Establish certification programs where vendors' equipment must pass interoperability tests before being deployed in the network.
4. **Unified Management Systems**:
    - Implement unified management systems that can manage and monitor equipment from multiple vendors through a single interface. These systems should support multiple protocols and data formats, enabling centralized control and monitoring.
    - Use network management software that includes abstraction layers to handle the differences in vendor implementations.
5. **Customized Integration Solutions**:
    - Develop customized integration solutions that address specific incompatibilities between different vendors' equipment. This might involve writing custom scripts or using adapters that translate data and commands between different systems.
    - Work with vendors to create customized firmware or software updates that improve compatibility and standardize certain functions.
6. **Collaboration and Communication with Vendors**:
    - Foster open communication and collaboration with vendors to address non-standard implementations proactively. Engage in joint development efforts to create more standardized solutions.
    - Provide feedback to vendors regarding the challenges faced due to non-standard implementations and encourage them to adopt more standardized practices.
7. **Training and Knowledge Sharing**:
    - Train network operators and maintenance personnel to handle and mitigate issues arising from non-standard implementations. This includes understanding the specific quirks and requirements of different vendors' equipment.
    - Promote knowledge sharing and best practices within the industry to tackle the challenges of non-standard implementations more effectively.

8. **Adoption of Open Standards**:

    - Advocate for the adoption of open standards across the industry, reducing the reliance on proprietary technologies and promoting greater interoperability.

    - Support and participate in industry groups and initiatives that aim to develop and promote open standards for network equipment and management.

4.3. Process

4.3.1. Data Collection

Inefficiencies in data collection can significantly impact the performance of a PNM operation. The two primary sources of data, CMTS and CM, present unique challenges. Here are potential solutions to improve data collection processes:

1. **Parallelized Data Collection from CMs**:

    - **Distributed Data Collection Agents**: Deploy distributed data collection agents to gather data from multiple cable modems (CMs) in parallel. This reduces the load on any single data collection point and improves data acquisition speed.

    - **Optimized Polling Intervals**: Adjust polling intervals for CMs to balance the load and ensure timely data collection without overwhelming the network or the data collection infrastructure.

2. **Efficient Data Collection from CMTS**:

    - **Queueing Mechanisms**: Implement robust queueing mechanisms to manage the data requests from CMTS. Prioritize critical data points and use intelligent scheduling to minimize delays. Platforms such as a common collection framework (CCF) provide a RESTful API and methods to reduce the burden on the CMTS. Offline data processing solutions are available as well.

    - **Hardware Optimization**: Optimize CMTS hardware configurations to reduce the need for constant channel switching and reconfiguration. This might involve upgrading hardware or implementing software optimizations to handle data collection more efficiently.

    - **Scalable Infrastructure**: Utilize scalable infrastructure solutions, such as cloud-based platforms, to handle the data processing load from CMTS. This can help offload some of the processing requirements from the CMTS itself.

4.3.2. Data Analysis

The large volume of data collected in PNM operations requires efficient analysis methods to identify network issues promptly. Here are potential solutions:

1. **Automated Data Analysis Tools**:

    - **Heuristics**: Implement heuristics to automate the detection of performance anomalies and emerging issues. Algorithms can analyze large datasets more efficiently than manual methods.

  - **Real-Time Analytics**: Use real-time analytics platforms to process data as it is collected. This enables quicker identification of issues and reduces the time to resolution.

  - **Anomaly Detection Systems**: Implement anomaly detection systems that use statistical and machine learning models to highlight unusual patterns that may indicate network issues.

4.3.3. Decision Making

Inefficient decision-making processes can hinder the effectiveness of a PNM operation. Solutions to improve decision-making include:

1. **Standardized Procedures**:
   - **Decision-Making Frameworks**: Establish standardized decision-making frameworks that define clear roles, responsibilities, and escalation paths. This ensures that issues are prioritized and addressed efficiently.
   - **SOPs and Checklists**: Develop standard operating procedures (SOPs) and checklists for common network issues. This ensures consistent and efficient decision-making.
2. **Enhanced Communication**:
   - **Collaboration Tools**: Use collaboration tools to facilitate better communication among stakeholders. Tools like instant messaging, video conferencing, and shared document platforms can improve information sharing.
   - **Regular Meetings and Updates**: Hold regular meetings and updates to ensure all stakeholders are aware of current network issues and the decisions being made to address them.

4.4. Changing Our Approach

In the realm of PNM operations, the primary goal is to maintain and enhance network performance to ensure high-quality service delivery to subscribers. Traditional PNM metrics, such as signal levels, error rates, and signal-to-noise ratios, provide crucial technical insights into network health. However, while these metrics are invaluable for identifying underlying network issues, they do not always correlate directly with the customer experience. After all, their intent is to find problems before the customer is impacted, so we would not expect them to correlate. Instead, the impact of PNM has to be modeled in terms of its avoided impact.

As service quality and user satisfaction are paramount, leveraging customer experience data can significantly improve the prioritization of network repairs and maintenance efforts. Customer experience data, including achieved throughput and network connectivity, offers a real-world perspective on network performance from the user's standpoint. Achieved throughput reflects the actual data transmission rates that customers experience, providing a realistic measure of network performance. Network connectivity data highlights the stability and reliability of customer connections, revealing issues that might not be apparent through technical metrics alone. By integrating these customer-centric metrics into PNM operations, network operators can more accurately identify and address areas where subscribers are experiencing the most significant issues.

This section explores how customer experience data can enhance the prioritization of network repairs compared to traditional PNM metrics. It discusses the direct impact on user experience, the benefits of targeted interventions and efficient resource allocation, and the advantages of real-time and dynamic adjustments in maintenance strategies. Additionally, it emphasizes the importance of combining customer experience data with PNM metrics to create a holistic view of network health, ultimately leading to better decision-making and improved service quality. By focusing on the metrics that matter most to customers, network operators can ensure that their maintenance efforts have the greatest positive impact on user satisfaction and overall network performance.

4.4.1. Benefits of This Approach

1. **Direct Impact on User Experience**

- **Real-World Performance Metrics**:

    - **Achieved Throughput**: This measures the actual data transmission rate experienced by customers, reflecting real-world performance. Unlike theoretical or maximum throughput values that PNM metrics might provide, achieved throughput gives a realistic view of network performance from the customer's perspective.

    - **Network Connectivity**: This indicates the stability and reliability of a customer's connection to the network, highlighting issues like frequent disconnections or long downtime periods.

    - **Example**: If many customers in a specific area report low achieved throughput, this directly points to a performance bottleneck that affects user satisfaction more than a technical metric like MER or SNR might indicate.

2. **Customer Perception and Satisfaction**:

- **User Feedback**: Metrics derived from customer experience data capture the perceived quality of the service, which is crucial for maintaining customer satisfaction and loyalty.

    - **Example**: If customers consistently report poor connectivity or slow speeds, prioritizing repairs in those areas will likely have a more immediate and positive impact on customer satisfaction compared to focusing solely on technical metrics that might not directly correlate with perceived issues.

3. **Enhanced Prioritization and Resource Allocation**

- **Targeted Interventions**:

    - **Identifying Critical Areas**: Customer experience data helps identify specific geographic areas or network segments where users face the most significant issues, allowing for more targeted interventions.

    - **Example**: A neighborhood with numerous complaints about connectivity issues would be prioritized for repairs over another area with slightly degraded PNM metrics but no significant user complaints.

4. **Efficient Resource Utilization**:

- **Prioritizing Repairs**: By focusing on areas with the worst user-reported performance, network operators can allocate their resources more efficiently, addressing the most critical issues first.

  - **Example**: If customer experience data shows that users are experiencing frequent disconnections in a particular region, repairing infrastructure there can lead to a noticeable improvement in service quality and customer satisfaction.

5. **Complementing PNM Metrics**

- **Holistic View**:
  - **Combining Data Sources**: While PNM metrics provide valuable technical insights into the network's health, combining them with customer experience data offers a more comprehensive view of network performance.
  - **Example**: A combination of high uncorrectable codeword rates (a PNM metric) and low achieved throughput reported by users provides a clear indication of where technical issues are translating into poor user experiences.
- **Balanced Decision-Making**:
  - **Integrating Insights**: By integrating customer experience data with traditional PNM metrics, operators can make more informed decisions about where to prioritize repairs and how to allocate resources effectively.
  - **Example**: Even if PNM metrics in an area appear within acceptable ranges, if customer experience data indicates significant user dissatisfaction, it might warrant further investigation and potential intervention.

4.4.2. Proposed Implementation

4.4.2.1. Customer Experience and Network Delivery Relationship

Understanding the Customer Experience and Network Delivery Relationship Landscape involves exploring the intricate connections between how customers perceive their interactions with a company and the efficiency and reliability of the underlying network delivery systems. This relationship is pivotal, as the quality and performance of network delivery directly impact customer satisfaction and overall experience.

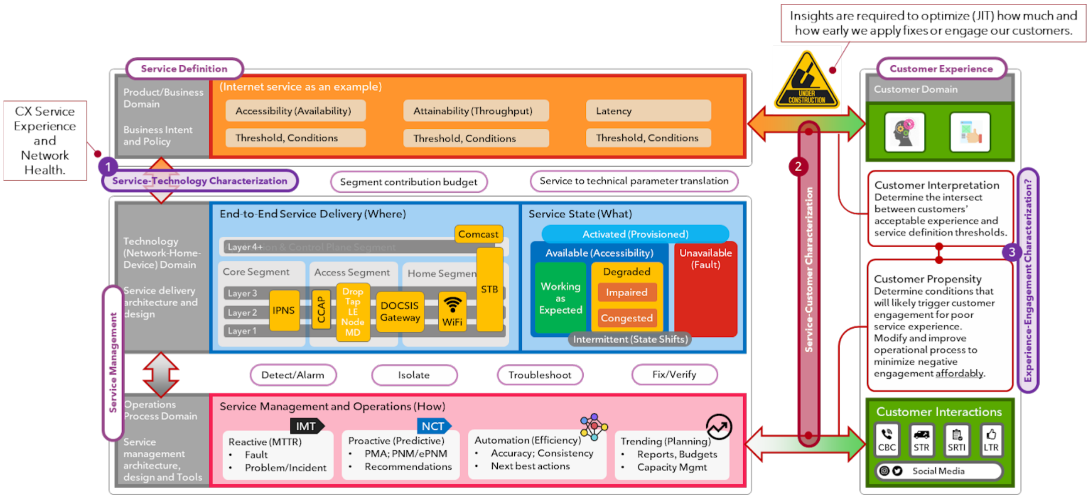
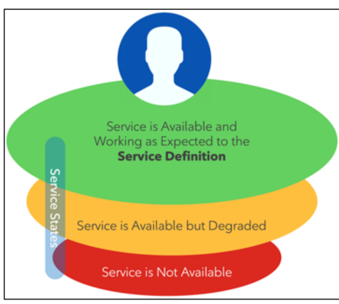


Figure 4 - Customer experience and network delivery landscape

4.4.2.2. Introduction of the Service Definition and Service Experience Model



Service Definition

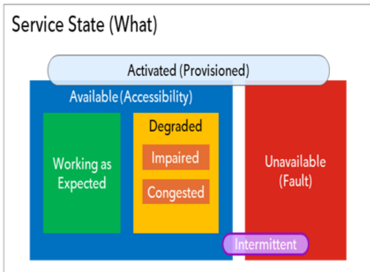
- Top-of-mind, meaningful service dimensions with appropriate thresholds, from the user/customer perspective.
- Measure of our success criteria.
- Statement of business intent and policy.
- Directly drives the underlying technology architecture, platform and business process requirements.
- Requires a critical application of judgment on both the measurement selection and associated threshold.

Figure 5 - Service Definition

Service Experience Model (SEM)

- Measure of what the customers will experience relative to service definition.
- Modeled a high-fidelity delivery network for accurate service performance.
- Selected Internet product as the basis for model development, focusing on the aspects that customers care about most: availability and speed.
- Built service management capabilities to support and achieve service and operational objectives.

4.4.2.3. Service Definition State and Delivery



Proposed Internet Service Definition for Access Segment [Timeframe] per customer experience (CX):

•Availability: >=[xx]%, and
•Intermittency: Combined [xx]-min windows containing offline events and daily total offline counts >=[xx] points*, and
•DS Degraded: Throughput >=[xx]% of purchased Tier speed [choose tier]; 100% of rest of the tiers >=[xx]% of the time, and
•US Degraded: Throughput [xx]% of purchased US tier speed >= [xx]% of the time.

Figure 6 - Service definition state and delivery

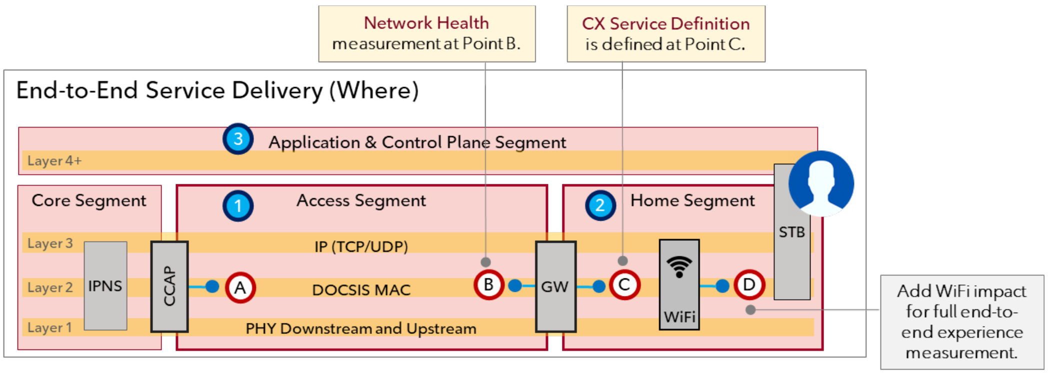


Figure 7- End to end service delivery

Service Experience Measurement per customer experience (CX):

- Covers the access segment
- Availability measures the modem online state with the CCAP.
- Throughput measures are provided at three points in the delivery flow:

  A. Network Configured throughput, shared across the media access control (MAC) Domain/US Port

  B. Network delivered throughput at the RF-side of the CX modem, independent of CX purchased tier, often referred to as goodput.

  C. CX offered throughput at the CX-side of the modem; maximum throughput is determined by the purchased tier speeds.

- The CX offered throughput is what the CX will experience due to the access segment only.

Hi-fidelity measurement.

- CX experience of our service via applications.
- Application performance is universally impacted by packet error rate.
- SEM determines the integrated packet error rate (PER), which in turn is affected by the combined effects of the underlying conditions measured through CER, MER, SNR, TX, and RX levels.

- SEM measures at individual CX level; their results can be aggregated at the serving group level or MAC domain levels.

Underlying drivers and measures

- Lower level KPIs are useful indicators but do not provide accurate nor complete estimation of application layer impact.
- They are, however, needed to isolate and identify root causes affecting PER.

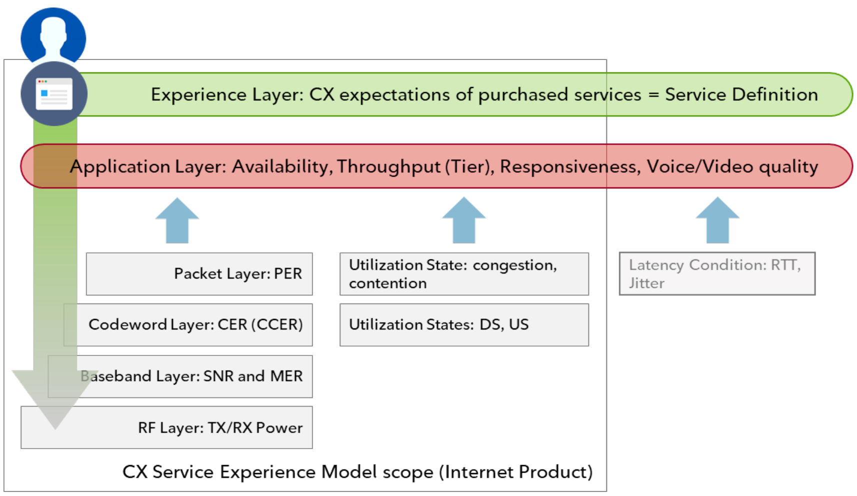


Figure 8 - Customer experience top-down composition

4.4.2.4. Service experience model development

Detect	Identify and count all CX that fail on any of the Service Definition dimensions.
Rank	Determine severity of failed conditions, both in intensity and in chronicity.
Localize	Distinguish between Area problem versus Individual CX issue.
Isolate	Diagnose probable root cause attributes.
Troubleshoot	Furnish detailed, granular reports at the Area and Individual CX levels for deeper insights into the underlying conditions.
Verify	Evaluate effects of applied efforts in near real-time basis and over time.

Figure 9 - Support a full problem-solving process.

4.4.2.5. Service Definition Outcomes

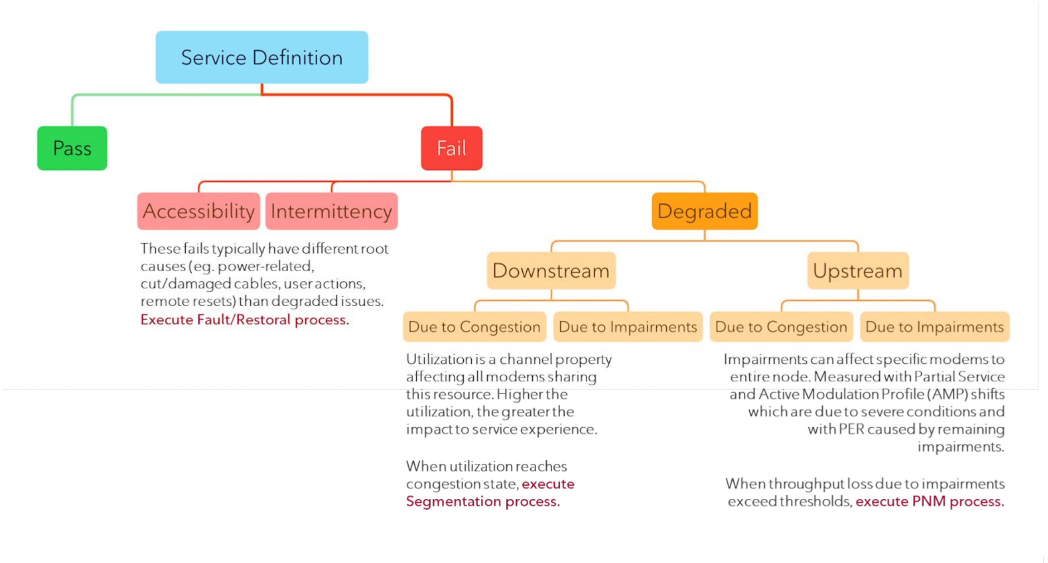


Figure 10 - Service definition outcomes

4.4.2.6. Degraded Service State (Throughput Experience) Causes and Impacts

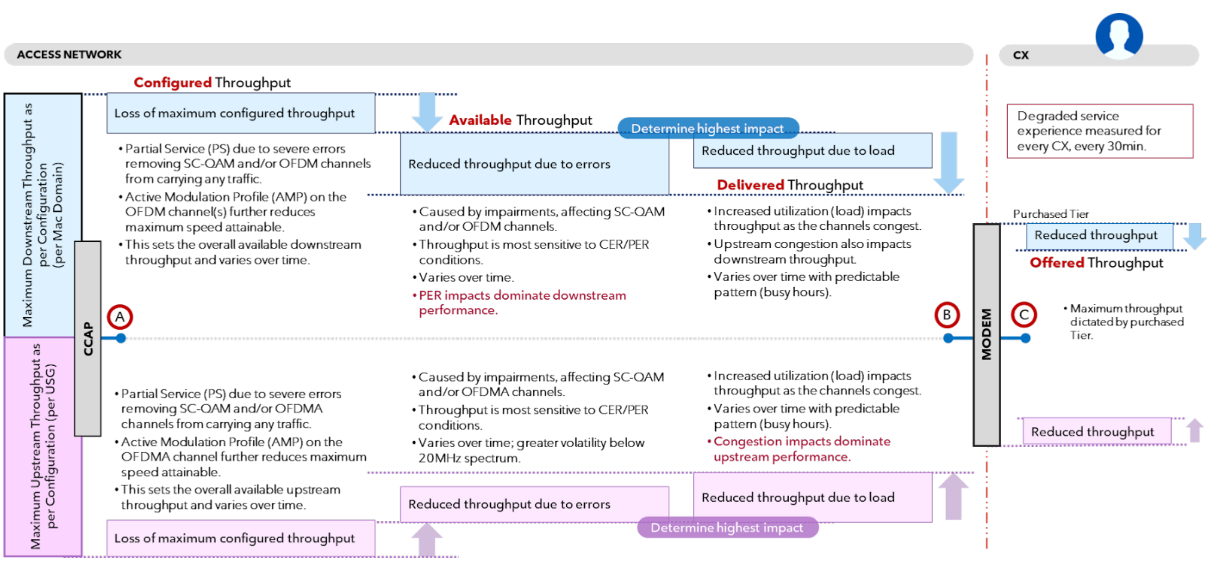
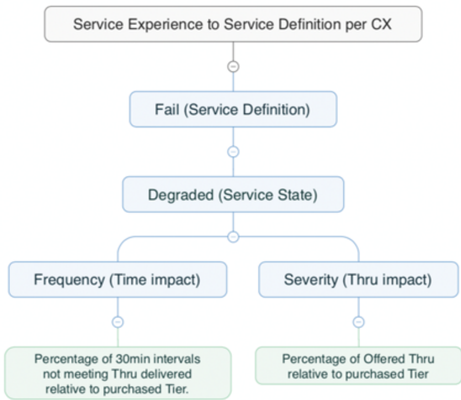


Figure 11 - Cascading loss of throughput from configured to offered to CX

4.4.2.7. Degraded Fail CX Ranking: Combined Degraded Score



Service Definition for the Degraded state has two components: time and performance.

- The % of time not meeting throughput threshold and the % throughput relative to the purchased Tier is multiplied to produce a Combined Degraded Score.
- Lower the score, the worse the experience (severity).
- The Combined Score is measured for downstream and upstream separately, for every CX daily.
- The % throughput relative to the purchased Tier is converted to Mbps to see the delivered throughput, averaged across the serving day.

Figure 12 - Methodology

5. Case Studies

5.1. Challenges In Identifying Impactful Issues

5.1.1. Problem Statement

Identifying and assessing the impact of network impairments through PNM techniques is challenging because the data showing the impairment is actually the result after DOCSIS automatic correction is applied to the signal. Therefore, even though an impairment is detected, it may not be impactful to the service (yet). This is especially true when assessing the channel frequency response obtained from pre-equalization coefficients. To determine the impact of an impairment, it is crucial to use other PNM techniques to confirm the results. In the examples below, two impairments with similar frequency responses are compared: one does not affect network performance at the time it was identified, while the other likely contributes to distortions and noise in the network. These cases explain two types of proactive opportunities.

5.1.2. Examples

A powerful PNM technique is the evaluation of equalization response for each channel. The equalization response can be translated to frequency response as well as CM transmit power required to compensate for the effect of the impairment. For example, a suckout caused by an impaired component, such as a corroded tap, requires higher transmit power at the suckout frequency to compensate for the suckout. Such an impairment may cause noise-like distortion if the transmit power headroom is reached, or it may be the point where noise enters the network (ingress). Alternatively, this impaired component might not have any significant impact on the performance of the network.

The examples below show two impaired components with severely distorted equalizer frequency responses. Potentially, both can be impactful in the ways described above.

Figure 13 shows the frequency response of an impaired network components, impairment 1, as seen by a modem behind this point. Although the frequency response has strong variations in frequency, the CM transmit power levels depicted in Figure 14 are within the normal range, and there is still enough transmit power headroom left for the CM to function without a problem.

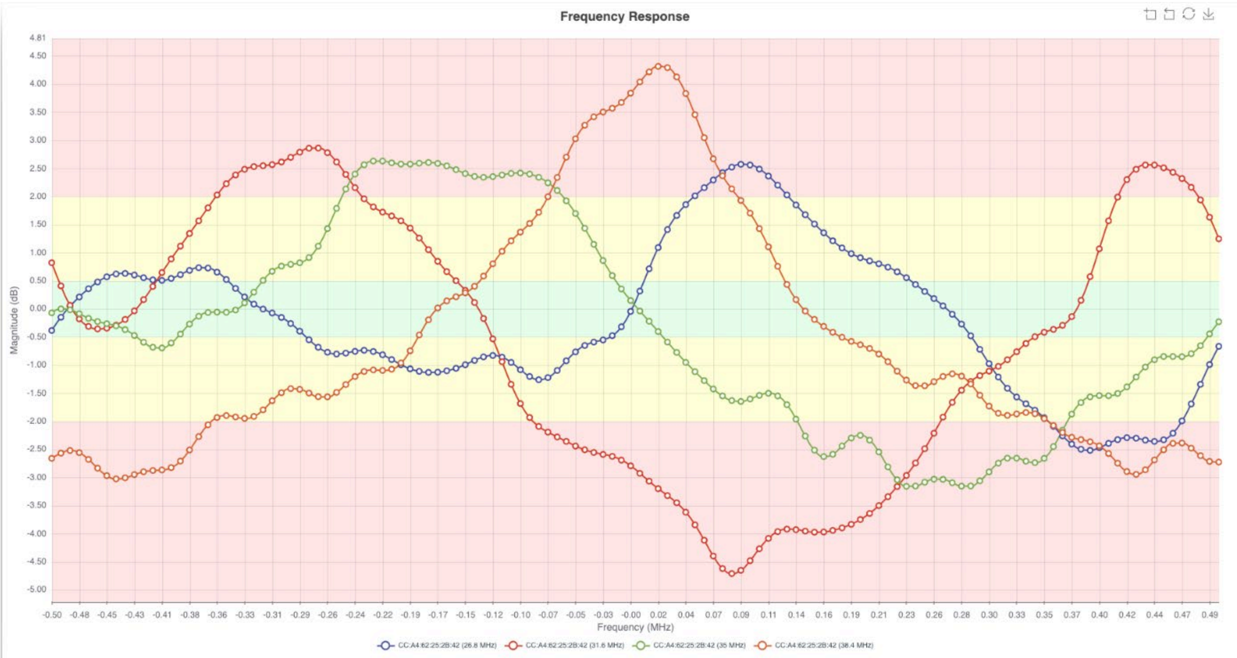


Figure 13 - Frequency Response of Impairment 1 as seen by CM MAC: CC:A4:62:25:28:42

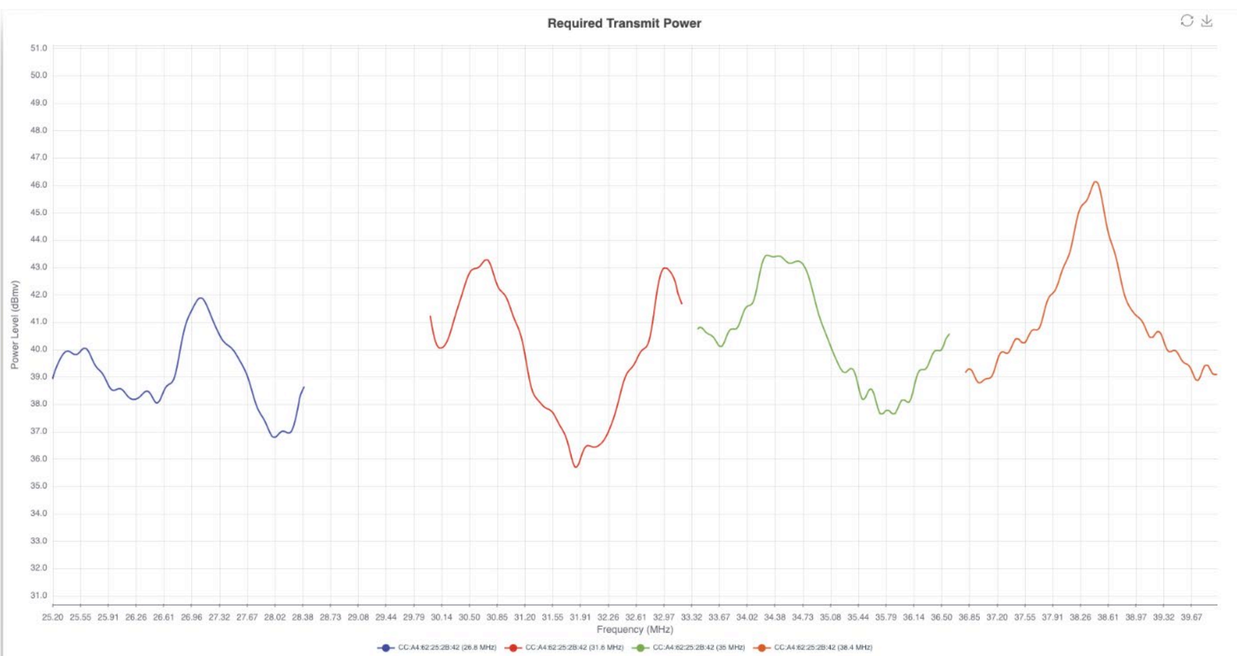


Figure 14 - Power Level transmitted by CM MAC: CC:A4:62:25:28:42 behind Impairment 1

Figure 15 shows the frequency response of a different impaired component in the network, Impairment 2, which has a similarly distorted frequency response to Impairment 1. However, in contrast to Impairment 1, the transmit power level in Impairment 2, depicted in Figure 16, is completely out of the acceptable range and is most likely the cause of severe noise-like distortion in the network.

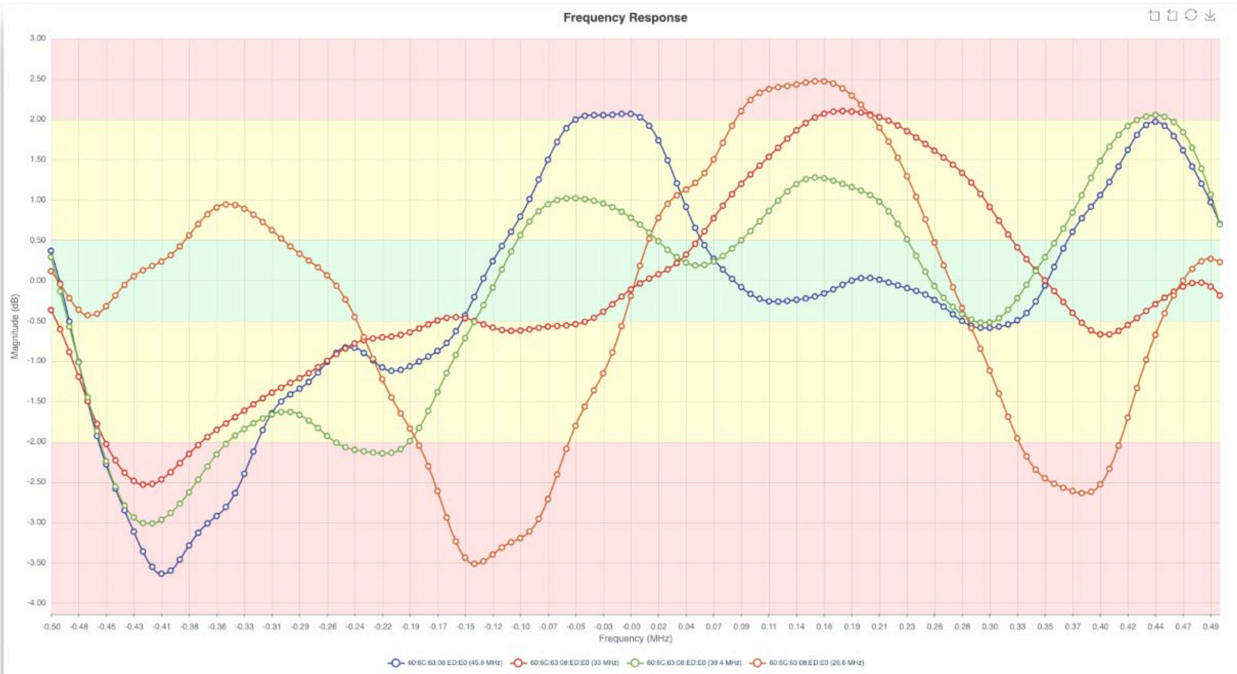


Figure 15 - Frequency response of Impairment 2 as seen by CM MAC: 60:5C:63:C8:ED:E0

Figure 16 - Power Level transmitted by CM MAC: 60:5C:63:C8:ED:E0 behind Impairment 2

Impairment 2, although not impactful in terms of noise-like distortion due to excessive transmit power levels, may still be the cause of noise entering the network from outside (ingress) if noise is present in the environment. To determine if Impairment 2 is causing ingress, additional analysis steps are required. In a manual approach, experienced analysts must evaluate various other metrics derived from DOCSIS telemetry data, their variations in time and frequency, and their correlations. Alternatively, an automated approach using machine learning techniques can be employed.

5.2. Challenges in Correlating Data to Indentify and Localize Issues

5.2.1. Problem Statement

One of the most effective and powerful approaches to identifying and localizing network issues is using multiple metrics derived from the variations and correlations of DOCSIS telemetry and PNM data over time and frequency. This approach can effectively tackle issues such as time-varying impairments and noise localization. However, the main challenge with this method is that, due to the large number of data sets and the numerous possible metrics, manual analysis can be extremely time-consuming even in simple cases. For complex cases, such as when multiple impairments or noise sources are present, it can be very difficult, if not impossible.

5.2.2. Simple Case: Noise Localization by Correlating Upstream and Downstream SNR - Manual Analysis.

Correlating upstream and downstream SNR in cases where noise originates from an impaired component, such as a radial crack in the hardline shield, and where the noise has a wide spectrum close to white noise, can provide good results. This method can identify a cluster of modems whose common point may be the impaired component. To perform the analysis manually, analysts typically visualize the modems on a map and highlight the correlation between SNR of both downstream and upstream channels at different time stamps when noise is present or strong and when noise is weak or absent.

Figure 17 depicts a cluster of modems in a service group. These modems' downstream SNR follows the upstream SNR shown in the graph above the map. This graph represents the overall upstream SNR per channel polled from the CMTS. In this figure, multiple time stamps are selected by the markers in the upstream SNR graph. One marker is placed at a time when the upstream SNR is high (less upstream noise) and the second marker is placed at a time when the upstream SNR is low (higher upstream noise). The cluster of modems highlighted in purple are those whose downstream SNR dropped by more than 4% from the first timestamp to the second one.

From this result, we can deduce that the common point for the modems in this cluster is a likely location of the impaired component, which is causing noise and ingress.

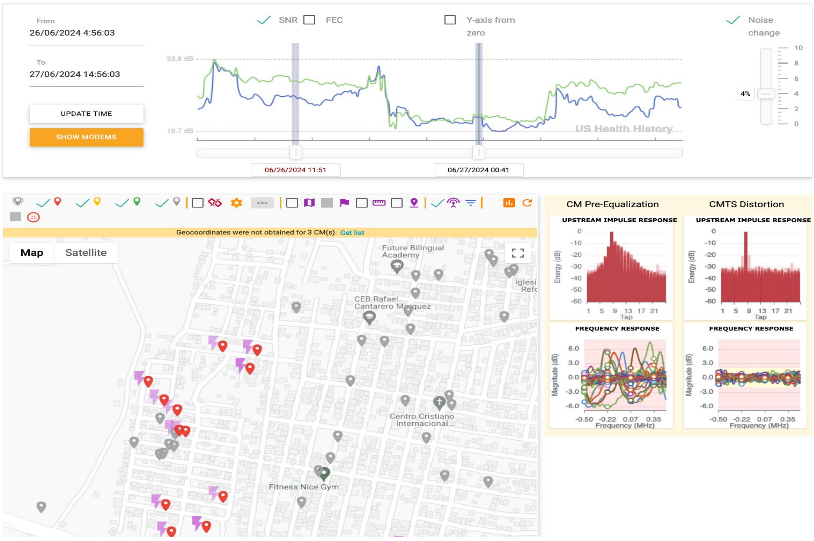


Figure 17 - A cluster of modems in a service group, showing that their downstream SNR follows the upstream SNR depicted in the graph above the map

The challenge with this process is that it can be time-consuming and sometimes yields no results, as the noise may be of a different type and not affect both downstream and upstream. A more complex case, such as the one presented in Figure 18, shows upstream SNR and codeword errors for a group of modems in a service group over time. In this scenario, there are likely multiple impairments and noise sources present, some of which may originate within the network due to nonlinear distortion. The slow-varying SNR could be caused by distortion from a misaligned amplifier. In such cases, the modems behind the amplifier contribute to noise when they transmit signals. If these modems go offline one by one due to adverse network conditions, the upstream SNR gradually improves.

For complex cases like this, an artificial intelligence (AI) and-or machine learning (ML)-based approach is required. Such an approach considers multiple metrics, their variations in time and frequency, and their correlations to identify and localize multiple impairments and noise sources, providing a comprehensive picture of the network condition.

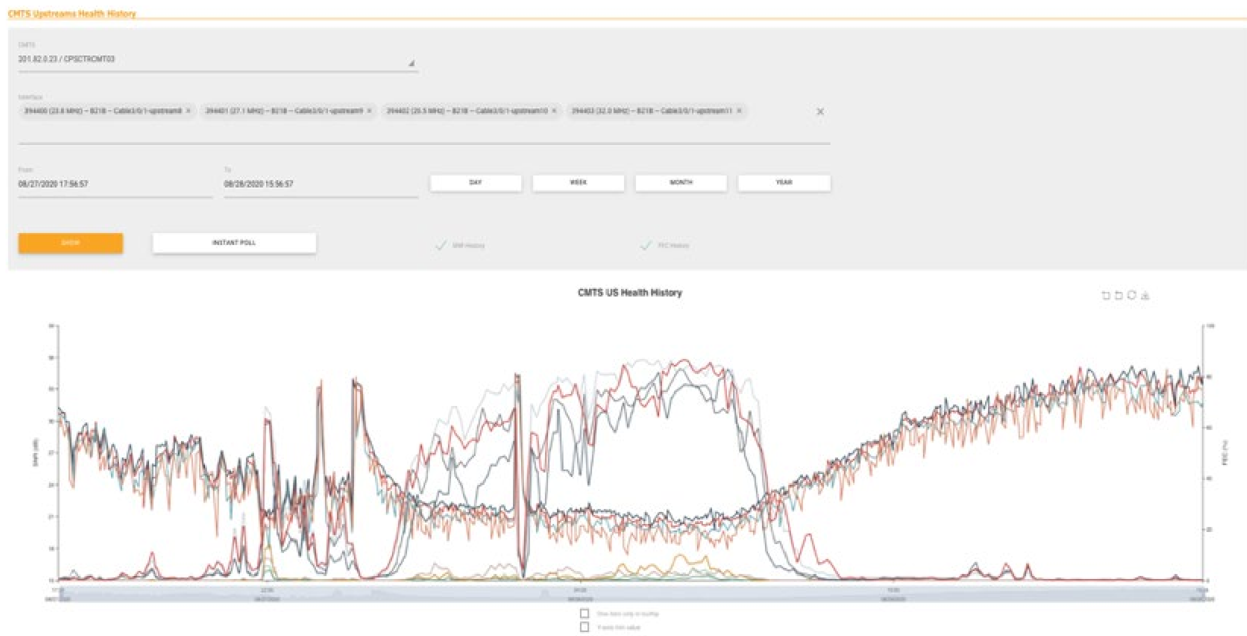


Figure 18 - Upstream SNR and Codeword Errors of upstream channels in a service group over time, showing a complex noise and impairment situation in the network

5.2.3. Medium Complexity Case: Upstream Noise Localization by Correlating Transmit Power Levels and One or More Noise Metrics - Semi-Automated Analysis

In some cases, noise entering the network exists only in the upstream frequency spectrum, affecting one or more upstream channels. In these instances, the technique used in Example 1 is not applicable, as the noise has no effect on downstream channels. One effective approach to localize the impaired component causing noise is to evaluate the correlation of modems transmit power with one or more metrics sensitive to the presence of upstream noise. Suitable metrics for this approach include MTR[3] or NMTER[4], derived from PNM pre-equalization coefficients.

This works because an impaired component in the network, such as a loose splice connector on a hard coaxial line, can cause variable attenuation for the signals passing through it and introduce noise to the network to varying degrees, especially under environmental changes such as temperature or wind. By correlating the effects of these phenomena, we can identify a cluster of modems behind the impaired component. Figure 19 shows a cluster of modems, highlighted in dark blue, with a high level of correlation between their transmit power level and NMTER in this case.

[3] MTR - main tap ratio. For SC-QAM channel is a ratio between main tap energy and other tap energies combined. Reference CM-GL-PNMP-V03-160725 [3].

[4] NMTER - non-main tap to total energy ratio. For SC-QAM channel is a ratio between combined energy of non main taps to total energy CM-GL-PNMP-V03-160725 [3].

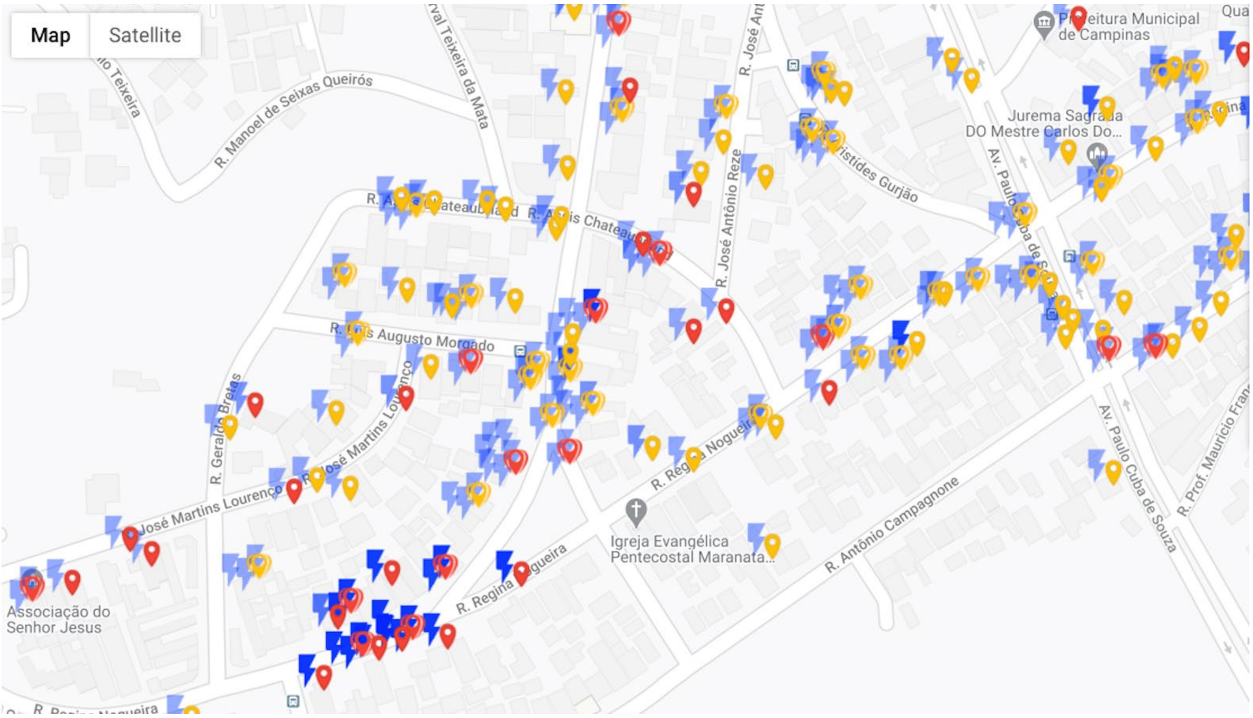


Figure 19 - A cluster of modems in a service group, showing a high-level correlation between their transmit power level and NMTER.]

The main challenge with this approach is that analysts need to spend time calculating the correlation of parameters over different time periods at various time stamps. During these periods, other impairments or noise may become present and skew the results, making the process time-consuming. Additionally, this approach shares the same limitations as the technique in Example 1, as it will not work in more complex cases. This includes scenarios with multiple impairments and, especially, cases with noise-like distortions originating within the network.

5.2.4. Complex Case: Localization of Complex Noise and Impairments by AI and ML Techniques

To perform a comprehensive analysis of the network condition, identifying and localizing multiple noise sources and impairments, an AI-ML-based approach can work. The primary objective is to find the type and location of impairments and their impact on network performance. This approach can also prioritize network maintenance work, provide instructions, and receive feedback from field technicians to further enhance the performance of the ML model.

The challenges with this approach are significant in the early stages. One or more ML models need to be developed and tested, and labeled data must be gathered for training the models. The primary labels used in this approach include:

1. Types of impaired network components, such as components with physical or water damage, loose connectors, missing seals, or misaligned amplifiers or fiber nodes.
2. Types of noise and distortion entering or originating within the network.
3. Locations where the impaired components are affecting network performance.

There are also secondary labels that include the brand and model of the modems and CMTS. Another challenge is characterizing impaired components and noise sources as labels because not all loose connectors impact the network in the same way. Both impaired components and noise sources need to be characterized with parametric models that are comprehensible for the ML models.

Once the model is developed and trained, the analysis work becomes almost non-existent, and troubleshooting reports and instructions can be delivered to field technicians via a mobile device. Figure 20 shows an example of a noise and impairment report. In this report, four points of interest (POIs) are identified by the ML model. These POIs, with very high probability, are the sources of noise and impairments, and they are the locations where field technicians are instructed to start troubleshooting the issues.

Figure 20 - Noise and Impairment report on Mobile screen generated by a ML based analysis system

6. Conclusion

The success of a DOCSIS PNM operation is contingent on overcoming several critical challenges, including data overload, ineffective reporting, inefficient processes, and non-standard vendor implementations. Addressing these challenges requires a comprehensive and strategic approach that encompasses efficient data collection, robust data analysis, clear decision-making frameworks, timely action implementation, and optimal resource allocation.

Data overload, which can impede timely decision-making and obscure critical insights, can be mitigated through the implementation of advanced analytics tools such as machine learning algorithms and real-time analytics platforms. These tools enhance the accuracy and efficiency of data analysis, allowing for quicker identification of network issues. Additionally, establishing standardized data governance frameworks and reporting systems ensures data quality, consistency, and security, facilitating better decision-making and reporting.

Inefficient processes, particularly in data collection from CMTS and CMs, can be addressed by adopting parallelized data collection methods, optimizing polling intervals, and utilizing scalable infrastructure solutions. Automated data analysis and visualization tools further streamline the identification of network issues, while standardized decision-making frameworks and enhanced communication tools improve the prioritization and resolution of these issues.

Efficient action implementation and resource allocation are crucial for resolving network issues promptly. Workflow management systems, task management tools, and real-time resource monitoring can optimize these processes. Prioritization frameworks and dynamic resource allocation techniques ensure that critical issues are addressed first, minimizing the impact on network performance and subscriber satisfaction.

Incorporating a well-defined service definition and leveraging customer experience data, such as achieved throughput and network connectivity, provide significant benefits. This data can help prioritize repairs more effectively than traditional PNM metrics by offering direct insights into the customer experience. By focusing on customer impact, operators can ensure that maintenance efforts are directed towards areas that will have the most significant positive effect on service quality.

Furthermore, the inherent flaws and unintended consequences of applying conventional statistical analysis to raw DOCSIS data underscore the need for more sophisticated and accurate methods. Ensuring complete and up-to-date network topology, geo-location of network elements, and entry point documentation is essential for enabling advanced processing, analysis, and reporting methods.

Ultimately, a successful PNM operation requires a holistic approach that integrates advanced technological solutions, standardized processes, effective communication, and collaboration among stakeholders. By addressing the identified challenges and implementing the proposed solutions, including leveraging customer experience data, and defining clear service standards, network operators can enhance the reliability, efficiency, and effectiveness of their PNM operations, leading to improved network performance and higher levels of subscriber satisfaction.

Abbreviations

AI	artificial intelligence
API	application programming interface
BER	bit error rate
CER	codeword error rate
CM	cable modem
CMTS	cable modem termination system
CX	customer experience
DFT, iDFT	discrete Fourier transform forward and inverse
DOCSIS	data over cable service interface specification
FEC	forward error correction
FFT, iFFT	fast Fourier transform forward and inverse
GPU	graphical
HFC	hybrid Fiber/Coax System
IT	information technology
KPI	key performance indicator
MAC	media access control
MER	modulation error rate
ML	machine learning
MTR	main tap ratio
NCTA	National Cable & Telecommunications Association
NMTR	non-main tap to total energy ratio
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiplexing with multiple access
PER	packet error rate
PNM	proactive network maintenance
PNM-WG	PNM working group
POI	Point of interest
QAM	quadrature amplitude modulation
QoS	quality of service
RPHY	remote PHY
RX	receive
RxMER	receive (channel) modulation error rate
SCTE	Society of Cable Telecommunications Engineers
SEM	service experience model
SNR	signal to noise ratio
SOP	standard
TPU	tensor processing unit
TX	transmit

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