Exploring the Benefits of Network Intelligence Applications to Optimize HFC Networks Using a Data-Driven Design Approach

A Technical Paper prepared for SCTE by

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1. Introduction

The ever-increasing demand for high-speed internet connectivity has led to the continuous evolution of Hybrid Fiber-Coaxial (HFC) access networks. To meet these demands efficiently, the adoption of data-driven design and operational approaches has become crucial. This paper delves into the benefits of data-driven design in HFC access networks, outlining how it can lead to improved efficiencies. Through the integration of advanced analytics, predictive modeling and optimization techniques, data-driven design empowers network planners and operators to make informed decisions, allocate resources more efficiently, and enhance network performance, which can lead to additional benefits including: reducing HFC networks' operational costs and their environmental impact through improved energy efficiency; extending the lifespan of network components, enhancing their reliability, and reducing the need for maintenance; improved signal quality and performance for end-users; and creating a more harmonious coexistence with adjacent frequency bands and other networks and services, enhancing overall network stability and customer satisfaction.

In the era of digital transformation, access networks play a pivotal role in delivering high-speed internet services to end-users. HFC networks, a combination of fiber and coaxial cable technologies, have long been a cornerstone of broadband infrastructure. However, the growing demand for bandwidth-intensive applications and the advent of new technologies necessitate innovative approaches particularly for network design. Data-driven design, which involves utilizing data analytics and modeling techniques to guide decision-making, emerges as a powerful tool to optimize HFC access networks.

The paper begins with an overview of traditional HFC architecture. Then we discuss key factors that influence Radio Frequency (RF) level optimization, including signal quality, noise, power levels and modulation schemes. Next, we explore challenges related to RF level optimization. Following that, we present the benefits of implementing Artificial Intelligence and/or Machine Learning (AI/ML) tools. Here we examine ways to leverage Cable Modem (CM) data to drive AI/ML tools to optimize HFC network design, performance, and efficiency. We will explore using CM data to dynamically optimize amplifier gain, output level, and performance while staying well above amplifier thermal noise floors and avoiding operation within the amplifier non-linear distortion region.

Then we explore the use of a data-driven approach using machine learning techniques for identifying RF signal issues and developing automated solutions for the detection and resolution of signal-impacting events.

We conclude with an analysis of signal data collected from approximately 14,000 CMs. The analysis examines the range of RF transmit and receive levels across all CMs to determine available operating margins for a given desired performance. We will also explore how CM RF operating margins can be used to help set the appropriate RF gain for outside plant amplifiers. This approach will seek to take advantage of the smart amplifier capabilities expected to be part of the next generation of 1.8 GHz amplifiers. Optimizing amplifier gain to better reflect actual network conditions may reduce the maximum gain requirements for individual amplifiers and lead to more optimal RF designs and deployments.

2. Factors Influencing RF Level Optimization in Hybrid Fiber Coax (HFC) Networks

The HFC network has been a foundation for the cable industry for decades. It combines optical fiber and coaxial cable technologies to deliver broadband services. Fiber optic and coaxial technologies enable operators to deliver multiple services to numerous users simultaneously.

As demand for high data rates and reliable communication increases, operators assess factors that affect connectivity. Thus, factors such as RF levels and signal quality are critical because they directly impact the internet connection's performance and stability. These factors also influence range and coverage for active devices. For instance, a strong and stable RF signal allows active equipment in the HFC network to communicate over longer distances without significant signal degradation. Conversely, weak or low-quality signals can limit the effective transmission range and may result in areas with poor connectivity.

2.1. RF Levels

In an HFC network, each active component receives the proper RF signal level from the previous active device and passes the correct signal level on to the succeeding active device. If the RF signal level is too low, the signal can be obscured by noise or interference. On the other hand, if the RF signal level is too high, the active device performance is nonlinear, which may cause distortions or, eventually, damage. Therefore, RF levels and signal quality are crucial for CMs' optimal operation. However, the strength of the RF signal alone does not necessarily determine how well the CM will perform in an HFC network. Thus, signal level into the CM should be carefully managed to prevent RF energy from being wasted.

Later in the paper we will explore the benefits of network intelligence applications that implement machine learning techniques to dynamically adjust RF parameters in active devices to optimize and better control RF input levels.

2.2. Signal Quality

RF signal quality is one of the most influential factors affecting the overall performance and reliability of HFC networks. It will dictate the highest levels of modulation orders the HFC network will support. Therefore, maintaining high-quality RF signals ensures downstream data remains accurate and undistorted when reaching the CM. Similarly, in the upstream direction, data integrity is crucial to optimizing performance at the input of the CMTS. Poor signal quality can lead to data errors, corruption, and even complete information loss, which may result in degraded performance or even system failure. How well the quality of the signal is managed will determine the service tiers and data rates that the network will support.

Later we will examine how network operators can determine correlations using a data-driven approach. For instance, how signal quality, CM received power levels, and performance (Modulation Error Rate (MER) in the downstream) combine to affect overall downstream and upstream throughput. We will then discuss how to leverage these correlations for the optimal configuration and set up of CM devices.

2.3. Noise and Nonlinear Distortions

RF signals are susceptible to various types of noise, which may significantly degrade signal quality. Noise and impairments that can degrade RF signals include: thermal noise, impulse noise, flicker noise, phase noise and intrinsic noise. These noise types may lead to poor signal reception, data corruption and communication errors. Thus, to provide high speed internet services that are reliable and efficient, network operators must understand the different types of noise, their sources, and how to minimize their impact. For example, optimal performance can be achieved by managing the input level into the amplifiers and staying as far away as possible from the thermal noise floor of all active devices. However, to avoid overdriving the power amplifier and CM devices, the optimal input level must be balanced against amplifier gain and output levels so as not to create unacceptable distortion levels.

In HFC networks, nonlinear distortion limits RF output levels and determines RF signals' maximum reach. It also determines the maximum number of RF carriers supported by active devices. Now that HFC networks use only digital carriers, the resulting nonlinear distortions are noise-like signals, described as Composite Intermodulation Plus Noise (CIN), which are generally indistinguishable from random noise. CIN products are signals generated by nonlinear interactions in RF amplifier components and changes in the input signals that may affect the frequency and amplitude of these intermodulation products [1]. This is why it is critical to carefully manage Total Composite Power (TCP) in active devices.

This kind of optimization requires continuous data analysis which is why network intelligence tools are extremely beneficial. Intelligent networking tools can help operators identify noise in HFC networks and take appropriate corrective action.

2.4. Modulation Technologies

Network operators have implemented advanced Orthogonal Frequency Division Multiplexing (OFDM) modulation technologies to increase transmission rates and overall throughputs. However, as the number of symbols and QAM modulation orders increases, sensitivity to noise and distortions also increases. Consequently, symbols are more difficult to isolate at the CM receiver [2]. OFDM uses low-rate subcarriers (long symbol times) orthogonal to each other and closely spaced with a cyclic prefix to ensure robust and efficient transmission. Moreover, OFDM subcarriers are modulated and spread over a wide frequency range. This allows a large amount of data to be transmitted in parallel over a single channel. The cyclic prefix acts as a guard interval that ensures that the transmitted symbols are orthogonal and the signal is faded [3]. OFDM technology allows operators to provide a variety of services to a wide range of users and applications, and allows operators to prevent narrowband interference by nulling sub-carriers.

However, OFDM can have a high crest factor, which is defined as the ratio of the peak to the average value of a signal. At the amplifier output stage, it contributes to determining the power margin to be reserved. Because of this, OFDM systems require efficient power amplification techniques to mitigate the impact of the crest factor.

Statistical functions, such as the complementary cumulative distribution function (CCDF), will be critical to specifying the power characteristics of the signals that will be amplified, mixed, and decoded in communication systems. For instance, CCDF can help reveal how an RF power amplifier may distort a complex modulated signal such as an OFDM channel. By comparing CCDF plots with different amplifiers at different average power levels, it could validate the linearity of the device. It can also reveal the introduction of data errors that can be caused by amplifier compression. The power of machine learning will help us leverage the use of CCDF plots as another tool for network operators to characterize and optimize device performance [4].

3. HFC Network Optimization Opportunities

As network operators begin 10G upgrades, complexities related to the expansion of the spectrum need to be addressed for HFC networks to perform optimally.

The complexities presented in this section have traditionally been addressed by network operators through a combination of technical expertise, manual processes, and collaboration between network engineers, operation teams, and vendors. We will present later how network operators can tackle complexities more efficiently by implementing network intelligence tools.

3.1. Coexistence with Legacy Systems

Over time, upgrading an HFC network to 10G will require operators to replace Customer Premises Equipment (CPE), which cannot be completed for all subscribers instantaneously. For a period of time, operators will need to support both legacy CPE and DOCSIS 4.0 CMs. To support legacy CPE while upgrading the HFC network, tap output power levels in the legacy spectrum must remain close to their pre-upgrade values. During the RF spectrum expansion period, optimal performance of both legacy CPE and CM could be at risk. RF spectrum expansions will also drive tap replacements and updated faceplate values to ensure proper RF input to CMs [5]. CM performance is also affected by the drop. It is noteworthy, however, that cable length and type will vary across installations.

3.2. Interference and Noise Mitigation

Operators focus on minimizing distortion and noise to improve HFC network alignment, allowing CMs to use higher-order modulation schemes. In an ideal HFC network, there would only be downstream and upstream modulated RF signals. There are unwanted signals, however, that are a consequence of real-world applications, such as HFC networks that transmit RF signals using coaxial cables that are subject to noise and distortion. Challenges in RF level optimization include identifying the sources of interference and noise, designing a system that is resilient to interference and noise, and maintaining a constant level of signal power across the length of the coaxial cable. Thus, when network operators implement network intelligence tools, interference and noise mitigation should be considered as part of the optimization process. Some AI tools are already being deployed to predict and adapt to changes in the environment.

3.3. HFC Network Reliability and Redundancy

Identifying and resolving potential network issues fast and accurately is imperative for network operators. However, doing so in remote areas may be particularly difficult as gaining access to the physical network can be time-consuming and costly. This concern is why network operators implement redundant systems such as power backup to ensure uninterrupted operations in case of failure. In a later section, we will discuss the benefits of deploying AI-based network analytics and monitoring tools to proactively identify and address network issues. Such tools can reduce network maintenance and operations costs, particularly in remote areas.

3.4. Capacity Expansion and Future-Proofing

As demand for bandwidth grows, network operators may implement several strategies to expand capacity and enhance their coverage. These include adding additional spectrum, upgrading HFC infrastructure and raising modulation orders. Modulation orders in particular can be optimized to fit those portions of the network that can reliably support higher transmission rates by utilizing AI/ML tools.

3.5. Network Monitoring

Due to a large number of components in the HFC network, implementing monitoring tools has sometimes been a challenge for network operators in that identifying issues maybe complex and time-consuming and network operators have often relied on manual debugging and troubleshooting. This method may delay the identification and resolution of network issues. We will present some of the benefits of implementing the right AI tools to help network operators automate the detection, diagnosis, and resolution of network issues to reduce operational time and improve the customer experience.

3.6. Upstream and Dowstream Power Balance

Because residential consumers are typically consumers versus producers of information, HFC networks operate with asymmetric data traffic, mimicking consumer behavior with downstream traffic being much higher than upstream. Though outside the scope of this paper, this asymmetry may be challenging when higher upstream capacity is needed since it traditionally requires a physical change of diplex filters in active devices. However, emerging technologies such as full duplex (FDX) seek to implement dynamic allocation of upstream and downstream bandwidth without the use of diplex filters and leveraging AI/ML tools. There are several interesting papers and articles to explore this topic further [11], [12].

4. An Updated HFC Network Upgrade Design Approach

Generally, operators' primary objective when planning HFC capacity upgrades will be to expand usable RF spectrum while maintaining as many existing network components as possible. HFC network upgrades will typically focus on maintaining amplifier spacing and legacy levels to minimize customer impact. Thus, HFC RF spectrum expansions require updating RF parameters such as gain, tilt, input, and output RF levels for all actives, as well as updating tap output level specifications to overcome higher drop losses at higher operational frequencies.

Traditional network operators implement a drop-in approach to maintain amplifier legacy locations by installing a new amplifier module with higher downstream and/or upstream bandwidth, helping minimize upgrade downtime and cost. As higher attenuation values are introduced at 1,794 MHz, amplifier output levels must be raised. This requires low noise, high gain amplifiers with a high degree of linearity that can handle large signal swings without distorting the signal, while maintaining efficiency so the amplifier does not exceed existing power consumption. Operators have mainly relied on semiconductor technology to maximize amplifier TCP and performance over existing coaxial cable spans while maintaining a quality output. This also ensures consistent amplifier RF gain and output levels to maintain unity gain and facilitate amplifier alignment. Advances in power amplifier (PA) technology are allowing operators to expand their bandwidth up to 1.8 GHz while leveraging their existing infrastructure. Despite the semiconductor industry's continuous efforts to increase TCP, it might not be enough to sustain a linear tilt due to power amplifier limitations. Thus, TCP has become a limiting factor, which may become increasingly important as operators implement higher frequencies. To ensure TCP is managed properly, operators must control amplifier parameters tightly and optimize output levels and gain levels.

Another challenge in traditional HFC designs is that RF parameters are conservatively set to accommodate a wide variety of deployment scenarios. RF amplifier gain is maximized to ensure enough RF budget to overcome the longest coaxial spans in the HFC network and maintain a unity-gain based design. However, this approach could lead to excess RF levels into amplifiers deployed over shorter spans. The excess RF would then need to be padded down at the input of the RF amplifier to target prescribed operational input levels and to avoid excessive distortions after RF amplification. However, this classic approach to HFC design fails to take advantage of input and output operating margins that may be available in RF amplifiers. Depending on desired minimum performance, RF input levels to an amplifier have the ability to vary over a range of values and still maintain performance, so lower-gain amplifiers may be just as effective. Tap levels that are universally designed to accommodate a "standard length" RF drop may similarly lead to unnecessarily high RF levels into home CMs connected to shorter drops.

Operators have traditionally relied on static conditions to determine the best design for an area. As an example, the process for downstream design can generally be summarized as the following:

- Determine a worst case or reasonable worst-case scenario for span losses.
- Determine a worst case or reasonable worst-case scenario for drop losses.
- Determine the optimal receive level of the end devices (modems and set top boxes).
- Determine the maximum output power and gain of amplifiers and nodes to meet the criteria mentioned above.

Although this has served operators well, it could lead to inefficiencies and higher construction costs if we were to analyze RF statistics typically available from subscriber terminal devices today. It should be noted that historically operators have not had full access to these data points which now include not only terminal devices but newer smart amplifiers as well. This is the primary reason why selecting a worst-case scenario has worked well.

Statistically the reason a worst-case design scenario works can be explained using the histogram below. Such histograms can be used to represent the range of CM input levels in a typical HFC network. We know almost every similar distribution can be represented as a normal or Gaussian type of distribution with a bell curve shape. Although the shape and skewness of the distribution can vary from operator to operator, for this example let us assume an ideal normal distribution.

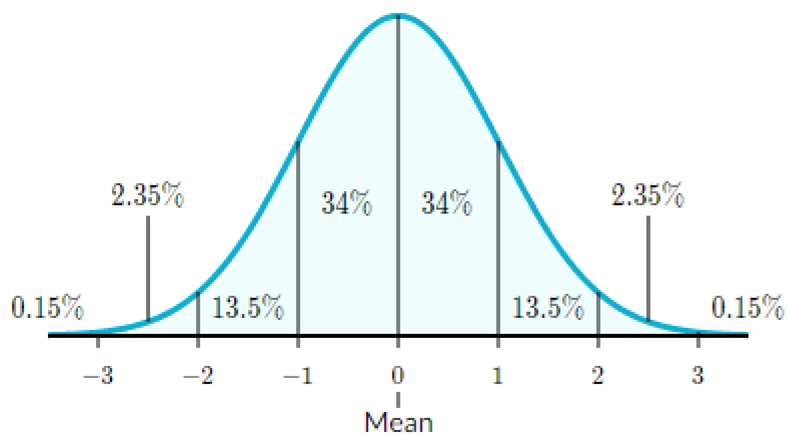

Figure 1 – Gaussian distribution [7]

To select a reasonable worst-case scenario in this case, we must choose an area that statistically is somewhat of an outlier, but not as far as three standard deviations from the mean. The reason for this approach is to cover as much of the farther ends of the network during the design phase and avoid making outliers of those areas, which would result in too much operational burden. While it might seem intuitive to maximize the output power of each amplifier and node to maximize reach, this can lead to over-engineered plants, a reduction in the useful life of amplifiers, and an overall reduction of the dynamic range of the system.

HFCs are always designed with an end device in mind. It is inherent that any design should be oriented toward an end device; in this case, a CM. This is true even if the outside plant designer might not design specifically for it. The complexity lies in the number of parameters to be accounted for, including (but not limited to): cable length, cable type, passive type, number of passives, and amplifier type. The HFC network design can be optimized with these factors in mind.

Because each segment of the network can be unique, it is not possible to account for every potential variation in the outside plant. A network is comprised of a series of insertion losses throughout, from the port of each active device to the port of each receiving device. This high variability makes outside plant design very challenging and can result in over-engineered HFC networks.

An outside plant amplifier's function is to provide adequate RF to the next amplifier in line to ensure enough level and to allow the signal to be repeated with the highest Signal-to-Noise Ratio (SNR). However, if an HFC network was designed to account for a certain span loss, but the actual loss is lower, extra actives are unnecessarily added to the network, which may result in amplifiers with high-value pads in their input ports and which can indicate excessive RF signal levels and, potentially, an overdesigned HFC network. Therefore, a different – and arguably more efficient – way of designing would be to allow each amplifier to use enough output power to reach the next amplifier with enough level. A detailed discussion of these benefits will be presented later, both from the perspective of signal quality and plant stability.

In addition, intelligent tools can be used to establish and leverage optimal RF operating margins for amplifiers and CPE to increase design effectiveness. CM data, including downstream and upstream signal strength and MER performance and errors, can also be analyzed to glean information about RF signals' health and performance through the HFC network. Similarly, telemetry from smart amplifiers and nodes can be collected and combined with CM data to select optimal amplifier gain profiles. Such optimized profiles will reach all CMs within a given geography while minimizing excessive RF levels into the home.

4.1. Statistical Analysis Tools to Enhance HFC Network Design

As mentioned above, TCP is a limiting factor when expanding downstream spectrum to 1.8 GHz. Expanding the downstream spectrum to 1.8 GHz requires the introduction of a step down in the output power spectral density (PSD) in the Outside Plant (OSP). As amplifiers cannot introduce this step down, the step down must be introduced in the node. With every dB of step down in the node output PSD, a one-to-one reduction in SNR can be expected in the node.

This approach results in a significant amount of capacity wasted. Figure 2 illustrates the difference between a high starting MER versus a low one, representing a 3-dB and 6-dB step down scenario. Note that carrier to composite noise ratio has been used instead of MER. The reason behind this is the fact that CCN is the true measure of plant performance, as it is not tied to any measuring device. While MER is directly tied to the measuring device's performance, making it a limited measure of performance.

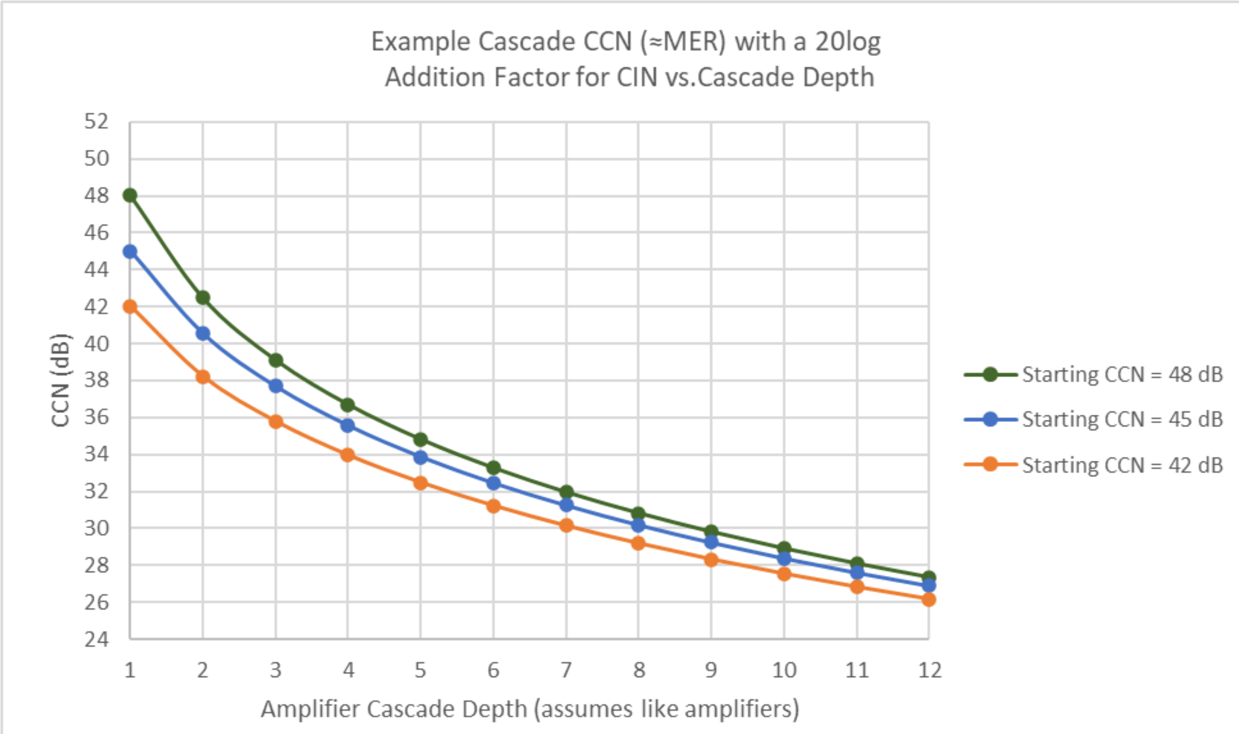

Figure 2 – CCN (≈MER) with a 20log addition factor for CIN vs Cascade Depth

Figure 2 is incredibly informative when it comes to design decisions and optimizations. In the bottom right hand of the graph, it can be seen that, as amplifier cascade length increases, a slow convergence occurs around a common value for CCN performance, regardless of the starting CCN or MER. This result is primarily due to the fact that noise and distortion products in the cascade dominate the signal quality aspect. By contrast, focusing on the left side of the graph, see that there is a wider gap in signal quality up to N+3. This result is also further emphasized knowing that the performance of each span is dictated by the active device, being the node or the amplifier.

As a result of implementing step downs, and the corresponding one-to-one SNR reduction for those frequencies impacted by the step down, quite a bit of aggregate capacity is sacrificed in the node as modulation orders for the higher frequency carriers are reduced in the stepped down areas. It can be argued that the use of step-downs to better manage TCP inadvertently sacrifices performance over shorter cascades for the sake of reaching the most distant ends of a network. Although historically designers may have focused on the last tap of the last amp, the results shown here further support the thesis that worst-case design methodologies can still be improved upon for even more optimal RF designs.

HFC networks are complex systems that often require time-consuming and costly simulations to optimize design and performance. AI-powered simulations can significantly speed up this process. Based on predefined performance metrics, automation can identify the most efficient setups by iterating through different scenarios. HFC systems can be fine-tuned for optimal performance using this accelerated design process not only by saving resources, but also by considering all factors that affect performance.

5. Incremental Benefits of Optimizing HFC Networks with AI and ML

A key component of operators' efforts to improve performance, reliability, and efficiency is optimizing their HFC networks. Monitoring system parameters, such as RF signal quality and CM received and transmitted levels, provides operators with valuable information for enhancing service reliability and user experience. Operators can benefit from network intelligence applications to analyze and optimize network performance based on CM data. Network intelligence applications that leverage data and automation can enhance service reliability and the user experience. Automation can help identify and resolve issues faster, while network intelligence can provide insight into HFC plant health by monitoring CM and amplifier behavior. This can allow for proactive optimization and quicker troubleshooting. Automation and network intelligence can also help reduce operational time and cost, while providing faster response times and improved reliability. Finally, integrating advanced analytics and automation tools into the network design process can help to ensure the best performance and reliability of the network.

HFC systems' inherent inter-complexities make manual optimization and troubleshooting daunting tasks. With AI, analysis of vast and intricate datasets becomes manageable. ML models can identify patterns, anomalies, and correlations that human operators might overlook, allowing for proactive identification of potential issues. In addition to improving overall efficiency and reducing downtime, ML-driven systems can help identify noise and interference, enhance HFC network capacity and potentially extend HFC network reach.

5.1. Improve Signal Quality and Performance

Robust RF signal quality ensures consistent and dependable communication while minimizing connectivity failures. The RF signal quality has an impact on the modulation schemes supported by CM, as mentioned previously. High-quality signals result in faster data transfers. RF signal quality cannot be overemphasized. It directly influences HFC networks' performance, reliability, and efficiency, making it a fundamental consideration in design and operation. With the use of network intelligence applications in HFC networks, it is possible for network operators to regularly monitor and diagnose signal quality with real-time data from CMs and active devices. Using network intelligence applications, operators can continuously monitor and analyze signal quality metrics such as SNR, MER, and bit error rate (BER) to diagnose signal quality problems. Using network intelligence, for instance, can help operators detect a range of impairments, from simple channel interference to more complex ones such as micro reflections. By continuously learning and adapting AI algorithms based on network data, operators can pinpoint the approximate location of the impairment and recommend appropriate solutions.

HFC systems that are AI-driven can dynamically adapt to changing network conditions, which is one of their major advantages. HFC network performance is influenced by factors such as user demand, signal noise, and signal degradation over amplifier cascades. Implementing AI algorithms that can continuously analyze these variables and adjust signal amplification, modulation orders, and profiles ensures optimal signal quality throughout the network. Adaptability results in consistent and better end-to-end performance, minimizing disruptions and improving the user experience.

5.2. HFC Predictive Maintenance

AI-driven automated management and monitoring systems can help operators quickly identify and address issues without having to physically access the network. Furthermore, AI-driven design introduces a level of proactive maintenance that is invaluable in HFC systems. This foresight enables operators to replace or repair components before they lead to network disruptions. As a result, system downtime is minimized and maintenance becomes a planned, rather than reactive, process. Predictive maintenance allows operators to use data analytics to anticipate potential problems. AI-driven analysis enables network operators to detect subtle changes in the system that would otherwise remain unnoticed. This proactive approach can help operators identify and address potential issues before they occur. This will reduce system downtime and encourage them to plan for maintenance and repairs in advance.

5.3. Enhance Network Capacity and Efficiency

Advances in network optimization and virtualization also help operators manage their networks more effectively. Virtualization is being promoted deeper in the access network to bring services, resources, and intelligence closer to subscribers in the HFC plant. A virtualization platform that applies numerous applications and software-driven technologies powered by AI enables operators to expand revenue streams and optimize operations across their networks. Operators can also gain insights from multiple sources and make informed decisions efficiently by using data from multiple sources. Furthermore, it helps minimize risks associated with deploying new applications by scaling operations with increased demand [6].

For instance, virtualized cable access networks can dynamically manage network traffic more efficiently, resulting in increased throughput. With ML, operators will be able to identify and analyze more efficient network paths, thereby optimizing their network resources and maximizing bandwidth usage. With ML, operators can identify and predict traffic patterns to ensure that network demands are met during peak periods, for example.

Another benefit is that network intelligence can also be used to forecast demand and capacity needs, helping operators plan for the future.

5.4. Minimization of Interference and Noise

Intermodulation products and noise can be predicted through careful analysis, so their impact can be minimized. This reduces signal noise and increases network efficiency. Based on historical data and usage patterns, AI models can predict potential noise and interference-related problems in active RF devices. In addition, network intelligence applications implement AI algorithms to extract relevant features from the data. These features may include frequency, amplitude, phase, and time-domain characteristics. By analyzing these features, AI algorithms can identify abnormal patterns indicative of noise, interference, or distortions. Machine learning algorithms can also be used to learn from datasets containing both clean and noisy examples of RF signals. The classification of signals as noise-free or noisy can be done using supervised learning techniques including support vector machines (SVMs) [8], decision trees, random forests, and convolutional neural networks (CNNs) [9], as well as unsupervised learning to identify anomalous patterns or deviations from expected behavior that may indicate noise or distortion [13,14].

5.5. Extending the Reach of HFC Networks

By optimizing the amplifiers, HFC networks can be improved to provide better coverage and higher data speeds, in addition to ensuring the signal is strong enough to reach the user without being excessively strong to avoid distortions that may compromise the signal quality. Improved distortion and noise analysis are imperative to ensuring CMs can operate with higher modulation orders.

Operators can take advantage of CM received level margins to optimize amplifier performance by dynamically adjusting signal strength across the network, mitigating both over-amplification and the risk of creating distortions.

5.6. Power Efficiency

The HFC outside plant can benefit significantly by operating at peak efficiency, meaning lowering amplifier output power and reducing power draw. The first benefit of this strategy is that it can **reduce HFC networks' operational costs and their environmental impact through improved energy efficiency**. Amplifiers may consume a considerable amount of power in HFC systems, which can be decreased by reducing their output power and power draw. This may result not only in cost savings, but also in contributing to a greener and more sustainable infrastructure, which aligns with the growing emphasis on energy conservation in the telecommunications industry [10].

The second benefit of reducing amplifier output power is that it can **extend the lifespan of network components, enhancing their reliability and reducing the need for maintenance**. Increasing output power may result in overheating components, signal distortions, noise or other impairments, which may degrade the quality of transmitted signals and increase error rates. Operating amplifiers at lower power levels allows for signal integrity to be maintained, leading to more robust network performance which may result in fewer service interruptions, less downtime and, ultimately, improved customer satisfaction.

Third, reduced amplifier output power can lead to **improved signal quality and performance for end-users**. Lower power levels reduce signal distortion and noise, leading to cleaner and more reliable signals reaching subscribers' homes, meaning cable TV and internet service providers can deliver higher-quality video and audio.

Lastly, maintaining tighter control over signal power through lower output power levels can mitigate issues related to signal leakage and ingress, giving HFC operators **a more harmonious coexistence with adjacent frequency bands and other networks and services, enhancing overall network stability and customer satisfaction**.

Using AI algorithms, amplifier bias can be adjusted to optimize amplifier power efficiency in real time, allowing for dynamic changes to the amplifier and enabling it to operate at peak efficiency, saving energy and reducing operating costs.

6. Future Directions and Emerging Technologies

AI-driven design in HFC systems holds immense promise for enhancing efficiencies and end-to-end performance due to the intricate inter-complexities of the variables inherent in such systems. HFC networks, which combine optical fiber and coaxial cable, are the backbone of modern broadband services. The complexity of a network arises from the need to balance factors like signal quality, bandwidth allocation and network maintenance. With AI's ability to analyze vast amounts of data and optimize these variables in real-time, HFC systems can operate with greater precision.

The integration of AI-driven design into HFC systems marks a transformative leap in efficiency and end-to-end performance. The complex interplay of variables inherent in these networks is effectively managed through real-time adaptation, proactive issue identification, proactive maintenance, and accelerated design optimization. AI empowers HFC systems to operate at their peak potential, delivering reliable and high-quality services to users while minimizing downtime and operational costs. As technology continues to evolve, AI's role in enhancing HFC systems' efficiency and performance is bound to become increasingly indispensable.

AI has also emerged as a transformative force in the realm of technology, and its application within Software-Defined Networks (SDNs) in HFC systems holds immense promise. SDNs have revolutionized network management by decoupling the control plane from the data plane, allowing for centralized control and dynamic configuration. When integrated with AI capabilities, SDNs in HFC systems can greatly enhance network performance and efficiency. AI algorithms can analyze massive datasets generated by HFC networks, identifying patterns and anomalies that might be missed by traditional network management systems. This data-driven insight enables predictive maintenance, where potential issues are detected in advance and network resources are optimally allocated, leading to minimized downtime and improved user experience.

Moreover, AI can play a pivotal role in optimizing bandwidth utilization within HFC systems. By leveraging machine learning algorithms, SDNs can intelligently allocate bandwidth based on real-time demand, ensuring that network resources are dynamically allocated where they are needed the most. This capability is particularly beneficial in HFC systems, which serve as a critical infrastructure for broadband internet and cable television services. With AI-powered SDNs, operators can adapt to varying traffic patterns, allocate bandwidth for streaming services during peak hours and prioritize critical applications for seamless performance. As a result, end-users enjoy smoother streaming experiences, while service providers can make more informed decisions on capacity planning and network upgrades.

Figure 3, below shows the traditional silos associated with each segment of the HFC:

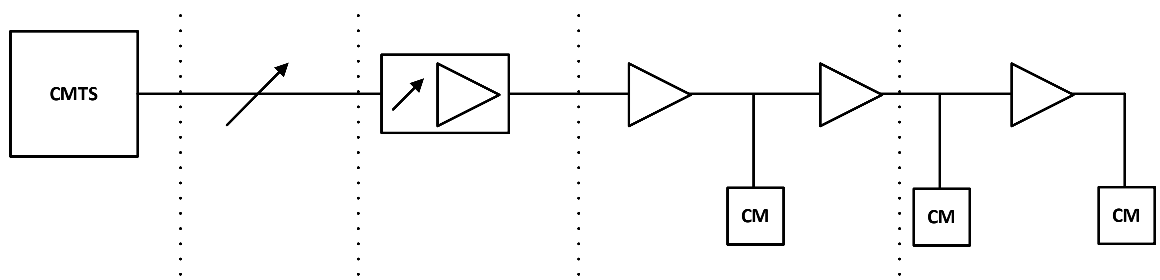

Figure 3. Traditional HFC segment

In an SDN environment, the HFC network is treated as an end-to-end system, which dramatically increases the efficiency and quality of the system as shown in Figure 4:

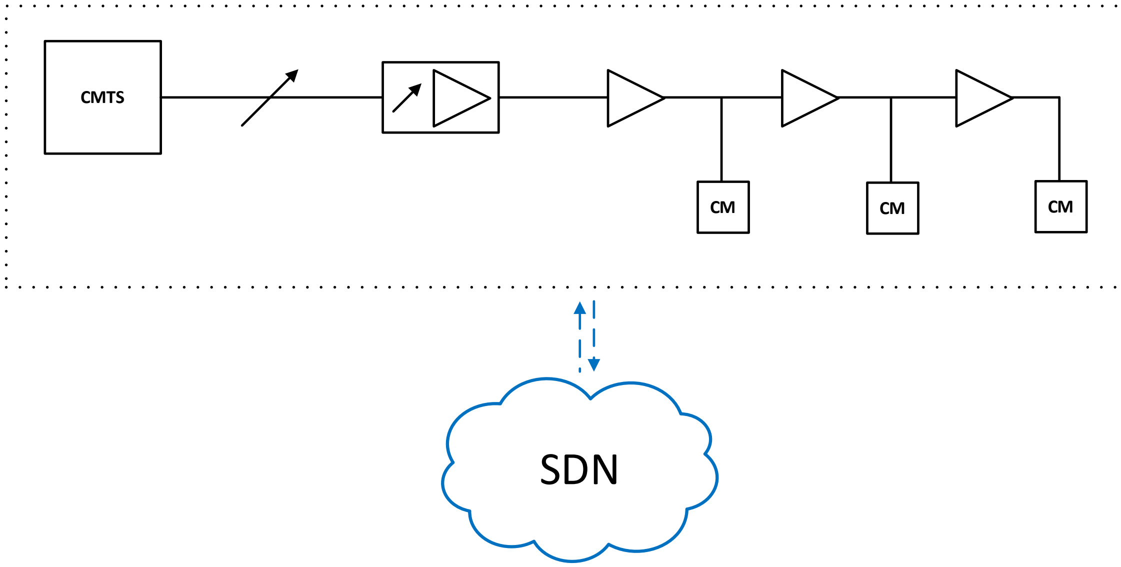

Figure 4. HFC segment with SDN

As AI algorithms become more sophisticated, they can also be used to predict future user demand and network requirements. This allows proactive optimization of HFC networks and can also automate complex manual tasks, freeing up personnel to work on innovating tasks that can drive the organization forward.

As AI algorithms evolve and network convergence is implemented, operators can enable self-healing capabilities in their networks. AI algorithms can, for instance, reroute traffic when noise or interference is detected. They can also dynamically adjust RF parameters or perform other corrective actions to maintain optimal performance.

7. Case Study

The following analysis is based on data collected from approximately 14,000 production CMs. From received (Rx) level histogram in Figure 5, it is observed that there is a wide range between the lowest and highest CM Rx levels; with few CMs as low as -17 dBmV/6.4 MHz, and CM Rx levels as high as +17 MHz/6.4 MHz. While CM received levels span a wide range, roughly 85% of them are above -5 dBmV/6.4 MHz. This is an indicator that traditional HFC design does not always result in a converged set of CM Rx levels. This confirms that HFC networks usually produce levels above the minimum specifications due to reasons previously mentioned.

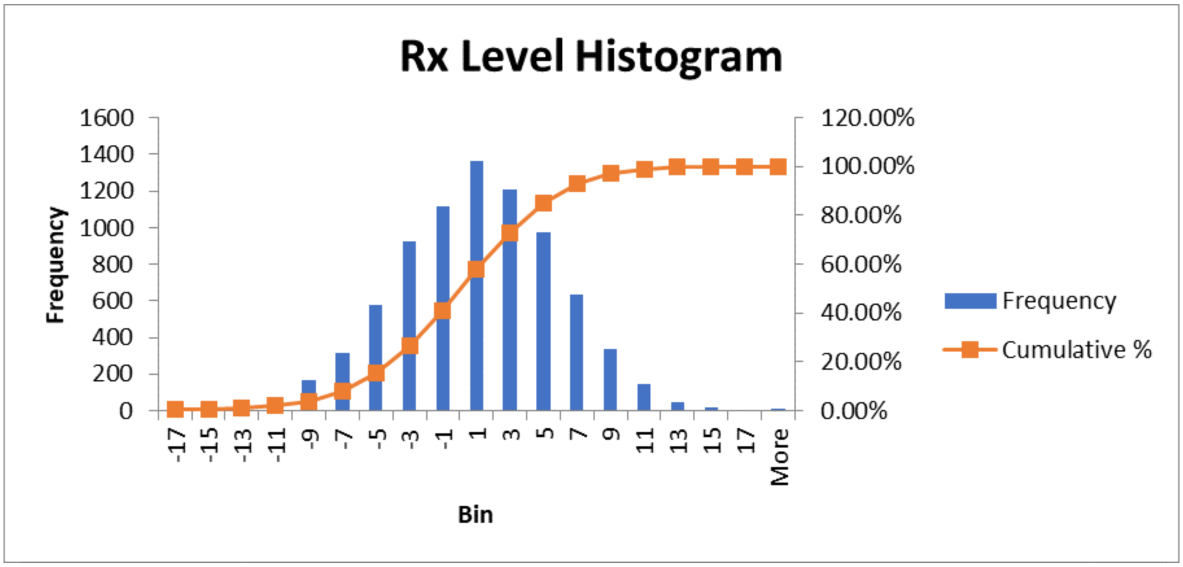

Figure 5. CM Rx level histogram and cumulative curve

The same holds true for CM transmit (Tx) levels. As shown in Figure 6, the Tx level histogram has a wide range. Despite the expectation that all CM Tx levels should converge based on target tap input if drop engineering assumptions are followed in the field, the conventional HFC design using static numbers to maintain unity gain results in a wide range of transmission levels due to the factors mentioned above.

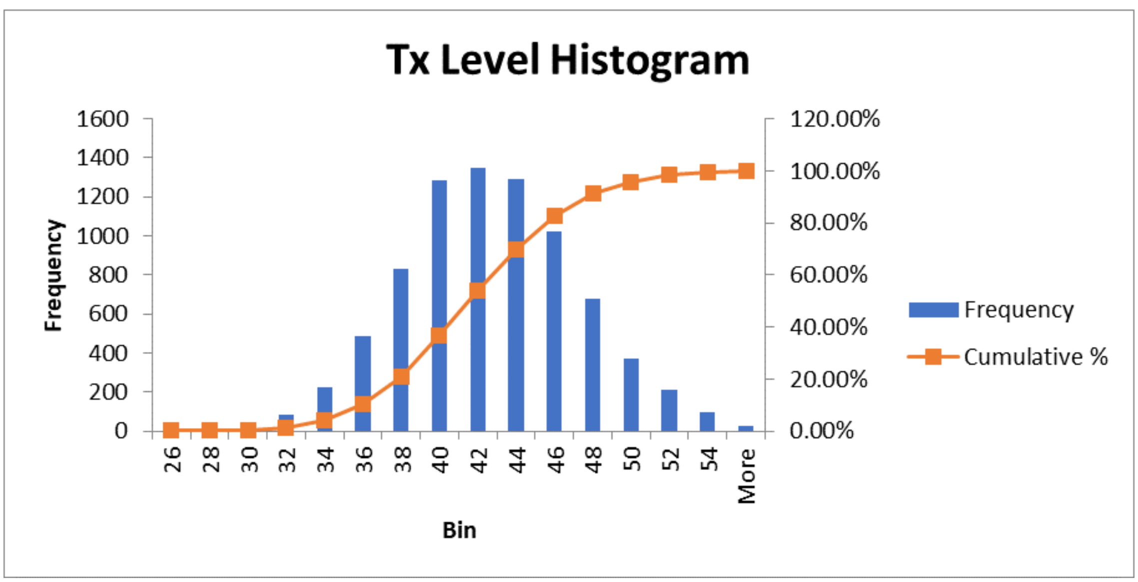

Figure 6. CM Tx level histogram and cumulative curve

It can be seen that the two distributions in Figures 5 and 6 are very close to perfect Gaussian distributions. Some interesting observations can be made. Let's begin by focusing on the CM receiving levels shown in Figure 5. There is a wide range between the lowest and highest RF receiving levels that CMs report. This is an indicator that the historical approach to design does not result in a converged set of receive RF levels. Remember that on paper many designers and engineers would consider a modem receive level range of between -5 dBmV to +5 dBmV to be ideal. In this example, however, the range is much wider, indicating the need for further optimization of the distribution network than can be achieved through a traditional approach.

The same observation holds true for transmit levels. The wide range indicates that setting a static number at the unity gain point for the return path will result in a wide range of transmit levels. The traditional design for modems would consider a transmit level range of between +40 dBmV and +48 dBmV to be ideal. This also offers opportunities for further optimization.

To assess the receive signal quality for each modem, let's consider both the upstream and downstream levels. Figures 7 and 8 show the histograms for downstream and upstream signal quality, measured at the cable modem and the CMTS, respectively.

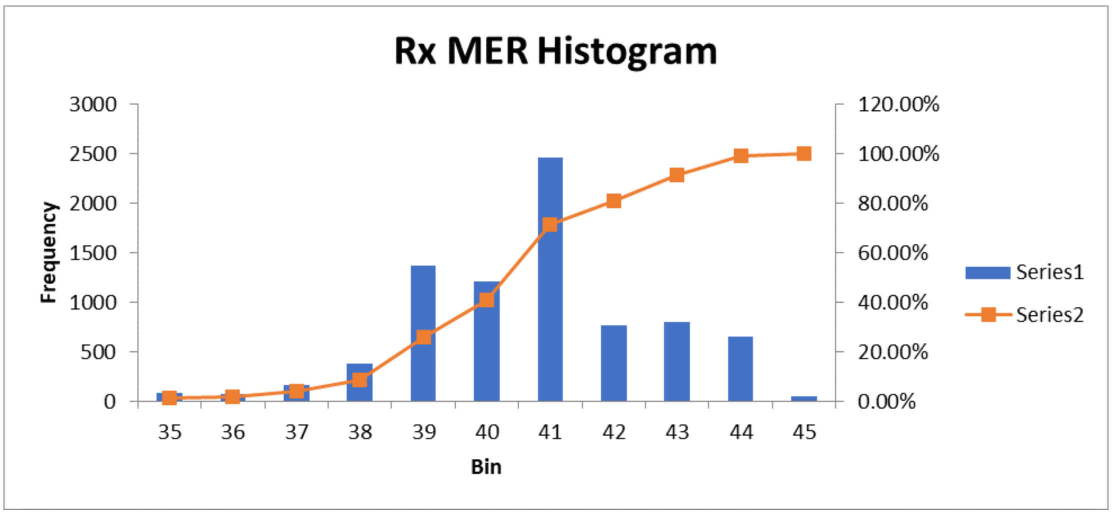

Figure 7. CM Rx MER Histogram and cumulative curve

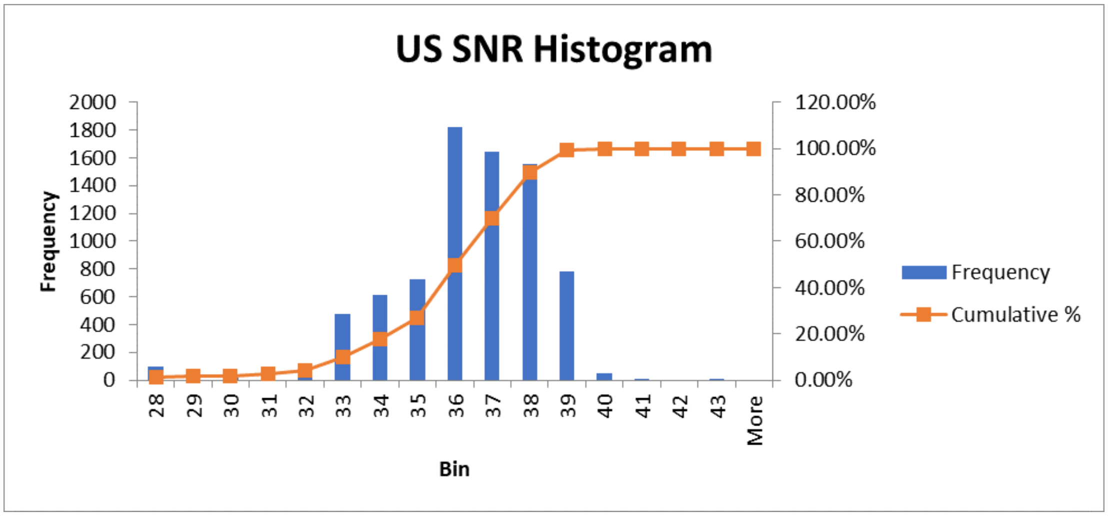

Figure 8. CM US SNR histogram and cumulative curve

It can be observed that both distributions are heavily skewed to the left with downstream MER skewness measured at -1.65 and upstream measured at -1.86. Although this may seem surprising, it is a perfect example of the design artifacts discussed in previous sections. In a cascade, particularly after the 2nd and 3rd amplifiers, downstream performance is dictated by cascade depth (noise and distortion) rather than signal level. This is further confirmed in the upstream by the fact that from the data set, there is a loose correlation between upstream transmit level and upstream MER (0.14).

Furthermore, the analysis of this study suggests that higher transmit levels from the cable modem in the upstream and higher receive levels in the downstream do not necessarily correlate with higher SNR/MER as predicted earlier in this paper. This indicates that the SNR/MER values are not necessarily dependent on the transmit/receive levels. Therefore, it is important to consider other factors when determining the optimal SNR/MER values for a modem.

8. Conclusion

AI and ML based tools have begun to play a key role in the management of HFC networks and should also be considered to help design and optimize HFC networks to improve efficiency. The power of AI and ML tools comes from the following.

- Collection of device telemetry in real time.
- Data analysis and identification of performance trends in real time.
- Recognition and diagnosis of potential network impairments in real time.
- Identification of optimal operating margins for amplifiers and CPE devices.
- Selection and application of optimal gain profiles for active devices.

Data-driven design revolves around the collection, analysis and utilization of network-related data to drive better decision-making processes. In the context of HFC networks, this encompasses data on subscriber usage patterns, network topology, equipment performance and environmental factors. By harnessing this wealth of information, network planners can gain valuable insights into network behavior, capacity requirements, and potential bottlenecks, which allow for operations at peak efficiency.

Operating at peak efficiency delivers a number of benefits, including: reducing HFC networks' operational costs and their environmental impact through improved energy efficiency; extending the lifespan of network components, enhancing their reliability and reducing the need for maintenance; leading to improved signal quality and performance for end-users; and creating a more harmonious coexistence with adjacent frequency bands and other networks and services, enhancing overall network stability and customer satisfaction.

Abbreviations

AI	Artificial intelligence
BER	Bit error rate
bps	Bits per second
CCDF	Complementary cumulative distribution function
CIN	Composite intermodulation plus noise
CNN	Carrier-to-composite noise ratio
CNNs	Convolutional neural network
CM	Cable modem
CPE	Customer premises equipment
FDX	Full duplex
FEC	Forward error correction
HD	High definition
HFC	Hybrid fiber coaxial
Hz	Hertz
MER	Modulation error rate
MHz	Mega hertz
ML	Machine learning
OSP	Outside plant
PA	Power Amplifier
PSD	Power spectral density
Rx	Received
TCP	Total Composite Power
Tx	Transmitted
SCTE	Society of Cable Telecommunications Engineers
SDN	Software defined networks
SNR	Signal-to-Noise Ratio
SVMs	Support vector machine

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