Real World Strategies for Hyper Scaling Success

OFDMA in Action

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Table of Contents

List of Figures

List of Tables

Title **Page Number**

1. Introduction

In 2023, Comcast made the bold decision to dramatically expand our orthogonal frequency division multiple access (OFDMA) deployments across our hybrid fiber coax (HFC) footprint. Our unwavering focus on expanding the OFDMA capabilities, along with the subsequent enablement across the data over cable service interface specification (DOCSIS®) 3.1 devices on our networks has significantly improved upstream (US) capacity across our markets. This strategic initiative has given us an advantage, leading to the introduction of new high-speed US offerings for our valued customers.

Throughout this journey, we encountered various obstacles and challenges, from plant-related issues to compatibility problems with end-user devices. However, overcoming these challenges is a testament to our commitment to delivering exceptional products to the customers and businesses we serve with a focus on learning, scaling, and efficiency.

Adopting OFDMA has met a vital market demand, significantly enhancing customer experience and satisfaction. Our initiatives have played a key role in facilitating the successful nationwide deployment of DOCSIS 3.1. This document will cover the lessons learned, the tools and processes utilized, and the improvements observed as we continue implementing OFDMA across the network.

2. Understanding DOCSIS OFDMA

2.1. OFDMA

OFDMA allows effective use of the upstream radio frequency (RF) spectrum in the cable plant and additional functionality and flexibility when using DOCSIS. An OFDMA channel has several advantages over single-carrier quadrature amplitude modulation (SC-QAM) signals. OFDMA channels are more efficient because they leverage overlapping orthogonal parallel narrow-band channels called subcarriers. OFDMA provides more granularity for configuration which allows spectrum to be used optimally and helps cope with common plant-related issues.

SC-QAM and OFDMA channels differ significantly both at the physical layer and with the amount of DOCSIS configurable parameters available. Since the subcarriers are orthogonal, it eliminates crosstalk and inter-symbol interference, removing the need for guard bands. Multiple cable modems (CMs) can share the upstream spectrum more efficiently using OFDMA.

Figure 1 compares a single SC-QAM and an OFDMA channel in the frequency domain. Each subcarrier can carry an independent data stream and support different modulation orders to adapt to noise events. The many configurable parameters allow operators to optimize each OFDMA channel and may assist with overcoming impairments.

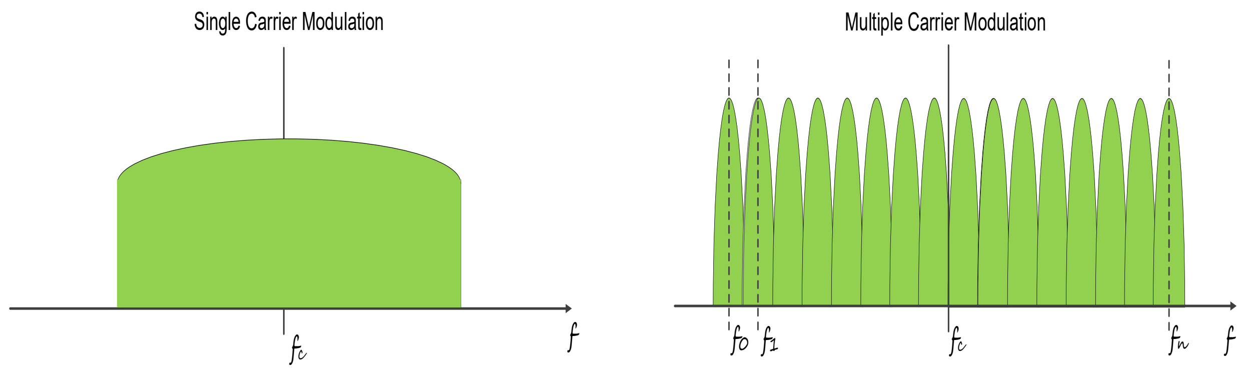


Figure 1 – Single Carrier vs Multiple Carrier

2.2. OFDMA Additions Beyond Traditional SC-QAM

A DOCSIS OFDMA channel consists of several components, all of which add to what was available with traditional SC-QAMs.

- **Subcarriers**: The physical layer of an OFDMA channel comprises numerous orthogonal subcarriers. These are narrowband frequencies that overlap for spectral efficiency. Each subcarrier can carry an independent data stream.
- **Subcarrier Spacing:** The distance between adjacent subcarriers can be 25 or 50 kHz based on the desired configuration.
- **Frequency Range:** DOCSIS 3.1 OFDMA channels can occupy the frequency range of 5-204 MHz and can have a channel bandwidth of up to 96 MHz (95 MHz occupied bandwidth). The wider available spectrum, OFDMA channel bandwidth and better efficiency of OFDMA enables much higher data rates than D3.0 SC-QAM channels.
- **Pilots:** These are reference signals embedded within the OFDMA channel to assist the CMTS in accurately demodulating the data and correcting for impairments. The pilots act as a feedback mechanism to the cable modem termination system (CMTS) about the channel under use.
- **Data Symbols:** These carry user data and are modulated onto individual subcarriers using quadrature amplitude modulation (QAM).
- **Guard Bands**: These are unused frequency spaces at the edges of the OFDMA channel to prevent interference with adjacent channels. They are commonly used when adjacent channels are SC-QAM since adjacent OFDMA channels do not interfere with each other as a spectrum efficiency advantage that OFDMA provides.
- **Precoding**: low-density parity-check (LDPC) is the technique used in precoding that improves the robustness of the OFDMA signal against noise and interference, enhancing the channel's overall performance.
- **Adaptive Modulation and Coding (AMC):** This allows the cable modem to dynamically adjust each subcarrier's modulation and coding scheme to optimize data throughput and error correction based on the channel conditions. Comcast uses a tool we developed called Octave based on profile management application (PMA) to take advantage of these features.
- **Higher Modulation Orders:** D3.1 introduced higher modulation orders and by consistently analyzing the OFDMA channel, we can leverage the higher modulation orders and achieve more throughput. In Figure 2 you can see a visual example of these modulation differences and supported modulations in OFDMA.

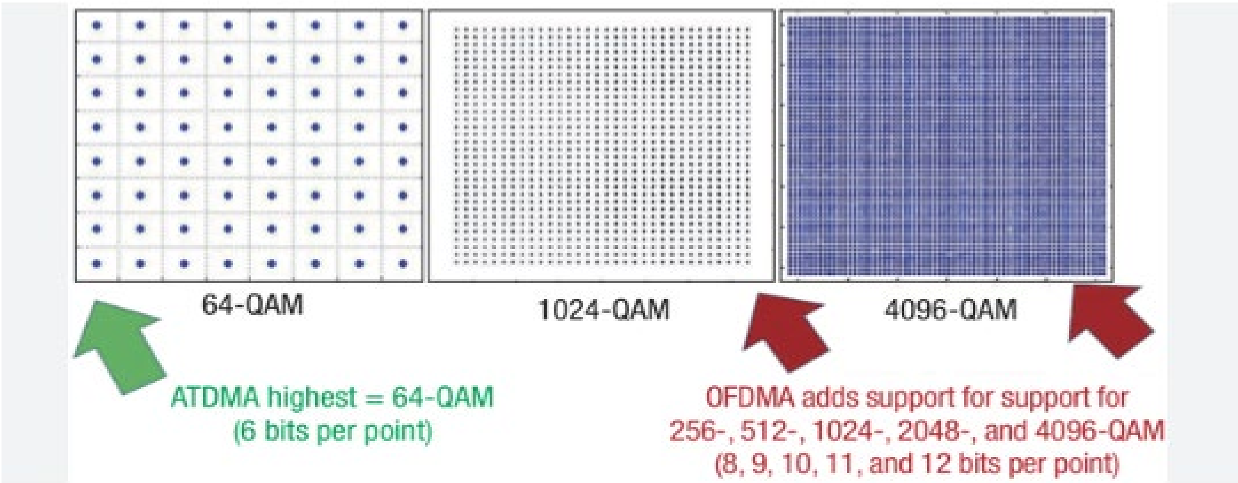


Figure 2 – DOCSIS Modulation Comparisons

All these components above work together to create an efficient and flexible channel for transmitting data in DOCSIS 3.1 networks.

Adding OFDMA in new spectrum regions not previously used means that we will encounter new interferences that the DOCSIS signaling must overcome. When impairments are in the network and reside under our active DOCSIS channels, using the higher modulation orders for error-free transmission is not always applicable. By using combinations of the parameters in the OFDMA channel we can create specific configurations that allow us to overcome challenges and continue to deliver our highest speed rates by using the highest available modulation rates as often as possible.

2.2.1. FEC and OFDMA Operation In Impaired Environments

LDPC is an improved error correction process that helps achieve performance close to the theoretical Shannon limit, stated as the maximum achievable rate for reliable communication over an impaired channel. Loss of packets and DOCSIS messaging can interrupt the delivery of services. Forward error correction (FEC) is used to overcome and mitigate the loss of data codewords. LDPC is a type of FEC encoding that D3.1 leverages. LDCP is a mechanism meant to improve the reliability and efficiency of data transmission over undesirable conditions, within noisy channels and active channels in well-known ingress spectrum regions. It works before transmission and the original data goes through an encoding process. The LDCP process adds redundant parity bits that allow the damaged data to be recovered at the receiving end. It is configurable, and flexible, while consistently doing comparisons and calculations to determine ways to recover the originally transmitted data.

2.2.2. OFDMA on a Spectrum Analyzer

Viewing OFDMA channels on an analyzer is a crucial part of deployment, whether measuring the signal in the lab or meters in the field. Knowing the distinct difference between SC-QAM and orthogonal frequency division multiplexing (OFDM) or OFDMA channels is important. Paying special attention to a notable difference in the distinct gaps between SC-QAM channels versus the continuous set of overlapping subcarriers observed in the OFDMA block should be noticeable in the analyzer capture below. Figure 3 depicts four 6.4 MHz SC-QAM channels and a single 45.6 MHz wide OFDMA block spanning from 39.4 MHz to 85 MHz, as seen on a lab spectrum analyzer. The display offers a comprehensive view of the time and frequency domain, with power markers for measuring the integrated band power of the channels. It is important for efficiency in deployments to first check the accuracy of metrics with actual measurements of signals for early comparison. Then when using tools that leverage these metrics you can understand reported tolerances and limitations.

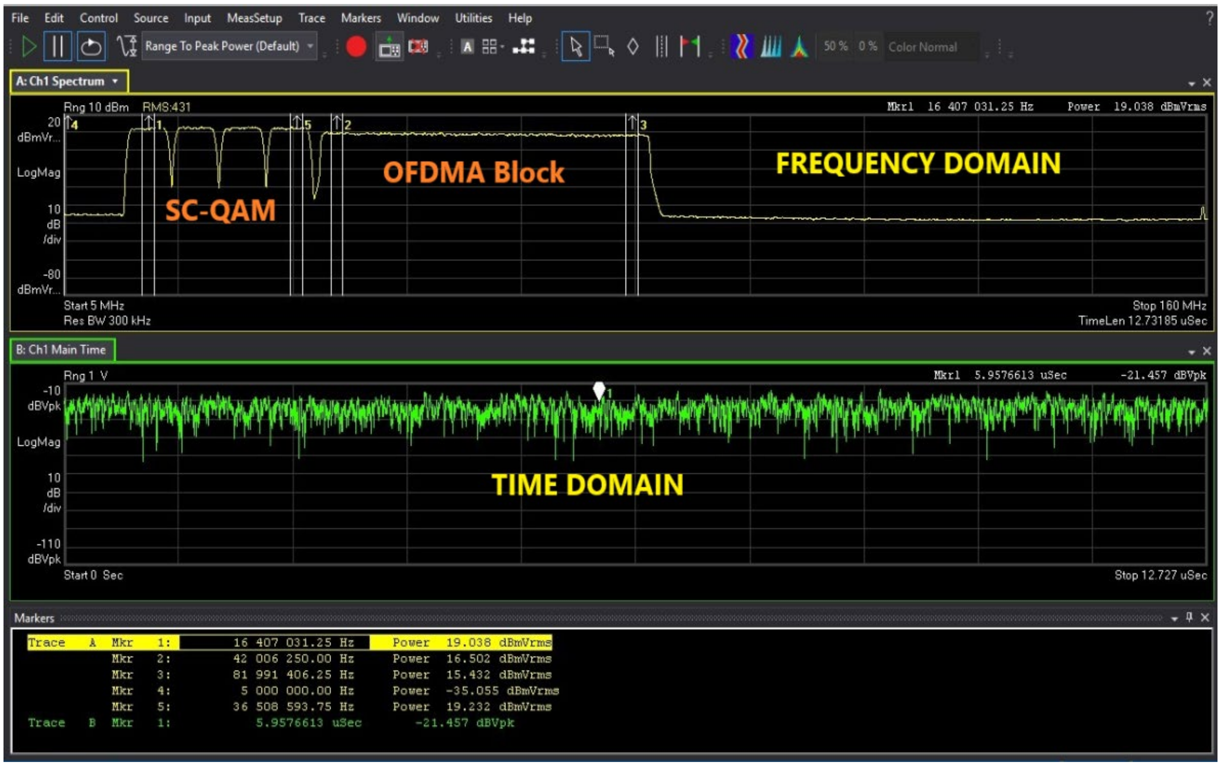


Figure 3 – RPD Upstream on Analyzer Capturing SC-QAM and OFDMA Active Channels

Proactive network maintenance (PNM) is a DOCSIS specification that users can build upon to enhance spectrum analysis tools. Management information base (MIB) data for full band capture (FBC) represent signals received at the RF port of the modem. Similarly, the remote physical layer device (RPD)/CMTS can report these values from its respective view. The tools can utilize data from the RPD telemetry query and be stitched together to represent spectrum analysis in a regularly monitored and updated graphical user interface (GUI). Comcast developed the **Yeti** tool for this purpose. The tool is close to real-time and can also be coupled with other channel-related metrics in one place. Figure 4 shows four 6.4 MHz SC-QAM channels and a 45.6 MHz wide OFDMA channel spanning from 39.4 MHz to 85 MHz as a visual example from the Yeti tool.

Figure 4 – YETI – Upstream Capture of RPD/CMTS RF Port Along With FEC Statistics

2.3. OFDMA Spectrum Allocation

In traditional sub-split deployments, many network devices limit the upstream spectrum to 42 MHz. Examples include amplifiers, customer premises equipment (CPE), nodes with diplex filters, and other network passives, such as equalizers (EQs). As we work to enable mid-split, ensuring the network is ready to support the new configuration is crucial.

The key to our enablement efforts was ensuring all equipment between the CMTS and CPE could fully support the broader 5 MHz to 85 MHz upstream spectrum. Once we have passed this step, we can leverage this previously unused spectrum for new OFDMA channels. Depending on the operators' requirements, the OFDMA channel can be configured anywhere in this newly expanded 5 MHz to 85 MHz region. However, adding an OFDMA block to this spectrum can lead to new challenges.

Along with the new spectrum allocation for upstream and downstream (DS) operations, we had to understand the potential impact on customers' legacy devices, such as set-top boxes, when using OFDMA in the US spectrum. In addition, we needed to understand the difference in the HFC plant when using this new spectrum, including new noise challenges. Furthermore, we had to understand the modem and CMTS configuration changes, OFDMA bonding in general, and supporting new OFDMA partial alerts.

Overall, proper internal education was needed. Many teams and dedicated resources had to work together effectively to ensure OFDMA and mid-split deployment were successful and continually managed. Some of these challenges forced us to develop new tools and monitoring to work through issues.

3. Proactive Process and Tooling

3.1. Configuration Changes

Reconfiguring the CMTS to accommodate for mid-split and OFDMA additions was required. We had to decide what spectrum to allocate for OFDMA and configure the OFDMA channel with DOCSIS available parameters to meet our desired optimizations.

Configuration changes included adjustments to the downstream as well as upstream. Downstream video QAM channels need to be moved above 108 MHz, and the number of downstream video and SC-QAM channels needs to be adjusted to account for the new overall downstream spectrum. We needed to be mindful of where we placed leakage tones. The operator must consider the support of video, legacy devices, local channel insertion, and leakage.

With the addition of OFDMA, several specific considerations for the upstream came into play. These included ensuring ranging frequencies are not placed in noisy spectrum, managing forward error correction, configuring channel templates, media access control (MAC)-domain, bonding groups, and adding service classes as needed.

3.2. Configuration Automation

Automation and version control are necessary when configuring the changes needed to move the spectrum and configure new channel parameters. Tools must be in place to quickly roll out, revert, validate, view, and compare configurations. Operators must automate for efficiency and utilize version control since each part of the process should work together cohesively. These tools work together using application programming interface (API) access and sharing information with a set of best practices and a well-defined methodology.

Automation is fully implemented and embraced in our validation and ongoing monitoring and is integral to many aspects of network deployment. We employ various tools, including Watchtower and XMeter Edge (XME) lens developed by Comcast, to understand plant issues and conditions. Other critical tools such as Morpheus, which fall under the umbrella of network deployment automation, include pre and post-checks, online and offline device monitoring, configuration implementation, rollback automation, post-cut validation, and management of trouble calls related to configuration and deployment changes. Close engagement with the field is crucial to prioritize work, manage the workforce, and address issues before deployment, ensuring a smooth and stable network.

Figure 5 below, is a screenshot of Morpheus. As mentioned above, this tool is key for managing deployments. Morpheus allows you to link to the correlating change ticket, GitHub to view the changes, and Concourse that supports the implementation including the pre and post-check validations.

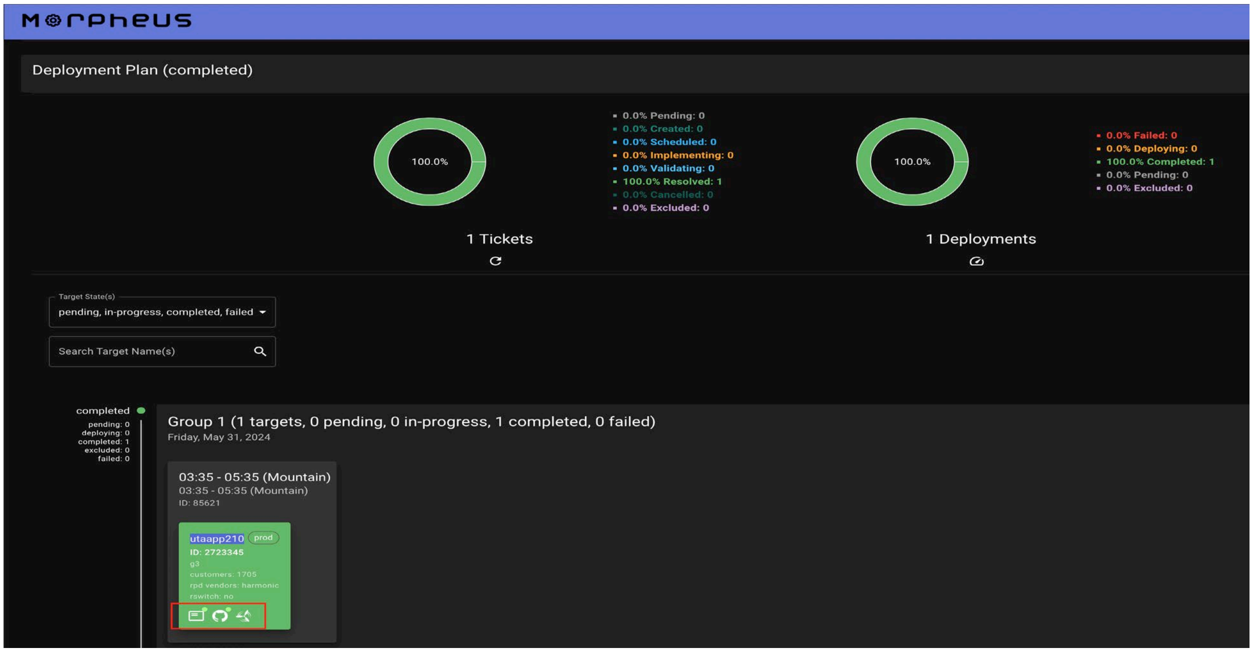


Figure 5 - Screenshot of Morpheus

3.3. Channel Mapping – Shifting Channels and Modem Steering.

Spectrum allocation and reclamation are vital to adding and enabling OFDM and OFDMA channel deployments. Downstream channel plans vary from region to region, and we needed to move or consolidate channels. For available upstream channels, we shifted from using six SC-QAM channels to four SC-QAM channels with the addition of OFDMA.

Plant conditions may vary, often requiring upstream OFDMA parameters and spectrum adjustments. In-home assessment tool (iHAT) is a valuable tool in identifying potential video interference and determining a device's suitability for the OFDMA spectrum. Suppose iHAT detects that a device cannot utilize the OFDMA spectrum due to a drop amp or other network device blocking the spectrum, or it detected set-top box (STB) video interference. In that case, we can employ dynamic bonding changes (DBC) to redirect modems to bonding groups without OFDMA, reducing the impact on customer video experience, or limiting partial alerts.

Additionally, to support efficiency, we developed an automated channel mapping system that assists us with channel configurations. This automated tooling analyzes the current configuration and determines the optimal configuration and necessary changes. The tools can generate candidate configurations and apply them when ready.

3.4. Metrics to Assist With Efficient Deployments

We use many tools to view and track this data, including Victoria metrics, Genome, Grafana, Thanos, Elastic, and many more. Even before deploying, it became clear that the new knobs available for data collection in DOCSIS could be used for improvements to our tooling. In addition to new education needed for some team members, changes and alterations would be needed to our tools to accommodate these new and more granular knobs in DOCSIS 3.1. Specifically, for OFDMA we had to think of ways to use these new sources of information. We emphasized query tools and dashboards; all the while utilizing automation to collect and coordinate the data. We had to be as efficient as possible by testing and incorporating these metrics into deployment and monitoring tools proactively well before deployments.

Modem data is paramount for near real-time and historical monitoring. Modem metrics remain outlined in the CableLabs specifications and modem metrics are still leveraging DOCSIS MIBs and our tools continue to incorporate those. There were traditional MIB changes to the DOCSIS information from devices we had to address and understand the new data sources.

Some callouts for metric changes we proactively implemented include the CMTS DOCSIS MIBs (***CmtsCm)*** and the transition to yet another next generation (YANG)-based telemetry when deploying distributed access architecture (DAA). The metrics provided by the modems and traditional CMTS still apply, but now additionally we have new specified resources to consider with the implementation of DAA and virtual cable modem termination system (vCMTS). The sources changed with the introduction of distributed access components, along with naming conventions and the content. It was good to understand when creating monitoring tooling that the new telemetry will often combine multiple modem remote queries and couple it with information from DOCSIS messages to the telemetry logging. The deployed tools needed updating to reflect the differences and changes.

More components and granularity meant more sources of data to collect and process. The use of data in various tools and dashboards with gains from streaming consistent telemetry updates when compared to traditional operational support system (OSS) MIBs become very advantageous. The ***CmtsCm MIBs*** (also referred to as remote query) for DOCSIS information is now being managed in the vCMTS telemetry. These queries will follow the ***YANG model*** and DOCSIS specification for reporting and may include some specialized vendor-specific information in a single query. As mentioned, the source of both CMTS and cable modem info can now come from the vCMTS core in a DAA network. Think of this source as a regularly updated system log. This log is constantly capturing everything about systems, DOCSIS messaging and the OFDMA channel. The telemetry source is used for collection of historical analysis, dashboards, debugging, status and more. The new dataset is incorporated into our monitoring tools.

OFMDA has specific telemetry differences such as **CmRegStatus**, which is a good example of combined YANG telemetry. Items like modem capabilities, ranging status, registration status, partial services and modem transmit power can now be observed in this one query. The queries from the vCMTS coupled and corroborated against traditional MIBs is a powerful check and balance. An example of OFDMA channel signal level incorporates the new D3.1 DOCSIS spec and is measured as a reference at 1.6 MHz – called power measurement relative to 1.6 MHz of measurement bandwidth (P1.6). This change affects metrics for upstream or downstream channel power when compared to a D3.0 query or measurement that references the channel's symbol rate or width. With D3.1 all measurements reference P1.6 as the least common denominator to compare even to legacy DOCSIS channels. This change had to be made to our tooling and calculations.

Another good example of data we needed to add for monitoring was OFDMA modulation error ratio (MER) per mini slot. This data is gleaned by the CMTS in ranging messages and provided in the telemetry at a regular minimum configurable interval. By understanding what mini slots are affected by noise, we can discern what frequencies are being affected by impairments and mitigate or work around these problems proactively and before the customer notices an impact.

3.5. iHAT- In Home Assessment Test

Comcast developed the iHAT tool before actual OFDMA deployments began. Legacy set-top boxes utilize bandwidth that overlaps with the mid-split upstream spectrum. We realized legacy devices like set top boxes co-located with mid-split enabled cable modems could be susceptible to interference from the mid-split CM's OFDMA signals. To avoid the devices being interfered with and the customer potentially being impacted, we leveraged iHAT and OFDMA upstream data profile (OUDP) sounding supported in the CMTS and remotely pre-tested if a legacy device sharing a passive in the home with the mid-split enabled CM would be affected.

Our support team can execute iHAT testing on modems, as necessary. iHAT gives us a view into the home to see in advance if turning on OFDMA for a customer is viable. If video interference is detected, we steer the CM to continue to use low split and not use the OFDMA channel. If the test passes, then we enable OFDMA, providing for higher upstream throughput. When enabling OFDMA, we steer the modem to a bonding group that includes the OFDMA channel using dynamic bonding changes in DOCSIS.

3.6. Power Spectral Density – OFDMA vs SC-QAM

As we progressed with the crucial task of OFDMA enablement, we had to make critical decisions regarding the configuration of the OFDMA channel. We considered the impact of power spectral density (PSD). PSD remains the same between channel types, but this creates a spectrum analyzer phenomenon that appears as if the SC-QAM channel is lower in signal level than the adjacent OFDMA block. The two-channel types compared visually side-by-side will look to be at different signal levels on a meter and cause unwarranted concern from a technician.

Our solution to this challenge involved a modification to the CMTS/RPD receive power. This adjustment to the receive power is a 6 dB difference between the two channel types. This change forces a modem to transmit less on the OFDMA channel and thereby aligns the channels. By adjusting the configuration, we maintained the desired modem dynamic range and transmission levels and compensated for the issue. This adjustment had a practical effect and ensured that the visuals of the meter tools would display the OFDMA levels flat across the spectrum when compared to the adjacent SC-QAMs. Figure 4 is a visual representation of a flat frequency response.

These changes were done proactively before the OFDMA deployments were pushed to the field. This minor adjustment met our needs and helped to avoid confusion amongst the end users, underscoring the importance of our role and expertise in this process.

3.7. Education

There are different training requirements for OFDMA and SC-QAM. The physical layer differences are just one part of the bigger picture. The amount of configuration parameters that can be adjusted for the OFDMA channel is 10 times what we were used to configuring in DOCSIS 3.0 and SC-QAM channels. The engineering teams down through the deployment teams will require training.

The need for proactive education is fundamental to success when deploying new DOCSIS features. Not just general education at an elevated level, but also specific deeper level education. The key to efficiency is to educate the right people in the process. Since with complex details, the information in the hands of the end users may only add to confusion, and the best approach is an educational ladder from advanced to end users that can be leveraged as needed. Said another way, keep it simple with a red or green button for some users and make sure the resources and training are there if an issue needs to escalate.

At Comcast, we spent time training at all levels and began with Engineering at a deep level to address their questions and concerns. After training the engineering teams, we helped to develop internal learning modules to then be distributed at differing levels to the correct teams that required the knowledge. We leveraged subject matter experts at each level and on each team to then work on things specific to those teams.

4. Benefits of DOCSIS OFDMA

Using the wider mid-split band and OFDMA significantly increases the US throughput compared to sub-split with SC-QAMs. DOCSIS 3.1 allows for much higher modulation orders, up to 4096 QAM on an OFDMA channel. With the OFDMA subcarrier and mini-slot structure, impairments that affect a portion of the band can be mitigated by adjusting the impaired subcarriers and mini-slots without affecting the overall OFDMA channel.

4.1. US Capacity With SC-QAMs and OFDMA

A typical sub-split system utilizes four 6.4 MHz wide SC-QAM channels and two smaller channels above and below at the band edges. Ingress and noise at lower frequencies force the lower band edge and lower 6.4 MHz SC-QAM channel to use a lower modulation order. The smaller upper band edge channel is in the band's roll-off portion also uses a lower-order modulation.

The theoretical throughput of a 64 QAM 6.4 MHz upstream channel is 30.72 Mbps, while a 3.2 MHz wide channel can achieve a theoretical throughput of 10.2 Mbps. The actual throughput is slightly lower after overhead and error correction are applied. See Table 1 for the calculated throughput for our 6-channel sub-split channel plan.

Table 1 - Calculated Throughput for 6 Channel Sub-Split Configuration

SC-QAM Channel	Center Frequency (MHz)	Channel Bandwidth (MHz)	Modulation Order	Capacity (Mbps)
6	10.4	3.2	32	6.7
1	16.4	6.4	64	20.7
2	22.8	6.4	64	25.7
3	29.2	6.4	64	25.7
4	35.7	6.4	64	25.7
5	39.6	1.6	32	5.8
Total Capacity				110.3

Adding an OFDMA channel in the upstream mid-split spectrum provides significant additional capacity and throughput. Comcast has standardized on removing the 5th and 6th SC-QAM channels in our legacy sub-split systems at the sub-split return frequency band edges and adding a 45.6 MHz wide OFDMA channel from 39.4 MHz to 85 MHz.

The lower end of the upstream spectrum is susceptible to interference, primarily due to the typical low-frequency ingress noise and the funneling effect of the upstream RF combining of multiple modems at the CMTS or RPD. This interference can be a significant challenge. The 40 MHz to 85 MHz band, which is typically low in noise, allows for higher bit loading. With OFDMA utilizing this band, we can effectively mitigate off-air ingress and other narrow-band ingress signals using PMA without affecting the rest of the channel. See Figure 4 for a typical “clean” upstream response and Figure 5 for a response that shows off-air ingress in the OFDMA band.

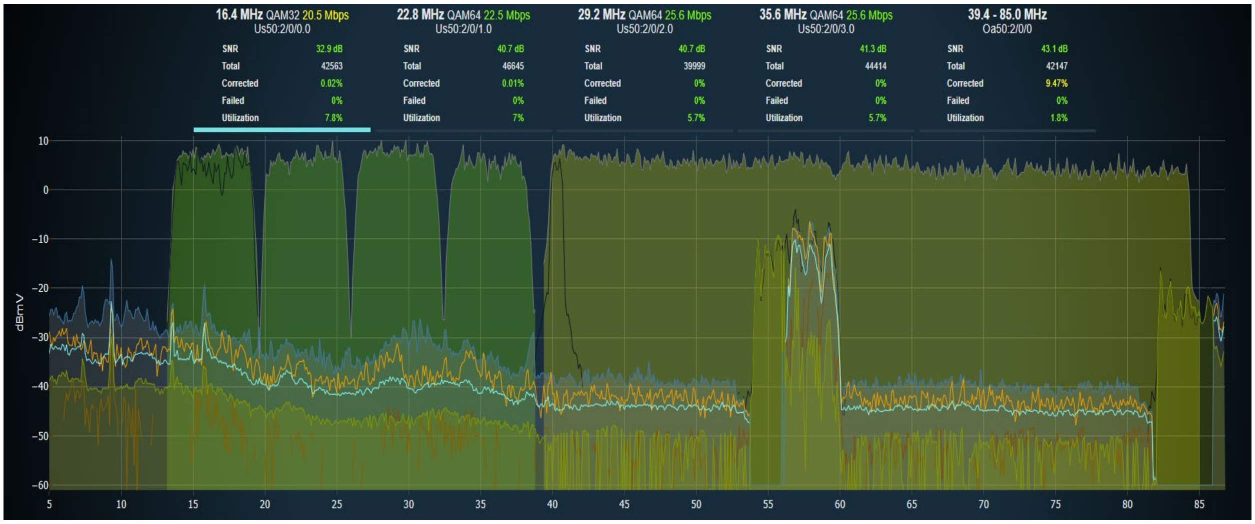


Figure 5 – Upstream Spectrum Capture With Off-Air Ingress in OFDMA Band

An OFDMA channel with a bandwidth of 45.6 MHz, 25 kHz subcarrier spacing, and 4096 modulation order has a theoretical capacity of 547 Mbps. Error correction overhead, edge mini-slots, cyclic prefix, exclusion bands, mini-slot spacing, pilot pattern overhead, and guard bands all affect the actual throughput. An OFDMA channel with the characteristics in Table 2 taken into consideration, has a throughput of 430 Mbps, which is four times the capacity of the existing 5 MHz to 42 MHz sub-split band with four SC-QAM channels.

Table 2 - OFDMA Channel Parameters

Parameter	Value
Subcarrier Spacing (kHz)	**25**
Cyclic Prefix (us)	**1.5625**
Frame Duration (us)	**748**
Lower US Edge (MHz)	**39.4**
Upper US Edge (MHz)	**85**
Occupied Bandwidth (MHz)	**45.6**
Mini-slot Subcarriers Q	**16**
Mini-slot Symbols K	**18**
Potential Signal Subc.	**1824**
Excluded Subcarriers	**40**
Guardband (MHz)	**1**

The key to maintaining high modulation orders across the entire channel is the active PMA on these RPDs and cable modems. PMA is active on these RPDs and cable modems and allows noise in the OFDMA band to be mitigated without lowering the modulation order across the entire channel. With PMA-enabled, traffic distribution per QAM modulation order across Comcast's population of mid-split enabled 3.1 devices is shown in Figure 6.

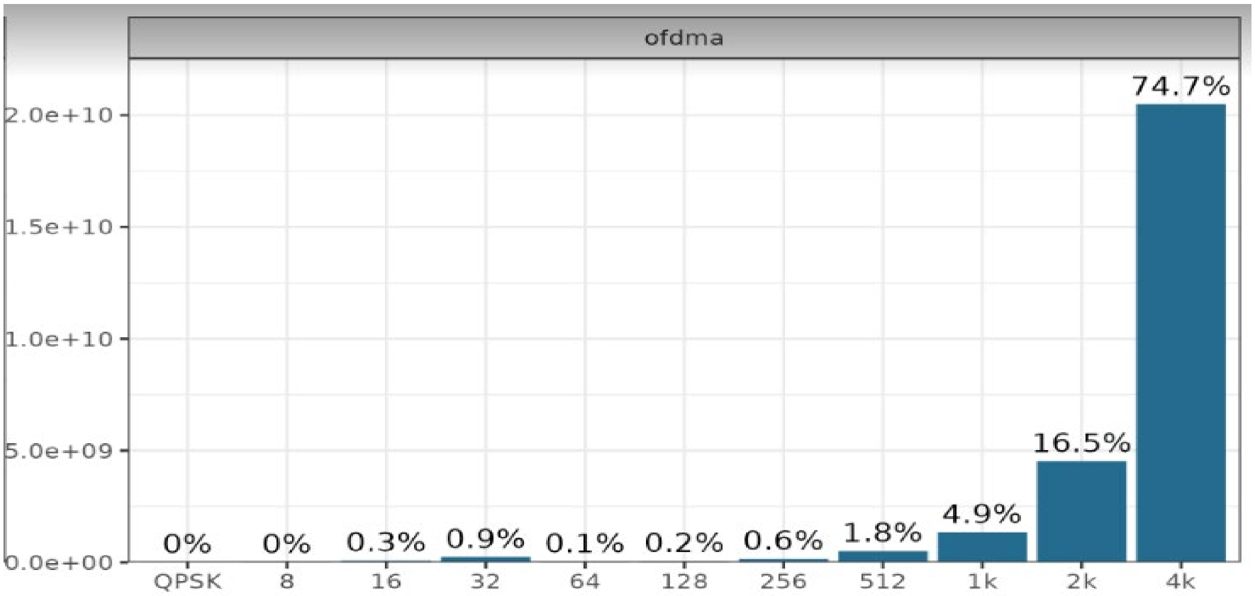


Figure 6 – Modulation Order Distribution

With this distribution of modulation order and the channel characteristics in Table 2, the average capacity and throughput of the mid-split OFDMA channel across Comcast's network is 415 Mbps. The throughput of the entire mid-split upstream spectrum with four SC-QAM channels and an OFMDA channel is 512 Mbps, as shown in Table 3.

Table 3 - Total Throughput Capacity With OFDMA in the Mid-Split Spectrum

Channel #	Center Frequency (MHz)	Channel Bandwidth (MHz)	Modulation Order	Capacity (Mbps)
SC-QAM 1	16.4	6.4	64	20.7
SC-QAM 2	22.8	6.4	64	25.7
SC-QAM 3	29.2	6.4	64	25.7
SC-QAM 4	35.7	6.4	64	25.7
OFDMA	62.2	45.6	Variable	415
Total Capacity				512

The addition of the mid-split spectrum and OFDMA provides close to five times more upstream capacity compared to the sub-split band with six SC-QAM channels. With continued plant improvement and mitigation of noise and other impairments the overall throughput will continue to increase.

5. Tangible Advantages of OFDMA vs SC-QAM

5.1. Overcoming Common Noise

Noise is a frequent problem we face in the HFC cable plant. In the upstream spectrum, noise is typically high at the low end of the spectrum, frequency-modulated (FM) ingress noise can be present from 88 MHz to 108 MHz and there is the potential for over-the-air channel ingress noise in the mid-split band. These noise occurrences are common and may altogether disable the use of a legacy SC-QAM channel. However, the subcarriers present in an OFDMA channel can accommodate for noise events without disrupting the entire channel. This is accomplished by using exclusion zones, lowering the modulation order, and zero-bit loading an impaired set of subcarriers.

Figure 7 is an upstream capture at the RPD showing how noise in the HFC plant may altogether take out a DOCSIS SC-QAM channel. This is demonstrated by the lowest SC-QAM channel in red. The FEC and red color coding indicate the channel is being affected by noise. Note as well the signal-to-noise ratio (SNR), corrected FEC, and failed FEC for the impacted SC-QAM channel.

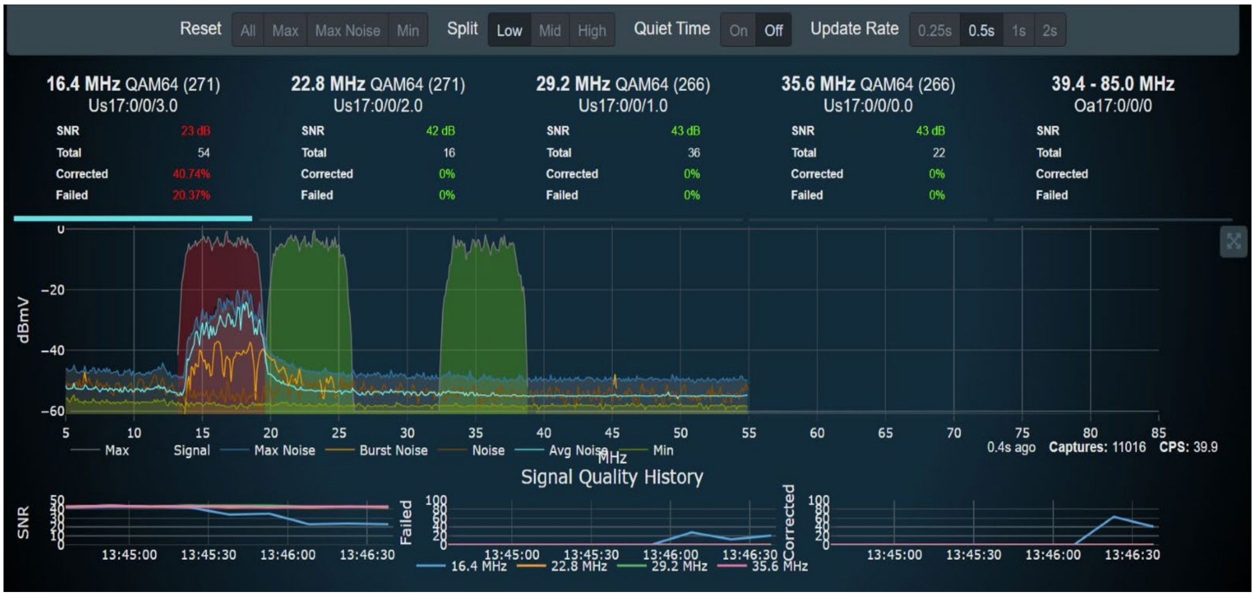


Figure 7 – Visual of Upstream – Showing SC-QAM Being Disabled by a Noise Event and With Poor FEC Stats

Figure 8 is the OFDMA channel being shown with noise under the carrier, and the display indicates that the channel can continue to be in operation by adjusting only the impaired subcarriers and leaving the non-affected subcarriers to use the maximum modulation order for the least amount of channel degradation.

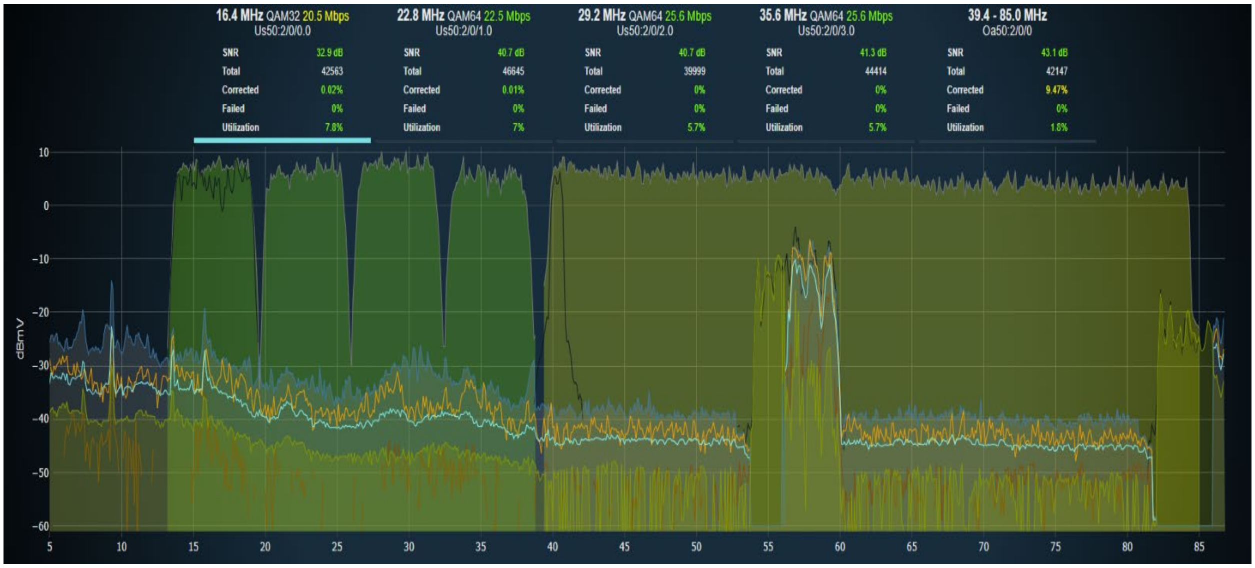


Figure 8 – Visual of Upstream - Showing Ingress Under the OFDMA Channel and Still Operational With Good FEC Stats

6. Supporting Enablement of DOCSIS OFDMA

Supporting mid-split involves starting with a solid foundation, including a supported DOCSIS 3.1 CPE and an adequately configured CM configuration file. Additionally, a supported access network, CMTS, RPD if DAA and associated configuration are also critical. These elements provide the backbone for enabling OFDMA across the HFC network.

The DOCSIS 3.1 modem plays a pivotal role in this endeavor as it must utilize the spectrum location for the newly configured OFDMA channel. To support the new OFDMA channel, the internal diplexer setting on the DOCSIS 3.1 device must be appropriately configured. In our case, the OFDMA channel placement is alongside the traditional SC-QAM channels, located between 39.4 MHz and 85 MHz. To ensure proper communications, the diplexer must be set accordingly.

Once nodes are updated to utilize the mid-split configuration, the MAC domain descriptor (MDD) messaging begins instructing supported devices to come up in this mode. To ensure this is controlled and managed accordingly, we use a specific type of type-length-value (TLV), TLV-84, used in DOCSIS 3.1, to force the DOCSIS 3.1 modems to utilize sub-split until we verify that they meet our mid-split requirements. Once we confirm that the modems meet our requirements, we remove the TLV-84 setting from the boot file and allow them to use their highest capability based on the node and system configurations.

To further expand on this topic, in the initial DOCSIS 3.1 device releases, vendors managed and controlled the upstream diplexer settings on the supported devices through vendor-specific TLVs or Object Identifiers (OIDs). This functionality allowed for the device's internal diplexer setting to be configured to a specific range, depending on the chosen implementation as outlined in Table 4. Based on the configured diplexer setting, the D3.1 cable modem can advertise its potential capabilities to the vCMTS platform. This setting was usually pre-configured out of the box in a sub-split mode. Regardless of the chosen diplexer setting, operators must ensure the CMTS platform and CM device configuration are set appropriately to support the desired enablement. In our case, the CMTS had to be enabled to support mid-split, and the device had to be configured appropriately to utilize the mid-split configuration.

Table 4 - Traditional Upstream Diplexer Configurations

Mode	Diplexer Setting
Sub-split	5-42 MHz
Mid-split	5-85 MHz
High-split	5-204 MHz

Once the device configuration is in place, the next step is to ensure the device can bond and utilize the OFDMA channel. One invaluable tool in this process is iHAT, a reliable and proven solution detailed in previous SCTE publications. iHAT is crucial in facilitating seamless connectivity between supported CPE devices and the RPD, ensuring the supported CPE can effectively utilize the OFDMA channel. This tool serves as a litmus test, confirming that OFDMA is operational and paving the way for efficient data exchange on the OFDMA channel.

By diligently addressing these foundational aspects and leveraging the right tools and technologies, we can establish a robust framework for supporting mid-split, enabling the network to meet the evolving demands of modern connectivity.

6.1. PMA and OFDMA

Comcast has pioneered the use of a profile management application in our upstream DOCSIS 3.0 applications. PMA is an application that monitors the health of the upstream channels and adjusts the modulation profiles to accommodate channels and areas of the band with impairments. If a channel impairment is detected, rather than the channel being dropped, the modulation profile of the channel is reduced to allow the channel to continue to operate at a reduced capacity.

With the deployment of OFDMA, PMA becomes an even more critical and valuable tool in our arsenal. It plays a pivotal role in optimizing the upstream capacity and throughput of our network. DOCSIS 3.1 can configure a set of interval usage codes (IUCs) for an OFDMA channel. If an OFDMA channel is impaired and has a low SNR, or if a specific group of subcarriers and mini slots is impaired, the CMTS will select an IUC to accommodate the lowest SNR across the OFDMA channel. This will lower the modulation order for all the subcarriers and mini slots when only a small portion of the band is affected.

Operating PMA on upstream OFDMA channels overcomes the need to lower the modulation order across the entire channel. PMA actively monitors the upstream MER across the OFDMA channel, configures a tailored profile to accommodate areas of the band as needed, and maintains the highest order modulation in the unaffected regions of the band. Figure 9 shows an example of off-air ingress and PMA configured profile that closely matches the degradation due to the ingress. These configurations are for the same node and a different grouping of cable modem characteristics. Figure 9 and Figure 10 show more zero-bit loading below 60 MHz and lower-bit loading in the upper part of the spectrum. In both instances, if the PMA feature were not in use, the ingress and associated low SNR in the ingress areas would cause the channel to drop altogether. PMA keeps the channel up and functioning, and most of the band uses the high modulation order and bit loading to maximize throughput.

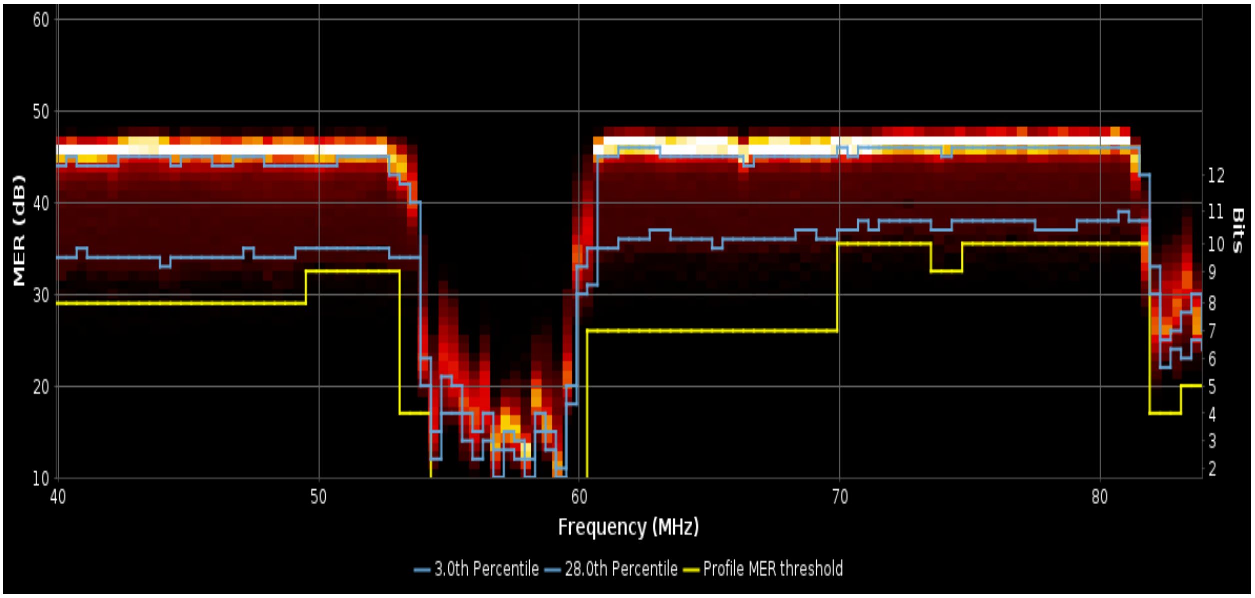


Figure 9 – PMA Configuration 1 for Upstream OFDMA Channel With Off-air Ingress

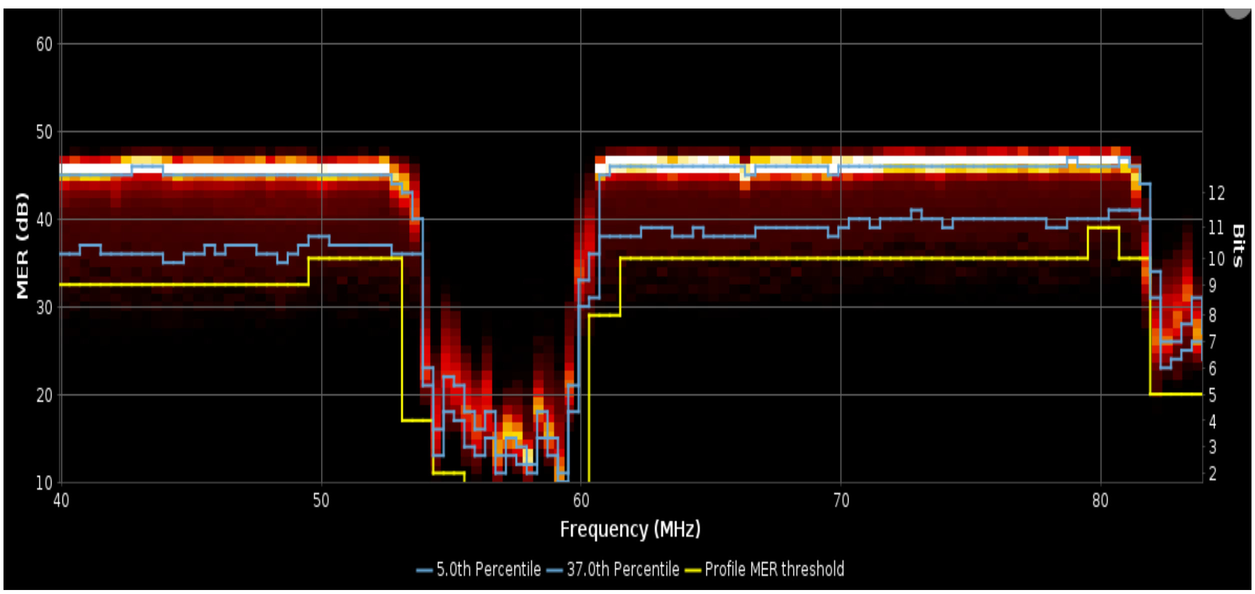


Figure 10 – PMA Configuration 2 for Upstream OFDMA Channel With Off-air Ingress

7. Challenges With Enabling OFDMA

Enabling OFDMA presented several challenges that providers must address for seamless integration and enablement. Identifying potential issues, including incompatible CPE devices, general plant problems, and in-home system configuration challenges, is crucial for success.

At the onset of mid-split enablement, we adopted a strategic approach. A pivotal step in this process was utilizing our top 100 racks, a representative sample of our network's most deployed devices. This strategic move enabled us to comprehensively understand the potential impact on our customer's existing modems, ensuring they behaved as expected when operating on a mid-split enabled network.

In the subsequent phases, we followed a well-defined sequence of steps. Our priority was to align supported devices to leverage TLV-84 and MDD messaging, instructing the CM to operate in mid-split as a critical step for ensuring consistent diplexer management across devices.

Another challenge we faced was removing unsupported sub-split outside plant amplifiers and diplexers which block the ability to use the mid-split spectrum. This can be extraordinarily complex in specific scenarios with undocumented amplifiers that are not shown in any of the plant topology documents. In this effort, iHAT played a crucial role, ensuring the CPE could range and bond to the OFDMA channel. It was also instrumental in identifying issues across the plant and inside the home, providing a comprehensive view of where issues existed and enabling us to tackle them most efficiently.

Additionally, it was essential to ensure that legacy STBs functioned as expected. Leveraging iHAT, we could detect potential adjacent channel interference (ACI) impacting legacy set-top boxes when mid-split was activated, and OFDMA was in use. Mitigation for ACI includes correcting in-home wiring issues, removing in-home sub-split drop amplifiers, and in some cases converting customers to all internet protocol (IP) video. In cases where iHAT helped discover ACI and STB issues, we proactively moved the customers to a bonding group that did not contain the OFDMA channel to eliminate ACI. This identification of potential interference allows for proactive service calls to be scheduled and limits the impact on customer video services until we can resolve the in-home issues.

In summary, enabling OFDMA comes down to appropriately identifying potential roadblocks and ensuring a plan is in place to address issues. Ideally, it starts with validation and ensuring the network devices are ready and resilient to changes. Furthermore, aligning vendors to utilize the same standards, such as TLV-84, helps reduce some complexity related to device management and mid-split enablement. Lastly, using iHAT to identify issues across the plant and inside the home provides a holistic view of where a problem exists so the support team can efficiently understand and address any issues.

7.1. Partial Service Devices

When deploying OFDMA, it was essential to understand that we now have a new contributor to what can cause a device to report a partial state. In the previously deployed sub-split implementations, the device would report a partial alert if it had an impacted upstream or downstream SC-QAM channel or impacted downstream OFDM channel. Adding the additional upstream OFDMA channel created one additional factor that can cause a partial state. OFDMA partial status can be more apparent and increase the number of devices reporting a partial state due to sub-split drop amps or other devices within the plant that could potentially block OFDMA.

8. OFDMA Performance Monitoring – Tools and Resources

Tooling is an important aspect of supporting successful OFDMA enablement. As we progressed through various issues, we had to ensure that we had various tools to provide visibility. These include tools focused on capacity reporting, physical layer status, field, and operational support.

8.1. Grafana

With our internal vCMTS development and deployment of DAA, we have better control and access to network and device information. RPD and CPE device polling occur regularly, and the data is stored in a time series database, which the support teams can easily access. This data is invaluable in monitoring the network's health and providing information for troubleshooting. Many tools and dashboards have access to this data, which development engineering, operations, and field-facing engineers and technicians use.

Grafana is one of the main tools used to graph network performance data. Figure 11 shows the CM on-demand health dashboard with a seven-day view. This page shows CPE online status, upstream SC-QAM and OFDMA transmit (Tx) and receive (Rx) levels, OFDMA IUC, upstream MER and FEC statistics, and RF upstream parameters.

Figure 11 – Grafana Dashboard Showing CPE Characteristics

Figure 12 shows the RPD statistics, including physical RF and optical parameters, traffic, and CM statistics. Figure 7 and Figure 8 show the MER and bit loading of an OFDMA channel, and Figure 13 shows the iHAT results. There are numerous additional dashboards and an unlimited ability to create new dashboards as needed to monitor the health of the network and devices on the network.

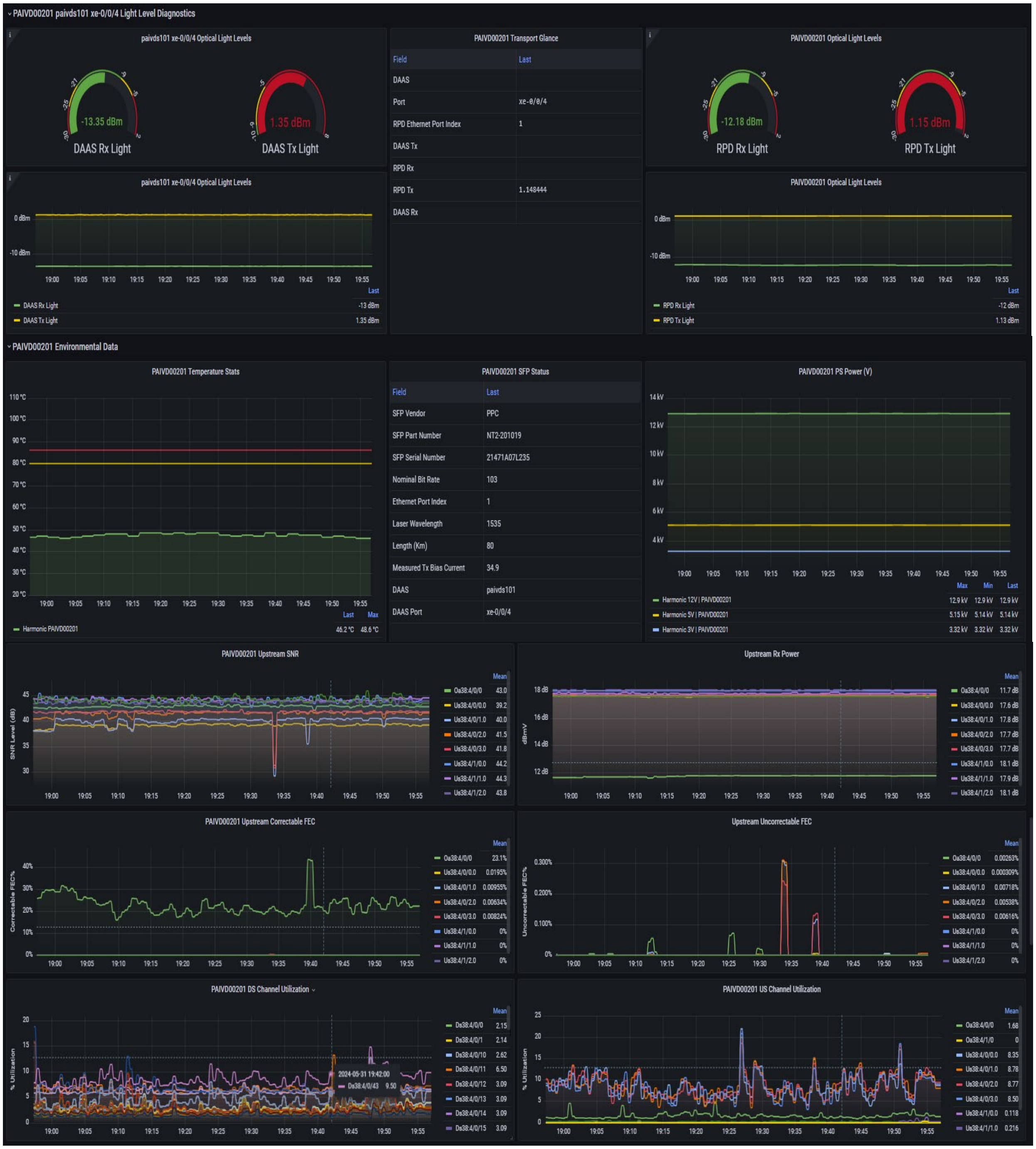


Figure 12 – Grafana Dashboard Showing RPD Characteristics

8.2. iHAT Summary Dashboard

The iHAT summary dashboard has been critical in monitoring the performance of the iHAT tooling. In the example dashboard depicted in Figure 13, the iHAT was executed 420 times on 299 RPDs. In total, iHAT performed 19,708 tests. The iHAT validation resulted in 15,538 successful passes, confirming that OFDMA was enabled, and the modems bonded to the OFDMA channel. Additionally, we identified 2,291 devices where OFDMA was blocked and an additional 247 tests where video interference was detected and mitigated by moving the customer to a sub-split configuration. As we continuously work to detect these issues leveraging iHAT, it helps us isolate areas where we can focus our remediation efforts and limit the impact on the customer experience.

Figure 13 – iHAT Results Dashboard

8.3. Prometheus Telemetry

Telemetry data is key for understanding what is happening in the vCMTS environment. Queries can be on-demand or at regular update intervals. See Figure 14 for a query for a telemetry tool called Prometheus. Example 1 below is a device that is bonded to the OFDMA channel, which we can determine by looking at the details in this query.

Example 2 is a device that should be bonded to the OFDMA channel. However, based on the **usBondingGroup** and the **maxUsableUSFreq** a user can determine the registration state of a modem. In this instance although the device supports OFDMA it has been steered due to a problem that was detected by iHAT and as a result is using a SC-QAM-only configured bonding group.

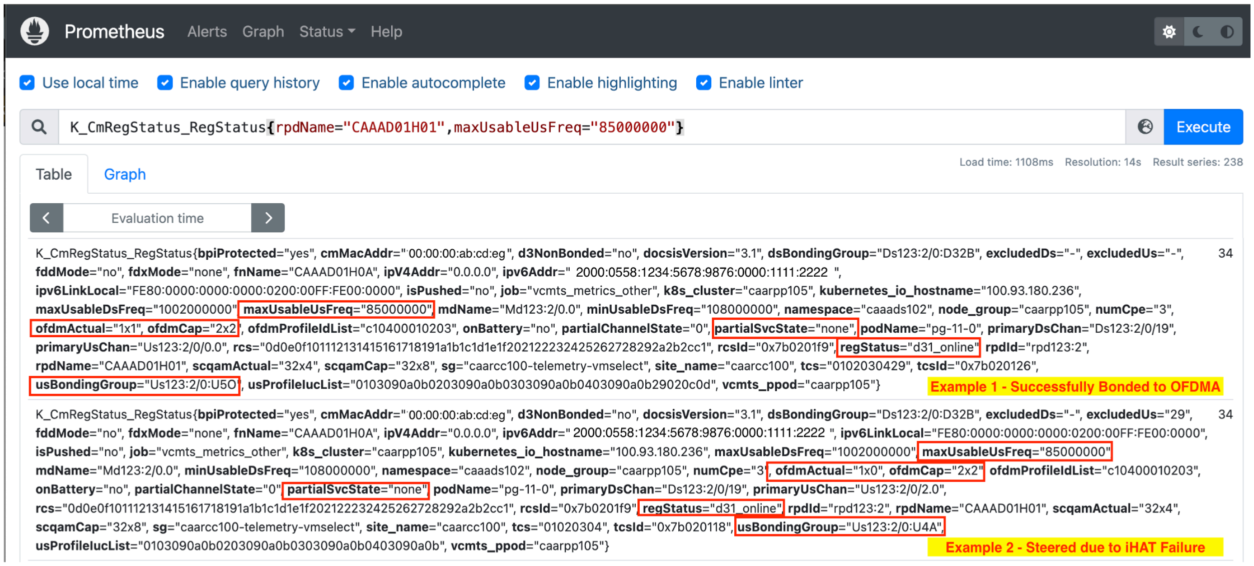


Figure 14 – Prometheus

8.4. OFDMA Real-Time Alerting via Slack

Moody OFDMA, a tool created for real-time alerting via the Slack messaging platform, was built to support the Engineering Team. It provides data that helps us determine if we are dealing with RPD-specific or vCMTS application-related problems. This tool has been vital in supporting problem identification, tooling improvement, and automated fix actions, along with efforts to resolve technical issues with the divisional support teams.

Figure 15 – Moody Alerts Slack

8.5. Network Efficiency Optimization and Intelligence (NEON)

After OFDMA has been active, it is essential to monitor the use of the channel and ensure the expected capacity improvements occur. Upstream capacity restraints are one of the main reasons for node splits. Activating the upstream spectrum can provide the additional capacity needed instead of splitting a node. When OFDMA is activated and the spectrum is not being utilized significantly, this may show as a capacity constraint, indicating a node split is needed. However, there may be several reasons why OFDMA capacity is not being utilized at its potential.

1. There may be a line amp in the system that was missed during the plant upgrade to mid-split/OFDMA. These could be undocumented amps installed after the initial system installation.
2. There may be only a few DOCSIS 3.1 devices on the RPD.
3. There may be in-home drop amps blocking many cable modems from using OFDMA.
4. There may be “top talkers” who are customers using a significant amount of data and overutilizing the SC-QAM channels with DOCSIS 3.0 devices or DOCSIS 3.1 devices with the OFDMA band blocked.

Effective tools for monitoring OFDMA usage are essential in identifying nodes with low usage and pinpointing the reasons for underutilization. This knowledge is instrumental in guiding troubleshooting efforts and ensuring OFDMA is used as expected.

Comcast provides a range of tools for assessing OFDMA efficiency, usage, and plant health. One such tool is the NEON DOCSIS 3.1 efficiency tool. This dashboard/tool offers a scatter plot of OFDMA and SC-QAM utilization, enabling the identification of nodes with high SC-QAM and low OFDMA utilization. Refer to Figure 16 for a visual representation.

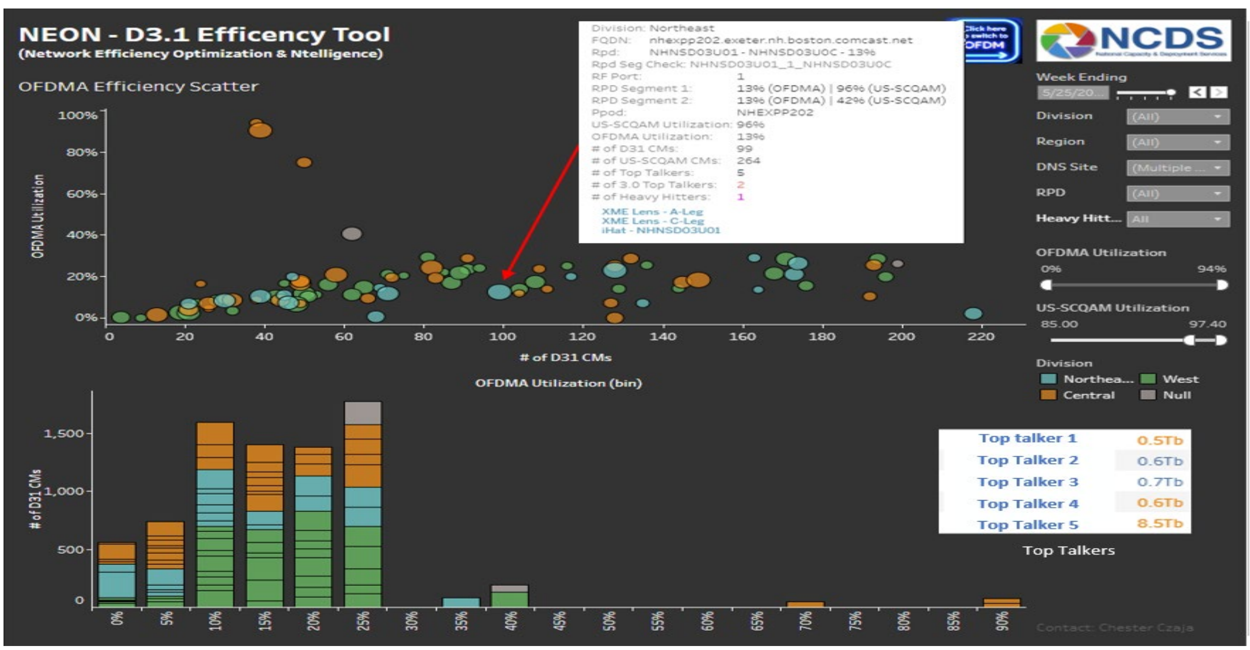


Figure 16 – OFDMA D3.1 Efficiency Tool

The top part of Figure 16 shows the OFDMA utilization vs the number of D3.1 modems installed on a system. There are selections for SC-QAM and OFDMA utilization ranges which can be used to target specific ranges. The bottom bar chart shows similar information grouping nodes into specific OFDMA utilization ranges. Selecting a specific bubble or data point shows additional information.

In the bubble selected in Figure 16, the OFDMA utilization is only 13% and there are five "top talkers" with two of them on D3.0 devices. The top talkers with 3.0 devices can be upgraded to D3.1 devices increasing OFDMA utilization and as a result, decreasing the SC-QAM upstream utilization. Selecting a bubble can link to other tools directly and show additional data for the selected node or RPD.

8.6. XME - ICFR, MER and Spectrum

One of the tools NEON links to is XME. The tool XME shows all the devices on an RPD and some health metrics, including upstream transmit, downstream receive, SNR, MER, in-channel frequency response (ICFR), MER per mini-slot, and FBC. SNR and MER are an indication of channel fidelity, while ICFR is related to discontinuities at the physical layer.

XME also can analyze data on multiple devices and identify node and pocket issues. A pocket issue is where all devices in proximity that are not using the OFDMA channel are identified. XME associates a common network element as a potential cause of the pocket issue. A node issue is identified when all devices on a node are not using the OFDMA channel. Figure 17 shows a screen capture of XME of a node with two pocket events. These are identified with a high probability of a network issue affecting multiple devices. Each account is represented by color coding. In this view, the inner circle is the OFDMA status. A green inner circle means the device is using OFDMA. A red inner circle shows the device is not using OFDMA.

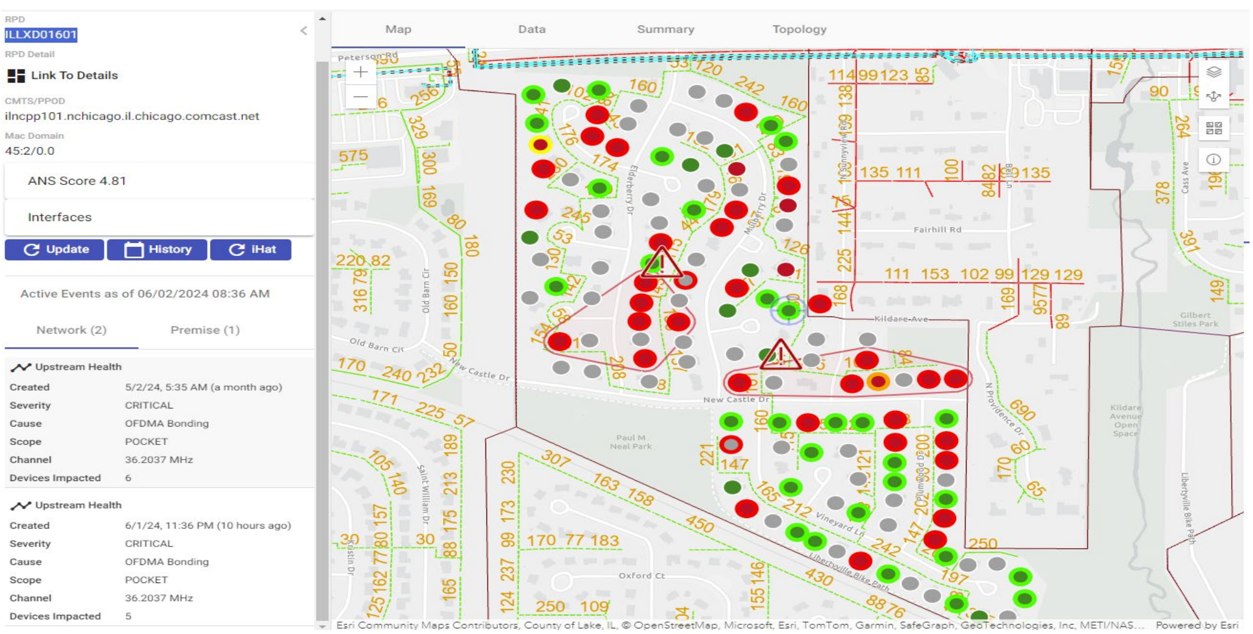


Figure 17 – XME Showing Node OFDMA "Pocket" Events

Other OFDMA parameters reported by XME are upstream Tx power, MER, ICFR, MER/mini-slot, and return spectrum at the CPE device. Being able to view all these parameters is key in determining device health and ensuring devices are utilizing OFDMA. See Figure 18.

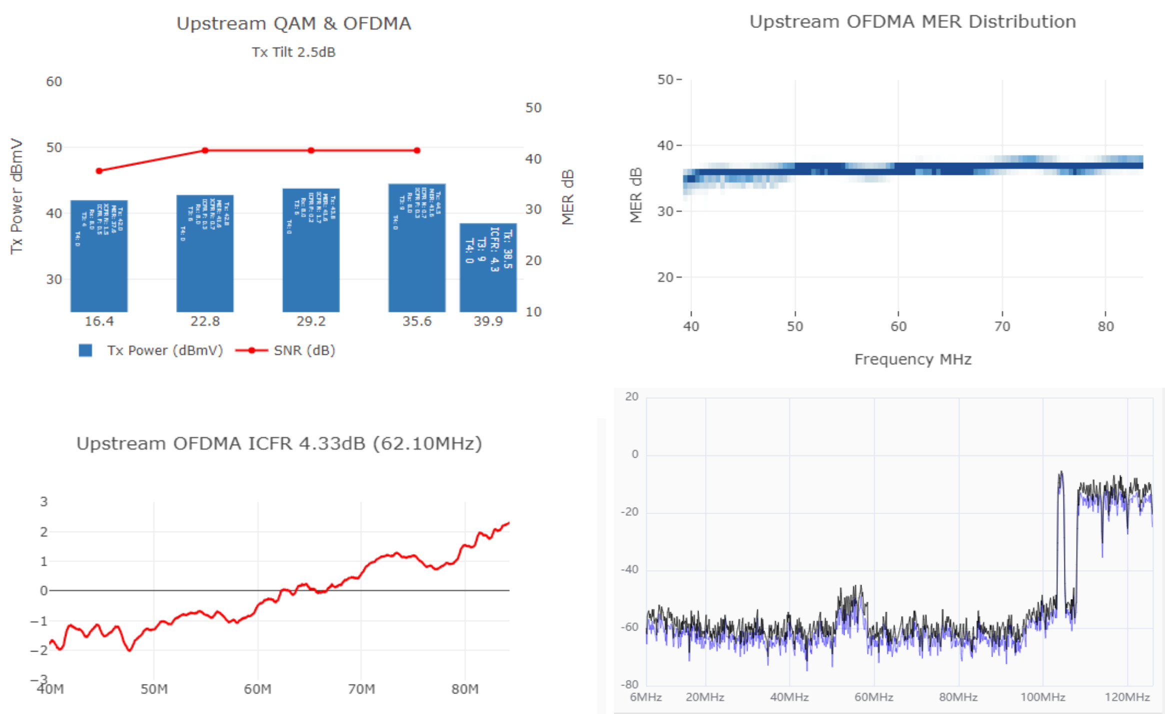
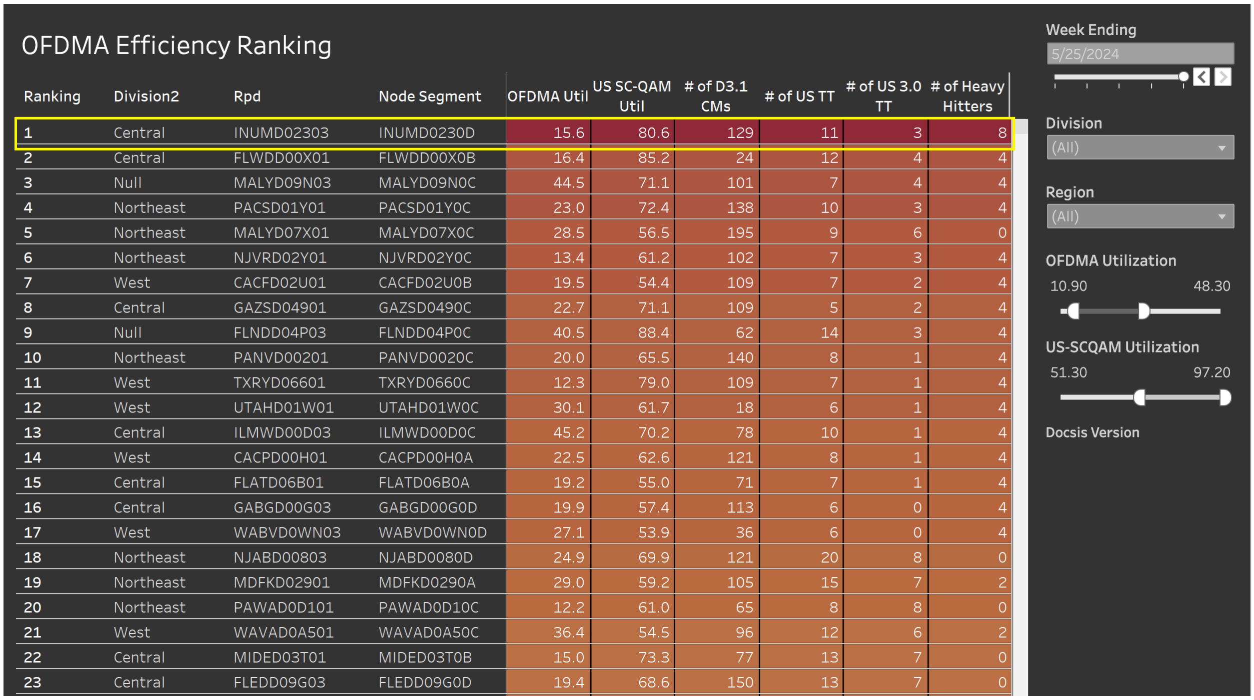


Figure 18 – XME OFDMA Parameters: TX Power, MER, MER/Mini-slot, ICFR, Return Spectrum

8.7. Efficiency Ranking (Capacity Monitoring)

The OFDMA efficiency ranking tool provides a view of potential issues that we may need to investigate. In the example highlighted, we have over 129 devices capable of using OFDMA. However, the OFDMA utilization is low and the SC-QAM utilization is high. In this case, an investigation would be performed to determine if we have an issue with D3.1 devices being able to bond to the OFDMA channel or if other causes are making the channel usage less than anticipated.

Modems in a partial OFDMA bonded state means the device is not operating as expected. We gather modem partial reporting patterns via tools like Figure 19 that is from an efficiency ranking report dashboard. With this report, we have one place where metrics have been gathered and tallied together, which will lead to the next steps for discovery and remediation. From this dashboard alone we may be able to determine if the issues with the OFDMA channel usage have to do with heavy hitters (using all the bandwidth), OFDMA partials, or other factors. Like all tools we have developed this dashboard may work in conjunction with others to resolve problems proactively.



Ranking	Division2	Rpd	Node Segment	OFDMA Util	US SC-QAM Util	# of D3.1 CMs	# of US TT	# of US 3.0 TT	# of Heavy Hitters
1	Central	INUMD02303	INUMD0230D	15.6	80.6	129	11	3	8
2	Central	FLWDD00X01	FLWDD00X0B	16.4	85.2	24	12	4	4
3	Null	MALYD09N03	MALYD09N0C	44.5	71.1	101	7	4	4
4	Northeast	PACSD01Y01	PACSD01Y0C	23.0	72.4	138	10	3	4
5	Northeast	MALYD07X01	MALYD07X0C	28.5	56.5	195	9	6	0
6	Northeast	NJVRD02Y01	NJVRD02Y0C	13.4	61.2	102	7	3	4
7	West	CACFD02U01	CACFD02U0B	19.5	54.4	109	7	2	4
8	Central	GAZSD04901	GAZSD0490C	22.7	71.1	109	5	2	4
9	Null	FLNDD04P03	FLNDD04P0C	40.5	88.4	62	14	3	4
10	Northeast	PANVD00201	PANVD0020C	20.0	65.5	140	8	1	4
11	West	TXRYD06601	TXRYD0660C	12.3	79.0	109	7	1	4
12	West	UTAHD01W01	UTAHD01W0C	30.1	61.7	18	6	1	4
13	Central	ILMWD00D03	ILMWD00D0C	45.2	70.2	78	10	1	4
14	West	CACPD00H01	CACPD00H0A	22.5	62.6	121	8	1	4
15	Central	FLATD06B01	FLATD06B0A	19.2	55.0	71	7	1	4
16	Central	GABGD00G03	GABGD00G0D	19.9	57.4	113	6	0	4
17	West	WABVD0WN03	WABVD0WN0D	27.1	53.9	36	6	0	4
18	Northeast	NJABD00803	NJABD0080D	24.9	69.9	121	20	8	0
19	Northeast	MDFKD02901	MDFKD0290A	29.0	59.2	105	15	7	2
20	Northeast	PAWAD0D101	PAWAD0D10C	12.2	61.0	65	8	8	0
21	West	WAVAD0A501	WAVAD0A50C	36.4	54.5	96	12	6	2
22	Central	MIDED03T01	MIDED03T0B	15.0	73.3	77	13	7	0
23	Central	FLEDD09G03	FLEDD09G0D	19.4	68.6	150	13	7	0

Figure 19 – Efficiency Ranking Report

8.8. HyperScaling OFDMA Deployments

As we wrap up this paper it is important to see the progress we made by looking at the changes with mid-split and OFDMA deployment. Our approach to incorporating tools efficiently and with automation has yielded great returns on investment. The Figure 20 below shows how we have increased RPD deployments and enabled OFDMA across our footprint. As of April 2024, we have close to 110,000 OFDMA enabled RPDs.

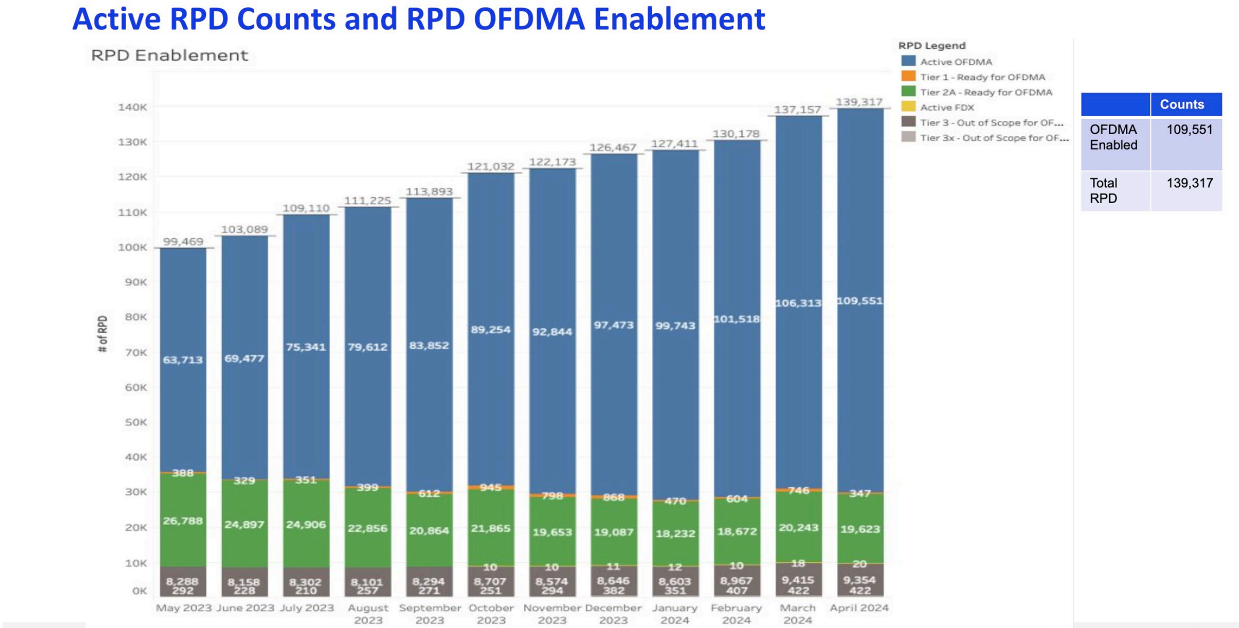


Figure 20 – Active RPD Counts and RPD OFDMA Enablements

The Figure 21 below is a trend of OFDMA usage between October 2023 and May 2024. The usage pattern has close to doubled over this period. As of May 2024, we are pushing up to 6 TBs. This trend will only continue to grow, allowing us to unlock new product offerings for our customers.

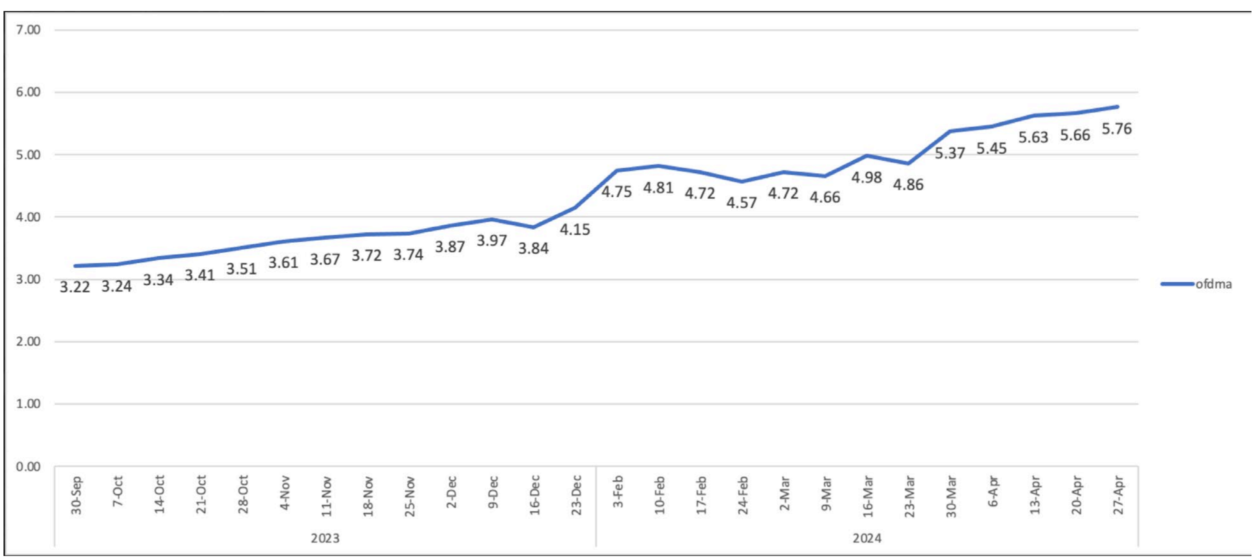


Figure 21 – OFDMA Traffic Trends

9. Conclusion

As demand for increased upstream capacity grows year over year, we must enhance our HFC networks to keep pace with market trends. Implementing OFDMA on our DOCSIS networks is a significant advancement in broadband technology, promising enhanced efficiency, capacity, and performance. However, the implementation process is not without its challenges. Every aspect requires meticulous planning, collaboration, and expertise, from optimizing spectrum utilization and managing interference to seamlessly integrating new hardware and software components.

Overcoming these challenges when enabling OFDMA on our HFC networks necessitates a strategic approach, robust testing protocols, stakeholder alignment, and ongoing monitoring and optimization efforts. By adopting this strategic approach, organizations can unlock the full potential of OFDMA on our DOCSIS networks, paving the way for a more agile, resilient, and future-ready broadband infrastructure. As we work through these challenges and continuously learn and apply new strategies, this will help guide the way to successful DOCSIS 4.0 and FDX deployments nationwide.

Abbreviations

ACI	adjacent channel interference
AMC	adaptive modulation and coding
API	application programming interface
CM	cable modem
CMTS	cable modem termination system
CPE	customer premises equipment
dB	decibel
dBmV	decibels relative to one millivolt
DAA	distributed access architecture
DBC	dynamic bonding change
DOCSIS	Data Over Cable Service Interface Specification
DS	downstream
EQ	equalizer
FBC	full band capture
FM	frequency modulation
ft	feet
Hz	hertz
ICFR	in-channel frequency response
IP	internet protocol
IUC	interval usage codes
iHAT	in-home assessment tool
K	Kelvin
kHz	kilohertz
MAC	media access control
MDD	mac domain descriptor

MER	modulation error ratio
MIB	management information base
MHz	megahertz
OID	object identifier
OFDM	orthogonal frequency-division multiplexing
OFDMA	orthogonal frequency-division multiple access
OSS	operational support system
OUDP	ofdma upstream data profile
P1.6	power measurement relative to 1.6 MHz of measurement bandwidth
PHY	physical layer
PMA	profile management application
PNM	proactive network maintenance
PSD	power spectral density
QAM	quadrature amplitude modulation
RF	radio frequency
RPD	remote PHY device
Rx	receive
SC-QAM	single channel quadrature amplitude modulation
SCTE	Society of Cable Telecommunications Engineers
SNR	signal-to-noise ratio
STB	set-top box
TLV	type-length-value
Tx	transmit
US	upstream
vCMTS	virtual cable modem termination system
XME	XMeter edge
YANG	yet another next generation

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- Figure 5: Comcast, F. Wade, Screenshot of Morpheus
- Figure 6: Comcast, J. Chrostowski, YETI – Upstream Spectrum Capture With Off-Air Ingress in OFDMA Band
- Figure 7: Comcast, J. Chrostowski, Modulation Order Distribution
- Figure 8: Comcast, D. Tracy, YETI– Visual of Upstream – showing SC-QAM being Disabled from a Noise event and with poor FEC stats
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- Figure 13: Comcast, F. Wade, Grafana Dashboard showing RPD Characteristics
- Figure 14: Comcast, F. Wade, iHAT Results Dashboard
- Figure 15: Comcast, F. Wade, Prometheus
- Figure 16: Comcast, F. Wade, Moody Alerts Slack
- Figure 17: Comcast, F. Wade, OFDMA D3.1 Efficiency Tool
- Figure 18: Comcast, J. Chrostowki, XME OFDMA Parameters
- Figure 19: Comcast, M. Tan, C. Czaja, Efficiency Ranking Report
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