Real World HFC Plant Migration To 1.8 GHz

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Abstract[1]

HFC cable technology has provided a robust and flexible architecture that has allowed the industry to continue to evolve their networks to meet expanding capacity demands and higher product speed offerings for nearly three decades. The DOCSIS® 4.0 specifications, and in particular, the FDD (Frequency Division Duplex) option of DOCSIS 4.0, is just another example of that continued evolution capable of targeting in excess of 10 Gbps of downstream network capacity. While much is understood about operating a cable network in a FDD mode below 1 GHz, the expanded 1.8 GHz downstream frequency range provides for this incredible leap forward in capacity. HFC architectures commonly encompass nodes with amplifier cascade depths of 4 amplifiers or more. The amplifier cascade depth directly impacts signal quality and modulation levels achievable within the network and thus, network capacity. Cox has developed detailed models to aid in predicting performance within these cascades; however, it is critical that actual field testing be conducted to validate those expectations. In this paper, Cox will present results from a field test conducted with DOCSIS 4.0 downstream RF signals between 804 and 1764 MHz on a 20+ year old plant within Cox's production network with a cascade depth of N+4 (5 amplifiers). The testing validates our assumptions and provides confidence in our ability to deliver the promise of 10Gbps.

1. Introduction

Since the first release of the DOCSIS specification, the cable industry has benefited from an evolving standard which continues to exceed the product and capacity requirements of broadband customers. From initial offerings in the late 1990's of 1 Mbps which greatly outpaced the 56 kbps dial up telco offerings of the time to 2024 DOCSIS 3.1 speeds of 2 Gbps, DOCSIS has proved itself as a robust networking technology for serving broadband customers across the HFC access network.

With the introduction of DOCSIS 4.0, the industry is enabling that same HFC architecture of 30 years to theoretically provide downstream capacity in excess of 10 Gbps[2] with a potential single customer speed in excess of 9 Gbps, or a 9000x improvement from the initial offerings. DOCSIS 4.0 Frequency Division Duplex (FDD) achieves this by expanding the frequency spectrum up to 1.8 GHz and utilizing OFDM introduced in DOCSIS 3.1.

2. Predicting Performance using Modeling

In the earliest days of DOCSIS 4.0 spec development, Cox wanted to understand the performance that a network based on DOCSIS 4.0 FDD technology might be expected to achieve in our HFC plant. We developed a model to allow us to estimate that performance and have made ongoing improvements since, allowing us to estimate the impacts that various factors might have, such as downstream amplifier cascade depth, amount of RF step-down in the extended spectrum, and amplifier RF output tilt.[3] The results from this model have been a key early tool used by Cox leadership across the board supporting: our engineering team in defining requirements, our vendors in exploring design tradeoffs, our capacity planning team to anticipate future node actions, and our product team in understanding future competitive product opportunities.

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[1] The authors want to express our appreciation to Jeff Laliberte, Kraig Neese, the Cox Phoenix outside plant (OSP) construction/engineering team, and the Teleste and ATX engineering staffs without whose efforts and expertise, the success of this project would not have been possible.

[2] DOCSIS 4.0 1.8 GHz High-split yields a theoretical downstream capacity of 14.0 Gbps (after overhead)
DOCSIS 4.0 1.8 GHz Ultra-High-Split (396) yields a theoretical downstream capacity of 11.7 Gbps (after overhead)

[3] Additional details for Cox's DOCSIS 4.0 model structure are contained in the Appendix of this paper.

3. Beyond the Theory

At the same time that Cox has been developing a model, the industry vendors - including silicon, node, amp and tap - have been working diligently to develop products that meet or exceed these DOCSIS 4.0 requirements. Operators have been rewarded by the industry's hard work with production-ready 1.8 GHz tap/passives and amplifier products readily available today, with node and vCMTS (virtual Cable Modem Termination System) products anticipated in early 2025. With amplifiers and taps commercially available,[4] we wanted to validate the expectations guided by our model and while Cox had built test nodes up to N+6[5] cascades, these nodes were based upon new construction leveraging new cable, connectors, power supplies, etc. With these nodes being new build, we are assured that all the connections were tight and that the new cable met manufacturer specs. A live production node offers real-world effects that cannot be easily replicated in a newly constructed test node. Such things as aged cable and connectors that have suffered the effects of temperature, weather, and physical damage do not enter into the performance picture for a newly constructed node but are significant for real world performance.

4. Field Test Design and Execution

To continue our D4.0 study, we selected a 20+ year old node from our Phoenix market.[6] This node was considered representative of a typical Cox N+4 Node and was thought to have endured more stressful environmental conditions than your average node due to extreme temperatures in our Phoenix location. Figure 1 provides a diagram of the node that was selected. While the node is larger than what is shown in the diagram including other amps and passives, the drawing has been simplified to reflect only components of particular interest to the test, namely 2 cascades of N+4 and N+3. While we planned to use production amplifiers and taps/passives, we were constrained by the fact that only prototype equipment (designed for lab use only) was available for the DOCSIS 4.0 CMTS and DOCSIS 4.0 cable modem elements. This meant they weren't designed to remain in outside conditions and did not incorporate the full suite of configuration options and services which are necessary for continued use on a production node. As a result, the prototypes could not be left permanently in the field and we were forced to conduct our test during a maintenance window. This allowed us to minimize customer impact and risk while still meeting the requirement for a real-world aged plant.

[4] Cox is currently deploying 1.8 GHz amplifiers as a part of other network upgrade activities.
[5] N+4 is a common HFC architecture designation that defines a node followed by a maximum amplifier cascade depth of 4 amplifiers. Cascade depth is a key factor in determining downstream signal quality performance.
[6] Portions of this node were constructed as early as 1991.

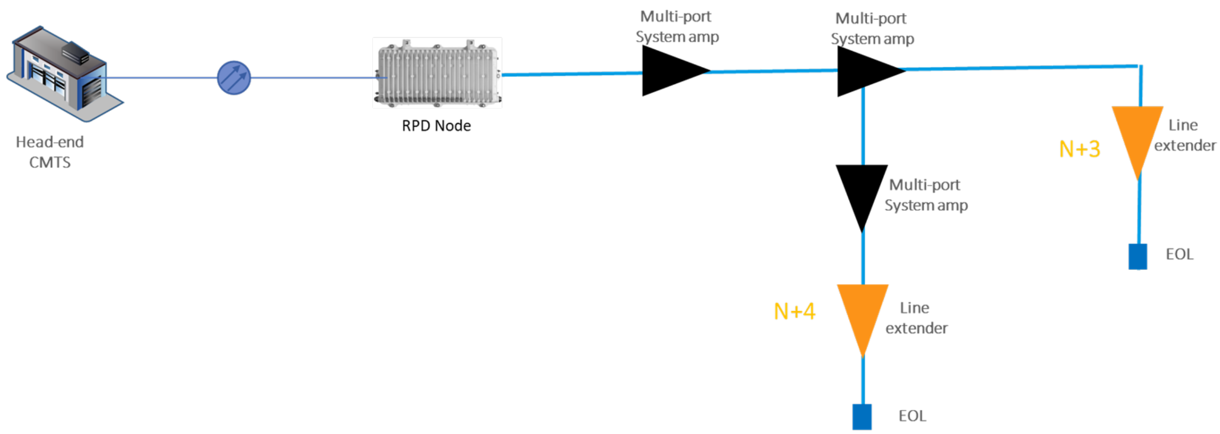

Figure 1 - DOCSIS Field Test Production Node with Key Components of Interest.

About a week prior to the field test maintenance window, the entire node was upgraded with drop-in replacement 1.8 GHz amplifiers, taps and passives. The replacement amplifiers were configured to run in 1 GHz mode. A forward sweep to 1.0 GHz was conducted during the upgrade before the node was returned to active status providing 1 GHz mid-split service. During the subsequent 6-hour long maintenance window allocated for testing with downstream RF loading to 1.8 GHz, the team would need to: 1) reconfigure the amplifiers for 1.8 GHz operation with our prototype DOCSIS 4.0 CMTS and cable modems, 2) collect our test measurements, and 3) return the amplifiers to their original 1.0 GHz mid-split configuration for servicing the existing customers. If any cable spans required replacement after activating the 1.8 GHz spectrum, the maintenance window test would need to be delayed. The completion of so many tasks within such a short window was only made possible by leveraging advanced 1.8 GHz smart amplifiers which can be quickly reconfigured and auto aligned for operation as well as automation software that Cox had developed as a part of our DAA deployments.

Figure 2 illustrates the 1.8 GHz node state which was tested during the maintenance window. While testing, the original node outputs were disconnected, and an equivalent 1.8 GHz "node" was used in its place. The equivalent 1.8 GHz node included our prototype CMTS as well as an additional line extender to provide the launch signal levels that matched the original node. In effect, our test conditions would include the original cascade (N+3 and N+4) plus an additional amplifier, meaning cascades of 4 and 5 amps respectively. The test configuration also included multiple Windows 11 based laptops with 10 GbE interfaces to support throughput testing and signal quality measurements as well as a DOCSIS signal analyzer to enable additional signal quality measurements.

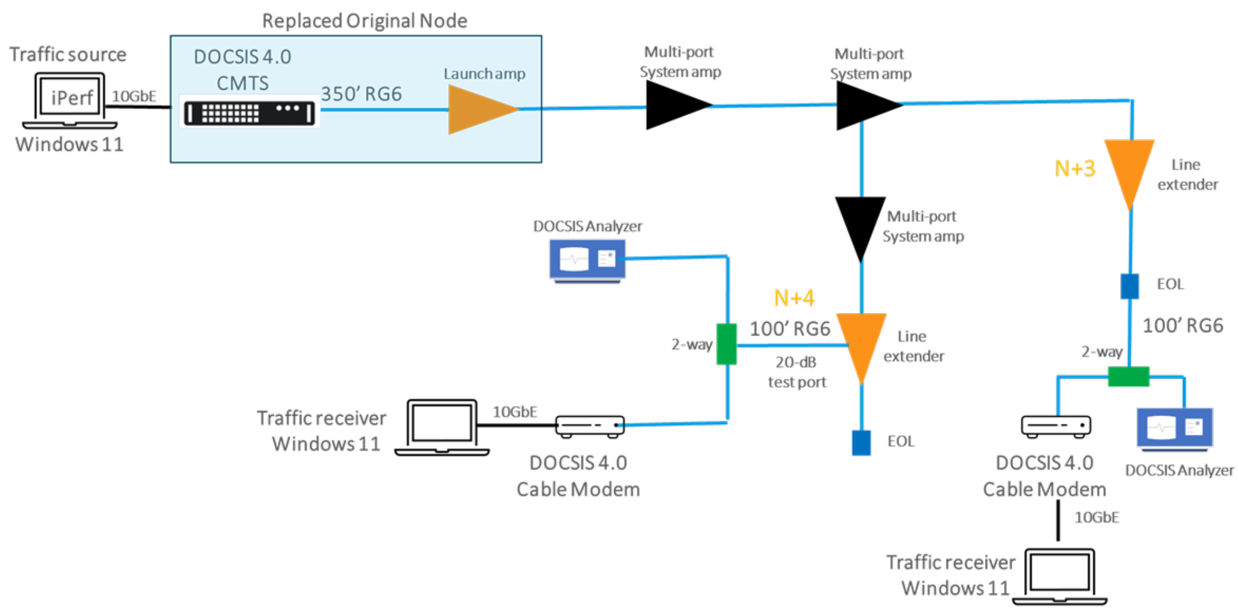

Figure 2 - DOCSIS 4.0 1.8 GHz Field Test Configuration.

Specific steps executed during the maintenance window test include:

1. Disconnect the legacy node and connect the prototype CMTS and launch amplifier in its place

2. Configure the CMTS for 1.8 GHz and adjust RF levels for the launch amplifier to match legacy levels provided by the original node. This meant reconfiguring the legacy Cox 1.0 GHz mid split profile with the new 1.8 GHz profile. The test utilized a 6 dB power step down at 1.0 GHz in order to maintain legacy levels below 1.0 GHz while maintaining total forward power below TCP (total composite power) constraints of modern amplifier silicon technology. (See Figure 3 and [1] Cooper et al, SCTE 2019). Cox is targeting a TCP of 68.4 dBmV for our 1.8 GHz UHS-396 profile which allows for adequate operating margin.

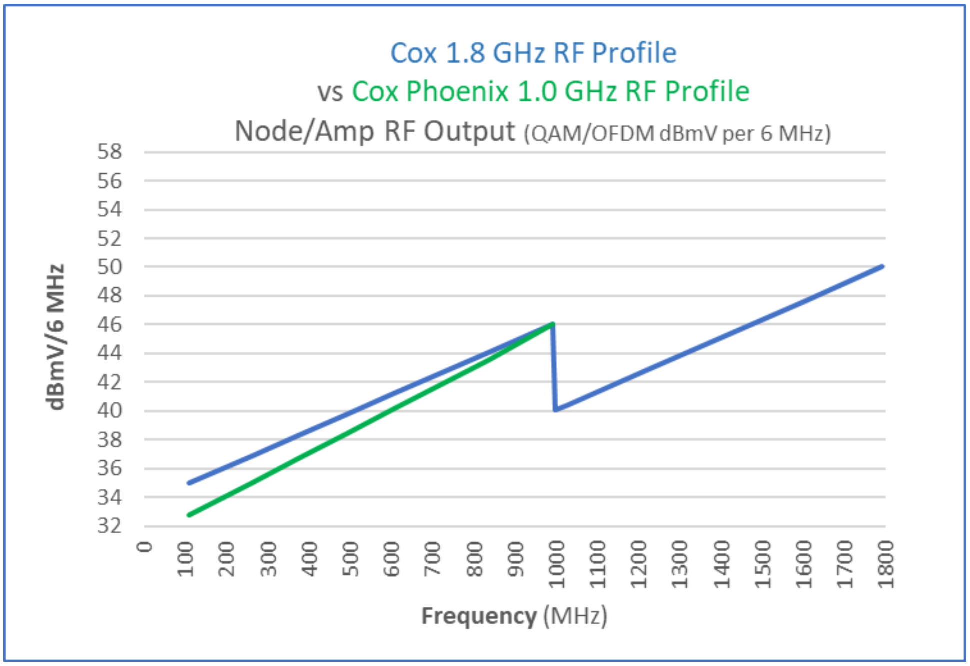

Figure 3 - Forward RF Profile.

3. Progressing from the node outward, reconfigure each amplifier with the 1.8 GHz profile and auto-align the forward and return. (Conversion to DOCSIS 4.0 1.8 GHz is complete after this step)

4. Perform throughput testing and signal quality measurements at: 1) N+3 end of line (EOL) and 2) N+4 (amplifier test point) locations.[7]

5. Disconnect the prototype CMTS and launch amplifier and reconnect the legacy node.

6. Legacy node remains configured with a 1.0 GHz mid-split profile. Progressing from the node outward, reconfigure and realign each amplifier with the 1.0 GHz profile.

As reflected from the multitude of steps during the short maintenance window, the team was extremely busy and managed to complete the activities and return existing customers to service with some time to spare.

5. Performance Results

5.1. Signal Quality and Modulation Level

Configuration options supported by the prototype CMTS limited our testing to 5 downstream OFDM channels. Since performance was well understood for DOCSIS 3.1 signals below 1 GHz within the Cox network, the configuration used in the test allocated those 5 192-MHz OFDM channels to spectrum from 808 MHz to 1768 MHz as shown in Figure 4.

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[7] Cox's initial plan was to test both cascades at EOL; however, passive locations within gated private property limited accessibility during our test.

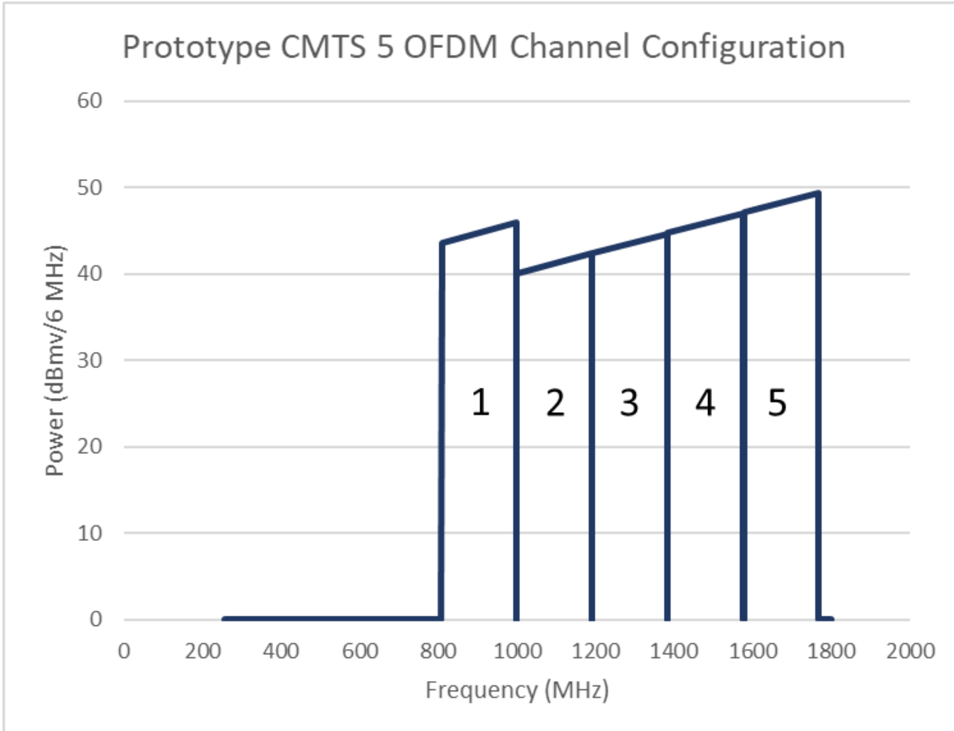

Figure 4 - DOCSIS 4.0 Test OFDM Channel Configuration.

A primary goal of the test was to quantify the cable modem downstream signal quality using MER (modulation error ratio) measurements and compare that performance against model predictions. Cox design plans call for targeting 4kQAM modulation for OFDM channels below 1 GHz (Channel 1 in Figure 4) and 2kQAM for OFDM channels above 1 GHz (Channels 2, 3, 4, and 5 in Figure 4). Any performance beyond those expectations would provide further margin for our deployments.

Figure 5 and Figure 6 provide the DOCSIS 4.0 cable modem measured MER performance results for each OFDM channel for the N+3 (4 amp) end of line (EOL) and the N+4 (5 amp) test port locations respectively. Cable modem measurements are shown in orange while predicted model performance is shown in gray. The step down in measured MER above 1 GHz is a direct result of the 6 dB step down in power Cox plans to use for signals above 1 GHz. For all but one case, actual performance was better than modeled results, with that one exception case reflecting a difference of only 0.3 dB and well within expected tolerances.

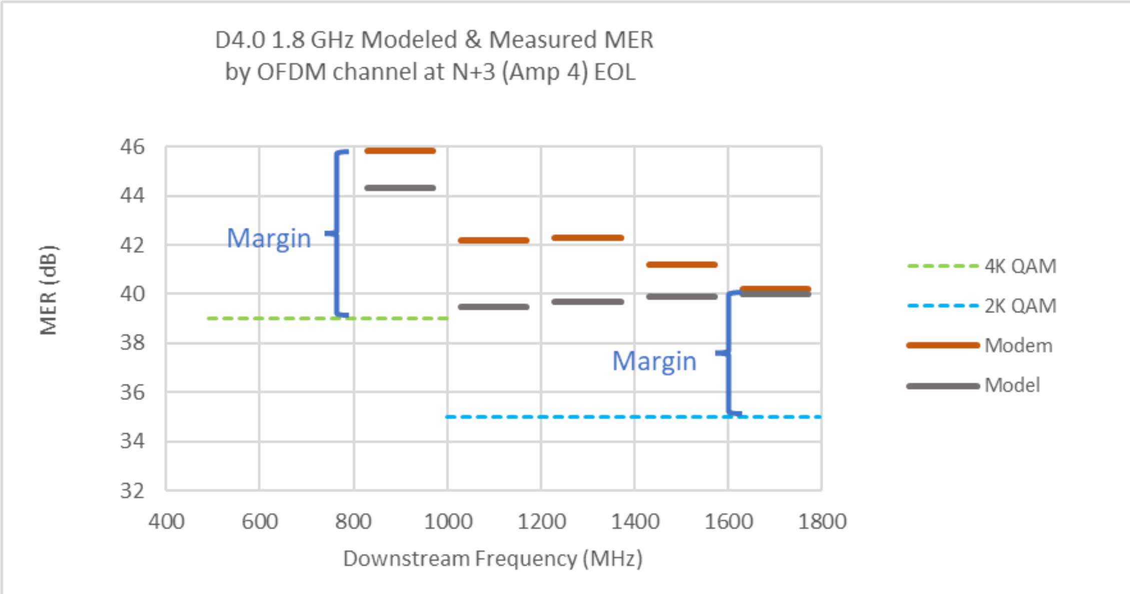

Figure 5 - Modeled vs Measured MER at N+3 (4th amp)

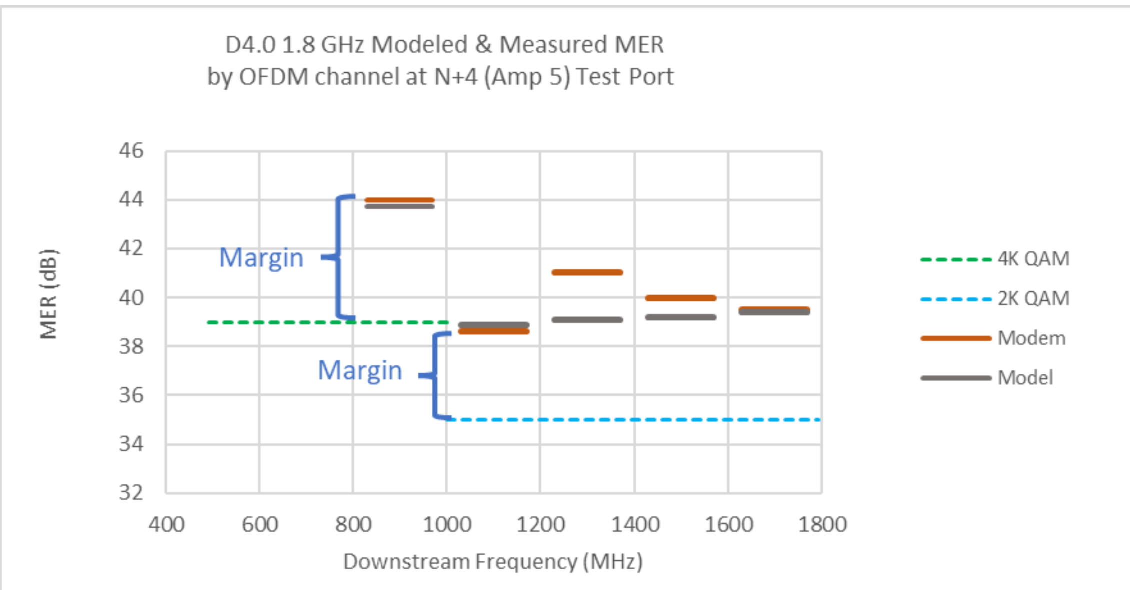

Figure 6 - Modeled vs Measured MER at N+4 (5th amp)

Expected modulation levels (which directly drive throughput performance) can be established based upon thresholds needed to meet near error-free performance at each modulation level. While the DOCSIS specification identifies minimum CNR thresholds for QAM levels, Cox's years of field experience with DOCSIS 3.1 and DAA deployments have shown these thresholds to be overly conservative and near error-free performance is achievable using more relaxed thresholds.[8] Table 1 summarizes the thresholds for: 1) the DOCSIS 3.1 Physical Layer Specification, 2) existing Cox

[8] As of May 2024, Cox has upgraded over 75% of our network to DAA and utilizes DOCSIS 3.1 OFDM across 99.5% of our footprint.

production deployments, and 3) values used in our 1.8 GHz model. Our 1.8 GHz model thresholds for 4kQAM (green dotted line) and 2kQAM (blue dotted line) are shown in Figure 5 and Figure 6.

Table 1 - Cox Modulation QAM Level Thresholds.

QAM Level	DOCSIS 3.1 Specification (dB) [9]	DOCSIS 3.1 Cox Production (dB)	Cox 1.8 GHz Model (dB)
4096	41	37	39
2048	37	33	35
1024	34	30	32
512	30.5	26.5	28.5
256	27	23	25

In the case of the N+3 EOL measurements (Figure 5), measured MER results indicate that 4kQAM should be achievable for all 5 OFDM channels with significant margin provided for channels 1 through 4. Similarly, for the N+4 case (Figure 6), 4kQAM is assured for the OFDM channel below 1 GHz (channel 1) and likely for at least two of the OFDM channels (channels 3 and 4). Significant margin is present for the 4 OFDM channels above 1 GHz to support 2kQAM. This leads us to believe that Cox's original target goal of 4kQAM below 1 GHz and 2kQAM above 1 GHz should be assured for N+4 cascades or less.

5.2. Cable Modem Throughput and Network Capacity

In order to confirm that these MER measurements translated into real-world modem performance, we needed to perform throughput testing over the cascade. Our testing focused exclusively on downstream throughput for a number of reasons. First, we did not have control over the upstream configuration in our CMTS. There were no parameters we could tune so we were at the mercy of the default settings. Second, the US/DS split of the CMTS did not match the diplexers available for use in the amplifiers, or in the cable modem, so we knew that the modem would be in partial service (at best). With no visibility into upstream performance and no way to either diagnose or troubleshoot any upstream issues, we decided to use downstream UDP testing. Using the channel configuration shown in Figure 4 and with modulations of 4kQAM below 1 GHz and 2kQAM above 1 GHz, we expected to achieve 8.1 Gbps of throughput. (See Table 2)

Table 2 - Field Test Downstream Expected Throughput to a Single DOCSIS 4.0 CM.

Start (MHz)	Stop (MHz)	BW (MHz)	Channel Type	Modulation	Throughput (Gbps)
808	1000	192	OFDM 1	4K	1.74
1000	1192	192	OFDM 2	2K	1.59
1192	1384	192	OFDM 3	2K	1.59
1384	1576	192	OFDM 4	2K	1.59
1576	1768	192	OFDM 5	2K	1.59
				TOTAL	**8.10**

In addition to being limited to downstream testing, the nature of our field test limited us in other ways. DOCSIS throughput testing is typically performed with a traffic generator wired to both the

[9] [2] CM-SP-PHYv3/1-I20-230419 DOCSIS 3.1 Physical Layer Specification Table 46.

CMTS and the CM in a closed loop. Since these devices were over 1500 meters apart, we had to use a client-server based approach. With a typical speed test initiated by a client against a server (such as openspeedtest.com's open source implementation), TCP is used for the download. We wanted UDP so that upstream would not be a factor, and decided to use iPerf instead.

As shown in Figure 7, our throughput test setup consisted of a Windows 11 computer with a thunderbolt 10 GbE dongle connected to the CMTS over Cat8 twisted pair and used to generate just over 9 Gbps. On the cable modem side, another Windows 11 laptop with the same dongle & cable was used to measure the received traffic.

Figure 7 - Throughput Test Data Flow.

Through trial and error, we determined that the sending computer reached its best throughput using the following iPerf command line traversing the path:

```
iperf -c 10.0.0.4 -b 1000000000 -t 9999 -P10
```

In our testing we found that iPerf3 did not perform as well as iPerf v1.7, when both were configured to use UDP. Furthermore, at the speeds we were using to test, iPerf statistics reporting was unreliable. Therefore, we had to rely on the rough bandwidth reporting of the Windows task manager "Performance" window of the Ethernet adapter. While not as precise as a data traffic appliance, it did give us a level of confidence that the cable modem was indeed passing traffic to the receiving computer at a rate that was very close to what was predicted.

Figure 8 and Figure 9 provide screen captures from the sending and receiving computers during a throughput test where the sender was outputting 9 Gbps via the iPerf command line shown above.

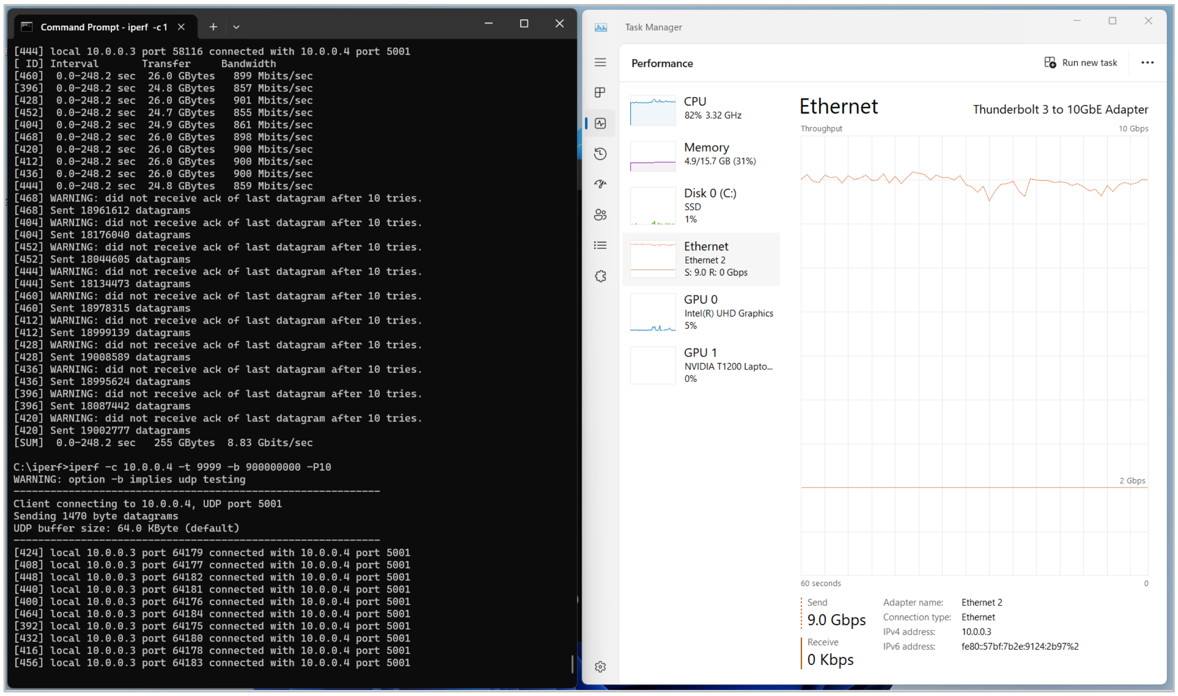

Figure 8 - Traffic source sending 9.0 Gbps.

The screen capture shown in Figure 9 represented the highest instantaneous value that we saw (8.2 Gbps). More typically, the throughput fluctuated between 8.0 and 8.1 Gbps. These results confirmed our expected single modem downstream throughput rates of 8.1 Gbps as projected in Table 2.

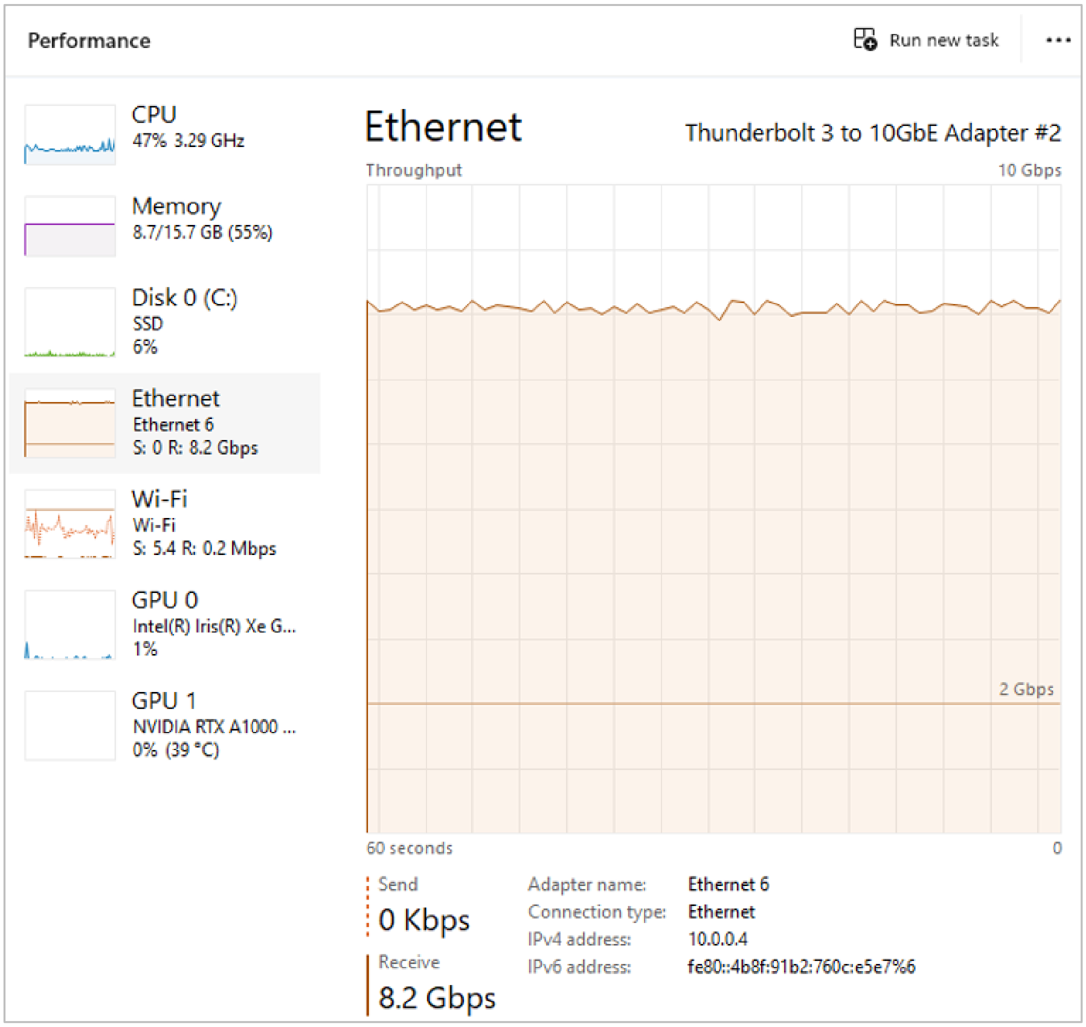

Figure 9 - Traffic destination receiving 8.2 Gbps.

5.2.1. Extrapolated Single-Modem Throughput

DOCSIS 4.0 requires a cable modem to support a minimum of 5 OFDM channels and 32 SC-QAM channels; (See [3] DOCSIS 4.0 Physical Layer Specification, Table 30) however, we were not able to include the additional SC-QAM channels in our lineup, due to a limitation of the prototype CMTS. As a result, our throughput testing was performed using 5x192 MHz OFDM channels only. Had we included 32 SC-QAM channels running at a fixed 256 QAM modulation, yielding 37.5 Mbps of throughput each, our bonded total for a single cable modem would be expected to be 9.3 Gbps. (See Table 3). Note, while the DOCSIS 4.0 specification identifies a minimum 5 OFDM channels and 32 SC-QAM channels support, discussions within the industry have hinted at additional OFDM channel support in future cable modems which would result in a single modem throughput beyond 10 Gbps.

Table 3 - More than 9 Gbps Downstream Throughput with a Single DOCSIS 4.0 CM.

Start (MHz)	Stop (MHz)	BW (MHz)	Channel Type	Modulation	Throughput (Gbps)	
		192	32 SC-QAM	256	1.20	
808	1000	192	OFDM 1	4K	1.74	this is the 8.1 Gbps we measured during the field test
1000	1192	192	OFDM 2	2K	1.59	
1192	1384	192	OFDM 3	2K	1.59	
1384	1576	192	OFDM 4	2K	1.59	
1576	1768	192	OFDM 5	2K	1.59	
				TOTAL	**9.30**	

5.2.2. Extrapolated Serving Group Capacity

Similar to single modem throughput expectations discussed in Section 5.2.1, DOCSIS 4.0 requires a CMTS to support a minimum of 6 OFDM channels and 32 SC-QAM channels. (See [3] DOCSIS 4.0 Physical Layer Specification, Table 30). While our prototype CMTS was limited to 5 OFDM channels and no SC-QAM channels, in the future Cox anticipates deploying a DOCSIS 4.0 UHS-396 diplex configuration with downstream channels as shown in Figure 10. Based upon both Cox's current production experience with OFDM channels as well as this field test, we expect to achieve 4kQAM for CPE devices using OFDM channels below 1 GHz.

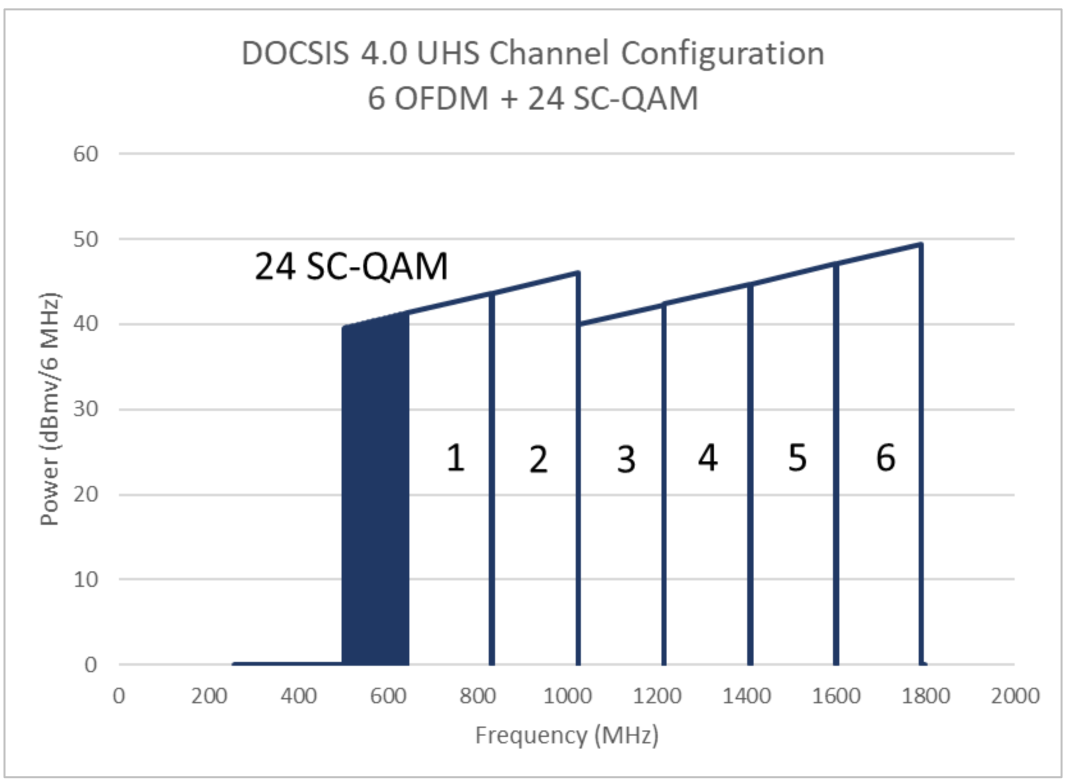

Figure 10 - Possible Future Cox DOCSIS 4.0 UHS-396 Channel Configuration.

If we include the additional 4kQAM OFDM channel and the 24 SC-QAM channels[10] (available spectrum between 498 and 642 MHz), our total downstream capacity from a DOCSIS 4.0 CMTS UHS-396 (492) serving area would be 10.74 Gbps. (See Table 4). Similarly, for UHS-300 and HS (high-split) diplexer configurations which other operators may be considering, we would expect 11.6 and 12.9 Gbps of downstream capacity.

Table 4 - More than 10 Gbps Downstream Capacity in a 1.8 GHz HS-396 Configuration.

Start (MHz)	Stop (MHz)	BW (MHz)	Channel Type	Modulation	Throughput	
498	642	144	24 SC-QAM	256	0.90	
642	834	192	OFDM 1	4K	1.74	
834	1026	192	OFDM 2	4K	1.74	this is the
1026	1218	192	OFDM 3	2K	1.59	8.1 Gbps
1218	1410	192	OFDM 4	2K	1.59	measured
1410	1602	192	OFDM 5	2K	1.59	during
1602	1794	192	OFDM 6	2K	1.59	field test
				TOTAL	**10.74**	

5.3. Other Observations - Spectrum Ingress

While we were operating in spectrum above 1 GHz, it wasn't surprising that we encountered traditional impairments commonly seen in HFC below 1 GHz. For example, ingress presented itself in the plant as illustrated in Figure 11. While present, the team was encouraged by the fact that any impairments we saw in these higher frequencies were easily overcome by the robustness of the DOCSIS downstream including such countermeasures as LDPC (low-density parity-check).

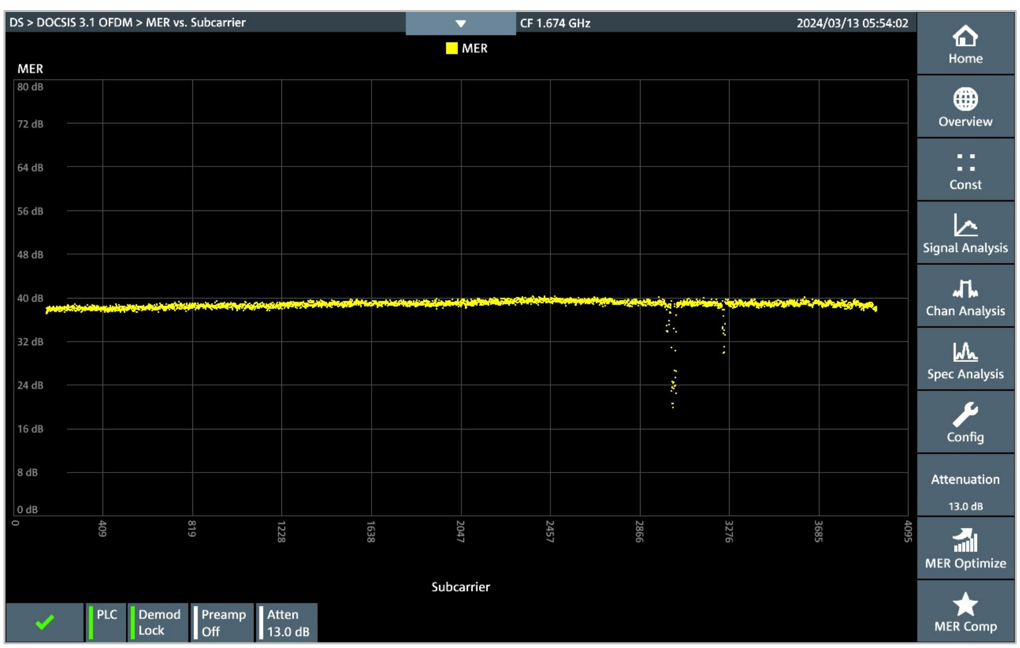

Figure 11 - EOL DOCSIS Signal Analyzer MER vs OFDM Subcarrier (1576-1768 MHz) – Ingress clearly visible ~1720 MHz (Fixed Mobile [4] FCC Table)

6. Extended Model Predictions

The field test results presented in Section 5.1 align well with the performance results predicted by the Cox model for the N+3 and N+4 cascades tested. Within the Cox network, more than 60% of our nodes are N+4 or less in depth (See Figure 12); however, if we were able to meet these same QAM thresholds in cascades up to N+6, then we could meet our capacity and throughput targets in more than 90% of the Cox network. Due to the timing of the field testing in early 2024, a deeper cascade than N+4 was not immediately available and while further field testing for these test cases should be performed, we were interested in what our model was predicting for these deeper cascades.

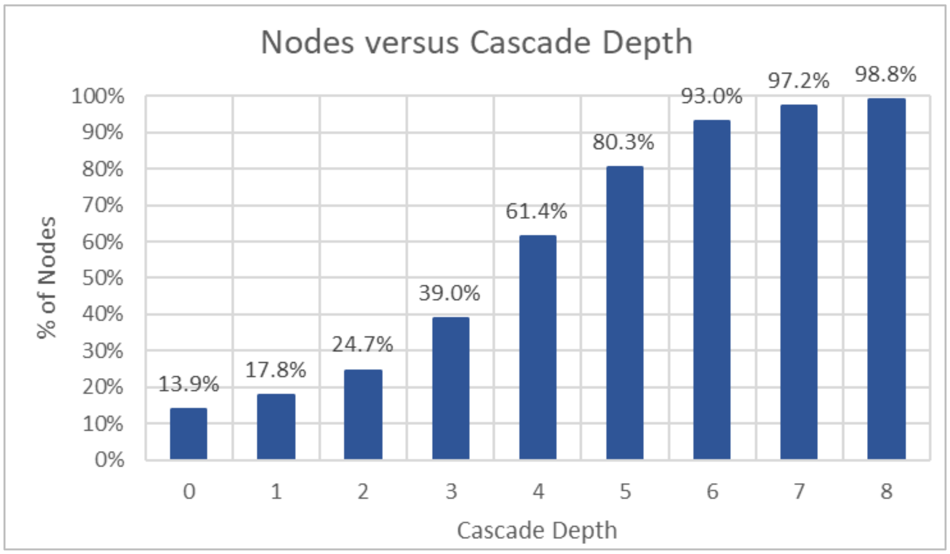

Figure 12 - Cox Node Cascade Depth Distribution.

Figure 13 illustrates Cox's model-projected performance for an N+6 cascade against our QAM level thresholds. (Note, for this projection, Cox utilized more stressful conditions which included: 1) a network configuration of N+6 with an additional booster amplifier which may be required for longer cable spans, 2) the full temperature operating conditions of -40 to +60° C operating environment, and 3) Cox's targeted full loading from 492-1794. This network configuration results in a cascade of 8 amplifiers: 1 launch amp in the node, 1 booster amp, and 6 traditional amps. Cox is currently projecting about 8% of our cable spans will require a booster amplifier.) According to the model, we would expect to easily achieve 4kQAM for OFDM channels below 1 GHz. For signals above 1 GHz, the predicted performance for N+6 indicates 2kQAM should be achievable; however, for amp cascades of N+6, the margin of error is relatively small.

The margin of error is an important factor to consider as other real-world conditions such as thermal variation and longer drop lengths could eat into that margin. In addition, operators would be wise to invest in the implementation of such features as PMA (Profile Management Application) which should enable them to operate closer to QAM thresholds while minimizing the impacts of any devices which don't quite meet the threshold and need to drop to a lower QAM. ([5] Sundaresan, INFORMED Blog, CableLabs 2019)

[10] Cox only deploys SC-QAMs in blocks of 8 channels.

Finally, if we are forced to utilize 1k QAM above 1 GHz for some edge cases, then the impact should be tolerable with overall capacity decreasing from 10.74 to 10.18 Gbps and our single modem throughput dropping from 9.3 Gbps to 8.74 Gbps, but only for those devices beyond N+5.

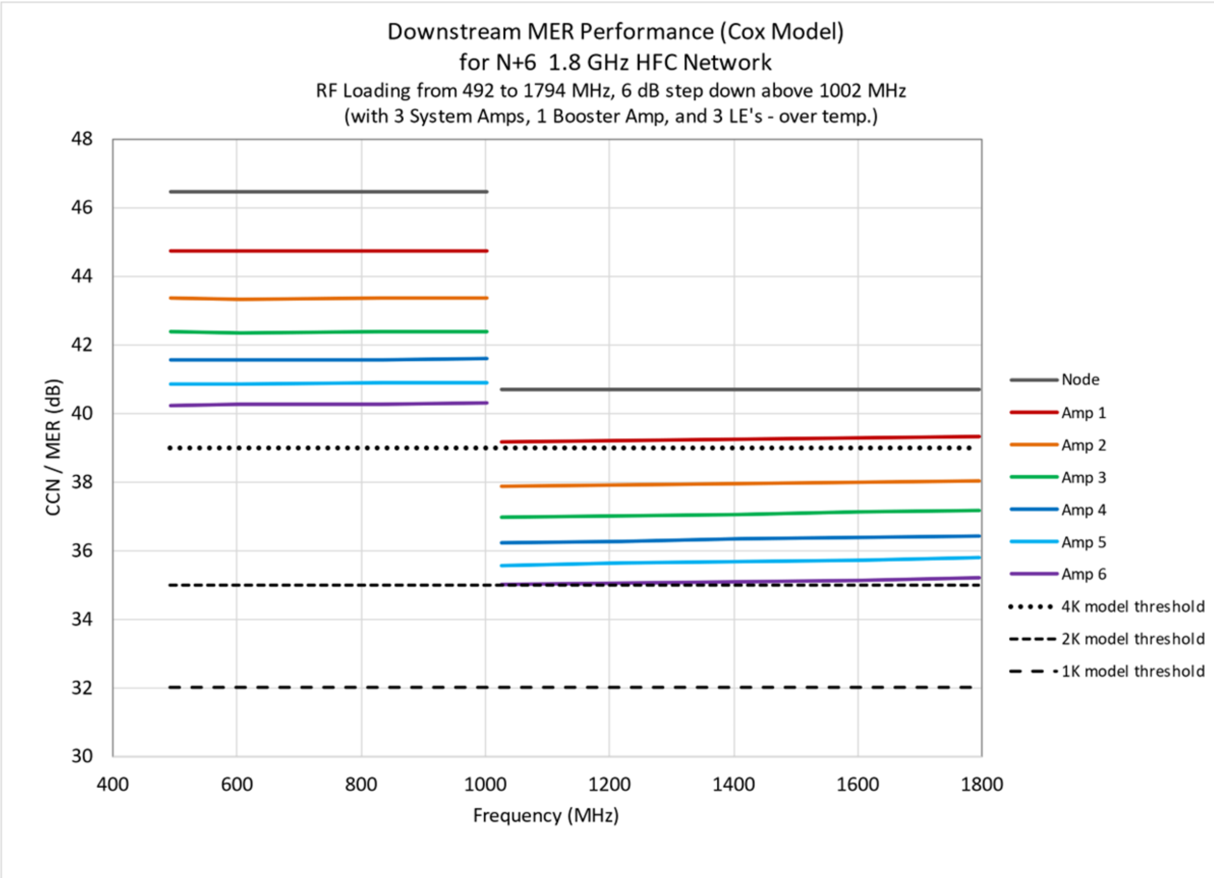

Figure 13 - Model predicted downstream signal quality performance for up to a N+6 cascade depth.

7. Conclusion and Next Steps

Within this paper, we have documented a field test Cox conducted in March of 2024 on a 20+ year old N+4 production node. This node was upgraded with commercially available DOCSIS 4.0 FDD amplifiers and taps/passive and was shown to support downstream capacity targets in excess of 10 Gbps without necessitating costly cascade reductions, node splits or reductions in service area sizes. Further, during the testing, we used DOCSIS 4.0 cable modems to record downstream OFDM MER performance for channels between 0.8 and 1.8 GHz which showed reliable support for 4kQAM modulations below 1 GHz and 2kQAM modulations above 1 GHz on a N+4 node cascade. The MER values recorded show significant margin to allow for degradation due to other operating conditions such as temperature variation and extended length drops. Subsequently, we used these results to validate our DOCSIS 4.0 FDD model and estimate performance on deeper (N+6) cascades. In addition, the test demonstrated that single-user throughput in excess of 9 Gbps is achievable within a DOCSIS 4.0 UHS-396 configuration on node cascades up to N+4.

Due to limited availability of deeper cascades at the time of this test, an N+4 node was used; however, in the future, we would like to perform additional measurements on deeper cascades, specifically an N+6 node which would represent coverage for more than 90% of Cox's network. In addition, the prototype CMTS that was available for our test limited our ability to configure upstream beyond the defaults but expanding our upstream characterization is a second target for further field testing. The expanded upstream spectrum offered by DOCSIS 4.0 FDD will almost certainly bring new challenges as operators seek to increase upstream speeds while dealing with noise funneling problems within spectrum that has traditionally been reserved for downstream operation.

Appendix – Modeling Details

In the early days of DOCSIS 4.0 specification development, Cox developed a performance model to allow us to estimate network performance and we have made ongoing improvements since, allowing us to estimate the impacts due to various factors such as downstream amplifier cascade depth, amount of RF step-down in the extended spectrum, and amplifier RF output tilt.

The following summary describes some of the important aspects of the performance model that Cox developed. While taken as a whole it appears complex, the majority of the required inputs and calculations used are fairly straightforward.

For downstream (which was the focus of the testing presented in this paper), the following attributes are entered into the model:

- Hardline coax cable type and footage per span (losses derived from a lookup table)
- Tap type, value and port count (tap port and insertion losses derived from a lookup table)
- Passive types – splitters, directional couplers, etc. – (losses derived from a lookup table)
- Drop coax cable type and footage (losses derived from a lookup table)
- Amplifier operational gain, slope, and noise figure (provided by manufacturer)
- Target amplifier RF output levels – including tilt and applicable RF step down for the extended spectrum band
- Carrier to Intermodulation Noise (CIN) ratio for the amplifiers – for given RF output levels, step down, and loading (more recently provided by amplifier station manufacturers, earlier derived from individual amplifier gain block performance measurements)
- LOG addition factor to be used for cascade distortion addition (i.e. 10LOG, 12LOG, etc.).
- Estimated MER (CCN) for the downstream RF source signals (generated by the RPD)

Based on the entries, the downstream RF input and output levels at select frequencies are calculated for all the components in the simulated network configuration. The expected variance from nominal station gain and slope for each amplifier (which necessitates additional attenuation and/or equalization) are calculated based on the station's RF input levels, target RF output levels, and the amplifier's nominal operational gain and slope. Any attenuation that is expected to be applied mid-stage (during auto-alignment) instead of at the amplifier's input is accounted for to derive the amount of input attenuation that would be expected. The expected input attenuation and equalization losses are subtracted from the station's RF input levels to determine the corrected RF input levels to be used in Carrier to Thermal Noise (CTN) calculations. The CTN ratios for each amplifier are calculated based on the station's RF input levels (after input attenuation and equalization losses), the amplifier station's noise figure, and the thermal noise in a 75-ohm circuit with a 6 MHz bandwidth, using the following formula:

CTN = RF input level/6 MHz (after input attenuation and EQ losses) – Noise Figure – (-57.4)

The CTN ratios for the individual amplifiers are summed (on a 10LOG basis) to calculate the cumulative CTN performance through the amplifier cascade, using the following summation formula (extended as needed to incorporate each of the amplifiers in cascade in the specific model):

$$\textit{Cumulative CTN at Amp 2} = -10 * \log \left(10^{-(CTN\ amp\ 1/10)} + 10^{-(CTN\ amp\ 2/10)}\right)$$

$$\textit{Cumulative CTN at Amp 3} = -10 * \log \left(10^{-(CTN\ amp\ 1/10)} + 10^{-(CTN\ amp\ 2/10)} + 10^{-(CTN\ amp\ 3/10)}\right)$$

Likewise, the distortion expected to be generated by each amplifier must be factored in. In modern CATV networks that no longer carry NTSC modulated video carriers and instead carry RF signals that are commonly referred to as "digital" RF signals, i.e. those using Quadrature Amplitude Modulation (QAM), the intermodulation distortion products are deemed to be noise-like in nature. The term Carrier to Intermodulation Noise (CIN) was defined by the SCTE to quantify the ratio of RF signal power to the power of the intermodulation distortion products that an amplifier creates, referenced to a specific RF bandwidth (typically 6 MHz in North America). The CIN value is linked to a given set of amplifier RF output levels, RF tilt, and spectral loading because changing any of those attributes can affect the CIN. Now that full 1.8 GHz amplifier stations are becoming available, CIN model values would preferably be provided by the amplifier manufacturer. The model sums the CIN ratios for the individual amplifiers (on a selectable 10-15LOG basis) to estimate the cumulative CIN performance through the amplifier cascade.

The cumulative CTN and CIN values for each amplifier are summed together (on a 10LOG) basis with the expected MER of the source RF signals (generated in the RPD module) to estimate the cumulative Carrier to Composite Noise (CCN) performance through the amplifier cascade, with the RF source contribution taken into consideration.

Note that for the purpose of the model, CCN (representing the summation of the amplifier related thermal noise and distortion components, plus the source MER) is considered to represent the approximate MER that would be expected at a given location in the network. Due to the complexity that would be involved the model does not factor in other aspects of network performance that can degrade MER (such as ingress, micro-reflections, frequency response build up due to amplifier and passive response signatures, etc.) but many of those impairments can be handled effectively by modern DOCSIS receivers. The model serves to provide an approximation of what the network may be capable of achieving, based upon the dominant noise and distortion impacts associated with the amplifiers.

The model also calculates the expected downstream RF input levels to the DOCSIS 4.0 gateway/modems at various locations in the network based on expected tap and drop cable losses. The CCN and the estimated RF input levels to the DOCSIS 4.0 gateway/modem are both used to estimate the expected order of modulation that should be achievable for a given OFDM channel. The expected order of modulation and the bandwidth of the OFDM channel are used to estimate the throughput in Gbps for each OFDM channel, after taking overhead into account. By summing the throughputs for all the OFDM channels and adding the expected throughput associated with any SC-QAM DOCSIS signals that would also be carried, the total throughput capacity at any point in the network can be estimated.

For the upstream, most of the same types of inputs and calculations described for the downstream are required but the cumulative CTN component must be calculated not only for a particular cascade of amplifiers in series, but for all the amplifiers whose upstream RF outputs are expected to funnel back to a particular upstream receiver in the RPD node. This is required due to the well understood noise funneling aspect of the HFC upstream network. The model accounts for this by incorporating a field that allows the user to input the quantities of each type of amplifier expected to be feeding back to a given upstream receiver in the RPD node. Those quantities are then used in the CTN summation calculations.

Another aspect of importance in the upstream is the fact that the DOCSIS 4.0 gateways/modems have upstream transmit power limitations that should not be exceeded. The model calculates the expected modem transmit power/6.4 MHz at various frequencies for modems positioned off any tap in the modeled configuration. The calculated modem transmit power depends largely on its location in the network (what tap it is connected to), the drop loss, and the target upstream RF input power per 6.4 MHz for the node and amplifiers. The drop loss and target upstream input power fields can be adjusted to see the impacts on modem transmit power (relative to transmit power limits) and the impacts on expected overall network performance.

Abbreviations

ADC	analog to digital converter
CCN	carrier to composite noise
CIN	carrier to intermodulation noise
CMTS	cable modem termination system
CTN	carrier to thermal noise
DAA	distributed access architecture
DOCSIS	Data Over Cable System Interface Specification
EQ	equalization
EOL	end of line
FDD	frequency division duplex
Gbps	gigabits per second
GHz	gigahertz
HFC	hybrid fiber coax
LDPC	Low-density parity-check
LOG	logarithm
Mbps	megabits per second
MER	modulation error ratio
MHz	megahertz
NCTA	National Cable Telecommunication Association
OFDM	orthogonal frequency division multiplexing
OSP	outside plant
QAM	quadrature amplitude modulation
PHY	physical layer
RF	radio frequency
RPD	remote phy device
SC-QAM	single carrier quadrature amplitude modulation (6 MHz digital carrier)
SCTE	Society of Cable Telecommunications Engineers
TCP	total composite power
vCMTS	virtual cable modem termination system

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