Operational Considerations and Optimization of OFDM Deployments

A Technical Paper prepared for SCTE•ISBE by

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Introduction

With the convergence of services to IP and the continued growth of bandwidth demands, the access network is stressed to greater and greater capacity limits, forcing cable operators to find the most efficient network configurations such that their networks are providing the largest capacity possible. Such configurations require the highest number of modems operating at the highest modulation order profiles in order to maximize the capacity provided by the networks RF spectrum. The introduction of DOCSIS 3.1 is one of the latest options for cable operators to optimize the performance and maximize the capacity of their networks. DOCSIS 3.1 provides a host of new levers for improving the bandwidth offered by the network. One such lever is the introduction of much higher order modulations than previously provided in earlier versions of DOCSIS. On the downstream, the DOCSIS 3.1 CMs and CMTSs must now support modulation orders up to 4096-QAM with options to support 8192-QAM and 16384-QAM. This is a significant increase over the limited SC-QAM modulations of 64-QAM and 256-QAM required in DOCSIS 3.0 and earlier, and offers as much as a 50% capacity improvement within the same spectrum.

With Cox's initial DOCSIS 3.1 deployments, we focused on a few select parameters in order to maximize the number of modems running the highest modulations. These parameters included:

1) OFDM channel placement within the RF spectrum
2) Power spectral density
3) Windowing
4) Adjacent channel interference and profile bit-loading
5) Profile assignment and MER thresholds, and
6) Channel metrics for monitoring the network.

This paper will explore the approach that Cox used to select each of these parameters and provide some details on the performance we were able to achieve with these configurations.

1. Selection of OFDM parameters

One of the key elements of the DOCSIS 3.1 PHY specification in general, and OFDM specifically, is the tremendous degree of flexibility afforded operators. In considering our OFDM deployment, it was necessary to select a set of parameters to be modified and define appropriate values for each that would result in optimizing the bandwidth of the channel. This section will detail the parameters that were considered and the decisions made regarding each.

1.1. OFDM channel placement within the RF spectrum

The acceleration of consumer bandwidth demands has driven Cox, as well as other operators, to expend significant resources to ensure that their HFC networks are operating as cleanly as possible. As a result, most networks are easily running 256-QAM across their full spectrum of downstream carriers with significant amounts of headroom. Excessive headroom means capacity is being left on the table. With 256-QAM as the highest modulation option in DOCSIS 3.0, and many networks running at over 40 dB MER, networks are running at sub-optimal configurations with DOCSIS 3.0 and prior versions. However, initial DOCSIS 3.1 deployments cannot convert all the RF spectrum to OFDM, as the population of 3.1 modems is relatively low, while the population of other legacy DOCSIS modems is high. As a result, spectrum will need to be slowly migrated from SC-QAM to the more efficient OFDM as modem populations move toward DOCSIS 3.1. A key question is in what portion of the RF spectrum should we begin that initial conversion from SC-QAM to OFDM channels.

As we explored this question, we recognized that certain regions of the RF spectrum (even the downstream spectrum) are less conducive to communications than others. For example, the 700 MHz frequency region commonly overlaps with the LTE band of cellular operation. As a result, these signals can often ingress into the cable operator's networks interfering with communications across the cable network within this spectrum. In addition, the upper frequencies (within 40 MHz of the upper band edge, e.g., 870 MHz, or 1 GHz) typically experience significant roll-off resulting in lower SNRs for channels nearer the band edge making them unusable for 256-QAM SC-QAM channels. Granted, while there are VHF and UHF interferers, the presence of LTE and roll-off is much more common across most nodes and often impacts a wider band of spectrum.

Because of several features of OFDM including long symbol periods, LDPC error correction, and wide channels in which to interleave symbols, it is a much more robust signaling protocol than legacy DOCSIS SC-QAM signals and as a result it is tempting to choose some of the most hostile areas of the frequency spectrum for initial OFDM deployment to take advantage of this robustness. While such a selection would increase the network's capacity, even more capacity benefits can be reaped by leveraging the high MERs from premium legacy SC-QAM channels where higher modulations could be run. For example, 32 SC-QAM channels running 256-QAM transitioned to OFDM running 4096-QAM yields about 500 Mbps of additional capacity within the same spectrum while enabling 42 MHz of spectrum at the top edge that was lost due to spectral roll-off, which would yield about 200 Mbps of additional capacity and require greater refinement in the bit loading of the profile. Using existing spectrum can also avoid the issue of significant performance issues with different cascade depths, which could be an issue in using the roll-off region.

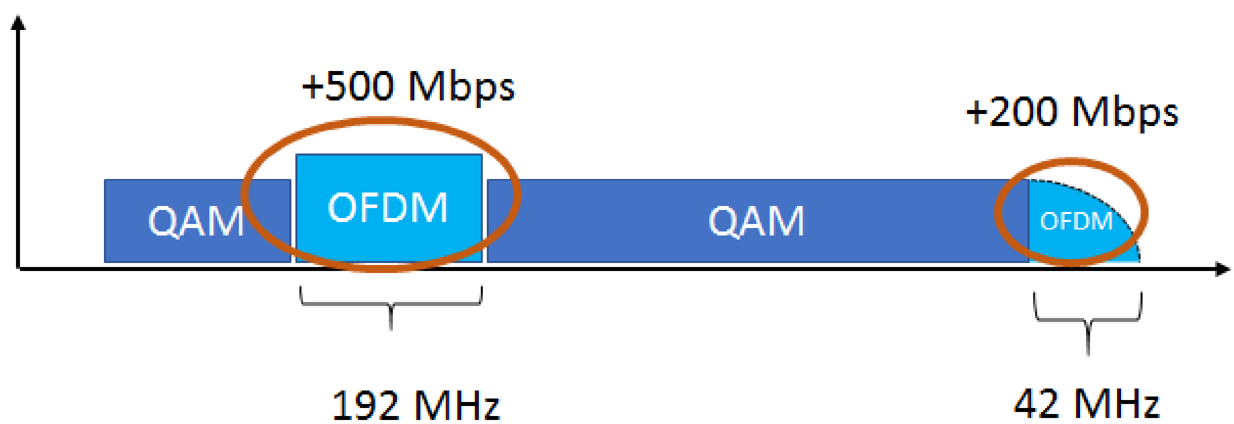

Figure 1 - Expanded Capacity Benefits of Converting Existing Spectrum to OFDM versus Roll-off Reclamation

As a result, Cox selected the lower frequency spectrum of 258 to 450 MHz (lowest frequency spectrum required by DOCSIS 3.1 for OFDM) for our initial OFDM deployments, likely allowing the highest modulations orders (and therefore highest bit rates) supported by the network. By targeting these premium areas of spectrum for OFDM channel deployments, the operator is able to maximize the benefit of DOCSIS 3.1 and OFDM. Spectrum where the existing margin for 256-QAM SC-QAM channels are at their highest should be considered the prime target for initial OFDM deployment and growth. By targeting these spectrum regions, the operator should be able to run the greatest number of modems at the highest modulations supported by the available spectrum. Subsequent expansion of OFDM will likely encompass reclaiming spectrum which is more hostile such as the LTE and roll-off regions.

1.2. Power spectral density of the OFDM Channel

Just as one must consider the placement of OFDM channels within the frequency spectrum, one should also consider the power level to run the OFDM signals as compared with that utilized with the SC-QAMs. The motivation for such a configuration change is similar to choosing the premium spectrum for OFDM, in that the elevated power of an OFDM channel yields even higher SNR allowing the modems to support higher modulations within the OFDM channel. For non-distributed access architectures (DAA), the optical margin within the analog link is a key limitation to consider as total power impacts the SNR that can be achieved on the operating channels. If all channels (OFDM and SC-QAM) are maintained at the same power level, the result is approximately equal SNR across all channels. Providing higher SNR for SC-QAM channels that are limited to running 256-QAM does not benefit the operator relative to network capacity; however, if the OFDM channels are raised in level, the added SNR on the OFDM channel improves the SNR allowing the channel to run a higher modulation.

In the case of Cox's network with our initial DOCSIS 3.1 deployments, we targeted a 3 dB increase in OFDM channel power as compared to a SC-QAM channel, effectively providing an additional single order of modulation benefit. With the evolution to distributed access architectures including RPD and RMACPHY, the specification only allows for 2 dB of variance of channels within the spectrum limiting the elevation that could be achieved with RPD type networks; however, this 2 dB is available. Because we selected a lower frequency for our OFDM channel and when considering spectral tilt, this additional 3 dB of elevated power has a minimal effect on the overall total composite power of the spectrum. As OFDM channels are enabled in the upper end of the spectrum, elevated signals will likely not be feasible as it will push optical links closer to compression; however the migration to DAA will remove the analog optical link limitation.

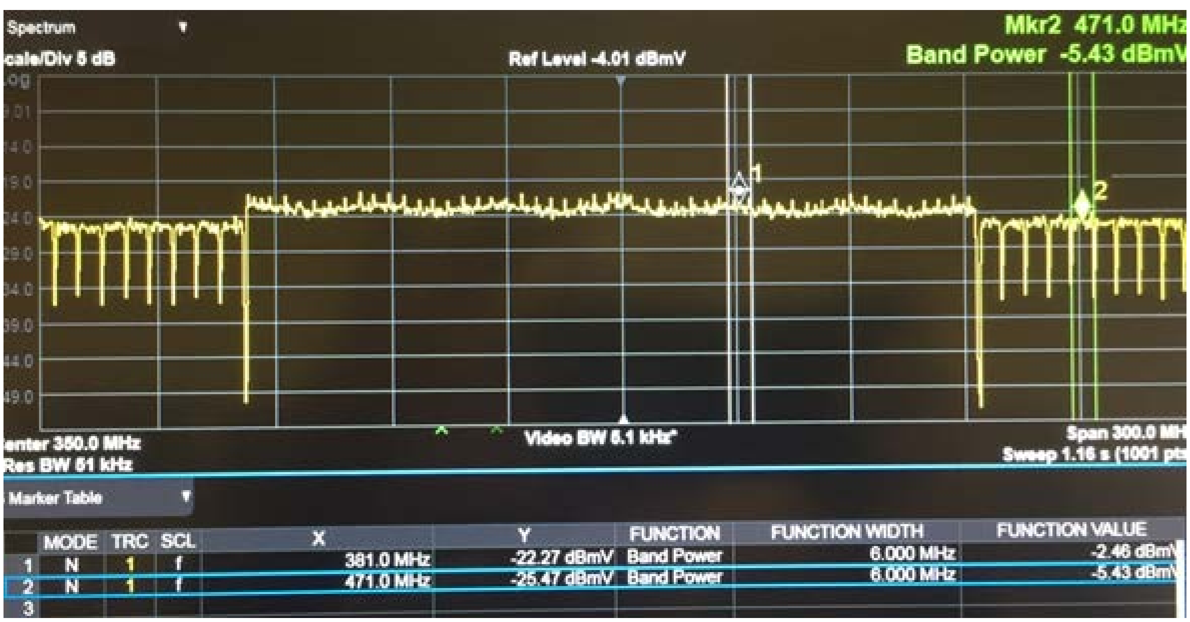

Figure 2 - Spectrum Analyzer Display of OFDM with 3 dB Higher Power Spectral Density

1.3. Windowing

Another consideration in efficiently using the bandwidth of the OFDM channel is selecting windowing parameters for the channel to be able to guarantee solid performance in a variety of plant conditions. An additional advantage of electing to use a lower frequency for the OFDM channel is that, generally, there are fewer and less severe impedance mismatches that cause reflections in the plant. It was our intent to minimize the overhead in the channel incurred by cyclic prefix and roll-off, which are explicitly designed to compensate for these plant reflections. We theorized that we should be able to use the lowest available settings for cyclic prefix and roll-off and still have good performance in the plant.

Of course, verification of this theory was needed. This was performed in a variety of steps, beginning with lab testing to verify that the CPE and CCAP would support these settings and that there was no variation in performance across settings in a lab environment. Once this was established, a field test in multiple markets on varying amplifier cascade lengths was performed. We collected MER per subcarrier data and uncorrectable FEC, along with other metrics, across various cyclic prefix and roll-off settings and saw, in our particular case, no degradation when using the lowest possible values.

One downside of reduced roll-off was the potential for additional interference with adjacent SC-QAM channels. The CableLabs DOCSIS 3.1 PHY specification (Table 75 in Appendix V and replicated below for convenience) proposes addressing this by increasing the guard band between the OFDM and the adjacent channel. In fact, some CCAP vendors chose to make this the default behavior and automatically adjust the guard band to higher values when smaller roll-off values are used. While this is certainly a safe approach, we suspected that we would be leaving bandwidth on the table, and we worked with our CCAP vendors to implement an override function to be able to configure the minimum 1 MHz guard band on the channel edge.

Table 1- Default guard band configuration from CableLabs DOCSIS 3.1 PHY Specification

FFT	Roll-Off Period Samples (N_{rp})	Taper Region (MHz)
4K	64	3.575
	128	1.875
	192	1.325
	256	0.975
8K	64	3.3375
	128	1.7125
	192	1.1625
	256	0.9875[1]
1. The taper region of 0.9875 MHz is in accordance with the requirement for a minimum taper region of 1 MHz minus half subcarrier spacing. Achieving up to approximately 0.5 dB impact to the noise power in the adjacent spurious emissions integration region would allow a taper region of 0.8625 MHz, if the specification did not mandate the minimum taper region to be larger than this.		

This required additional testing to determine the effect of the OFDM channel on the MER of the adjacent SC-QAM channels when reducing this guard band, especially given the previous decision to elevate the RF power level of the OFDM channel. In our testing, we determined that minimum roll-off, minimum guard band, with elevated power, resulted in adjacent SC-QAM channel MER readings in excess of 38 dB, and with non-elevated power, MER readings were in excess of 41 dB. Again, placement in the spectrum helped with this issue, as even the elevated power configuration has significant margin for the performance required for 256-QAM, especially in the lower portion of the spectrum.

1.4. Adjacent channel interference and profile bit-loading

Having determined that the effect from the OFDM channel on the adjacent SC-QAM channels was within acceptable limits, it was now important to determine the effect of those adjacent SC-QAM channels on the edges of the OFDM channel and compensate for it. Fortunately, with the DOCSIS 3.1 specification, the ability exists to define modulation order on an individual subcarrier basis (bit loading) to address a situation such as this.

In our testing, we measured the impact of adjacent channel SC-QAM channels on the individual sub-carrier MER measurements of the OFDM channel. As shown in Figure 3, MER degrades near the edge of the OFDM channel. For the shortest roll-off configuration, the DOCSIS 3.1 PHY specification recommends increasing the guard band to 3.575 MHz at the edge of the channel (7.15 MHz total channel impact when considering both edges) effectively eliminating an entire 6 MHz QAM channel. A more efficient use of this spectrum would be to bit-load the individual sub carriers near the edge with lower QAM levels, thus providing capacity with the spectrum while maintaining equal MER margin across the entire band.

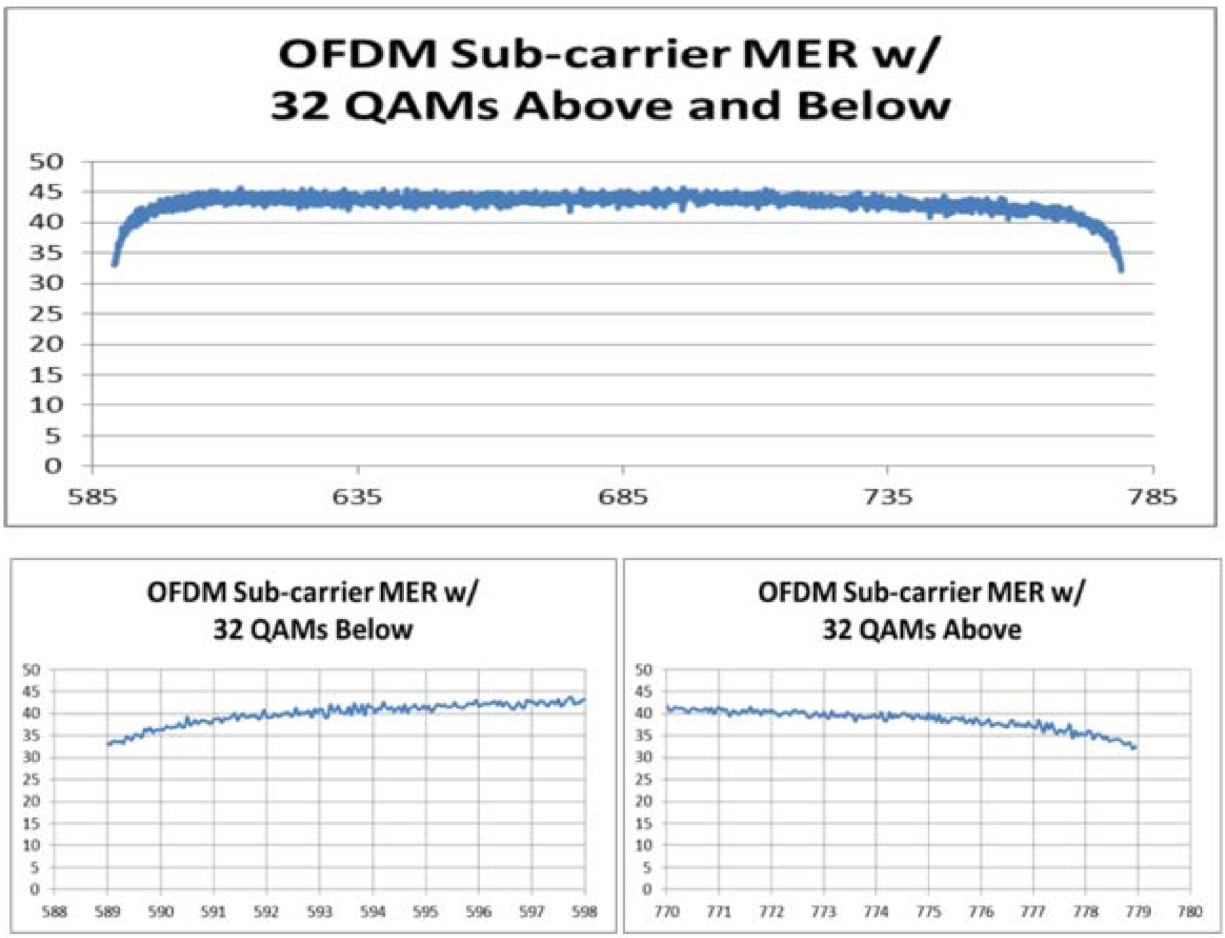

Figure 3 - OFDM Sub-carrier MER Impact of SC-QAM channels directly above and below the OFDM channel

Each modulation level requires the channel to meet a minimum MER threshold in order to meet a certain BER target. Based upon the sub-carrier MER and by applying appropriate QAM-level MER thresholds, Cox was able to define a bit-loaded profile for each of our desired modulation profiles (1024-QAM, 2048-QAM, 4096-QAM). That is, while a 4096-QAM profile is predominantly 4096-QAM for most sub-carriers, the sub-carriers at the edges of the channel would run lower QAM levels in order to maintain equal MER margin as the subcarriers in the center of the OFDM channel. Equal margin means that there is not a particular area of the spectrum which is more susceptible to channel impairments. Figure 4 illustrates the refined profiles that Cox developed to maximize the capacity of the OFDM channel.

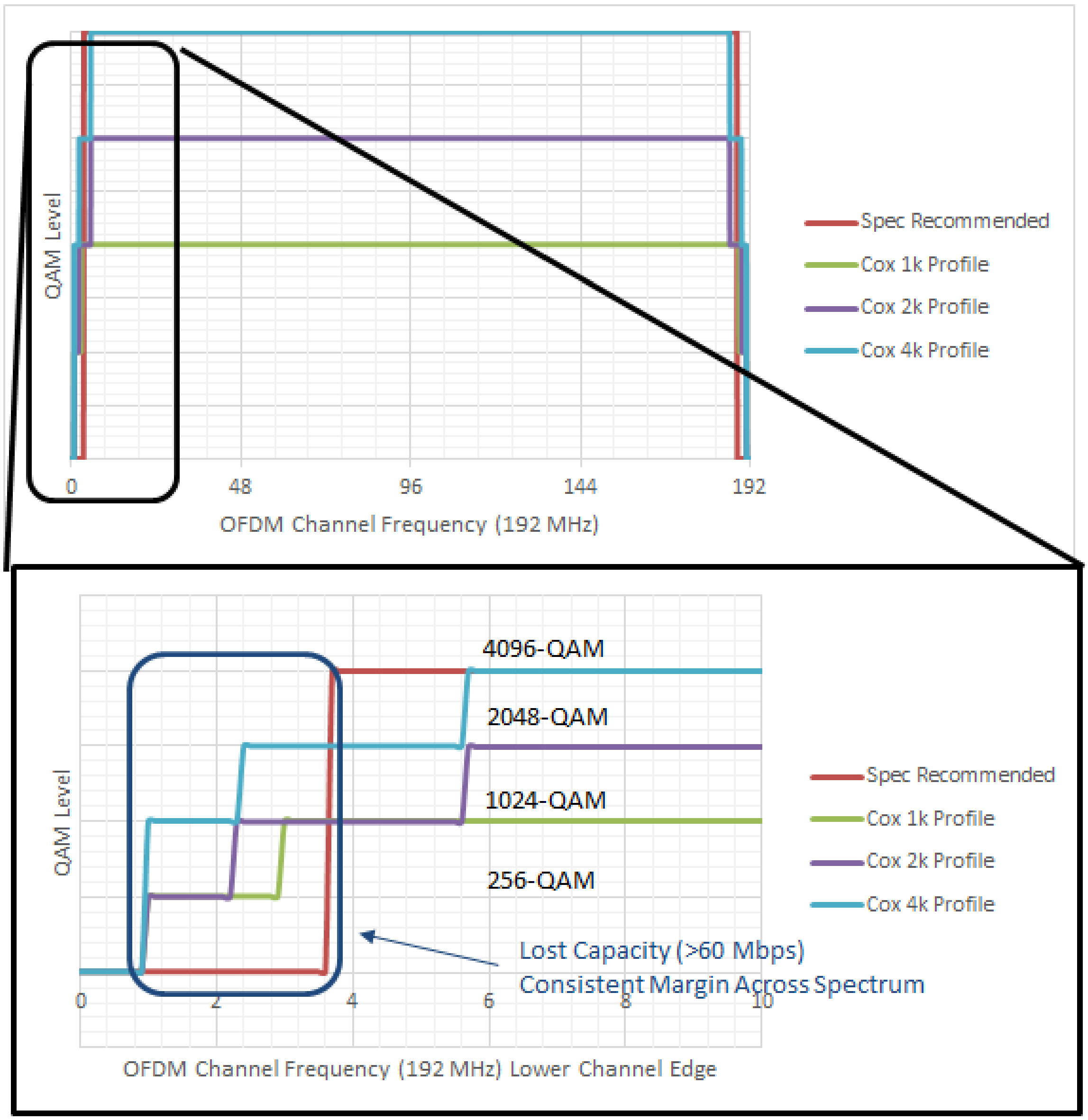

Figure 4 - OFDM Sub-carrier QAM bit-loading at the channel band edge for Cox profiles

The reader should note that if narrower OFDM channel widths are used (192 MHz is show in the figure), the number of sub-carriers that are bit loaded near the channel edge will remain the same as the adjacent SC-QAM channel impacts the same number of sub-carriers regardless of OFDM channel width.

1.5. Profile Assignment and MER thresholds

The use of multiple profiles within an OFDM channel allows one to maximize the capacity of the channel by assigning cable modems to profiles based upon their received signal quality within the plant. That is, cable modems with better downstream channel quality can utilize higher modulations without errors while cable modems with lower signal quality may utilize lower modulations to provide error free operation. Categorizing cable modems to appropriate profiles requires the establishment of appropriate MER thresholds.

The CableLabs DOCSIS 3.1 PHY specification (Table 46 in Section 7.5.12.1 and replicated below for convenience) establishes requirements for modulation performance for what is essentially error free post-FEC operation (10^{-6} PER (packet error rate) with 1500 byte Ethernet packets which is less than 10^{-10} BER). In addition, some CCAP vendors have chosen to utilize these performance requirements as their default thresholds to operate each of the QAM levels; however, a 10^{-10} BER requirement is extremely conservative, and while it would be a safe configuration, we believed that a quality customer experience could be provided with a lower BER requirement while at the same time, maximizing the capacity of the network. That is, such an extremely conservative requirement leaves bandwidth on the table.

Table 2 - Default MER thresholds from CableLabs DOCSIS 3.1 PHY Specification

Constellation	$CNR^{1,2}$ (dB) Up to 1 GHz	$CNR^{1,2}$ (dB) 1 GHz to 1.2 GHz	Min P_{6AVG} dBmV
4096	41.0	41.5	-6
2048	37.0	37.5	-9
1024	34.0	34.0	-12
512	30.5	30.5	-12
256	27.0	27.0	-15
128	24.0	24.0	-15
64	21.0	21.0	-15
16	15.0	15.0	-15

Table Notes:

Note 1 CNR is defined here as total signal power in occupied bandwidth divided by total noise in occupied bandwidth.

Note 2 Channel CNR is adjusted to the required level by measuring the source inband noise including phase noise component along with transmitter noise and distortion and adding the required delta noise from an external AWGN generator to achieve the desired CNR at the CM F-connector.

Note 3 Applicable to an OFDM channel with 192 MHz of occupied bandwidth.

As a result, Cox executed a series of lab tests to characterize acceptable profile PER performance against MER levels using an AWGN generator. These tests allowed us to better understand the benefits of LDPC error correction in an OFDM channel and better balance those benefits against utilizing the maximum QAM level supported while providing a high-quality customer experience. One thing that we were able to demonstrate during our testing is that the LDPC error correction algorithm is so powerful that we can see 100% correctable errors and still run error-free with some margin left before dropping the modulation. Table 3 provides a summary of our test results.

Table 3 - Profile MER Threshold Test Performance Results

AWGN Attenuator Setting (dB)	Average MER (measured via CM across all subcarriers) (dB)	2nd % MER (measured via CM across all subcarriers) (dB)	Highest Modulation Meeting Customer Experience Performance Requirements
35	39.0	37.3	4k QAM
34	38.3	36.6	4k QAM
33	37.5	35.8	4k QAM
32	36.7	35.1	4k QAM
31	35.9	34.2	4k QAM
30	34.9	33.2	2k QAM
29	34.1	32.4	2k QAM
28	33.3	31.5	2k QAM
27	32.2	30.5	1k QAM
26	31.3	29.4	1k QAM
25	30.3	28.4	1k QAM
24	29.4	27.4	256 QAM
23	28.4	26.4	256 QAM
22	27.4	25.4	256 QAM
21	26.4	24.7	256 QAM
20	25.4	23.7	256 QAM
19	24.4	22.7	256 QAM
18	23.4	21.7	None

When comparing our results with those thresholds defined in the CableLabs DOCSIS 3.1 PHY specification, our PER at the various QAM levels was performing acceptably when reporting an average MER that was nearly 6 dB below the CableLabs levels. Granted, one never wants to operate the network near the performance edges, so we chose to add approximately 1.5 dB of margin to the acceptable levels to establish the Cox thresholds. As a result, Cox's thresholds were 4 dB below the CableLabs levels as shown in Table 4 below.

Table 4 - Profile MER Threshold Recommendations

QAM Level	CableLabs Spec CNR (dB)	Cox Profile Threshold
4096-QAM	41	37
2048-QAM	37	33
1024-QAM	34	30

As another consideration, the ability of DOCSIS 3.1 OFDM channels to dynamically support multiple profiles where a cable modem may seamlessly move between profiles over time as plant environment changes is critical to the success of a multi-profile configuration and eliminates the need to run only the lowest profile supported by the entire modem population. Cox spent a significant amount of effort in early system testing to understand the behavior of this dynamic process and to assess its impacts on the customer experience before even considering deploying a multi-profile configuration. This testing included both downgrading the profile as well as the reverting back to higher profiles. By using a 1.5 dB margin on our thresholds, we assured that profile changes were made prior to a customer experiencing negative consequences. Because of the complexity of this dynamic process, early testing was quite beneficial for Cox as we were able to identify several software issues and work with our vendors to incorporate necessary changes. We would encourage other operators to do the same against the full spectrum of various DOCSIS 3.1 cable modems that they are expected to deploy within their network.

1.6. Channel metrics for monitoring the network

The final parameter that we considered for our initial DOCSIS 3.1 OFDM deployments was which metrics to add to support monitoring of our OFDM channels. OFDM channels introduced a number of significant changes from our traditional 6 MHz wide 256-QAM Reed-Solomon FEC-based channels. OFDM channels are wider ranging from 24 MHz to 192 MHz, with more common deployments expected to cover 96 MHz to 192 MHz. Historically, a 32 SC-QAM channels covering 192 MHz worth of spectrum would be providing a number of performance metrics (e.g., MER, Receive Power Level, FEC statistics, equalization, etc) for each channel. If we assume just 5 parameters per SC-QAM (which is certainly on the low side), we would be characterizing a 192 MHz portion of spectrum with 160 metrics (5*32). With an OFDM channel, we are now challenged to characterize and monitor that same 192 MHz portion of spectrum with what is likely a much smaller number of metrics.

In addition, with SC-QAM channels utilizing the less powerful Reed-Solomon FEC, which degrades more slowly when transitioning from corrected codewords to a condition of uncorrectable errors, the industry learned to use Reed-Solomon FEC corrected codewords as an early indicator that the network was beginning to operate near the edge with perhaps 2-3 dB of additional degradation margin before customer impacting conditions might occur. The movement to LDPC error correction in OFDM channels makes this much more complicated as LDPC offers significantly more margin (perhaps 5.5 dB) between the point at which corrected errors first manifest and where uncorrectable codewords are present. In order to maximize the capacity of our network by utilizing the maximum modulation levels possible, we will likely operate well unto the LDPC corrected codeword space. In addition, the margin between a small number of uncorrectable codewords (e.g., 0.1%) and a large number of uncorrectables (>2%) is very small and leaves little warning. While it is certainly important to collect these LDPC codeword statistics, Cox's sense was that their value maybe somewhat diminished with OFDM channels except to confirm customer-impacting conditions where uncorrectables are present.

Rather than 32 SC-QAMs, a 192 MHz OFDM channel has up to 8000 sub-carriers which is certainly too many MER values to monitor. The DOCSIS 3.1 specification combines those 8000 sub-carriers to produce just three MER measurements: Average MER, 2nd % MER, and MER standard deviation. The average MER and MER standard deviation are exactly what one would expect representing the average and standard deviation of each of the up to 8000 sub-carrier MER values. The 2nd % MER represents the MER level of the sub-carrier separating the highest 98% MERs from the lowest 2% MERs. While it may seem the 2% number would represent a good conservative metric to use to assess channel quality, it seems that this metric can be easily degraded while not being a good indicator of true channel performance. Specifically, Cox encountered this problem as a result of our bit-loaded profiles utilizing minimum 1 MHz guard band configuration. The subcarrier MER values near the band edges are significantly impacted by the adjacent SC-QAM channels resulting in significantly lower 2% MER values. However, because we have bit-loaded the profile with lower QAM levels for these sub-carriers, the low value doesn’t actually indicate a poorly performing OFDM channel. Similarly, narrow band interferers can significantly impact the 2% MER and their effects are almost always mitigated as a result of the powerful LDPC. Even LTE would degrade 2% MER but is often compensated for by LDPC. As a result, we found that the better metric was the average MER for the channel.

Another useful metric for assessing channel quality for a particular modem is the profile it is using. The CMTS instructs the modem to make MER measurements and return the results using the OFDM Profile Test (OPT) mechanism defined in the DOCSIS 3.1 MULPI specification. From this information, the modem is assigned a set of profiles that it may use. This provides an excellent indicator of channel quality for a particular cable modem. Similarly, for assessing the overall quality of the channel, measuring the modem counts or percent of the total model population within each modem profile is a good indicator of the overall health of the channel within or across network segments.

2. Early field trials and learnings

When first deploying DOCSIS 3.1 OFDM channels, we determined that because of relative immaturity of the technology, it would be best for Cox and for our customers to begin with simpler configurations and work our way toward more advanced features. Having tested our recommended configurations in the lab, we selected a group of parameters to be part of our initial deployments and a set of parameters to be added later.

For first deployments, we chose to use placement of the OFDM channel in the premium spectrum and to elevate the power spectral density of the channel by 3 dB relative to the adjacent SC-QAM channels. We also selected the cyclic prefix and roll-off to be the lowest overhead values available on our CCAP. For modulation profiles we elected to use a limited number of very straightforward, simple profiles and used the default guard band settings as specified in the CableLabs standards. Rather than push the limits of the technology in the early stages, we employed only two modulation profiles - one which placed all subcarriers at 256-QAM and the other with all subcarriers at 1024-QAM.

The reasoning behind using the simplified configuration was to allow us to get some real-world experience with OFDM deployments, see our monitoring tools in action, train our workforce, and allow us to collect more engineering data to validate our previous lab testing. We also had a keen interest in determining the stability of MER for modems operating in a live network, thus trying to determine how often we should expect modems to require a downgraded or upgraded profile.

As expected, when this was deployed, virtually all modems were placed on the 1024-QAM profile and remained there. While this was the expected result, we did also discover a drawback to the selected placement of the OFDM channel. The specific spectrum that was selected was being filtered by legacy data-only traps that still existed in our network. Fortunately, due to the design of our channel bonding groups, the modems were still able to function in a partial service mode using SC-QAM. This allowed us to react quickly to the situation and build tools around identifying the locations of these traps and have them removed. This was done through a combination of identifying potentially affected modems using scripting to poll the CCAP, followed by collecting spectral analysis data from the modem via the Proactive Network Maintenance (PNM) MIB and analyzing for the signatures of known traps. An illustration of the signature of one of these types of traps is shown in Figure 5.

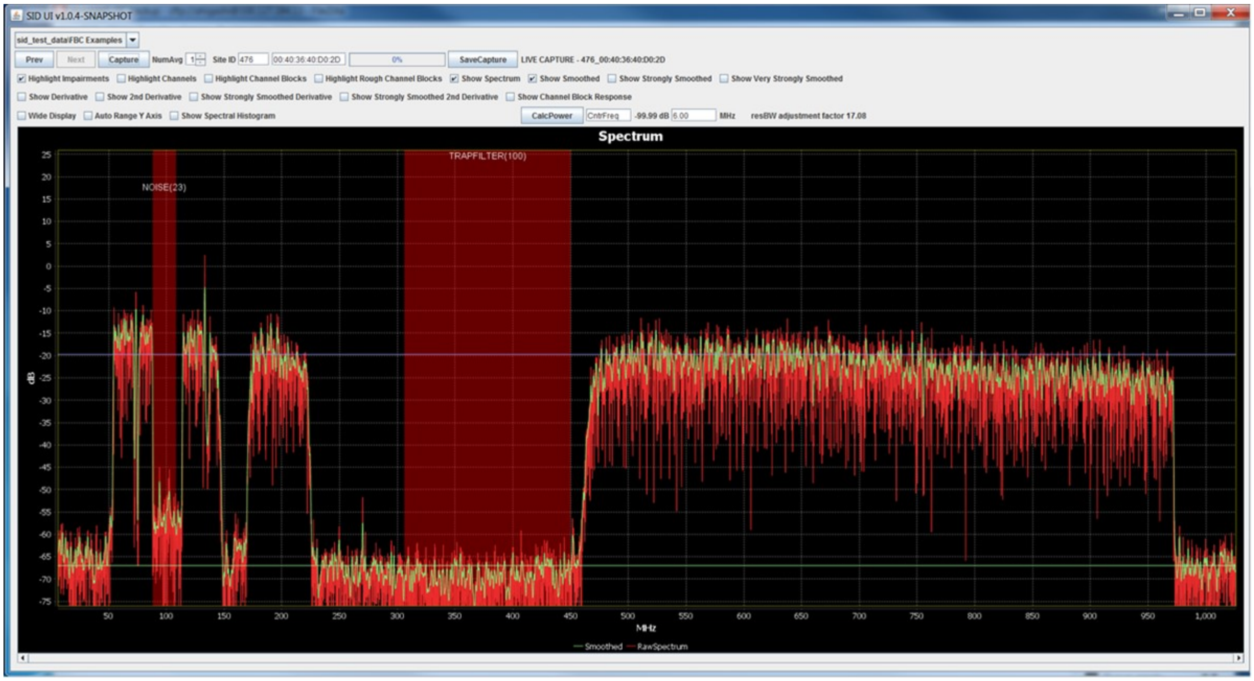

Figure 5 - Spectral analysis of DOCSIS 3.1 modem in the presence of a data-only trap

While the results were as expected for modem profile assignment at initial launch, we also were interested in longer-term stability. It would be considered an undesirable behavior for modems to be frequently changing modulation profile assignments, and we wanted to verify that we had left enough margin in our MER thresholds to allow the modem to remain on the profile to which it was initially assigned during normal operation, given no disruptions in the plant. To measure the stability of the performance over time, we elected to collect MER data per subcarrier for a sample of modems at hourly intervals and compare the results over a week. We intentionally chose areas of the longest amplifier cascades in the market where we were performing field trials in order to get the maximum RF receive level variation at the modem as well.

From a stability perspective, the results were quite good, with the MER varying by an average across subcarriers of roughly 2 dB over the course of 24 hours, and less than an additional 0.5 dB over the course of a week. This validated our assumption that leaving 3 dB of margin between the MER thresholds for initial profile assignment and the MER threshold at which the modem would downgrade profiles would be sufficient for stability purposes. An illustration of the hourly measurements of MER per subcarrier over the course of the week for a single modem is shown in Figure 6.

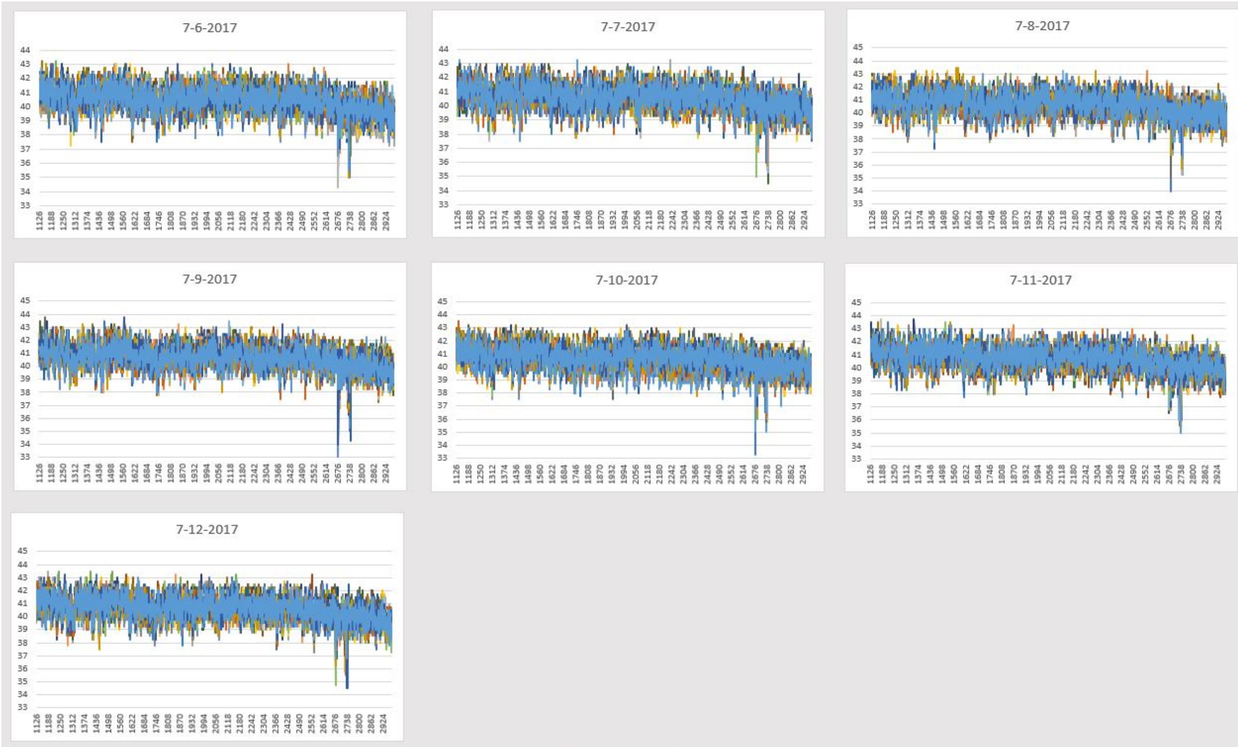

Figure 6 - MER per subcarrier, collected hourly for one week, single modem

3. Advanced office and field trials

Having established that we could achieve the expected performance with our initial, simplified set of OFDM parameters, it was now left to incorporate the remainder of our recommendations. As before, the process was to first perform lab testing of these new parameters to ensure support from both the CCAP and CPE devices. One early finding from this lab testing was that not all devices supported a mix of modulation orders on subcarriers within the channel, which was a critical piece of being able to reduce guard band. This was later resolved using firmware updates to both the CCAP and CPE, but underscored the relative immaturity of the technology and further validated our approach of beginning with a smaller, simpler set of parameters and progressing to the more advanced settings. This is also an example of why the cable operator should always be conservative in the rollout of newer technologies, especially when implementing the more advanced features of those technologies.

3.1. Office Trial

Once issues were resolved and lab testing was successful, the next logical step was to deploy these more advanced settings in a controlled office environment and verify the performance. The location for this test was our corporate office in Atlanta, with employees using modems at their desks as the test devices.

For this testing, guard band was reduced to 1 MHz on each side of the channel, and four profiles were created:

- Profile 0 = all subcarriers at 256-QAM
- Profile 1 = majority of subcarriers at 1024-QAM, edge subcarriers at 256-QAM
- Profile 2 = majority of subcarriers at 2048-QAM, edge subcarriers tapered at 1024-QAM and 256-QAM

- Profile 3= majority of subcarriers at 4096-QAM, edge subcarriers tapered at 2048-QAM and 1024-QAM

While the plant serving the office building is not a completely accurate simulation of actual plant, it would expose the changes to a larger user and device base. As shown in Figure 7, the results from the office trial showed a large majority of modems on profile 3, a smaller number on profile 2, and less than 5% of modems using profiles 1 or 0. Recognizing some of the unique challenges of an office environment, we believed that this would be a baseline result, and we could expect actual plant performance to be similar or slightly better.

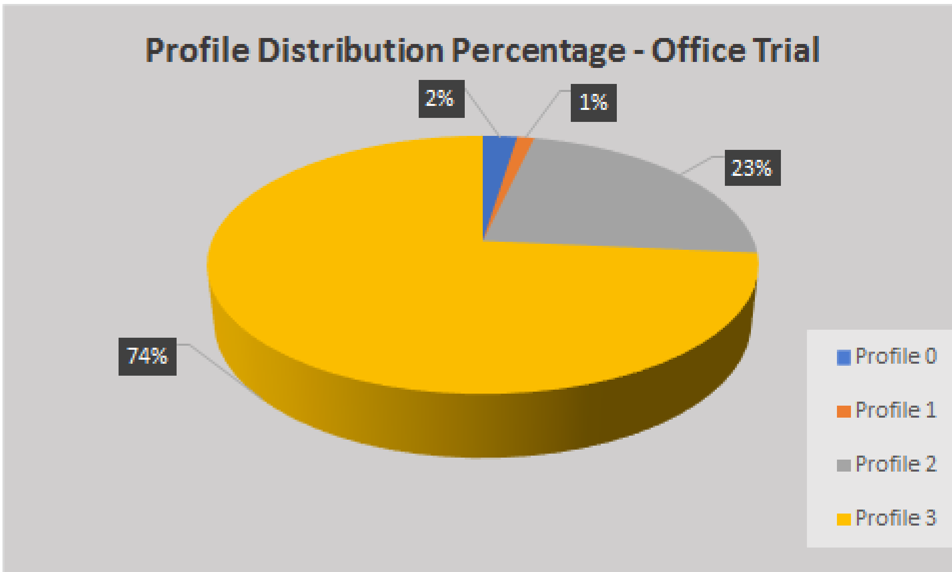

Figure 7 - Profile distribution in office trial using all recommended configurations

3.2. Field trials

The encouraging results from the office trial showed great potential for deployment, but in order to be more conservative in our approach and to follow established processes, we elected to trial the advanced configuration on a subset of the network before deploying nationally. The nodes for the field trial were selected using the following criteria:

- Geographic diversity - we wanted all regions to be represented
- High concentrations of DOCSIS 3.1 modems
- Where possible, whole CCAP line cards were selected, for simplicity
- Areas with friendly customers / employees who could test the service
- A variety of amplifier cascade depths

Having selected a set of nodes from each market, configuration changes to incorporate the more advanced parameters were put into place, and we began monitoring the outcome. After the first week, we had approximately 250 DOCSIS 3.1 modems on the more advanced configurations.

The initial measurement made was a profile distribution percentage, similar to the measurement made during the office trial. The results were encouraging across the 250 modems of the trial, with nearly 90% of modems using highest modulation order profile, and over 95% using profiles at 2048-QAM or greater, as shown in Figure 8.

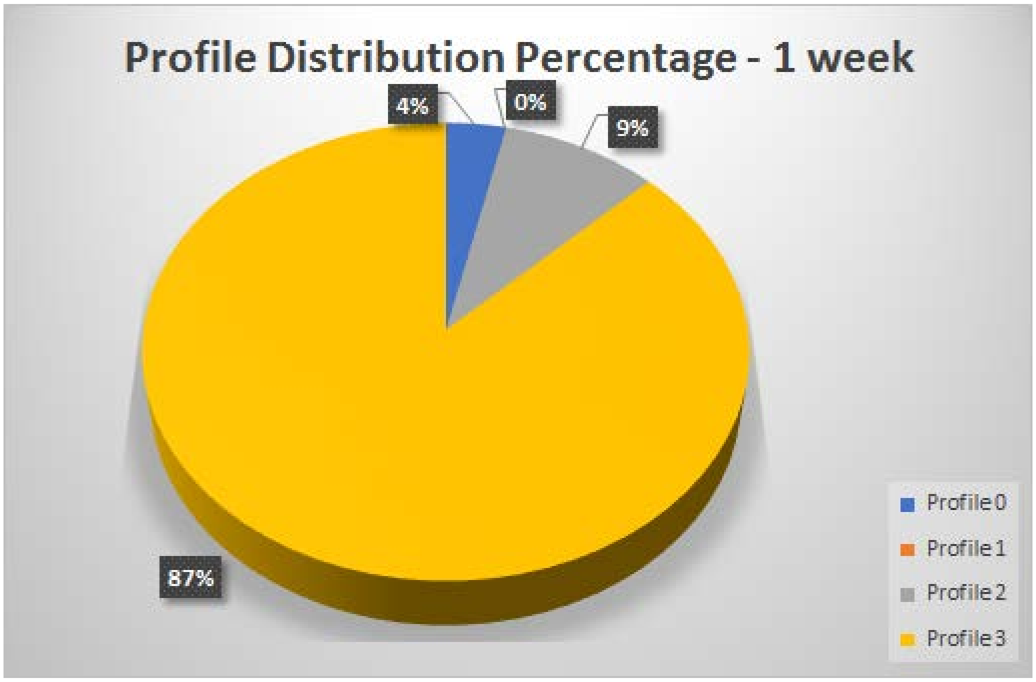

Figure 8 - Modem profile distribution after one week of field trial

The higher than expected percentage of modems on profile 0 was a concern, and we wanted to determine the cause of this. Investigation into those specific modems showed that in nearly every case, there was a data-only trap that was present. Despite efforts to remove these from the network, in this case, these were modems where they were missed.

The next steps were to add more modems and collect data over a period of time to look for changes in profile distribution. Another snapshot was collected two weeks after the first snapshot, and as expected, it showed similar results. This time, however, the number of modems was increased, and the sample represented 1500 modems. The results after three weeks of field trial are as shown in Figure 9.

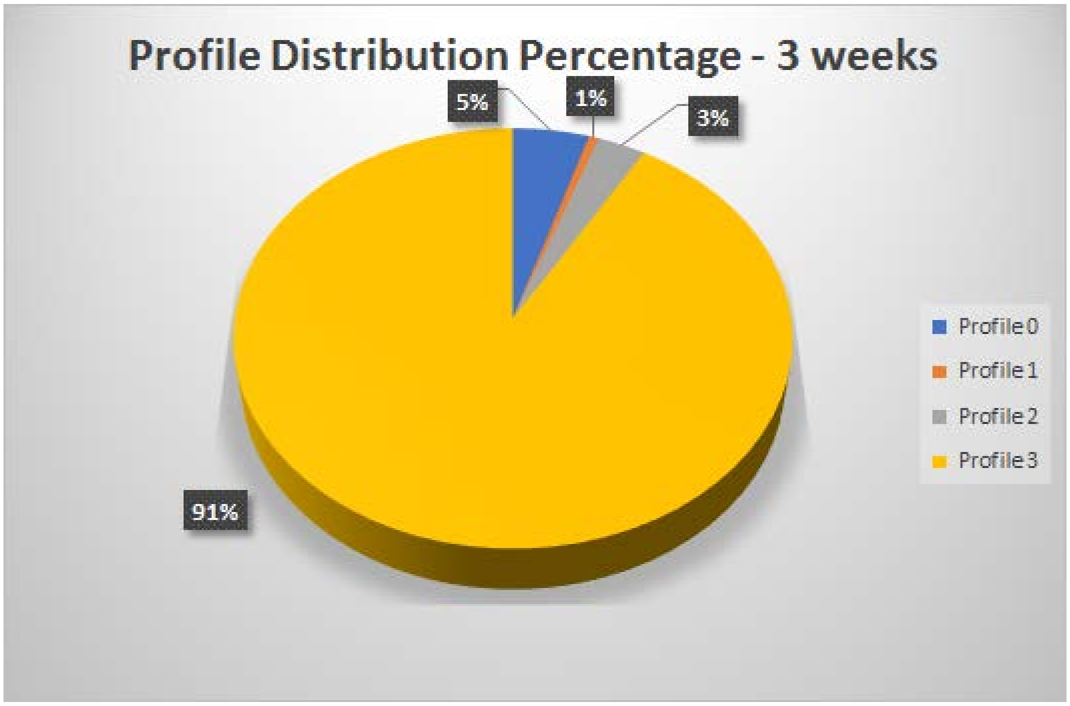

Figure 9 - Modem profile distribution after three weeks of field trial

These results showed also that the distribution of modems over time was consistent, which further reinforced conclusions from previous testing that the margin in MER thresholds for determination of initial profile assignment were sufficient.

Another key parameter that was an indicator of stability was the number of modems that were currently in a downgraded state, or currently utilizing a modulation profile that was not the same as the initial assignment for that modem. Out of 1500 modems, only 9 modems were in a downgraded state. Less than one percent of modems experiencing an event that caused a profile downgrade also seemed to support the conclusion that the system was stable. We also verified that uncorrectable FEC codewords were not being seen except in the rare case when a modem was required to downgrade.

Of course, we are also tracking the extremely important customer experience metrics such as call volume and truck rolls in the field trial areas, but that data is not currently available at time of this publication. Based on the measurements that we were able to make and the feedback from employees in field trial areas, we expect that it will be favorable, and if so, we will roll out these configurations across the enterprise.

4. Future Considerations

Through this process, the configurations that were selected certainly appear to be achieving the objectives. However, there were learnings from the process that we have not yet been able to incorporate, which we will discuss here.

4.1. Desired Future Metrics

As part of the testing process, we identified three metrics that we would find extremely useful. Two of these are already supported and simply require tools development, while the third currently requires more development in the DOCSIS 3.1 modem chipsets. These metrics will be discussed below.

4.1.1. MER per subcarrier graph

While we have developed proprietary tools using Microsoft Excel macros and/or scripts, it would be extremely useful to have an enterprise-level tool to plot the MER per subcarrier for a given modem or set of modems. One very valuable aspect of the graph is being able to see if there is ingress under an OFDM channel and if it has a signature that can help find the source. An example of where we used this capability in our lab is in tracking down an RF switch with poor isolation based on the plot shown in Figure 10.

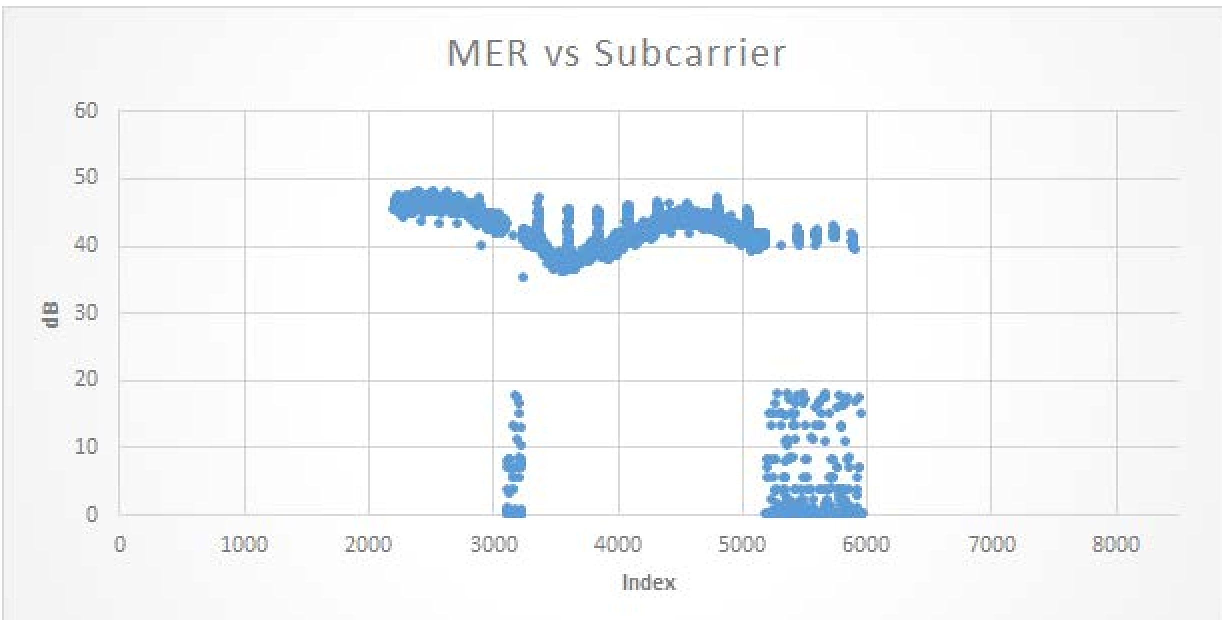

Figure 10 - An example of an MER per subcarrier graph used for troubleshooting

This graph showed what looked to be 6 MHz wide SC-QAM underneath the OFDM channel, which allowed us to then start troubleshooting to find the source. This is just one way in which a graph like this could be useful.

4.1.2. Profile distribution to identify "trouble nodes"

It is now possible to use modem profile distribution data to identify nodes that are not operating optimally. One aspect of OFDM is that it covers a much larger portion of the spectrum than a single SC-QAM, and it is far less susceptible to narrowband interference. This makes it a useful signal as an indicator of the overall health of the downstream spectrum. While we are not yet at the level of having an enterprise tool for this, it is possible to create thresholds for percentages of modems on a given profile to identify sub-optimal nodes. When tied into the customer location, modem profile distribution could also be used to localize and isolate issues.

4.1.3. MER Margin to Profile

This metric is defined in the CableLabs DOCSIS 3.1 OSSI specification, but is not yet supported in most CPE. We believe that this will be a useful metric when completing an install or truck roll to determine the quality of the installation or repair. It is preferred that when the technician leaves the house that there is margin to the lowest acceptable profile. While an estimate of this parameter can be made using average subcarrier MER, we feel that this metric is more accurate, and therefore, will be a valuable piece of information.

Conclusion

Having completed these lab, office and field tests, we feel confident in recommending the following for optimizing the use of OFDM:

- Choose clean spectrum for placement of the OFDM channel, if possible
- Where possible, use higher power spectral density for OFDM as compared to SC-QAM
- Use minimum windowing parameters unless plant conditions are extremely severe, and the use of minimum guard band is sufficient to avoid adjacent channel interference
- Use the flexibility of bit-loading to compensate for interference from adjacent SC-QAM channels
- The default MER thresholds for modulation orders can be reduced by several dB, depending on how much margin the operator prefers
- When using these recommendations, average subcarrier MER and assigned modem profile become the most important metrics, until more metrics become available

Use of these recommendations has demonstrated that greater than 90% of modems can operate in real HFC plant at 4096-QAM, resulting in nearly a 50% increase in efficiency as compared to using 256-QAM SC-QAM.

Abbreviations

AWGN	Additive White Gaussian Noise
BER	Bit Error Ratio
bps	bits per second
CCAP	Converged Cable Access Platform
CM	Cable Modem
CMTS	Cable Modem Termination System
CPE	Customer Premises Equipment
DAA	Distributed Access Architecture
dB	deciBel
DOCSIS	Data Over Cable Service Interface Specification
FEC	Forward Error Correction
GHz	GigaHertz
HFC	Hybrid Fiber Coax
Hz	Hertz
IP	Internet Protocol

ISBE	International Society of Broadband Experts
LDPC	Low-Density Parity Check
LTE	Long-Term Evolution
Mbps	Megabits per second
MER	Modulation Error Ratio
MHz	MegaHertz
MIB	Management Information Base
OFDM	Orthogonal Frequency Division Multiplexing
OPT	OFDM Profile Test
PER	Packet Error Ratio
PNM	Proactive Network Maintenance
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
RMACPHY	Remote MAC PHY
RPD	Remote PHY Device
SC-QAM	Single Carrier - Quadrature Amplitude Modulation
SCTE	Society of Cable Television Engineers
SNR	Signal to Noise Ratio
UHF	Ultra High Frequency
VHF	Very High Frequency

Bibliography & References

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