Automating Amplifier Analysis with PNM Full Band Capture, RxMER, for Activation of a Second OFDM Channel

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Table of Contents

Title **Page Number**

List of Figures

Title **Page Number**

List of Tables

Title **Page Number**

1. Introduction

There is an old saying, "With great power, comes great responsibility," and that holds true as we activate more radio frequency (RF) spectrum, adding additional power to the system amplifiers.

Comcast continues its evolution towards delivering multigigabit symmetric services over the hybrid fiber-coax (HFC) network as part of the 10G roadmap. Spectrum utilization is continuously optimized and downstream capacity is increased by deploying additional Data Over Cable Service Interface Specification (DOCSIS®) 3.1 downstream orthogonal frequency-division multiplexing (OFDM) channels.

In this paper, we focus on the operational aspects of deploying additional downstream channels and in particular the impact of increasing the downstream total composite power on amplifier performance and linear operation, which directly correlates to the overall system performance and achievable capacity due to the impact on the cable modem's receive modulation error ratio (RxMER). This becomes critical as operators work to maximize spectrum utilization and system capacity while minimizing any potential impact to customer experience during network upgrades.

This technical paper focuses on four topics related to the prediction, detection, and mitigation of amplifier non-linearities. First, reviewing the fundamental theory behind the phenomenon alongside examples obtained from lab measurements. Second, introducing a method for detecting amplifier nonlinearity based on measuring the distortion noise from a cable modem's full band capture (FBC). Third, introducing data analysis performed across the entire virtualized cable modem termination system (vCMTS) footprint to inform deployment priority groups such that spectrum activation proceeds on nodes where the risk of encountering amplifier nonlinearity is lowest. Finally, presenting a statistical model for the prediction of amplifier non-linearity based on features derived from the FBC, RxMER, and expected change in spectrum utilization post-2nd OFDM deployment.

2. Theory and Lab Testing

An amplifier accepts an input signal, conditions it, and boosts it to a higher amplitude. However, because all amplifiers have nonlinearities—that are dependent on the operational conditions of the amplifier—the output signal does not faithfully replicate the input signal; instead, it adds distortion to the signal. This distortion can negatively impact system performance. To ensure high-fidelity communications, it is essential to evaluate the linearity of an amplifier and to measure how the amplifier response changes over a range of conditions to establish best field practices.

Noise Power Ratio (NPR) is a technique used to assess the linearity of power amplifiers, particularly those operating in the context of wideband multi-carrier signals. The American National Standards Institute (ANSI)/ Society of Cable Telecommunications Engineers (SCTE) 119 (2018) standard defines NPR as "a test method that examines the amount of noise and intermodulation distortion in a channel. A test signal, comprised of flat Gaussian noise band limited to the frequency range of interest and with a narrow band (channel) of the noise deleted by a notch filter or other means, is injected into the Device Under Test (DUT). The NPR is measured at the output of the DUT as the test signal is swept across a power range" [1].

Figure 1 shows a typical NPR curve where the total input power or composite power is on the horizontal axis and the NPR is on the vertical axis. The various parts of the NPR curve are described in the ANSI/SCTE 119 (2018) and elaborated further below:

- **Noise Region**: This is represented on the left side of the curve and increases approximately at a 1:1 ratio as the input power increases. This is where the power in the notch is dominated by thermal noise. It sets a minimum input level to the amplifier to achieve the desired NPR performance.

- **Intermodulation Region**: As approaching the top of the curve, the NPR curve begins to peak. This region corresponds to the intersection where negative effects both from thermal noise and distortions from amplifier non-linearities are at a minimum.
- **Clipping Region:** At maximum output power levels, the clipping region emerges when the RF amplifier saturates. Here, high-order intermodulation noise governs the power within the notch. In this region, the NPR curve decreases rapidly with increasing input power. The contribution of amplifier non-linearity to the signal quality in this region has a 2:1 ratio for 2nd order distortions and 3:1 ratio for 3rd order distortions. Due to the 2:1 and 3:1 ratios, the slope of the NPR curve is higher than the slope in the noise region.
- **Dynamic Range**: The dynamic range is determined based on the target NPR. It represents the range of input powers where the amplifier operates effectively while maintaining the desired linearity. The target NPR can vary depending on system design criteria, such as the number of active devices in cascade.
- **Peak NPR Region**: Finally, the peak NPR region corresponds to the highest NPR measurement achieved during testing. It reflects the amplifier's optimal performance in terms of linearity.

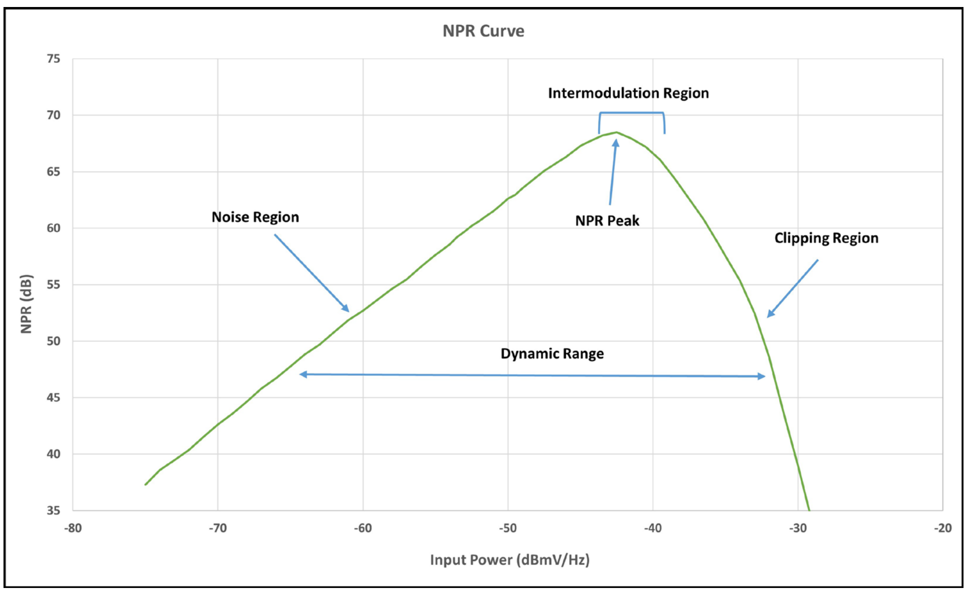

Figure 1 - NPR curve representative of typical amplifier behavior. The various highlighted features of the curve are described in the text.

Understanding these regions helps us evaluate amplifier behavior and optimize system performance. NPR has been the standard used to characterize RF upstream performance in the cable industry for several years.

While NPR curves have traditionally been used for upstream amplifier or upstream analog optical node measurements, downstream RF measurements have traditionally used carrier-to-noise ratio (CNR), composite second-order distortions (CSO), and composite third-order distortions (CTB) to characterize the performance of downstream analog carriers. However, analog measurements of CNR, CSO, and CTB have become less relevant as cable operators move to digital signals. The modulation error ratio (MER) is a measure used to quantify the performance of a digital radio or digital TV transmitter or receiver in communication systems utilizing digital modulation, such as quadrature amplitude modulation (QAM). Since the introduction of digital modulation in cable networks, MER measurements have become standard operating procedure.

However, signal MER measurements do not quantify the rate of change in signal quality due to the 1:1 ratio (thermal noise) versus the 2:1 and 3:1 ratio from amplifier non-linearities, nor does it provide the dynamic range over which the amplifier can operate. Measurement of the MER versus input signal levels to reproduce the noise, intermodulation and clipping regions in the NPR curve is necessary for cable operators to optimize amplifier settings. In other words, an "MER power ratio" equivalent to the noise power ratio (NPR) measurement is necessary. Furthermore, these measurements must be made over a wide range of frequencies to account for the stacking effects of distortion products generated by multiple frequencies.

Figure 2 shows a block diagram of a typical two-stage (forward) amplifier. Some amplifiers may have as many as four gain stages in the forward signal path. In the forward signal path, there are typically multiple points where signals are attenuated and equalized to ensure proper power or drive level at different amplifier gain stages. The drive level into the amplifier's initial gain stage, often placed after the amplifier station's input equalization and attenuator, is arguably the most crucial point in the amplification path. Today's complex outside plant designs can result in an extensive range of signal levels into the input of an amplifier station.

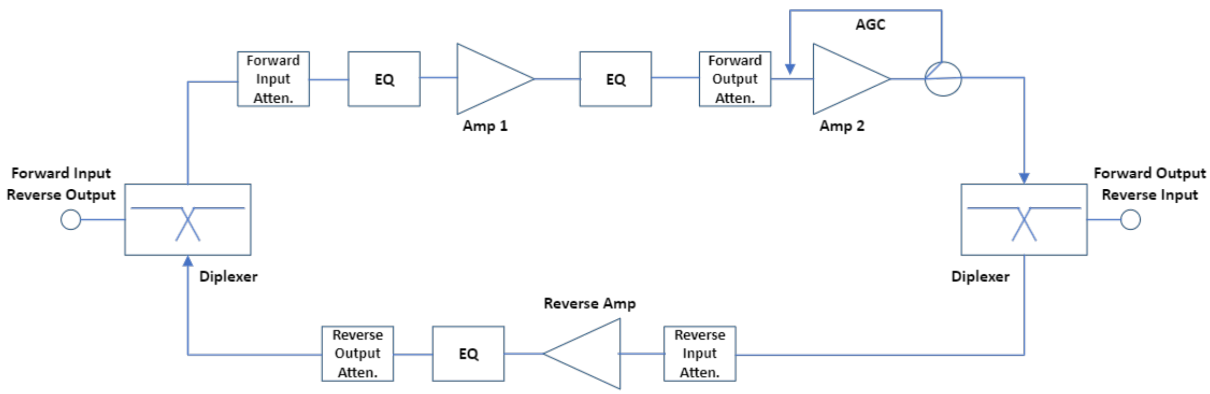

Figure 2 - Block diagram of a typical two-stage amplifier. The forward path (top) may include multiple stages of signal attenuation and equalization.

MER curves, as illustrated in Figure 3, can be generated by monitoring the MER of a specific channel at various input signal levels to the amplifier input port. The output signal level can be adjusted to the desired design level by altering the forward output attenuation. There are several common scenarios where an amplifier is aligned improperly, resulting in an input drive level in the noise region of the MER curve or the clipping region. Both extremes can result in poor overall system performance, resulting in negative customer experience. Using the MER power ratio curve, the appropriate amplifier input level and drive level required to get the best amplifier output quality is quantified.

The MER power ratio curve also defines the dynamic range for the amplifier and the slope of the amplifier's response, so that guidelines can be put in place for technicians to optimize amplifier configurations. Furthermore, with the advent of new full duplex (FDX) amplifiers that can be remotely configured, this data provides opportunities for developing software automation for configuring amplifiers for performance stability, MER optimization, and power consumption optimization.

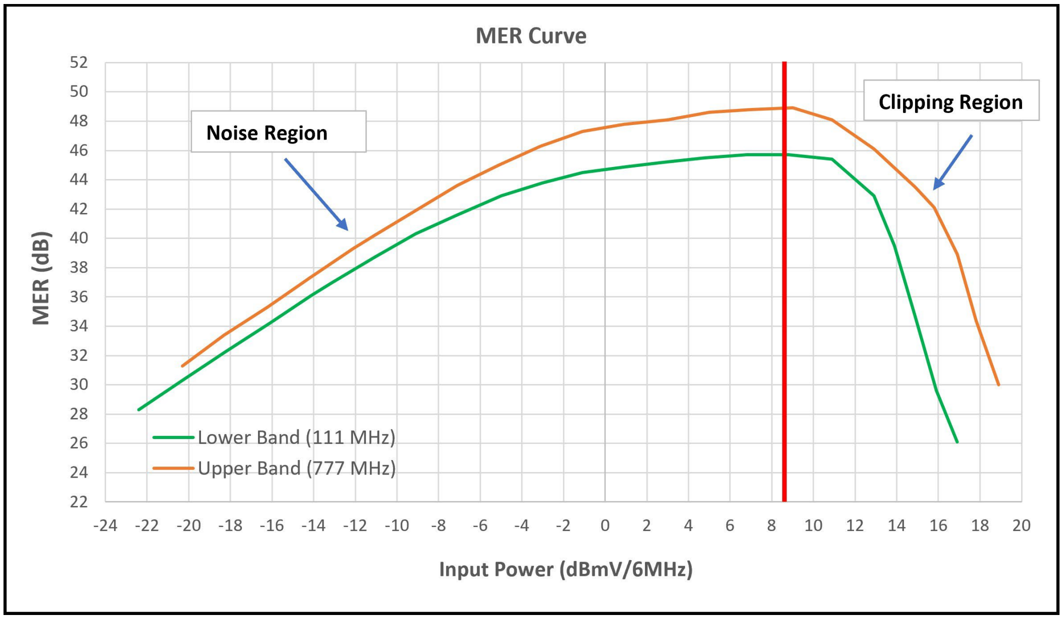

Figure 3 - MER power ratio curves of an amplifier obtained though lab measurements. For the two sets of measurements obtained at 111 MHz (green curve) and 777 MHz (orange curve), the optimal performance is at the input power marked with a vertical solid red line.

3. Distorion Noise Detection

Cable system amplifiers are important for maintaining signal quality over long distances, by boosting the signal power. In addition to gain, the slope (or tilt) is adjusted to compensate for passive cable loss over those respective distances. The proper set up of their gain stages and tilt are essential to ensure optimal performance as seen in the previous section. Ideally, these amplifiers should operate in a linear state, where the output signal is a direct and proportional representation of the input signal. Incorrect configuration of the gain stages can result in over-driving or under-driving of the amplifiers, causing them to operate in a non-linear state. When this is the case, distortions can manifest as 2nd and 3rd order products, which degrade the signal quality. When an amplifier becomes non-linear, increasing the power of the signal can inadvertently add distortion noise and reduce the performance of the system. This distortion noise will also get amplified as part of the signal as the signal passes through subsequent amplifiers down the line.

Distortion noise is detected from the cable modem's full band capture and calculated as the difference between the high & low frequency noise floors—adjusted for tilt. The challenge in measuring the noise floors is finding regions of the spectrum that are vacant and ingress-free. The current logic designates the low frequency range as the spectrum below 108 MHz and the high frequency range as the spectrum above 500 MHz. The FBC has a resolution of 117.65 kHz. To measure the noise floor in the respective high/low regions, the 25 bins with lowest power values are averaged. Figure 4 shows an example spectrum with high distortion noise. The colored areas overlaid on the FBC trace correspond to active spectrum (Video, DOCSIS, Tones, etc.) as indicated in the plot legend. This example spectrum has several vacancies (any region not marked with color), which offer an opportunity to measure the noise floor according to the method described above. The blue dotted (dashed) line designates the spectrum region at which the high (low) noise floor was calculated. For this example, the delta between high and low is 20.7 dBmV. Notice, however, that the power spectrum is somewhat tilted. A linear fit (orange solid line) to the trace estimates the amount of tilt to be 9.3 dBmV over the same frequency range corresponding to the distortion noise measurement. Therefore, the adjusted distortion noise for this example is determined to be 20.7-9.3=11.4 dBmV.

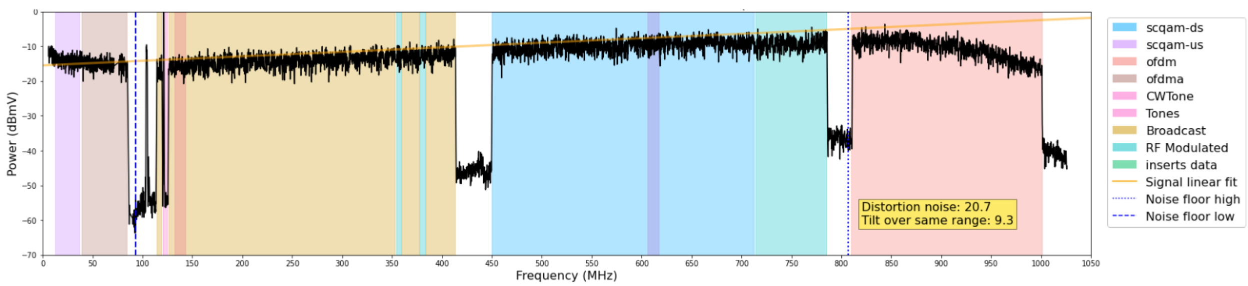

Figure 4 - Example FBC trace with active spectrum regions indicated as colored blocks. The dashed (dotted) blue line indicates the approximate location at which the high (low) noise floor was measured. The distortion noise is 20.7 dBmV corresponding to high – low noise floors. This is further adjusted for tilt by subtracting 9.3 dBmV.

The measurement of distortion noise is dependent on the availability of "clean" vacant spectrum, especially in the low frequency range where vacancy is limited to a narrow band between the upper edge of the orthogonal frequency division multi access (OFDMA) channel and the lower edge of the video/broadcast blocks. We did encounter instances in which the distortion noise detection failed due to frequency modulation (FM) ingress impacting the low noise floor measurement. Figure 5 is an example of such a scenario in which the distortion noise was incorrectly calculated to be -16.3 dBmV because of the erroneously high low frequency noise floor due to FM ingress in the ~100 MHz region. However, these examples are not impactful from the viewpoint of the method for constructing the 2nd OFDM priority groups as will be discussed in the next section. This is mainly because we are interested in extreme positive values for distortion noise (true positives), while some degree of extreme negative values can be tolerated even if they mask cases where amplifier non-linearity is present (false negatives).

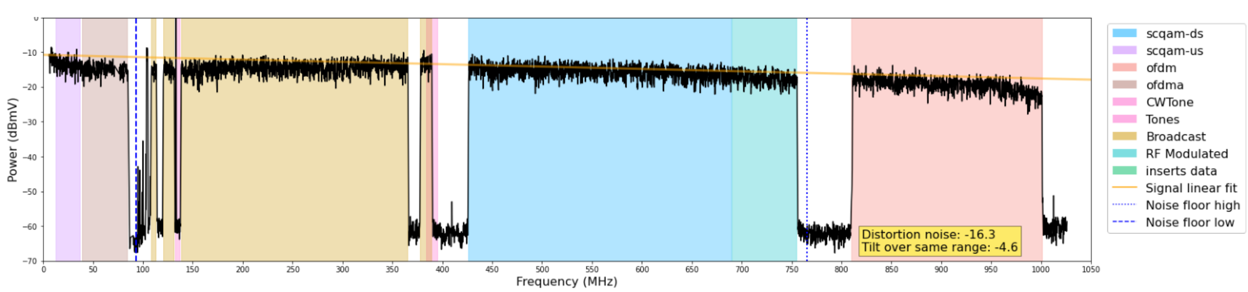

Figure 5 - Another example FBC trace. For this cable modem, FM ingress is present in the vacancy below 100 MHz, causing the low noise floor to be overestimated. Subsequently the distortion noise is incorrectly calculated as -16.3 dBmV.

Figure 6 shows the distribution of the distortion noise as measured for a population of ~1.7 million cable modems. Both a histogram (left panel) and a cumulative density function (CDF) (right panel) are included in the figure. The distribution is roughly normal, centered close to 0 dBmV and has a slight skew at the right end. As extreme positive distortion noise values indicate amplifier non-linearity and potential impact to customer experience, these are expected to be limited. The CDF shows that close to 100% of the cable modem population has distortion noise below 6 dBmV. The extreme values must be examined closely when activating the 2nd OFDM channel as discussed in the next section.

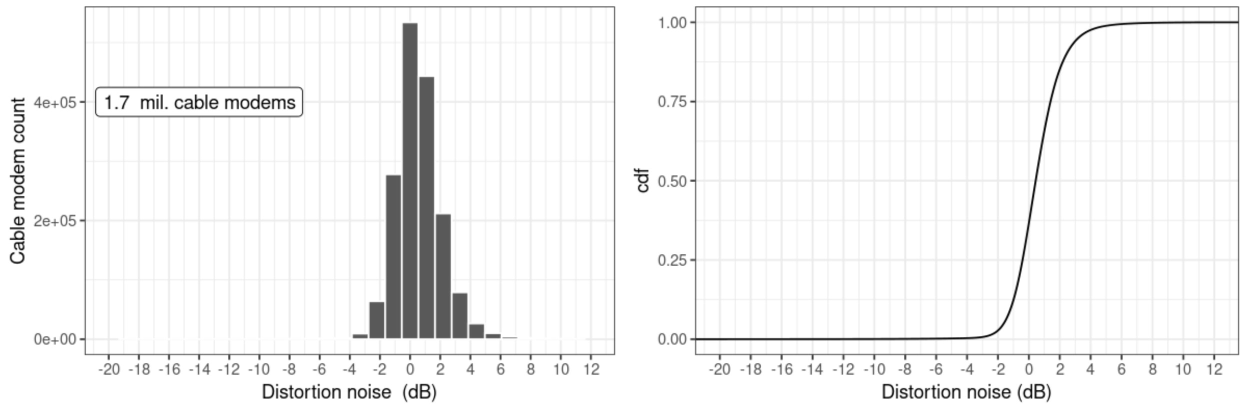

Figure 6 - Distribution (left panel) and corresponding cumulative density function (right panel) of the measured distortion noise for a sample of ~1.7 million cable modems. Close to ~100% of the modem population has distortion noise of less than 6 dBmV.

4. Priority Groups for 2nd OFDM Activation

As a step towards the 10G and FDX roadmap with multi-Gbps speeds, a 2nd OFDM channel is deployed on the virtualized cable modem termination system (vCMTS) platform to add additional capacity and to prepare spectrum for DOCSIS 4.0 FDX. The algorithms involved in qualifying the remote phy (physical layer) devices (RPDs) for 2nd OFDM and in generating a tailored spectrum recommendation were described in a previous SCTE technical paper [2]. One aspect of the problem that we haven't published a paper on so far is the impact of the increase in power consumption due to the increase in the amount of active spectrum. A concern here is the potential of driving amplifiers that currently operate at the edge of non-linearity deep into the non-linear regime due to the additional input power into the amplifier from the additional OFDM channel and thereby negatively impacting customers connected to these amplifiers. This has been experienced multiple times in actual deployments in several scenarios from incorrect pad configurations to amplifiers that have been configured to compensate for a high attenuation cable span and when replaced with a new mid-split amplifier at the design levels can result in sub-optimal power levels. Detecting distortion noise as an early signal of amplifier non-linearity is the cornerstone of the approach presented in this section.

This approach classifies RPDs (fiber nodes) into various priority groups according to the risk of driving amplifier non-linearity when automated SW spectrum management that increases total composite power occurs. First, we outline the key metrics that are considered in the construction of the priority groups:

- **Distortion noise**: As described in the previous section, this measure is directly correlated with amplifier operating in the non-linear regime. Moreover, distortion noise is adjusted to account for spectrum tilt.
- **Power delta**: This is an estimate of the increase in power due to activation of the 2nd OFDM channel. This is calculated as the logarithm of the ratio of active spectrum in MHz post 2nd OFDM activation to that before 2nd OFDM activation. Since the spectrum recommendation (and thereby the width of the 2nd OFDM channel) may be specific to a given RPD based on its channel

map previously adjusted for capacity or with additional video channels, the power delta is not fixed but varies across the RPD population.

- **OFDM RxMER**: The ultimate measure of signal quality. It is measured across the 1st OFDM channel (placed between 810 and 1002 MHz across the network) and used to assess how healthy the current spectrum is for a given cable modem.

4.1. Univariate Distributions

As a first step to informing the thresholds and rules governing the formation of the priority groups, the univariate distributions of the metrics of interest are presented below. Figure 7 shows the distribution (histogram and CDF) for the power delta metric. Not surprisingly, the distribution is not normal. Since the spectrum configuration is often common for a group of RPDs in the same market or locality, the distribution is highly influenced by the width of the 2nd OFDM channel to be deployed. But overall, the power delta is typically less than 2.5 dB.

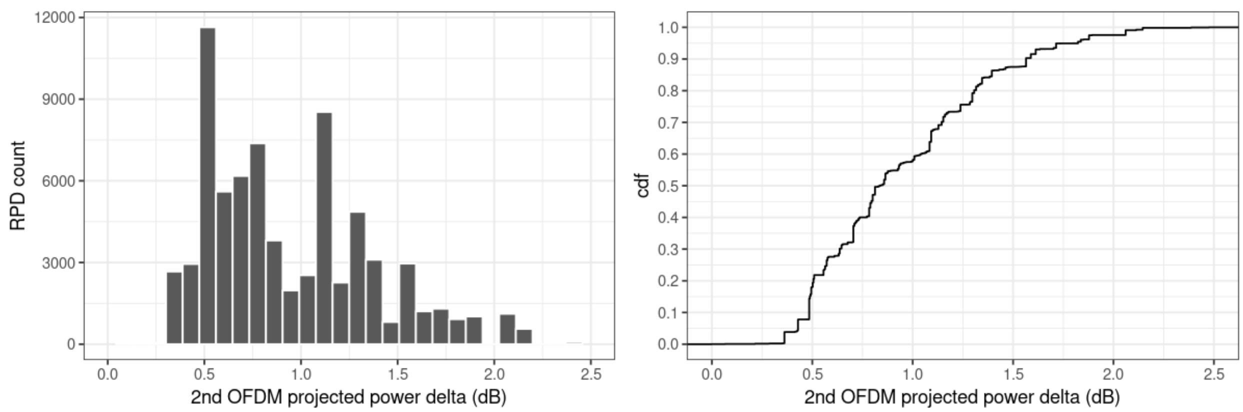

Figure 7 - Distribution (left panel) and corresponding cumulative density function (right panel) of the power delta metric for RPDs that are targeted for 2nd OFDM activation. According to the distribution, the increase in power due to 2nd OFDM activation is expected to be at most 2.5 dB.

The OFDM RxMER distributions for the OFDM channel in the 810-1002 MHz prior to adding the 2nd OFDM channel are shown in Figure 8. RxMER is polled from cable modems at an hourly frequency. The data collected for the distributions covered a 2-day time window (48 samples/cable modem). Thus, the distribution in the form of boxplots (left panel) considers different percentiles of aggregation across the time samples. For example, the 10th percentile is close to the worst-case scenario. Both boxplot (left panel) and CDF (right panel) views indicate that the OFDM spectrum is healthy and highly stable. The median RxMER varies only slightly by aggregation percentile (~40 dB at the 10th and ~41 dB at the 90th). The MER may vary for a variety of reasons such as cascade lengths or ingress from the cellular bands located in this spectrum in some nodes. The 37 dB level is of interest as the threshold above which 2k-QAM is supported. The CDF shows that ~85% of the cable modem population has RxMER that on average exceeds this value.

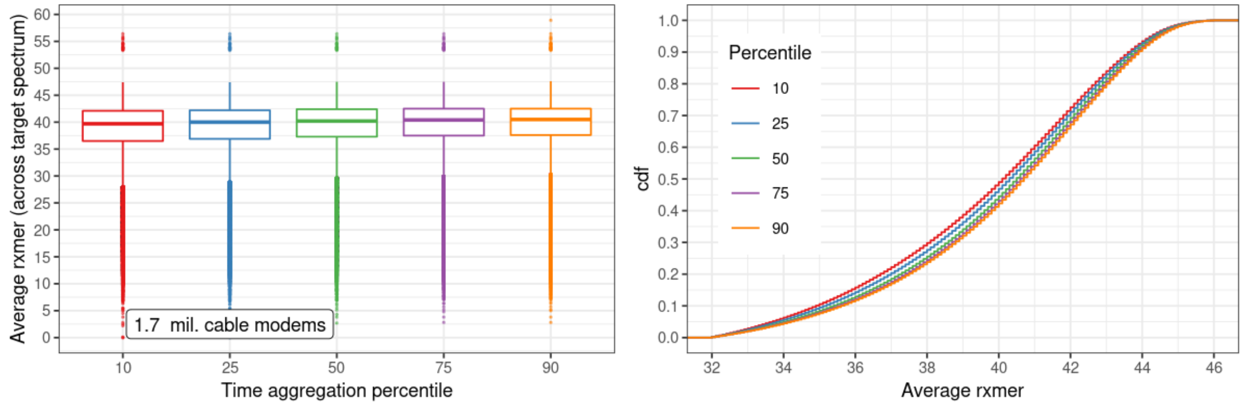

Figure 8 - Distribution in form of boxplots (left panel) and corresponding cumulative density functions (right panel) of the RxMER for the top OFDM channel for a sample of ~1.7 million cable modems. Different percentiles are considered to aggregate each cable modem's ~48 time-samples.

4.2. Multivariate Views

One more exercise that is helpful for validating the methodology is to consider correlations between variables and whether the observed trends agree with the expected physical behavior of the system. Figure 9 is a view showing the pairwise correlation between distortion noise and each of OFDM Rx Power, OFDM RxMER, and Total Rx Power of the spectrum. The view was constructed by binning the distortion noise values according to the ranges indicated on the plot *x*-axes and calculating the different percentiles of the metrics of interest for each distortion noise group. Both Rx power trends (panels 1 & 3) are similar and agree with what is expected. As the Rx Power increases, the amplifier operates at a higher power level and the likelihood of driving non-linearity increases. Thus, we see a clear positive association between Rx Power and distortion noise for all percentiles. The correlation with OFDM RxMER, on the other hand, has two separate features. At high distortion noise, non-linearities degrade the spectrum and so the RxMER levels drop (panel 2). This behavior is expected and confirms the soundness of the methodology. For the low distortion noise and low RxMER percentiles (cable modems with somewhat degraded spectrum), the trend is reversed. One possibility to explain this negative association is to consider confounding variables that impact both distortion noise measurement and RxMER for this population of cable modems. We suspect that the key confounding variable is negative tilt. Figure 10 shows an example spectrum with a high degree of negative tilt. It has severely degraded spectrum at the top OFDM channel, and at the same time, the measured distortion noise is negative since negative tilt may also impact the noise floors. For the construction of the priority groups, negative distortion noise values are ignored and are therefore inconsequential to the methodology.

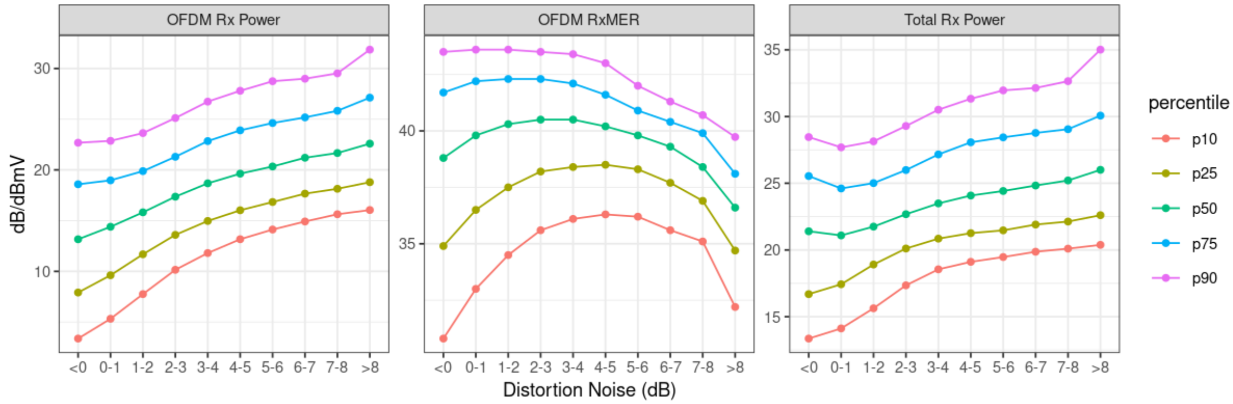

Figure 9 - Correlations between distortion noise and OFDM Rx Power (panel 1), OFDM RxMER (panel 2), and Total RX Power (panel 3).

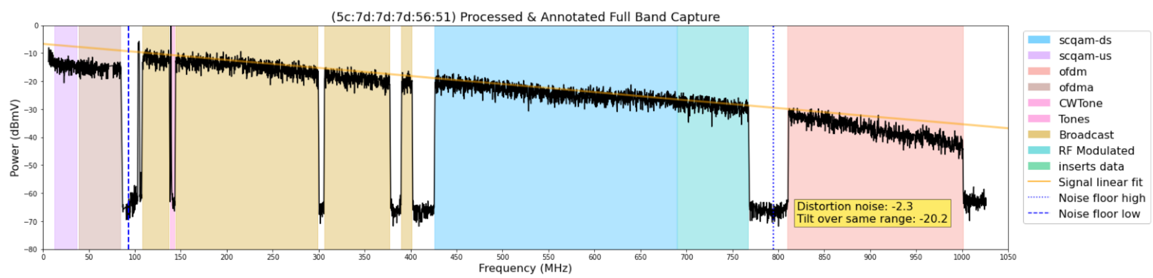

Figure 10 - Example cable modem FBC showing high degree of negative tilt. Even though the distortion noise is slightly negative, the RxMER of the OFDM channel (810-1002 MHz) is expected to be severely degraded.

4.3. Logic for The Priority Groups

For decisioning on whether an RPD poses risk of one or more amplifiers in its plant running into the non-linear operating regime post second OFDM activation, we introduce the logic outlined in Table 1 for creating the priority/risk groups. Priority 1 RPDs have cable modem population with high RxMER in the top OFDM channel and so they pose little risk for 2nd OFDM deployment. From the remaining RPD population, Priority 2 RPDs have low power delta indicating that the added spectrum is not significant enough to drive non-linearity. This is usually the case where the spectrum designated for placement of the 2nd OFDM channel is currently occupied with channels supporting active gain control (AGC) or expanded video QAMs. From the remaining RPD population, Priority 3 RPDs have cable modem population with low distortion noise. Lastly, the remaining RPD population makeup Priority 4 RPDs. These have cable modem population with high distortion noise and thus pose the highest risk of running deeper into the non-linear regime and can be rebalanced to mitigate the risk before expanding spectrum.

Table 1 - Decision matrix outlining how priority groups are designated based on the key input metrics (first 3 columns of the table).

RxMER	Power Delta	Distortion Noise	Non-linear Amplifier Risk	Priority	Interpretation
High	Low	Low	Very Safe	1	Very good
High	Low	High	Very Safe	1	Very good
High	High	Low	Very Safe	1	Very good
High	High	High	Very Safe	1	Very good
Low	Low	Low	Safe	2	Good
Low	Low	High	Safe	2	Good
Low	High	Low	Somewhat Risky	3	Maybe
Low	High	High	Very Risky	4	Bad

As far as the thresholds for designating each of the variables as High/Low, we conducted simulations exploring the impact of different thresholds on the count of RPDs placed in each of the priority groups. Since RxMER and distortion noise are measured per cable model, the logic for aggregation from the cable modem to the RPD is as follows:

- Per RPD, count the number of cable modems within each priority group.
- Drop priority groups where modem count (absolute or as percentage of total RPD modem population) is below a given threshold. For this illustrative analysis, the adopted threshold is 10 cable modems to retain the priority group. Note the varying this threshold plays the trade-off between achieving high precision vs. high recall.
- For the remaining priority groups, pick the lowest priority group as representative of the RPD (i.e., plan for worst case scenario, indicative of a cluster of cable modems in the node that are at risk).

Figure 11 shows the result of a set of simulations that explored the following thresholds, which were informed by the univariate distributions of each of the metrics:

- **RxMER**: 34, 37, 40 dB
- **Power Delta**: 1, 1.5 dBmV
- **Distortion Noise**: 3, 5 dBmV

It is seen that irrespective of the chosen thresholds, the majority of RPD population falls with the top 2 priority groups and a minority falls within the highest risk of Priority 4 (up to 1% using the most conservative set of thresholds). In addition, Figure 12 shows the sensitivity of the outcome against the threshold of cable modems needed to nominate a priority group as representative of the RPD.

Figure 11 - Results of simulations exploring different High/Low thresholds for Distortion Noise, RxMER, and Power delta. The left panel is for distortion noise threshold of 3 dBmV and right panel a threshold of 5 dBmV. Within each panel the columns correspond to Power Delta threshold of 1 and 1.5 dB and the rows correspond to RxMER thresholds of 34, 37 and 40 dB. The outcome is the number and percent of RPDs placed in each of the priority groups.

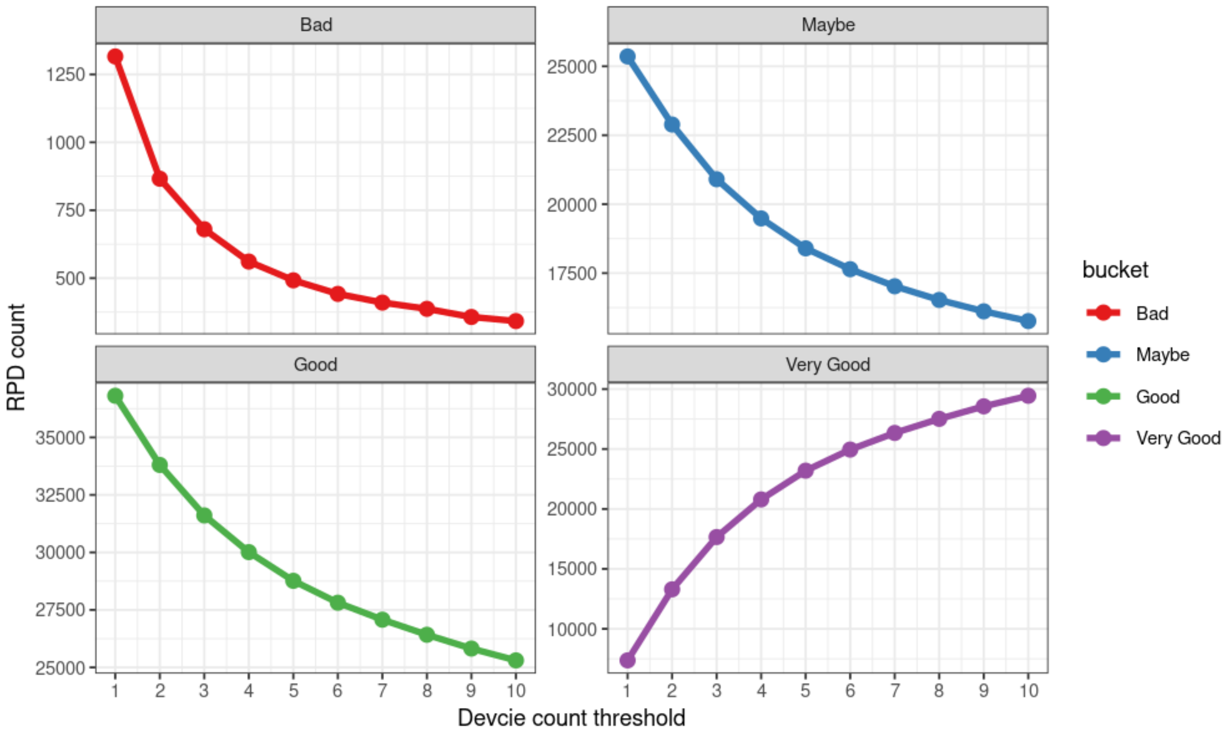

Figure 12 - Sensitivity analysis showing the number of RPDs in each priority group as a function of the minimum number of cable modems required in a group to retain it as representative of the RPD. We opted for a threshold of 10 to nominate a priority group as representative of the RPD.

Based on the sensitivity analysis, we opted for an RxMER threshold of 37 dB, a Power Delta threshold of 1 dB, and a Distortion Noise threshold of 5 dBmV. Now that the priority groups are constructed, two types of activities occur concurrently:

- Activating 2nd OFDM will start with the lowest risk priority (#1) group. The methodology will be further validated by comparing the pre and post metrics as spectrum gets turned on for this population. Note, that the process will occur gradually with a batch of activations (~few thousand RPDs) every week.
- The priority 4 RPDs will be investigated by field techs and corrective actions will be taken, such as recalibrating amplifiers to operate in the optimal region. Given that the data pipelines and algorithms run daily, any fixes implemented in the field will be reflected in subsequent pipeline runs. Therefore, Priority 4 RPDs will be able to migrate automatically to the higher priorities once the underlying issue gets addressed and telemetry reflects the improved outcome.

One thing to note, although the methodology we present here is used to evaluate the impact of adding a 2nd OFDM on amplifier performance and thus overall system performance, the distortion noise detection methodology and its correlation with the OFDM channels MER values can also be used to monitor amplifier performance in the field and detect issues routinely and proactively in an automated fashion for proactive maintenance activities.

The next section introduces some of the analyses & results from the post 2nd OFDM activation exercise on the live network.

5. Post Activation Analysis

Many RPDs have been activated with a 2nd OFDM channel at the time of writing this paper. Figure 13shows a sample distribution of the 2nd OFDM channel width for this population. Most of these RPDs belong to the Priority 1 & 2 groups. Though some lower Priority groups were also activated with 2nd OFDM driven by the need to alleviate high utilization in the downstream spectrum. A trade-off between risk of driving amplifier non-linearity and adding capacity can be balanced. In addition, Figure 14 shows the top 25 spectrum configurations for this population. Around 15k out of the 22k RPDs in this sample fall within the top 25 configuration. It is observed that the somewhat high variability in spectrum configuration is dictated by the variability in the video/broadcast channels. Figure 14 also shows that we now utilize most of the spectrum up to 1 GHz.

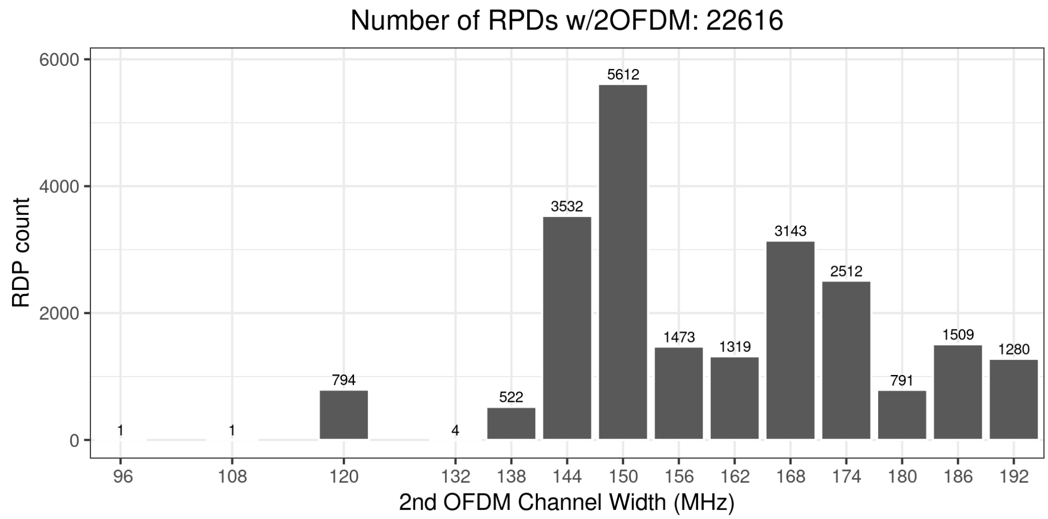

Figure 13 - Distribution of 2nd OFDM channel width.

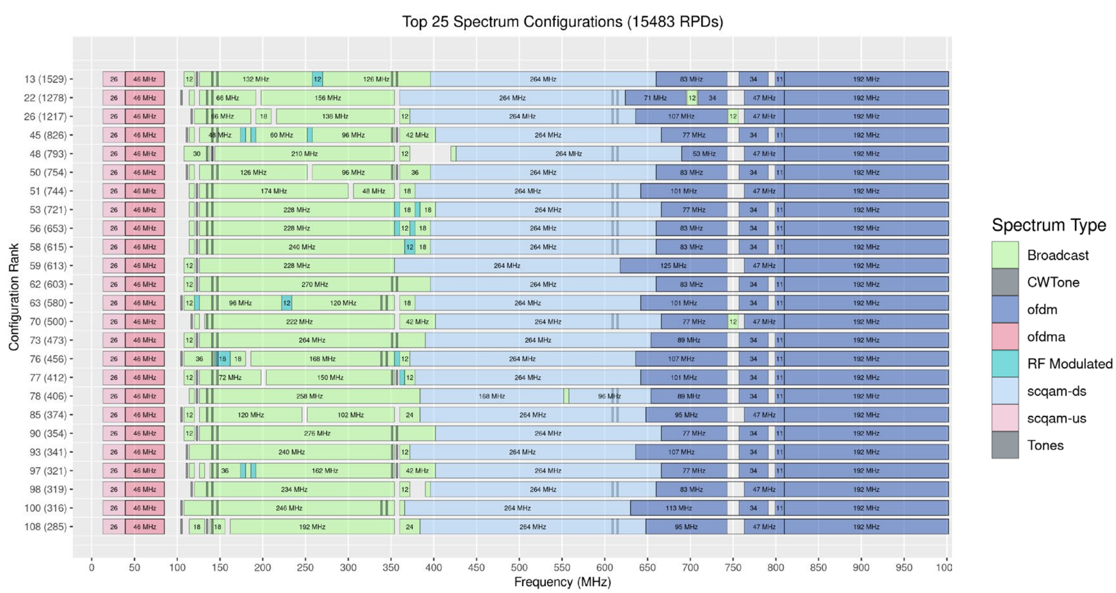

Figure 14 - Top 25 spectrum configurations for the RPD population with a 2nd OFDM channel.

We compared the pre and post RxMER for sample of thousands of these RPDs. The pre RxMER values were calculated by first computing the average across sub-carriers for each device poll, and then taking the average of those averages for 3 days prior to 2nd OFDM deployment for each device. Similarly, post RxMER values were calculated by considering the RxMER for 3 days post 2nd OFDM deployment. Figure 15 below shows the cumulative distribution of the difference between the post and pre RxMER values by RPD Priority. As anticipated, and even though the differences are marginal, we observe that in aggregate, Priority 1 RPDs experience a smaller drop in RxMER than Priority 2 RPDs, and Priority 2 RPDs experience a smaller drop in RxMER than Priority 3 RPDs. This analysis reaffirms that we are targeting the correct RPD population for 2nd OFDM deployment from the perspective of minimizing risk of amplifier non-linearity.

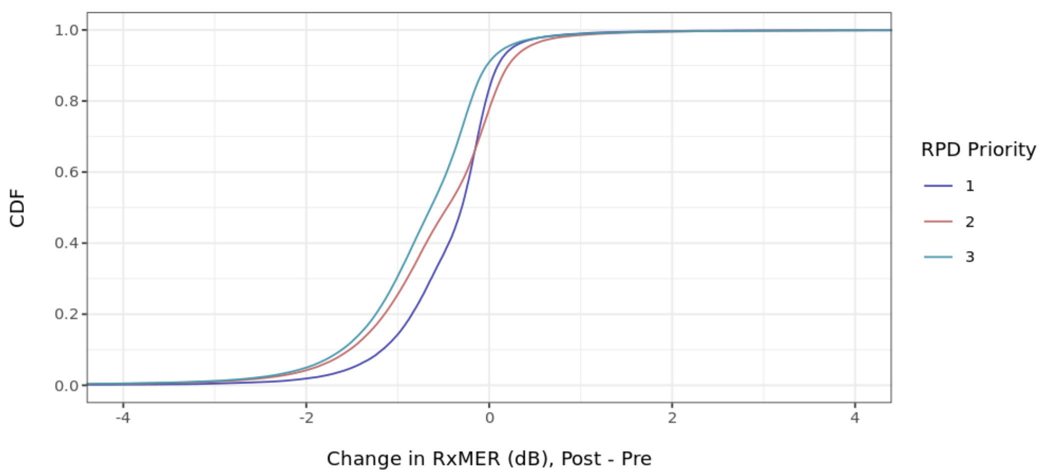

Figure 15 - Cumulative distribution of difference between post and pre RxMER values by RPD Priority

Table 2 below summarizes the differences in RxMER observed between different RPD priority groups. We observe that the bottom 5% of devices experience drops greater than ~1.5, ~1.9 and ~2 dB respectively across RPD priority groups 1, 2 and 3.

Table 2 - Comparison between post and pre RxMER values by RPD Priority

			(Post - Pre) RxMER				
RPD Priority	**Device Count**	**RPD Count**	**2nd Percentile**	**5th Percentile**	**10th Percentile**	**50th Percentile**	**90th Percentile**
1	79k	3.2k	-1.98	-1.50	-1.17	-0.30	0.09
2	255k	3.1k	-2.48	-1.90	-1.53	-0.46	0.21
3	158k	2k	-2.60	-2.00	-1.61	-0.64	-0.03

Finally, we also explored developing a linear regression model to predict RxMER values post 2nd OFDM deployment, and this model is able to predict RxMER with high levels of accuracy. Table 3 summarizes the model performance for different combinations of features (linear regression inputs). Mean squared error (MSE) is the objective function that the linear regression fit tries to minimize (e.g. using a least square—best fit type algorithm). The R-squared represents the amount of variability that is explained by the features included in the model. Post 2nd OFDM deployment, RxMER levels are very close to the pre-deployment levels, as seen in Figure 15. Thus, utilizing pre-RxMER by itself provides a high degree of explainability (close to 94%). Adding the Power Delta and Distortion Noise provides only marginal improvement to the explainability. One reason as to why additional features do not improve the model may be due to limiting deployments so far to the top 2 priority groups. This population of RPDs operate in the "safe" regime and pose minimal risk for running amplifier non-linearity post 2nd OFDM deployment. As such, it is expected that the RxMER for this population to be quite stable. Once a larger population of Priority 3 and even some Priority 4 RPDs are included in the analysis, we will reconsider the linear regression model for an indication that additional features hold predictive power for the post-activation RxMER.

Table 3 - Comparison between Linear Regression models for predicting RxMER post 2nd OFDM Deployment

Features	MSE	R-squared
Pre-RxMER	0.7273	0.9391
Pre-RxMER, Power Delta	0.7208	0.9396
Pre-RxMER, Pre-Distortion Noise	0.7273	0.9391
Pre-RxMER, Power Delta, Pre-Distortion Noise	0.7204	0.9396
Pre-RxMER, Power Delta, Pre-Distortion Noise + Polynomial Features	0.7052	0.9409

6. Conclusion

In this paper, we introduced a methodology for detecting amplifier non-linearity from the measurement of distortion noise from a cable modem's full band capture. We validated the methodology by showing that high distortion noise correlates with high Rx Power and low RxMER. That is, as more of the spectrum is utilized, input power increases and non-linear amplifier operation degrades signal-to-noise ratio as measured by the RxMER. The distortion noise-based technique was put to the test to support enablement of a 2nd OFDM channel on a virtualized cable modem termination system (vCMTS) platform. Distortion noise along with OFDM RxMER and the expected increase in spectrum utilization (2nd OFDM Power Delta) were used in combination to create RPD priority groups informing the risk of deploying 2nd OFMD from the viewpoint of driving amplifier non-linearity. Post 2nd OFDM activation analysis revealed that so far, our approach of limiting deployment to the top 2 priority groups ensured that RxMER levels remained healthy after activating the 2nd OFDM channel. As we continue the 2nd OFDM deployment journey, we will continue to monitor the health of the network and to look for signs of non-linearity as manifested in the distortion noise metric.

This method holds promise beyond supporting deployment of 2nd OFDM. With FDX on the horizon, and with the introduction of "smart" FDX amplifiers, we will be able to develop a closed loop system that automatically monitors and corrects for non-linearities by recalibration of the amplifiers to bring them back to the optimal operating regime.

Abbreviations

AGC	active gain control
ANSI	American National Standards Institute
CDF	cumulative density function
CNR	carrier-to-noise ratio
CSO	composite second-order distortion
CTB	composite third-order distortion
DOCSIS	data over cable service interface specification
DUT	device under test
FBC	full band capture
FDX	full duplex
FM	frequency modulation
HFC	hybrid fiber coaxial
MER	modulation error ratio
MSE	mean squared error
NPR	noise power ratio
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multi access
PHY	physical layer
QAM	quadrature amplitude modulation
RF	radio frequency
RPD	remote phy device
RxMER	receive modulation error ratio
SCTE	Society of Cable Telecommunications Engineers
vCMTS	virtualized cable modem termination system

Bibliography & References

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