Utilizing OFDM for Measuring Spectrum Performance Above 1 GHz

A Technical Paper prepared for SCTE by

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1. Introduction

Our industry is going through a development phase of our hybrid fiber/coax (HFC) networks. This next phase will rely on orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA) channels. With new spectrum being utilized for the first time, we can introduce a new activation process to maximize the quality of the spectrum prior to customer utilization. This paper covers the life cycle of plant development that can avoid risks. This new life cycle will utilize multiple data sources to identify potential impacts and provide a key performance indicator (KPI) that can monitor spectrum after service enablement.

2. Life Cycle of Plant Development

As Data-Over-Cable Service Interface Specifications (DOCSIS®) services increase the need for reliability and the HFC plant evolves, operators need to develop a strong spectrum development life cycle to maintain a high level of service. For existing customers, taking the time to assess post-construction state prior to service enablement can mitigate risks. It qualifies the success of the construction and provides data that demonstrates the readiness for service enablement.

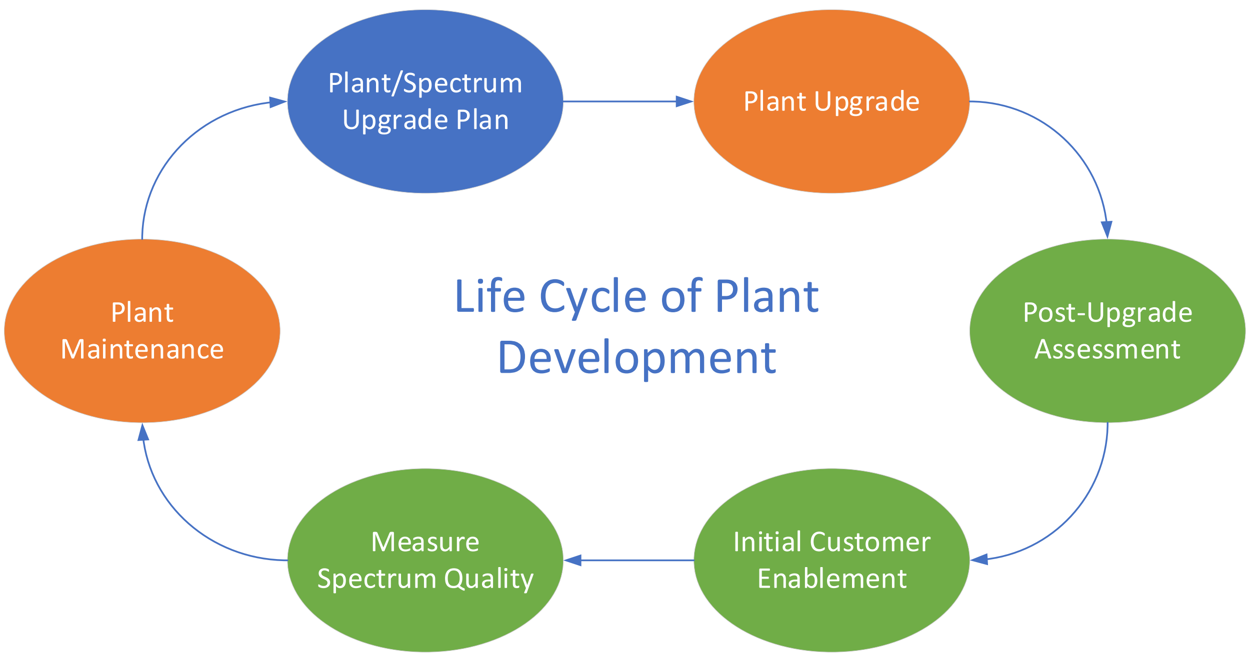

Figure 1 – Life Cycle of Plant Development

2.1. Plant/Spectrum Upgrade Plan

The first step in the process is to build the plan for the plant and/or spectrum upgrade. If spectrum changes are going to occur, it is key to identify the DOCSIS spectrum plan to support the construction process. For example, if a plant upgrade is occurring that will upgrade the HFC plant from 1 GHz to 1.2 GHz on the downstream, the plan for an additional OFDM channel above 1 GHz should be expected.

2.2. Plant Upgrade

The plant upgrade process typically starts with the node upgrade. As the node is upgraded, this is the ideal time to turn up the new DOCSIS carriers. These new carriers should be restricted from services on cable modems to avoid impacts. Every active and passive module upgrade after the node down the cascade will have this energy to provide a reference for setup and a validation of the success of the upgrade.

2.3. Post-upgrade Assessment

Once the plant upgrade has been completed all capable cable modems are able to collect proactive network maintenance (PNM) spectrum data. This data can provide information on frequency response roll-off, suck-outs, and other known spectrum impairment profiles. This can validate if additional maintenance is needed prior to activating the new spectrum for services.

2.4. Initial Customer Enablement

After successful assessment of the new DOCSIS carriers, cable modem restrictions can be removed by an update to the cable modem configuration files. By removing the restrictions, cable modems will be cleared for the new spectrum.

2.5. Measure Spectrum Quality Over Time

As the new spectrum is utilized it is important to measure the cable modems' performance within the new spectrum. Operators have their standard KPIs that can be utilized for this function. At Rogers Communications we use KPI called Spectrum Efficiency, which is covered in detail below.

2.6. Plant Maintenance

If your measurement crosses a trigger threshold, moving forward with plant maintenance or in-home service call(s) could be initiated. This workflow is about recovering from the issue and restoring services for your customer. This process could also recommend additional plant upgrades to correct issues.

3. Carrier Limitation Above 1 GHz

When utilizing spectrum above 1 GHz for DOCSIS technology, operators will be limited to OFDM-based channels for cable modems. Since this is the planned use of this spectrum it should not be looked at as a limitation, but as opportunity to assess performance. This information can predict how it will be utilized in the future by the customers' cable modems. Thus, the challenge is the limitation of cable modems from this assessment channel prior to activation. As an example, if you enable OFDM carriers between 1.2 GHz and 1.8 GHz, only DOCSIS 4.0 cable modems can be utilized for the assessment.

4. Restricting Cable Modems from Active DOCSIS Channels

The most effective way to restrict DOCSIS channels for cable modems under the DOCSIS specification is by utilizing the service flow attribute mask feature. This attribute mask can be utilized to require or forbid certain channels or bonding groups. From working with this DOCSIS feature, we find with bonded cable modems the required attribute mask is the easiest to work with.

In order to build a system that will restrict all DOCSIS 3.1 and 4.0 cable modems from a OFDM channel above 1 GHz you will need to do the following:

1. Determine attribute mask value

2. Build bonding groups
3. Update downstream service flows
4. Update cable modems

4.1. Determine Attribute Mask Value

For the purposes of this use case, we only require an attribute mask for bonding since non-bonded cable modems cannot access OFDM channels or spectrum above 1 GHz. One example cable modem termination system (CMTS) has the default attribute mask value for a bonding group configured to 0x80000000. The CMTS also requires a value greater than the default value to be used for a required attribute mask.

4.2. Build Bonding Groups

Typically, the CMTS utilizes dynamic bonding groups. Since we want to restrict the new OFDM channel we need to create static bonding groups for the modems that can access that new OFDM channel so a dynamic group can no longer be utilized. This mean that the created static bonding groups will all have the new attribute mask value applied to them. The dynamic bonding groups can remain at default.

4.3. Update Downstream Service Flows

Each cable modem that requires this restriction will need to have all of its downstream service flows updated with the required attribute mask and attribute aggregate rule mask. The value must match the value selected above.

4.4. Update Cable Modems

With the CMTS and cable modem configuration file updates in place a reset to the cable modem is needed. This update applies the attribute mask to the cable modem bonding groups upon registration. You can time these updates to occur at the same time of the OFDM channel configuration change to avoid multiple cable modem resets.

Now with all the required cable modems having the attribute mask in place they will be restricted from accessing the new DOCSIS assessment channel. Once the assessment channel has been cleared for service activation just revert the cable modems back to the default attribute mask with another update and they will start accessing the new capacity.

5. Utilizing PNM Spectrum Data to Identify Plant Impairments

Utilizing OFDM above 1 GHz, even without leveraging the bit-loading for throughput, can offer cable operators many advantages. Downstream DOCSIS channels can assist with new installations and cutovers serving as a carrier amplitude reference for sweep and alignment operations. Furthermore, it enables the operator to collect PNM spectrum data and receive modulation error ratio (RxMER) data per subcarrier from cable modems and digital hand-held meters. This provides insights into the noise floor for detecting potential ingress issues and other impairments that may be lurking in the coaxial plant and premises network above 1 GHz. Downstream DOCSIS channels also have the potential to aid in leakage monitoring that could reveal previously undetected shielding integrity problems, as well as help discover new measurement techniques and strategies to gauge the performance of the HFC network.

1.2 GHz frequency division duplex (FDD) deployments can leverage both legacy HFC nodes and distributed access architecture (DAA) nodes in the network. However, with OFDM deployed above 1 GHz traditional downstream active sweep systems face hurdles with limitations for the number of active sweep points that reduce the resolution of the active sweep tool, making it more challenging to identify frequency response issues. Sweep views are limited to a top-of-carrier amplitude reference called sweepless sweep. A sweepless sweep reference can be beneficial in networks that deploy additional OFDM carriers spread across all possible spectrum in the system. Sweepless sweep provides a good representation for the network conditions; however, it is important to note that it only works when carriers occupy the entire bandwidth through nodes, amplifiers and passive devices. Populating the entire radio frequency (RF) spectrum with OFDM also provides visibility into any alignment issues that may exist after upgrading to new 1.2 GHz and 1.8 GHz amplifiers. Figure 2 shows a proposed 1.2 GHz high-split downstream carrier loading plan with level reference.

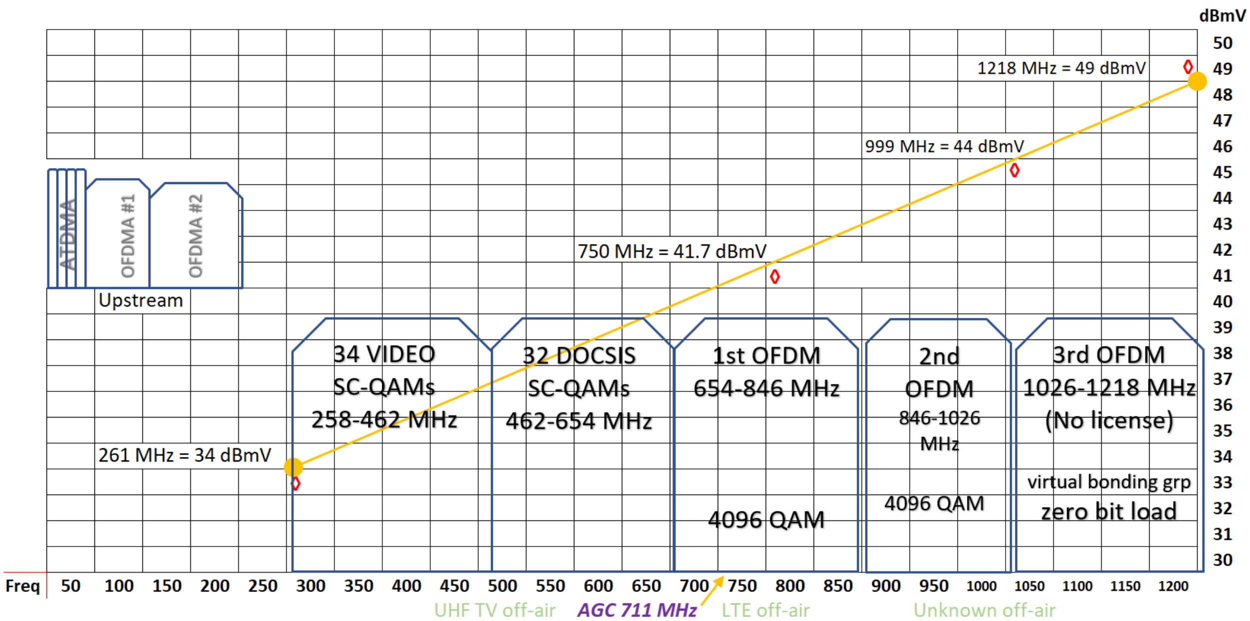

Figure 2 – Proposed 1.2 GHz High-Split Downstream Carrier Loading Plan with Level Reference

Besides having a downstream RF level and RxMER data, the additional loading also allows for over-the-air leakage monitoring, utilizing OFDM pilot carriers as leakage tones. One of the greatest realizations is that this newfound OFDM derived data collection is useful for RxMER evaluation with no impact to customer service. The operator can determine OFDM channel settings such as physical layer link channel (PLC) placement, next codeword pointer (NCP) location, data profiles, exception zones, occupied bandwidth, and more for a particular service group as part of a quality control exercise.

5.1. Case Study: Roll-off Impairment

One common impairment operators will see when deploying OFDM above 1 GHz is a roll-off frequency response characteristic related to many different network limitations. Sweeping and aligning each amplifier is good preventive practice, but what if an operator missed an amplifier or line passive that was supposed to be upgraded? What if there is an issue that only exists inside of the customer's drop network? We can utilize PNM spectrum data and RxMER tools that work with cable modems to help identify these issues in both the premises (single modem issue), and the plant (multiple modem issues). Figure 3 shows a spectrum analyzer view of a customer's drop that had a bandwidth-limited splitter in the home that caused severe 20 dB attenuated roll-off above 1 GHz.

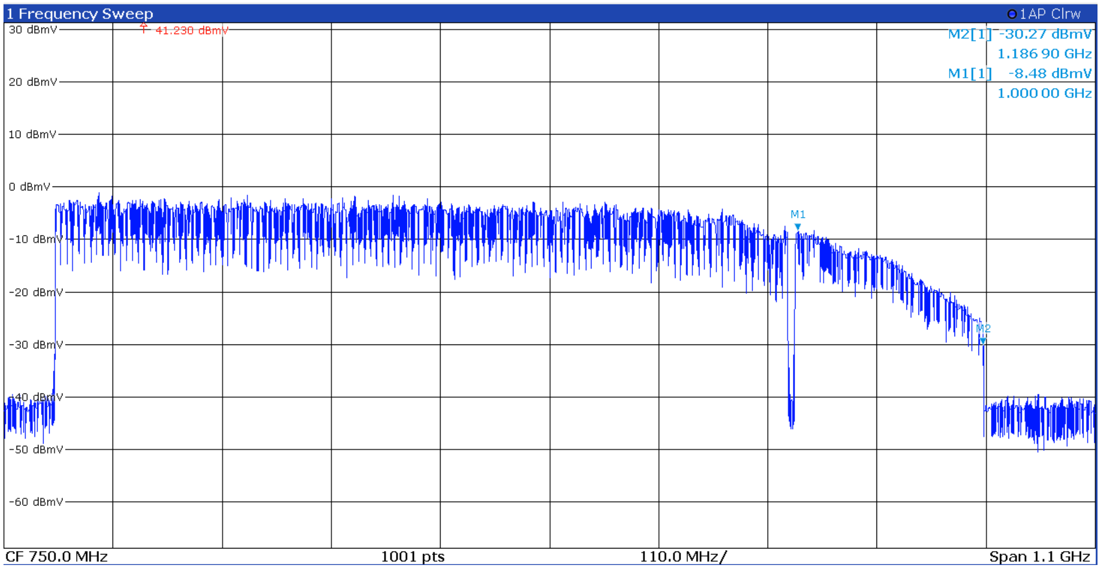

Figure 3 – Example of Customer Drop with Severe Roll-Off Caused by Bandwidth Limited Splitter – Spectrum Analyzer View

Figure 4 shows a closeup of the OFDM channel power spectrum. Again, the roll-off characteristic is very severe and will affect RxMER as shown in Figure 5. The red line represents the RxMER of the OFDM channel above 1 GHz at the customer drop with a bandwidth limited splitter installed, and the blue line represents the same customer drop with the splitter removed.

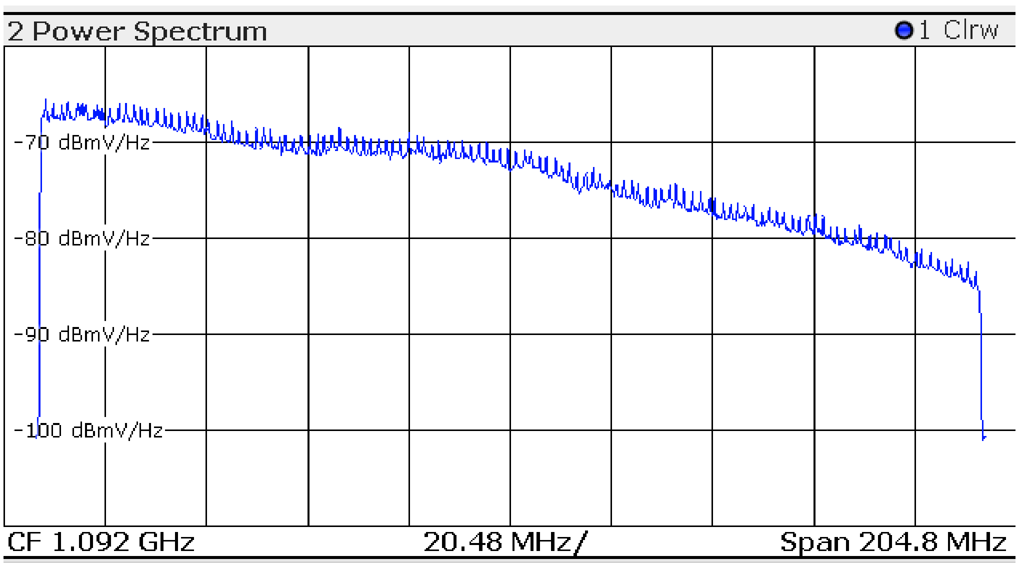

Figure 4 – Example of Customer Drop with Severe Roll-Off Caused by Bandwidth Limited Splitter – OFDM Power Spectrum View

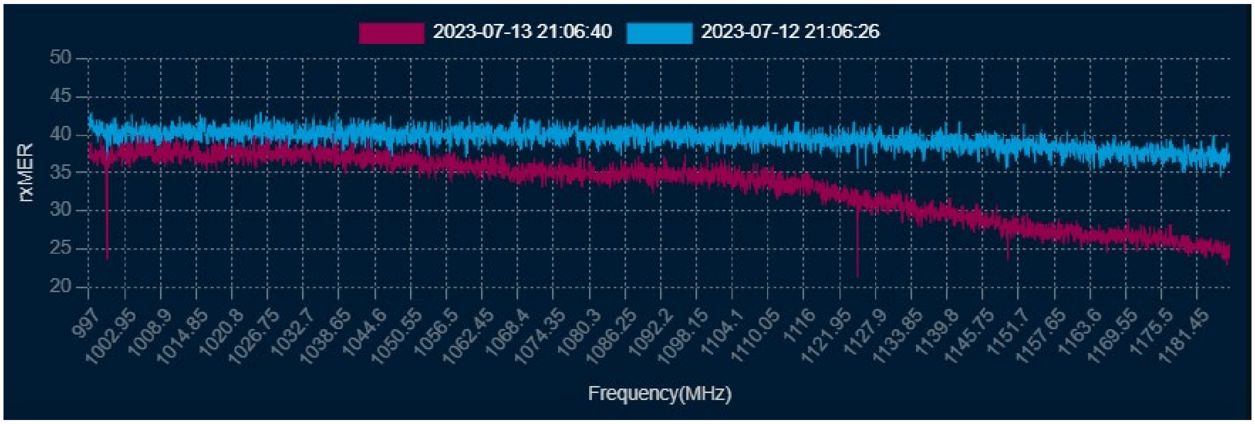

Figure 5 – Example of RxMER at Customer Drop With (Red) and Without Bandwidth Limited Splitter (Blue)

By removing the bandwidth limited splitter from the customer premises, the RxMER of the OFDM channel has improved greatly, and with an average RxMER of >38 dB, the modem should be able to receive a 4096-QAM data profile. In this customer drop simulation, there will always be some amount of roll-off seen above 1 GHz because the plant passive devices and taps were not upgraded to 1.2 GHz. This modem has four 1 GHz passive devices between the node and the customer drop. Figure 6 and Figure 7 show the spectrum and OFDM power spectrum view after the bad splitter has been removed from the customer's premise. The roll-off on the OFDM channel improved from 20 dB negative tilt to 10 dB negative tilt, and the level at 1 GHz has increased from -8.5 dBmV to 1.6 dBmV.

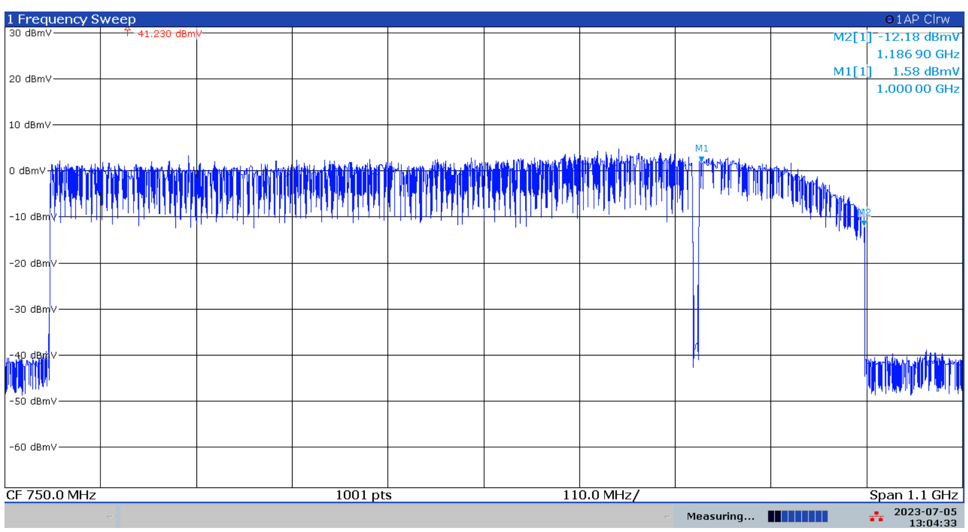

Figure 6 – Example of Customer Drop with Bandwidth Limited Splitter Removed – Spectrum Analyzer View

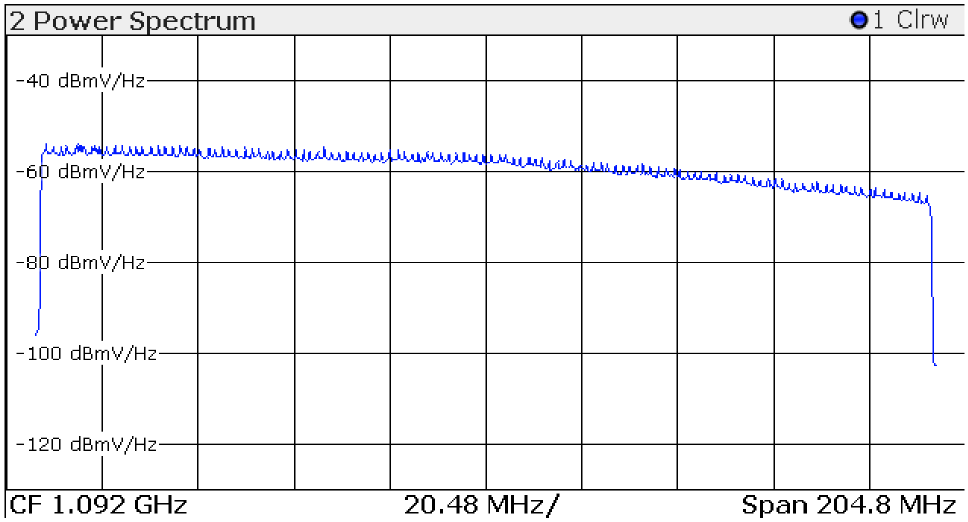

Figure 7 – Example of Customer Drop with Bandwidth Limited Splitter Removed – OFDM Power Spectrum View

6. Spectrum Efficiency

Spectrum Efficiency is a new KPI to give operators insight into how well the spectrum plan designed DOCSIS capacity is utilized by each modem. By combining (aggregating) this metric across multiple modems over time, this metric can highlight chronic plant issues on specific frequencies, groups of modems fed by an amplifier, nodes, or even larger areas (hubs, regions, or even nationally).

6.1. Why is Spectrum Efficiency Valuable?

Spectrum Efficiency provides a complementary measure to congestion. In some cases, poor plant performance can inhibit modems from achieving their capable speeds. This case will never be flagged in a node congestion report because the traffic levels can never reach a point of saturating the node. Spectrum Efficiency on the other hand will highlight such an issue.

Figure 8 shows how poor upstream Spectrum Efficiency on a node is acting as a “soft ceiling” that limits the upstream traffic.

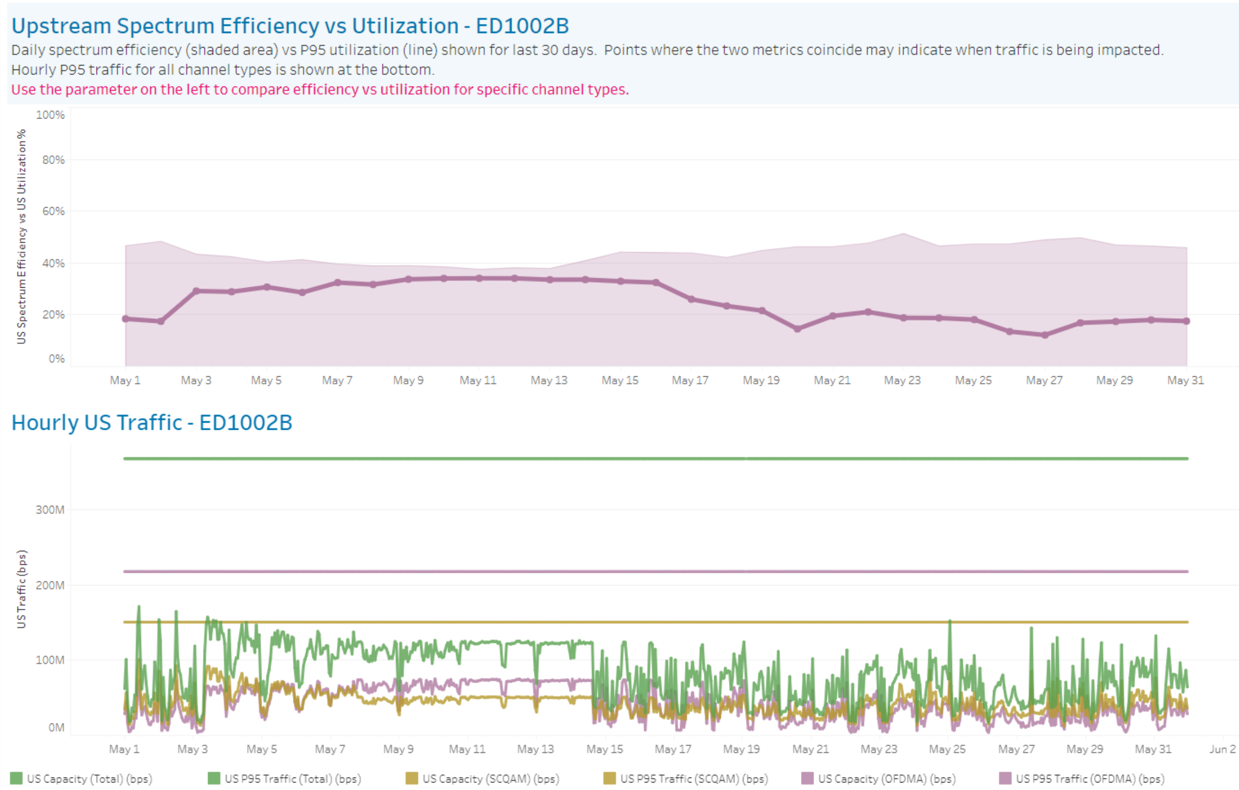

Figure 8 – Poor Upstream Spectrum Efficiency Limiting Upstream Traffic

In the upper half of Figure 8, the purple shaded area shows the daily upstream Spectrum Efficiency of modems using the OFDMA channel. In this example the OFDMA Spectrum Efficiency is close to 50% on average. The thick purple line shows the daily traffic demand as a percentage of engineered channel capacity. When the traffic demand pushes up against the available Spectrum Efficiency, it is being effectively limited from climbing higher. We refer to this condition as “traffic impact.”

The lower half of Figure 8 shows an hourly traffic chart. During the periods of traffic impact, a noticeable plateau occurred which may have the potential to cause a poor customer experience, even though the traffic usage is far from the full capability of the channel.

6.2. Data Collection Methodology

Spectrum Efficiency is measured from the modem perspective. Every four hours, modem statistics are polled from all CMTSs across the country. This anonymized data is stored as structured data in a database that can be queried. Historical data is maintained, as well for trending information.

Table 1 shows the data columns from a single poll of a modem with two OFDM channels.

Table 1 - Spectrum Efficiency Data Fields

polltime	CMid	networkid	chfreq	chwidth
2023-05-21-01-59	00:cb:7a:04:c8:51	CGCHDX7-5	798	192
2023-05-21-01-59	00:cb:7a:04:c8:51	CGCHDX7-5	606	192

chdir	impairment	vblspeed	ofdmSecondProfileCap
DownstreamOFDM	0	1451592704	1448953344
DownstreamOFDM	0	1502616832	1499884800

In the table above, the most important columns are *networkid* (serving group, used to associate the modem with a node), *chfreq* (OFDM channel frequency in MHz), *impairment* (a flag to indicate if the channel is impaired for the current poll), *vblspeed*, and *ofdmSecondProfileCap*.

The *vblspeed* column is from the DOCSIS 3.1 downstream OFDM channel capacity object identifier (OID), docsIf31CmtsDsOfdmProfileStatsFullChannelSpeed. This value considers channel width, exclusion zones, and accounts for variable bit-rate downstream profiles. This is used as the *numerator* of the downstream Spectrum Efficiency calculation. Note that if the *impairment* flag is non-zero (indicating some type of channel impairment), then the numerator is 0 for the current poll.

The *ofdmSecondProfileCap* column is based on the OFDM channel bit rate provided by a designed capacity downstream profile of 1024-QAM, including exclusion zones. This is used as the *denominator* of the downstream Spectrum Efficiency calculation.

Spectrum Efficiency for a particular modem and channel is therefore the ratio:

$$OFDM\ Spectrum\ Efficiency = \frac{vblspeed\ (bits\ per\ second)}{ofdmSecondProfileCap\ (bits\ per\ second)} * 100\%$$

Table 2 summarized OFDM downstream profile numbers and default modulation orders.

Table 2 – OFDM Downstream Profile Design

OFDM DS Profile Number	Default Modulation
0	64-QAM
1	256-QAM
2 (Designed Capacity)	1024-QAM
3	4096-QAM

6.3. Spectrum Efficiency Aggregation

Spectrum Efficiency can be calculated per modem, per node, per channel frequency, and over a specific period (for example every four hours, daily, weekly, or monthly).

To calculate the Spectrum Efficiency for a node over a two-week period we first sum all *numerators* from all modem samples on the node. Then we sum all *denominators*. We finally calculate the ratio of the sums to get the Spectrum Efficiency percentage.

Spectrum Efficiency can also be calculated per OFDM channel individually or across multiple OFDM channels (if dual OFDM channels have been deployed).

6.4. Field Applications/Tool Development

A two-week aggregation of Spectrum Efficiency of all modems on the node was found to be sufficient to bring chronic poorly performing nodes to the top of a list for action.

Figure 9 shows a Tableau dashboard that is used to rank Spectrum Efficiency so that the worst nodes are at the top of the list.

Optical Receiver	Serving Group	Spectrum Efficiency Average (%) (30-Day)	Peak DS Utilization (OFDM) (%) (30-Day)	Modem Total Average	4/15/2023 Spectrum Efficiency (OFDM) (%)	4/30/2023 Spectrum Efficiency (OFDM) (%)	5/15/2023 Spectrum Efficiency (OFDM) (%)	5/31/2023 Spectrum Efficiency (OFDM) (%)
VC993B	VCRIDX11-46	42%	31%	123	40%	40%	40%	44%
GV618A	GVCVDX16-20	47%	8%	21	55%	49%	48%	46%
TB249A	TBTBDX7-46	57%	20%	66	59%	58%	57%	57%
EK535E	EKFNDX4-35	57%	36%	114	98%	64%	57%	58%
WP2383C	WPSCDX19-35	59%	12%	49	61%	60%	60%	58%
SC15A	SCCHDX3-14	59%	18%	81	92%	75%	64%	54%
MJ125A	MJMJDX3-12	61%	29%	54	66%	64%	60%	63%
VA717B	VAAGDX3-5	62%	53%	190	59%	58%	60%	64%
TB610	TBFFDX3-6	63%	29%	30	64%	64%	63%	63%
ED3381A	EDCDDX5-34	65%	37%	104	66%	65%	65%	65%
GV385A	GVDTDX8-7	65%	15%	60	66%	65%	65%	66%
NB52C	NBDCDX3-13	66%	12%	17	66%	68%	67%	66%
CA110	CAMHDX3-11	67%	58%	245	87%	90%	84%	50%
VS147A	VSNEDX11-39	67%	17%	24	59%	66%	68%	67%
FM78B	FMFMDX8-3	68%	50%	156	89%	74%	67%	69%
ED652A	EDBFDX1-93	68%	4%	18	96%	75%	66%	70%
VC378C	VCSTDX15-48	69%	34%	99	67%	67%	68%	69%
VC391B	VCSTDX14-28	69%	20%	90	68%	67%	69%	69%
GV159A	GVMTDX6-55	69%	52%	106	68%	68%	69%	68%
VS1342D	VSWYDX12-45	69%	9%	11	87%	82%	68%	70%
RD3	RDHEDX11-41	69%	53%	150	72%	77%	74%	65%
VC4199B	VCBBDX14-46	69%	29%	50	71%	71%	69%	70%
VC1876A	VCSTDX15-11	69%	42%	163	70%	69%	69%	70%
VC1098A	VCANDX10-16	70%	25%	103	72%	71%	70%	70%
LB148B	LBTBDX2-5	70%	39%	81	74%	72%	71%	69%
GV1872A	GVEQDX6-23	70%	34%	68	74%	73%	71%	70%

Figure 9 - Spectrum Efficiency Tableau Dashboard

A star is shown in Figure 10 to indicate a node is suffering "traffic impact" from poor upstream Spectrum Efficiency. During the past month, if the median daily delta between traffic demand and Spectrum Efficiency is less than 10% then the traffic impact indicator is shown. This node will be chronically experiencing a traffic ceiling.

Incidents are then opened and tracked against traffic impacted nodes for further monitoring.

Traffic Impact Indicator:
(All)
-
☆

Modem Total:
10 1,711

Optical Receiver Search:

Rev. 5f - February 3, 2023

Optical Receiver	Serving Group	Spectrum Efficiency Average (%) (30-Day)	Traffic Impact Indicator	Modem Total Average	Incident Number	4/30/2023 Spectrum Efficiency (%)	5/15/2023 Spectrum Efficiency (%)	5/31/2023 Spectrum Efficiency (%)	6/15/2023 Spectrum Efficiency (%)
NO177	NOBBDX12-1	48%	-	188	-	48%	48%	48%	48%
ED1269A	EDWEDX6-19	49%	-	511	-	86%	58%	43%	55%
RD284C	RDHEDX14-49	50%	☆	997	-	90%	84%	48%	52%
ED1002B	EDCHDX7-44	51%	-	385	INC1240437	58%	42%	49%	53%
ED1398B	EDSHDX6-64	53%	-	773	-	80%	61%	53%	52%
CG543A	CGRUDX5-18	56%	-	199	-	92%	99%	60%	52%
WK80A	WKTRDX1-4	57%	-	1,069	-	90%	89%	67%	46%
ED23A	EDLODX6-48	58%	-	154	-	92%	93%	54%	61%
CG161B	CGDTDX5-48	58%	-	77	-	63%	95%	60%	56%
ED2672A	EDNIDX6-46	58%	-	467	-	83%	76%	57%	59%
LB513A	LBLBDX8-24	60%	-	645	-	90%	94%	59%	60%
WP123D	WPNVDX3-4	61%	-	219	INC1338198	79%	61%	61%	62%
BR8	BRBKDX2-9	62%	-	44	-	99%	86%	58%	66%
RD71	RDHEDX12-56	64%	-	643	-	82%	76%	64%	63%
LS402A	LSWRDX3-2	64%	-	140	-	63%	64%	64%	64%
ED2038A	EDNIDX7-32	64%	-	151	-	96%	90%	67%	61%
WP557B	WPCADX8-30	64%	-	649	-	63%	63%	65%	64%
WP2415C	WPSCDX16-19	65%	-	305	-	64%	62%	65%	65%
SU134A	SUHEDX2-86	67%	-	666	-	65%	67%	67%	67%
CG1013	CGMODX6-6	67%	-	24	-	75%	73%	69%	65%
VSSS11A	VSNWDX10-58	67%	-	725	INC1338169	66%	65%	68%	67%
WP2278B	WPTCDX5-34	68%	-	226	-	66%	67%	67%	68%
ED1869C	EDCHDX7-35	68%	-	476	-	67%	71%	67%	70%
WK240A	WKNLDX4-2	68%	-	481	-	42%	65%	66%	71%
VC815	VCRHDX11-29	69%	-	502	-	85%	77%	69%	69%
SS390A	SSHADX11-33	69%	-	604	-	85%	90%	66%	71%

Figure 10 - Traffic Impact Indicators

6.5. Further Analysis

Spectrum Efficiency can further be used by operators to spot issues in groups of modems that are spatially correlated (fed off a particular amplifier or tap), flag impairments on specific channels (one OFDM channel performing worse than the other) or even highlight intermittent impairments that occur over a span of time.

7. Conclusion

The life cycle of plant development builds a rigorous process that is focused on building a strong customer experience through an upgrade process. The development of proactive maintenance network data has provided this means to operators to improve our upgrade process. Utilizing the collaboration of DOCSIS technology with the RF plant construction brings together a powerful combination of data to improve the service activation process.

Abbreviations

CMTS	cable modem termination system
DAA	distributed access architecture
dB	decibel
dBmV	decibel millivolt
DOCSIS	Data-Over-Cable Service Interface Specifications
FDD	frequency division duplex
GHz	gigahertz
HFC	hybrid fiber/coax
KPI	key performance indicator
NCP	next codeword pointer
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OID	object identifiers
QAM	quadrature amplitude modulation
PLC	physical layer link channel
PNM	proactive network maintenance
RF	radio frequency
RxMER	receive modulation error ratio
SCTE	Society of Cable Telecommunications Engineers