Practical Considerations for Migrating the Network toward All-Digital

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I. Introduction

Analog reclamation has been a hot topic of discussion in the cable industry for several years now. Traditional loading conditions of 79 analog and 53 digital channels is quickly becoming a thing of the past as more and more QAM signals migrate into once occupied analog frequency locations. The inevitable migration towards an all-digital network is validated by the recent announcement that the SCTE is taking over responsibility for the ongoing maintenance and publication of NCTA Recommended Practices for Measurements on Cable Television Systems and that a group of engineers is working on revising the document to add recommended practices for measurements on all-digital networks. Though a seamless transition from traditional loading to a QAM-rich or all-QAM environment is something every cable operator dreams about, the reality is that this process is riddled with logistical complexity, which is why effective planning of all aspects of the transition with minimal customer impact is paramount.

Our goal is to present a QAM migration strategy and implementation approach. From an HFC performance perspective, this session will show the successes and challenges one cable operator has faced as they incrementally transitioned their plant to the QAM-rich environment it has become today. Through this experience, the authors hope to empower other cable operators with the tools that are needed in order to plan for a digital migration strategy that is both operationally effective and scalable, while recognizing that cable operators have important legacy service, capex, and network constraints that must be constantly considered. The presented tools will draw relationships between equipment performance requirements, incremental loading conditions, and system performance. Lastly, multiple tests for non-linearity assessment will be presented. Armed with these tools, cable operators will be in a better position to predict potential issues that require attention long before the new services and HFC multiplexes are deployed. The end result will be a smooth evolution to more and more capacity, ultimately leading to an enhanced mix of new services for the customer. Most importantly, executing a successful digital migration strategy both expands and improves the pipe, such that MSOs are well-positioned for the acceleration of personalized media consumption.

II. Performance Impact Assessment

A. Assumptions

The performance assessments discussed later in this paper will describe distortion behavior at every state of the digital migration. The relevant distortion parameters are the following;

(1) Composite Triple Beat Ratio, CTB
(2) Composite Second Order Ratio, CSO
(3) Third-Order Composite Intermodulation Noise, CIN3
(4) Second-Order Composite Intermodulation Noise, CIN2.

Prior to summarizing the performance impact of a digital migration, assumptions regarding the following key system characteristics must be considered;

(1) Channel Line-Up
(2) CW/Video Ratio
(3) Relative Digital Signal Level
(4) Operational Tilt
(5) Plant Deployment
(6) Migration Process
(7) Gain Control

The performance estimates derived in this paper reflect simulated changes to channel loading conditions, which have been based upon distortion modeling techniques described in [3] et al.

The performance assessments for CTB, CSO, CIN3, and CIN2 are only valid for the assumptions described here. Should the assumptions change, the performance assessments will also change. For example, the performance assessments provided in this paper would not be applicable for 1 GHz systems.

Channel Line-Up

The section describes the assumed traditional cable system channel line-up. 79 analog channels occupy the spectral frequency range of approximately 50 MHz to 550 MHz. 53 digital channels occupy the spectral frequency range of approximately 550 MHz to 870 MHz. All channel bandwidths are 6 MHz, though analog signal bandwidth is 4 MHz and a digital signal bandwidth is 5.360537 MHz for 256-QAM modulation. All center frequencies are based upon the Standard (STD) North American frequency plan per [1], excluding 3 FM band frequencies; 91.25, 97.25, and 103.25 MHz. The downstream spectrum is comprised of 132 channels total within approximately 50 MHz to 870 MHz.

CW/Video Ratio

The average power difference between a continuous-wave signal, CW, and live video is assumed to be approximately 4 dB. This number has been verified by tests which measured the average power of 79 analog CWs versus 79 analog video signals. If the total power of a channel load of 79 CW plus 53 digital channels is compared to the total power of a channel load of 79 analog channels (each with a power that is 4 dB lower than CW) plus 53 digital channels, the total power of the second scenario will be 3.14 dB lower than the first.

Because of this, optical transmitters ideally are configured with -3.14 dB CW/Video offset value. Some vendor equipment may not offer this flexibility, resulting in small variation. As the downstream spectrum is migrated toward digital, it is assumed that this value will be made more negative by the appropriate amounts illustrated in Figure 1. For instance, once the migration is completed, the ideal CW/Video offset would be -3.14-1.3 = -4.44 dB.

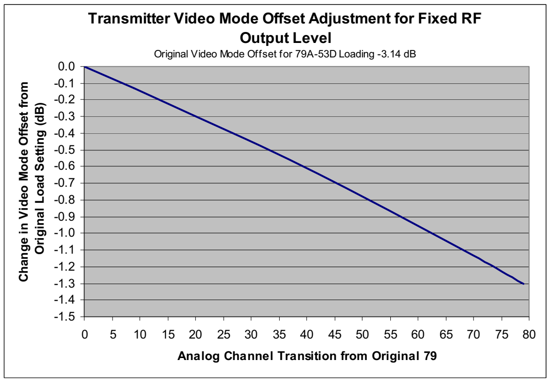

Figure 1 - Migration Video Mode Offset

Relative Digital Signal Level

All 256-QAM signals are assumed to be 6 dB lower than the peak analog signal power. On average, 256-QAM signals are approximately 2 dB lower than their analog video counterparts.

Operational Tilt

Operational tilt is defined as the virtual analog RF power level difference between the highest frequency signal and lowest frequency signal. Operational tilt values will vary based upon equipment and spectrum used. The assumed spectral range for all HFC equipment is the same as what has been assumed in the channel line-up section.

The optical transmitter operating tilt is assumed to be 0 dB. The node optical receiver operating tilt is assumed to be 7.7 dB. The node RF amplifier operating tilt is assumed to be 12.5 dB. The RF amplifier operating tilt is assumed to be 12.5 dB.

Plant Deployment

This section describes the assumed state of the HFC plant. All equipment has been deployed and is currently delivering live video analog and digital signals previously described in the channel line-up section. Representative estimate of performance for the HFC optics and amplifiers is known in terms of worst-case CCN, CTB, CSO, CIN3, and CIN2. Lastly, the only changes to HFC plant will be incremental replacement of analog signals with digital signals as defined in the following section.

Migration Process

This section describes the assumed process of migration. Analog signals will be replaced by 256-QAM digital signals. A contiguous block of the highest frequency analog signals will be replaced with an equivalent number of digital signals. Table 1 summarizes one possible migration process. The current state of the channel line-up, labeled state 0, represents the assumed channel line-up. The next state replaces a contiguous block of 9 analog signals with 9 digital signals. The remaining states replace contiguous blocks of 10 analog signals with 10 digital signals.

Table 1 - Assumed Migration Process

State	Analog Signals	Digital Signals
0	79	53
1	70	62
2	60	72
3	50	82
4	40	92
5	30	102
6	20	112
7	10	122
8	0	132

Gain Control

This section describes gain control assumptions for both the optical transmitter and RF amplifiers. Gain control will maintain RF level stability within the HFC plant as incremental changes, associated with a digital migration, are introduced. Appreciable changes in RF levels are expected to occur with each state of a digital migration.

Optical Transmitter

The gain control of the optical transmitter is assumed to be automated. It is assumed that the operational AGC of the optical transmitter will automatically compensate for loading condition variations, thus maintaining optimum transmitter performance at each state of the digital migration. However, in most cases, the operator would rather maintain constant plant levels than take advantage of a small increase in OMI. Figure 1 illustrates the expected optical transmitter OMI change due to the RF level variations expected with a digital migration. In most cases, it is desirable to take one of the following actions to maintain plant levels:

- Increase the CW/Video offset by the value in Figure 1
- Use a transmitter mode in which the target AGC level can be lowered by the value in Figure 1
- Operate the transmitter in manual mode.

Proper operation of the optical transmitter will be discussed more fully in Section B.

RF Amplifier

The gain control of the first RF amplifier is assumed to be automated. Further, it is assumed that the automated gain control monitors amplitude of a pilot frequency and automatically compensates for any changes in signal level, thus maintaining optimum amplifier performance at each state of the digital migration. Figure 2 illustrates the expected power loading change due to the digital migration.

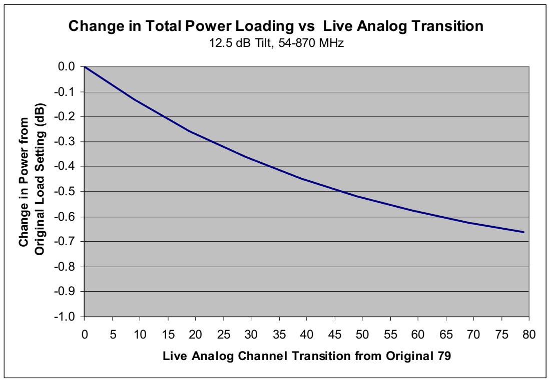

Figure 2 - Migration Total Power Loading

CTB Review

In analog video, CTB appears as horizontal streaks covering one or more lines of video [2]. CTB beats are typically found at carrier frequencies. CTB will degrade by approximately 2 dB for every 1 dB increase in RF level. Cascaded addition of CTB is 20LOG, though typically it measures less.

Consider three analog signals whose center frequencies are A, B, and C in increasing frequency, such that A < B < C. CTB is the accumulation of third order harmonic (3A, 3B, 3C), intermodulation (2A±B, 2A±C, 2B±A, 2B±C, 2C±A, 2C±B) and sum/difference (A±B±C) beats throughout frequency.

Intermodulation beats are approximately 6 dB lower than sum/difference beats. Harmonic beats are approximately 15.5 dB lower than sum/difference beats. As analog signals are removed from a channel line-up so too will CTB beats. For example, reducing our analog signal set A, B, and C to just A, and B will eliminate harmonic (3C), intermodulation (2A±C, 2B±C, 2C±A, 2C±B), and sum/difference beats (A±B±C). Reduction of the number of contributing beats will reduce the level of CTB.

The FCC requires that CTB < -51 dBc. However, CTB < -53 dBc is a more typical end-of-line performance. CTB performance is expected to improve during the course of a digital migration because the number of contributing analog signals will decrease.

CTB Performance

Figure 3 through Figure 5 summarize CTB behavior based upon the assumptions previously discussed. Each curve represents a state within the digital migration process. Each CTB curve is relative to the CTB of the assumed channel line-up. As expected, CTB reduces at each state of the digital migration.

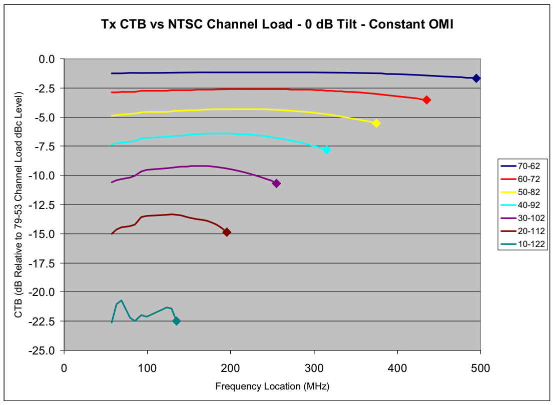

Figure 3 - Optical Transmitter CTB

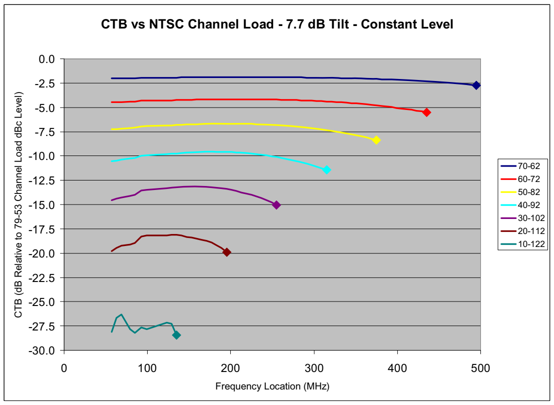

Figure 4 - Optical Node Receiver CTB

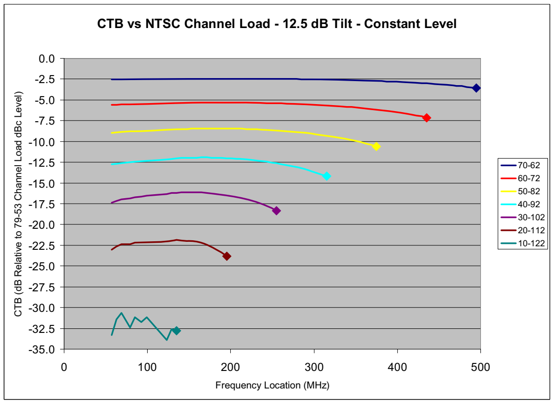

Figure 5 - RF Amplifier CTB

Further, operational tilt appreciably impacts the amount in which CTB improves because there are appreciable differences in the total power associated with each operational tilt scenario.

Consider a RF amplifier whose CTB performance is -74 dBc at state 0, based on the previously discussed assumptions. Reducing the analog signals to 40 will result in a CTB improvement of approximately 12 dB. The expected CTB performance at state 4 is -86 dBc.

CSO Review

In analog video, CSO appears as swimming diagonal stripes [2]. CSO beats are typically found at ±0.75 and ±1.25 MHz around the carrier frequencies. CSO will degrade by approximately 1 dB for every 1 dB increase in RF level. Cascaded addition of CSO is 20LOG, though typically it measures at approximately 15LOG.

Consider two analog signals whose center frequencies are A, and B in increasing frequency, such that A < B. CSO is the accumulation of second order harmonic (2A, 2B), and sum/difference (A±B) beats throughout frequency.

Harmonic beats are approximately 6 dB lower than sum/difference beats. As analog signals are removed from a channel line-up so too will CSO beats. For example, reducing our analog signal set A, and B to just A will eliminate harmonic (2B), and sum/difference beats (A±B). Reduction of the number of contributing beats will reduce the levels of CSO.

The FCC requires that CSO < -51 dBc. However, CSO < -53 dBc is a more typical end-of-line performance. CSO performance is expected to improve during the course of a digital migration because the number of contributing analog signals will decrease.

CSO Performance

Figure 6 through Figure 8 summarize CSO behavior based upon the assumptions previously discussed. Each curve represents a state within the digital migration process. Each CSO curve is relative to the CSO of the assumed channel line-up. As expected, CSO reduces at each state of the digital migration.

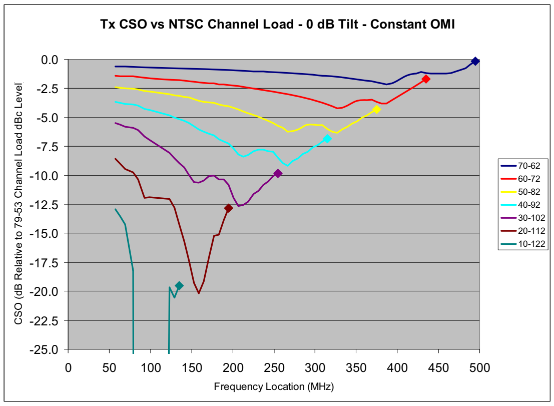

Figure 6 - Optical Transmitter CSO

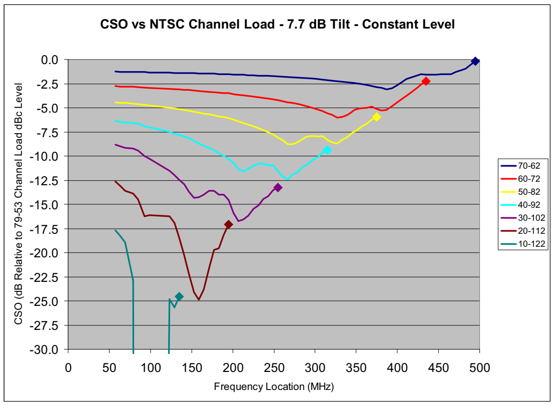

Figure 7 - Optical Node Receiver CSO

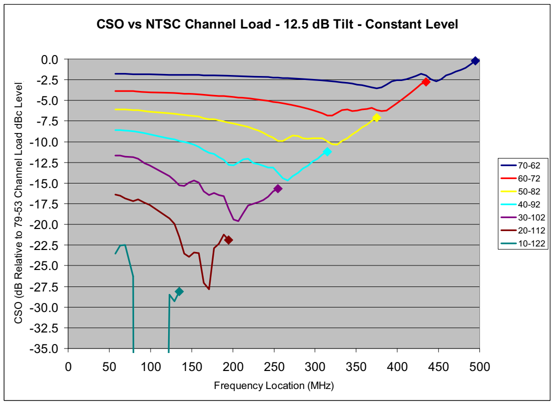

Figure 8 - RF Amplifier CSO

Further, operational tilt appreciably impacts the amount in which CSO improves because there are appreciable differences in the total power associated with each operational tilt scenario.

Consider a RF amplifier whose CSO performance is -74 dBc at state 0, based on the previously discussed assumptions. Reducing the analog signals to 40 will result in a CSO improvement of approximately 9 dB. The expected CSO performance at state 4 is -83 dBc.

CIN3 Review

In analog video, CIN3 appears as snow, much like how C/N degrades analog video. Beats from CIN3 are different from CTB beats in that they are the result of digital signals mixing with other analog and/or digital signals.

Many of the same characteristics of CTB also apply to CIN3. CIN3 will degrade by approximately 2 dB for every 1 dB increase in RF level. Cascaded addition of CIN3 is 20LOG.

The FCC currently does not have requirements regarding the levels of CIN3. However, there are requirements for Carrier-to-Composite Noise Ratio, CCN. Specifically, CCN ≥ 43 dB for a 4 MHz analog signal. Typically, performance is maintained to higher standard of CCN ≥ 48 dB for a 4 MHz analog signal. C/N performance is not expected to change during the digital migration because of the gain control assumptions and resultant RF level stability.

*CIN3 Performan*ce

Figure 9 through Figure 11 summarize CIN3 behavior based upon the assumptions previously discussed. Each curve represents a state within the digital migration process. Each CIN3 curve is relative to the CIN3 of assumed channel line-up. The results show that CIN3 reduces at each state of the digital migration.

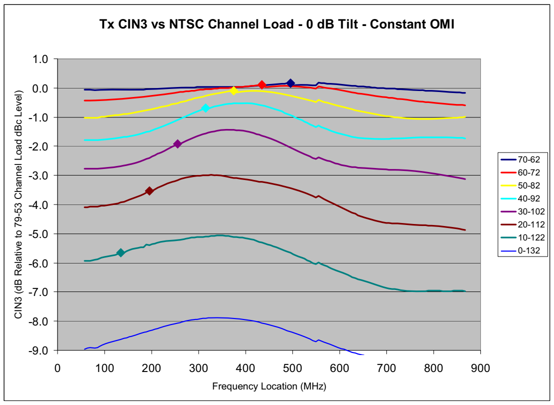

Figure 9 - Optical Transmitter CIN3

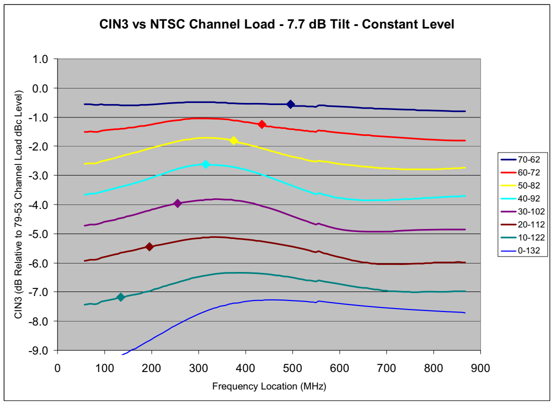

Figure 10 - Optical Node Receiver CIN3

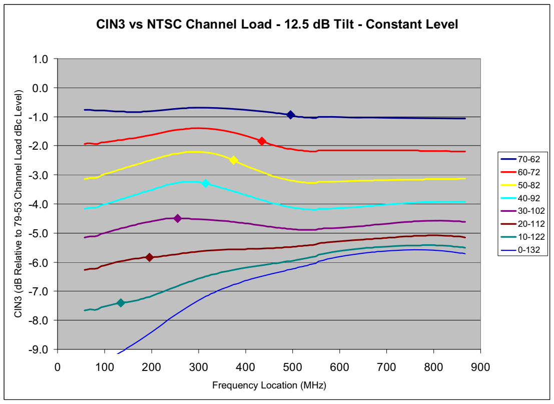

Figure 11 - RF Amplifier CIN3

Further, operational tilt appreciably impacts the amount in which CIN3 improves because there are appreciable differences in the total power associated with each operational tilt scenario.

Consider a RF amplifier whose CIN3 performance estimated to be -82 dBc at state 0, based on the previously discussed assumptions. Reducing the analog signals to 40 will result in a CIN3 improvement of approximately 3 dB. The expected CIN3 performance at state 4 is -85 dBc.

CIN2 Review

In analog video, CIN2 appears as snow, much like how C/N degrades analog video. Beats from CIN2 are different from CSO beats in that they are the result of digital signals mixing with other analog and/or digital signals.

Many of the same characteristics of CSO also apply to CIN2. CIN2 will degrade by approximately 1 dB for every 1 dB increase in RF level. Cascaded addition of CIN2 is 20LOG theoretically.

The FCC currently does not have requirements regarding the levels of CIN2. However, there are requirements for Carrier-to-Composite Noise Ratio, CCN. Specifically, CCN ≥

43 dB for a 4 MHz analog signal. Typically, performance is maintained to higher standard of CCN ≥ 48 dB for a 4 MHz analog signal. C/N performance is not expected to change during the digital migration because of the gain control assumptions and resultant RF level stability.

CIN2 Performance

Figure 12 through Figure 14 summarize CIN2 behavior based upon the assumptions previously discussed. Each curve represents a state within the digital migration process. Each CIN2 curve is relative to the CIN2 of the assumed channel line-up. The results show that CIN2 increases during the first 3 or 4 states, depending upon operational tilt, and then reduces from state 3 or 4 through state 8, again depending on operational tilt.

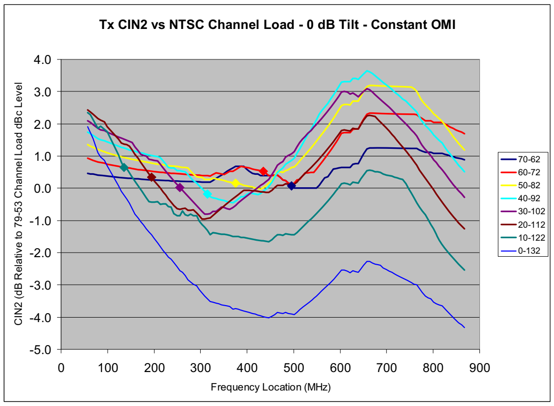

Figure 12 - Optical Transmitter CIN2

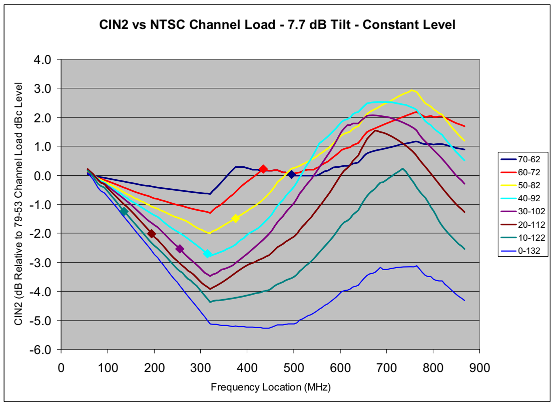

Figure 13 - Optical Node Receiver CIN2

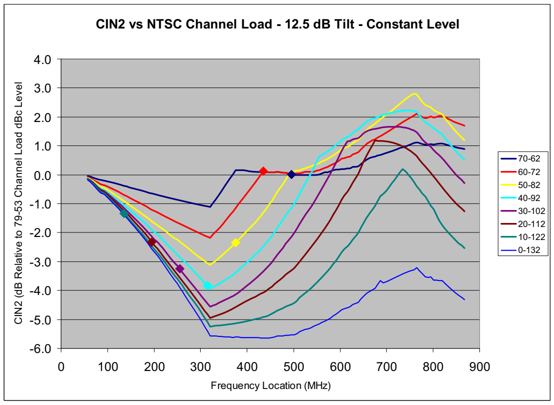

Figure 14 - RF Amplifier CIN2

Consider a RF amplifier whose CIN2 performance estimated to be -89 dBc at state 0, based on the previously discussed assumptions. Reducing the analog signals to 40 will result in a CIN2 degradation of approximately 2 dB. The expected CIN2 performance at state 4 is -87 dBc.

III. Application of Modeled Performance

A. Step-by-Step Analysis

This section describes a step-by-step analysis and implementation process where the data presented in the previous sections may be applied to a specific digital migration. Before proceeding with any analysis, ensure that all of the assumptions have been reviewed and are aligned with the digital migration to be analyzed. Any misalignment of assumptions would likely require revision of the estimates provided for CTB, CSO, CIN3, and CIN2.

Step 1

Define each state of the analog-to-digital migration in terms of number of analog signals, number of digital signals, and minimum acceptable performance.

Table 2 is an example of a proposed migration process for evaluation. Additionally, CCN $\geq$ 47 dB, CTB $\leq$ - 53 dBc, and CSO $\leq$ -53 dBc is the minimum acceptable performance criteria.

Table 2 - Proposed Migration Process

State	Analog Signals	Digital Signals
0	79	53
1	60	72
2	40	92
3	20	112
4	10	122

Step 2

Using the distortion information from the previous sections, identify impairment impact for CTB, CSO, and CCN for the optical and RF components and combination thereof.

The cascade under analysis is comprised of an optical link, followed by an N+6 RF amplifier cascade. The RF cascade is comprised of 1 Node, 2 AMP1s, 1 AMP2, and 3 AMP3s. Table 3 summarizes the performance and operational tilt of each device. AMP1, AMP2, and AMP3 represent different amplifier types.

Table 3 - HFC Equipment Performance and Operational Tilt

	TX	RX	Node	AMP1	AMP2	AMP3
CCN	53.7	52.0	72.0	57.2	56.2	71.2
CTB	-70.0	-71.0	-82.5	-75.0	-75.0	-74.0
CSO	-66.0	-65.0	-71.8	-71.0	-71.0	-74.0
CIN3	-88.0	-89.0	-100.5	-87.0	-93.0	-82.5
CIN2	-88.0	-87.0	-93.8	-87.0	-93.0	-86.5
OP TILT	0.0	7.7	12.5	12.5	12.5	12.5

Table 4 summarizes the data from the previous section in terms of relative distortion improvement based upon the proposed migration process of Table 2. For example, the optical transmitter's CTB performance is expected to improve by approximately 21 dB in state 4.

Table 4 - Migration Distortion Impact

State	OP TILT	CTB	CSO	CIN3	CIN2
0	0	0.0	0.0	0.0	0.0
1		-2.6	-1.4	0.1	2.3
2		-6.4	-3.7	-0.5	3.7
3		-13.3	-8.6	-3.0	2.4
4		-20.7	-12.9	-5.1	2.4
0	7.7	0.0	0.0	0.0	0.0
1		-4.2	-2.2	-1.0	2.2
2		-9.6	-6.4	-2.6	2.5
3		-18.1	-12.7	-5.1	1.6
4		-26.3	-17.7	-6.3	0.2
0	12.5	0.0	0.0	0.0	0.0
1		-5.3	-2.8	-1.4	2.1
2		-11.9	-8.6	-3.2	2.2
3		-21.9	-16.4	-5.1	1.2
4		-30.6	-22.5	-5.4	0.2

The values identified in Table 4 are used to adjust the individual device performance defined in Table 3. Degradation due to multiple like-amplifiers is also included in the end-of-line, EOL, performance. The cascade results of Table 5, illustrate performance improvement across all metrics and across all states of the migration.

Table 5 - Cascaded EOL Performance

	State	CTB	CSO	CIN3	CIN2	CCN	C/N
EOL	0	-54.9	-54.9	-67.5	-72.1	47.6	47.7
	1	-59.5	-57.3	-68.7	-70.0	47.6	47.7
	2	-65.2	-61.8	-70.4	-69.5	47.6	47.7
	3	-74.0	-68.3	-72.4	-69.9	47.7	47.7
	4	-82.1	-73.4	-73.0	-69.9	47.7	47.7

Step 3

If states have been identified with expected performance worse than minimum acceptable performance, then consider revising the proposed migration process of step 1, and repeat step 2.

For the example provided, the cascaded EOL performance improved across all metrics and across all states of the migration. The next sections will discuss classical and proposed measurement techniques that may be used to verify migration implementation performance is within planned estimates.

B. Implementation

Performing the Migration

Preparing for the Migration

When deciding which channels to migrate from analog to digital, the planners should consider some important operational considerations. Starting from the highest analog channel, and working down might make sense in many respects, but it's important to leave at least one and possibly two or three analog channels remain active on the plant. The most important channel to consider leaving on is the RF AGC pilot channel. The advantages of leaving that channel unaltered are discussed in the section on preparing the RF plant below. The second channel to leave on is a low frequency channel that can be used as a reference point for measuring signal levels at the laser, at the node receiver, and in the plant. This low frequency channel, along with the higher frequency pilot channel can be used to measure plant levels and tilts. The third channel to consider leaving on is one in the aeronautical band. If all channels are migrated to digital, it will be nearly impossible to measure plant leakage at practical levels. If leakage cannot be measured and corrected, ingress will increase. The subject of measuring leakage from an all-digital system is being presented at an SCTE Cable-Tec workshop in October, 2009 [5]. The basic conclusion of that paper is that the best way to make sure a plant is not leaking is to use an analog channel or CW carrier.

Other reasons to seriously consider leaving at least one low and one high frequency analog channel intact are:

- Low and high channels can be used as a reference point for adjusting levels of other channels as they are converted.
- Analog channels can be used to measure impairments.
    - Some impairments, such as hum, will ultimately impact QAM channels, but are not easily detectable on QAM channels until it's too late.
    - Techs are very good a diagnosing plant problems by looking at analog test patterns on a TV.
    - It's very hard to figure out why QAM is not working without having an analog channel to look at.

During the migration, it will be very beneficial to have a mid-frequency analog channel in addition to the low and high frequency analog channels. This will facilitate measurements of analog impairments such as CTB, CSO and CCN at several frequencies during each step of the migration.

Preparing the Headend and Optical Transmitters

Most optical transmitters have an AGC circuit that responds to the total average RF power. These AGC circuits have some type of CW / Video offset or adjustment parameter to compensate for the fact that the average power of an analog modulated channel is lower than the average power of a CW carrier. Consider the following generally accepted assumptions:

- The "level" of an AM video signal is measured during the sync tip. During the sync tip, the channel has the same power as CW.
- An RF carrier modulated with AM video has an average power that is about 3-8 dB less than a CW carrier. The amount of power reduction depends on video content.

- A large number of RF carriers modulated with AM video have, on average, about 3-4 dB less power than CW.
- 256-QAM is generally run 5 to 6 dB below analog sync tip level.
- The average power of 256-QAM channels is 1-2 dB lower than the average power of AM video channels.

When performing a migration, one must be careful to either disable the AGC and operate in manual mode or properly adjust the target level for the AGC to compensate for the change in total power. As the digital migration proceeds and analog channels are replaced by digital, the average power of each digital channel will be 1-2 dB lower than the analog channels. If a large number of analog channels are eventually replaced, this will result in a 1-2 dB <u>increase</u> in laser levels unless preventative steps are taken. Since many of the lasers involved in migrations are older lasers, operating them at excessively high OMIs could cause objectionable distortion performance.

The best way to maintain proper laser OMI is to monitor the laser drive RF test point on transmitters that have such a test point. This test point is after the laser RF AGC circuit and monitors the actual RF drive to the laser. The technician should select a channel that will remain untouched during the migration and monitor its level. As the channels are migrated, the level of that test channel should be held constant. This can be accomplished by either using the transmitter's manual mode or by adjusting the target level of the transmitter's AGC circuit. On GI/Motorola product the mode to use to change the AGC target level is called the "Set" mode.

If the transmitter does not have an RF test point to monitor levels after the AGC circuit, the technician has two options. One is to test the effect of the migration on a sample transmitter; the other is to rely on calculations. To test a sample transmitter, monitor the levels of unchanged channels at an actual node or at an optical receiver that's connected to a representative transmitter in the Headend. Determine how much the transmitter's AGC should be changed when the migration occurs, such that the level of the test channels at the optical receiver or node output do not change. If calculations are to be used, refer to Figure 1 for the proper offset.

The goal here is to make sure that the power per channel of non migrated channels does not change during the migration. This is important to making sure that the laser does not get over-driven.

Preparing the RF Plant

The RF plant is assumed to either be operating in manual mode (for very short cascades) or to be using an AGC circuit that is based on maintaining the level of a pilot channel. During the migration, it is assumed that the operator wishes to maintain the plant levels without change. There are two options for accomplishing this. The operator can either make certain that the channel being monitored by the AGC circuits in the RF amplifiers is not affected by the migration, or the operator can change the AGC drive unit in the RF amplifier to a type that's designed to work on a digital channel.

Maintaining current operation using an analog channel is technically very straightforward -- you simply keep the pilot channel unchanged. However, this solution is not programmatically simple, as the marketing and planning departments are likely to desire that the pilot channel be one of the first to be converted to digital, since it's generally operating in the 400-550 MHz region. If the engineering department can keep that one channel as an analog channel, the migration is greatly simplified.

If the operator wishes to convert the pilot channel to digital, the AGC drive unit must be switched out for a digital unit. Here are some suggested steps to follow:

- Determine a method to measure amplifier output levels.
    - Send a tech to the amps and measure levels.
    - Measure received levels at set tops and cable modems.
- Add the new QAM signal to the channel plan. You <u>cannot</u> use the same frequency that is currently being used as the analog pilot. It is necessary to use different channels by adding the QAM signal first to allow a controlled migration.
- Install a QAM-based AGC module in each amplifier in the cascade and readjust output levels.
    - Caution: There are compatibility concerns between older amplifier stations and the new QAM-based AGC circuits. Be sure to consult with your manufacturer to be sure that the QAM-based circuits will work in your amplifiers.
- The analog channel may now be removed.

Classical Measurements

The best source for information on making measurements on live plant is the NCTA Recommended Practices for Measurements on Cable Television Systems [4]. This document has been the standard for making measurement since the first version, produced in 1983. In 1993, the document was revised to synchronize the procedures with the FCC requirements in part 76. Since then, the FCC references the Recommended Practices as <u>the</u> standard for demonstrating compliance with FCC requirements.

The Recommended Practices contains procedures for measuring all the analog parameters discussed in this paper, including signal level, carrier-to-noise, CTB and CSO distortion, and frequency response. In addition, the Recommended Practices contains procedures for verifying the quality of digital signals, including signal power, BER and MER.

As discussed previously, we suggest dedicating test channels at low, mid, and high center frequency locations. Analog or CW signals should be used for aligning plant RF levels and verifying CTB, CSO, and CCN performance. Digital signals can be measured for MER and BER performance. To take these measurements, test sites need to be identified such that they are representative of the entire HFC plant affected by the migration.

Digital Demodulation Measurements

As analog channels are replaced with digital channels and few analog channels remain, it will be necessary to perform proof of performance tests on digital channels. The NCTA Recommended Practices contains several procedures for making measurements on digital channels. The more obvious and common ones are signal power, MER and BER. Other procedures in the Practices are peak to average ratio, digital in-channel flatness, reflections, and Error Vector Magnitude (EVM).

To measure the performance of digital channels in the network, we suggest dedicating test channels at low, mid, and high center frequency locations. Select frequencies most impacted by distortion -- low and high frequencies for CSO and CIN2 and mid frequencies for CTB and CIN3. Also measure MER on each channel tested. In addition, qualitative measurements like constellation diagram analysis may help to identify impairment sources such as noise, RF interference (including CTB and CSO interference), reflections, phase noise and amplitude distortion due to gain compression. All these impairments are explained and illustrated in section 11.1 of the NCTA Recommended Practices.

Once all analog channels are removed, it will be necessary to perform all proof of performance measurements on digital channels. The DOCSIS 3.0 Physical Layer Specification [6] and ANSI/SCTE 40 2004 [7] both specify the minimum performance required from the HFC network to assure proper operation of DOCSIS and digital video signals, respectively. Additionally, SCTE 40 is referenced in the FCC rules in CFR 47 §76.640b1i. In May, the SCTE announced that it is taking over the ongoing maintenance and publication of NCTA Recommended Practices for Measurements on Cable Television Systems [8]. Per the press release, the SCTE is “undertaking the vital task of updating the publication to cover current technology.” Part of that effort includes the creation of measurement procedures that can be used to demonstrate compliance with SCTE 40. When that effort is completed, MSOs will have a single source of information to assist in verifying the performance of all-digital networks.

Proposed Measurements

Diagnosing distortion based issues using classical measurements likely requires a team of technicians to be at multiple locations within the HFC plant simultaneously to inject test signals at the Headend location and assess performance at representative set of EOL locations. The problem with this diagnostic processes is that they are at risk of being time consuming and costly.

This section provides high-level descriptions for multiple test cases. Some test cases will use remote-controlled equipment operated via network connection. Others will leverage the DOCSIS terminal devices, by querying their MIBs via protocols such as SNMP.

An automated process, which leverages information distributed throughout the DOCSIS terminal device population, could not only reveal the nature of channel impairment, but also its location. One example would be employing a plurality of cable modems to identify sources of nonlinear impairments, such as an improperly configured amplifier resulting in higher than expected distortion performance, common to some cable modems but not all.

Peak-to-Average Noise Power Measurements

This test could be performed by connecting a Vector Signal Analyzer, VSA, at suspected locations. Remote control of this instrument would require network access, possibly via an installed cable modem.

In a distortion-dominated test channel, the Peak-to-Average Noise Power Measurements in test channel will result in Peak-to-Average CCDF that is different than what is typically expected in an AWGN CCDF. CCDF stands for Complementary Cumulative Density Function and is a plot of the statistical distribution of multiple noise-floor measurements. The VSA would be configured to measure the noise-floor of a vacated downstream test channel in a format that produces statistically significant CCDF curves for comparison with AWGN CCDF.

Signal Power Reduction Measurements

This test could be performed by leveraging one or many resident DOCSIS terminal devices within a suspected segment of HFC. Additionally, this test could be performed during a maintenance window, minimizing impact to subscribers.

The proposed test lowers the power of a DOCSIS test signal by 1 dB, while monitoring the effect on the signal's Modulation Error Ratio, MER, and Forward Error Correction, FEC, statistics in what may appear to be a noise-dominated channel. If the performance degradation is worse than theoretical expectations of a noise-dominant environment, then one could deduce that the test channel is operating in a distortion or interference-dominated channel.

Distortion Interleaver Tests

This test could be performed by leveraging one or many resident DOCSIS terminal devices within a suspected segment of HFC. Additionally, this test could be performed during a maintenance window, minimizing impact to subscribers.

The proposed test introduces changes in the DOCSIS variable-depth interleaver burst protection that would result in changes in MER, and FEC statistics. DOCSIS 2.0 supports 5 interleaver settings ranging in burst protection of 5.9 – 95 usec for 64-QAM, whereas DOCSIS 3.0 supports 13 interleaver settings ranging in burst protection of 5.9 – 759 usec. This proposed test would adjust burst protection in a systematic manner for a DOCSIS test channel, while noting changes in MER, and FEC statistics. This test may be able to discern between narrowband vs. wideband interferers, given threshold knowledge of interference burst periods.

IV. Comcast – Washington Region Case Study

A. Background

The Comcast, Washington Region system covers approximately 22,000 miles of plant and is comprised of a mixture of 750 MHz, 870 MHz and 1 GHz systems. Approximately four years prior to their current digital migration program, the Washington Region had migrated the majority of its 64-QAM signals to 256-QAM signals.

Many of the valuable lessons learned from prior experience has positioned the Washington Region well with respect to its current efforts to migrate the analog B2 tier to 256-QAM. The B2 tier is the frequency band between 265 MHz to 553 MHz. Blocks of 20 analog channels will be converted at a time. Once analog signals have been removed, 256-QAM signals are deployed on the vacated 6 MHz slots. The motivation behind these changes is to regain bandwidth in order to support delivery of enhanced digital services including high definition, HD, and video-on-demand, VOD.

Prior to the conversion of analog signals, a program was instituted to provide all participating customers with Set Top Boxes (STB) and Digital Transport Adapters (DTA). The DTA is a digital to analog converter that converts selected digital signal to an analog signal.

The experiences of the Washington Region team has been documented here as a case study for digital migration implementation. It is hoped that this information will aid development of future migration plans.

B. Migration Challenges

The previous sections have demonstrated that replacing analog signals with 256-QAM signals does not present new challenges relating to system performance. This too has been reinforced by the accomplishments of the Comcast Washington Region. The real challenge of digital migration is more operational in nature. The following are just of few operational considerations that will require effective management to control costs and keep the digital migration process on schedule.

Facilities

Headend combining network will require re-lashing for new channel lineup. Rack space and powering requirements will increase due to addition of required equipment, including VOD components.

The number of ad zones will increase due to the increases in narrowcast and broadcast digital channels, assuming narrowcast/broadcast architecture resulting in implications for proportional increments of PEG channels and narrowcast laser transmitter performance improvements. Relocation of traditional broadcast PEG channels into the narrowcast combining network must also be considered.

Personnel

Changes must be expected in personnel and warehouse space requirements in order to manage and support DTA and STB deployment programs. Standard operating procedures for billing and customer care system (phone, software, network) will require revisions in support of changing subscriber services.

Technician training, which would ideally occur several months prior to migration, will be required to effectively resolve issues relating to advanced equipment and services deployment. Focus areas within the subscriber community will include residential, MDUs, commercial properties, schools and federal buildings to ensure support of advanced equipment and digital signaling.

Customer care personnel, business units and technicians will likely require different strategies for fulfilling their responsibilities for these different sectors. For example, effective explanations to educate customers why new equipment needs to be installed will need to be socialized across all customer-facing personnel. Effective marketing using communications mediums including mailings, email, auto-dialers, website, and blogsites will be required to keep subscribers apprised of upcoming changes to their existing services and equipment.

C. Migration Considerations

Many considerations were made throughout the course of implementing the two 256-QAM migration plans in the Comcast Washington Region over the past several years. Those considerations have been captured here to benefit future migration plans of other cable operators.

Migration processes are primarily driven by; (1) business units, (2) engineering, and (3) operational decisions which minimize customer impact, total cost, and scheduling delays.

The HFC network must be fortified if a self install DTA program is to be successfully leveraged, because these devices may not be installed correctly by the customers. Potential exists for aggravating existing weaknesses in the HFC network including tap level issues and drop design. This is especially true when the DTAs are more likely to be installed in the spare room at the end of the largest split loss, where the spare TV used to be.

The typical snow effect of analog signals has been replaced by the block tiling of digital signals, which may generate additional trouble calls from customers who are less tolerable with block tiling of picture quality.

Though digital channel placement may be restricted because vacated analog slots are quickly replaced with QAM channels, other operators should take advantage of any freedom to place high value content in spectrum that would be relatively free from off air interference.

It may be useful to understand the impact of eliminating analog channels, and adding digital channels simultaneously using metrics such as CTB, CSO, CIN, and CCN before a migration. However, the MER of digital signals is more likely to be used for performance testing during the migration, with the danger being that MER provides only a limited perspective as to what may be impairing a channel.

Know the make, model, installation date, and serviceable life of the system components in the HFC network, including; transmitters, fiber nodes, amplifiers, and taps to ensure uninterrupted migration progress.

Maintain level stability throughout the HFC plant. Optical architecture requires close monitoring and re-alignment of RF input levels to achieve optimum performance based on changing loading conditions. Also, verify that gain control mechanisms within RF amplifiers are functioning properly.

Rigorous plant maintenance practices, including (1) optical connector maintenance, (2) fiber management practices and (3) leakage control programs are crucial for successful delivery of more advanced digital signals.

Incompatible equipment and/or wiring in the customer homes will be an issue. For example, truck rolls will be required to replace filters or 500 MHz splitters that prevent customers from receiving QAM channels using the DTAs.

Invest the time to properly survey the existing physical topology, including RF combining, ad insertion, and narrowcast/broadcast distribution. Plan appropriately the required changes for each state of the digital migration process.

V. Conclusion

Multiple aspects of 256-QAM migration have been presented in this paper covering relevant performance behavior and system analysis. Generally speaking, replacing higher energy analog signals with lower energy digital signals will result improved system performance.

Though the system performance picture is looking better, there is still much to address with implementation tests that will ensure that the digital migration performance and ongoing maintenance is within planned expectations. Many test programs are currently available, but will soon require revision as the downstream spectrum becomes all-digital.

Valuable perspective from those who have executed digital migration programs has also been included. Managing the operational complexities has been identified as the greatest resource-consuming aspect of a successful digital migration. Additionally, many lessons-learned have been presented to help with future migration plans.

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