The Full Duplex DOCSIS Amplifier – Why, How, and When

A Technical Paper prepared for SCTE by

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1. Introduction

The advent of Full Duplex DOCSIS® (FDX) technology is here as realized in a custom ASIC successfully implemented in an operational FDX R-PHY node reference design. This ASIC is also currently being ported to a node design for trial deployments in Node + 0 networks. A version of this ASIC is also being adapted for a prototype FDX amplifier utilizing the same echo cancellation technology employed in the node.

The original constraint in the DOCSIS 4.0 FDX specification anticipated deployments exclusively in a passive Node + 0 network without amplifiers. The initial evaluation in a demonstration of the implemented prototype FDX R-PHY node incorporating the first FDX RPD ASIC exceeded performance expectations [2]. The resultant performance of the echo cancellation technology suggests use in an FDX amplifier as a "repeater" of bidirectional FDX signals.

This paper considers this implementation for an FDX amplifier. Why this greatly expands the use of FDX technology in conventional Node + X amplifier networks is introduced. How the FDX amplifier is implemented and the resulting performance greatly increasing upstream capacity is analyzed. The performance of cascading FDX amplifiers is shown. Finally, the path to upgrading existing Node + X cable networks when the next generation FDX amplifier ASIC currently under development becomes available is discussed.

2. Origins of FDX DOCSIS

CableLabs launched a project to examine the potential of full duplex simultaneous upstream and downstream transmission and reception within the same cable system spectrum. The DOCSIS 3.1 specification provided the Physical Layer (PHY) transmission and reception based on OFDM/OFDMA as shown in Figure 1.

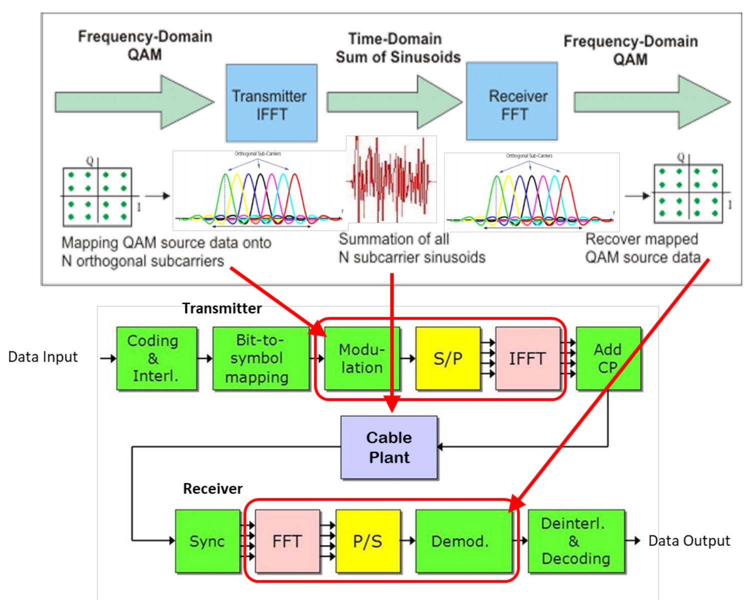


Figure 1 - DOCSIS 3.1 OFDM Transmission and Reception

The difference was the sharing of overlapping spectrum for simultaneous bidirectional transmission and reception. The addition of this spectrum sharing methodology was initially developed as an appendix to the existing 3.1 spec.

Eventually the addition was separated into a new DOCSIS 4.0 spec. The FDX node transmits downstream and receives upstream at the same time in the same bandwidth. FDX transmissions from node to modem and modem to node are overlapped both in time and frequency where new interference cancellation technology in the node allows this simultaneous bidirectional communication.

However, the simultaneous bidirectional communication between the node and the cable modems was limited to a passive coax plant without amplifiers due to the lack of diplex filters to separate upstream from downstream transmission. This is known as a Node + 0 plant where the node is connected to a passive cascade of taps and cable without additional amplifiers as shown in Figure 2.

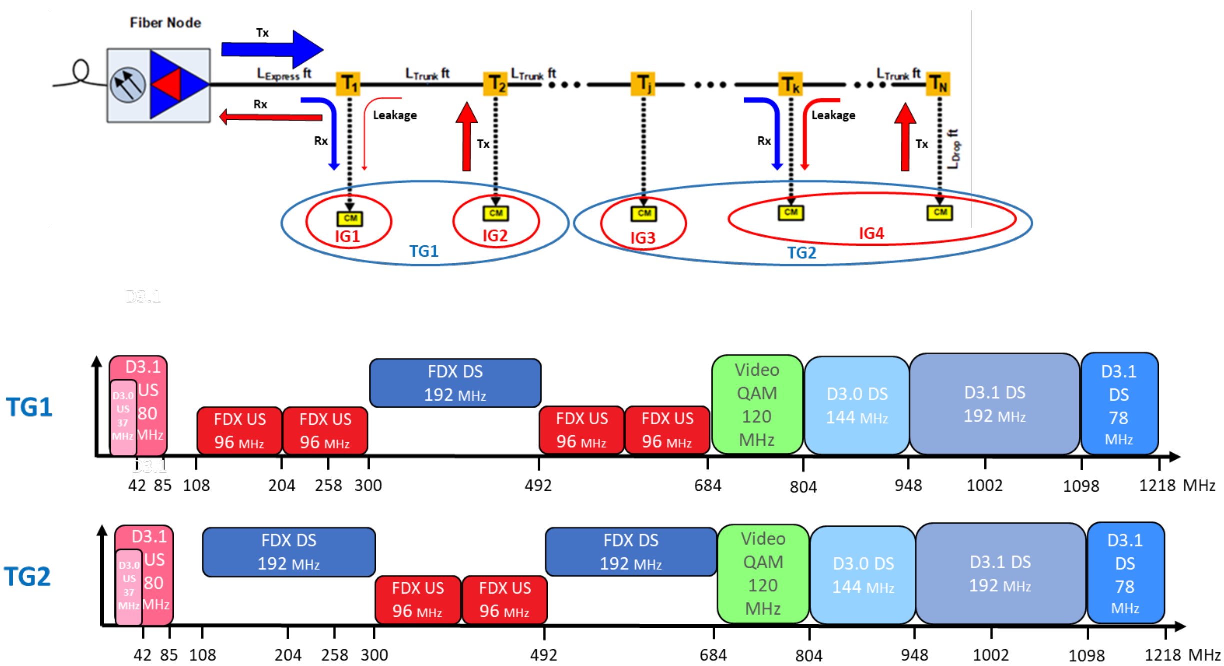


Figure 2 - Node + 0 passive cable system

Simultaneous true full duplex transmission and reception within the same frequency band only occurs at the node. Each cable modem utilizes Frequency Division Duplex (FDD) in a dynamic fashion across multiple channels within the full-duplex band. This is necessary to prevent upstream transmission of one cable modem in each channel from corrupting downstream reception of another cable modem in that same channel. Unlike the node where the transmitter and receiver are co-located, upstream transmitting modem and downstream receiving modem are located on a different tap or groups of taps with sufficient isolation from tap port-to-output leakage between them known as an Interference Group (IG) as depicted in Figure 2. Thus, the downstream receiving cable modem has no reference for the upstream transmitting cable modem signal making cancellation within the same frequency band impossible as discussed in [1].

The high-level node downstream signal is transmitted into the cable system of Figure 2 where that signal propagates down the cable transmission lines and encounters multiple taps with impedance mismatched to the coax transmission line by the tap return loss. A reduced amplitude reflection from each tap results as shown in Figure 3 using the model simulation approach derived in [1].

The node upstream received, downstream transmitted and cable system downstream reflected interference is shown on the right. All these signals combined from each TG occupy the same frequencies in the cable spectrum simultaneously as shown below.

Note in the upper right chart that the echo is well below the node transmission but is significantly higher (around 20 dB) than the low-level upstream received signal from the modems resulting in a negative upstream signal to downstream echo SNR.

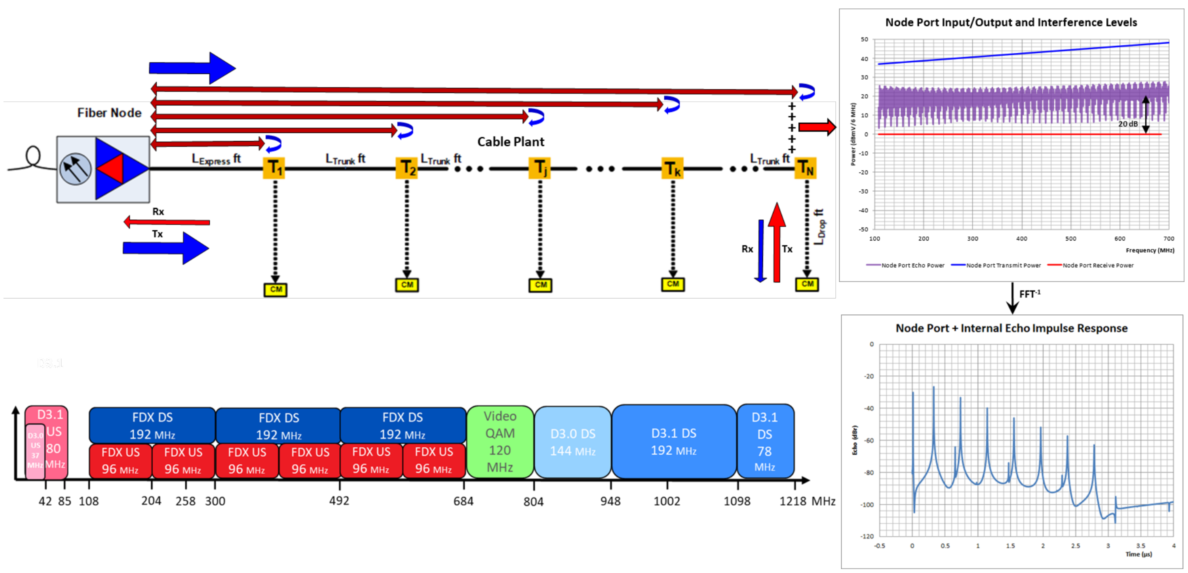


Figure 3 - FDX node operation with echo path interference

The node separates the received modem upstream signals from the transmitted downstream node signal using a directional coupler plus Echo Cancellation (EC) digital signal processing. The function of the FDX node is shown in Figure 4.

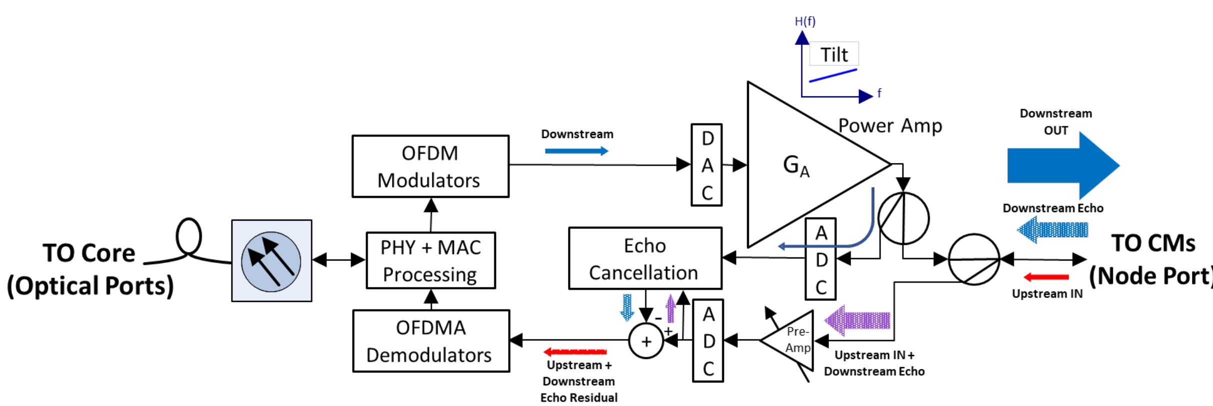


Figure 4 - FDX node with echo cancellation signal processing

A sample of the downstream signal is used as a reference for the EC of the reflected downstream signal. The upstream signal is filtered by an adaptive filter using the downstream reference to remove the echo in the same band. The filtering has a finite depth of EC which is a residual that is now lower than the upstream received signal as shown in Figure 5 resulting in a positive upstream signal to downstream echo residual SNR.

The first prototype FDX Node + 0 system with echo amplitudes producing a negative SNR with respect to the upstream received signal realized an EC depth resulting in a 35 dB SNR in a high downstream launch power Node + 0 cable system design. This demonstrated the power of the EC implemented in the first Broadcom FDX RPD IC as sufficient to consider embedding the same EC technology into an FDX amplifier IC.

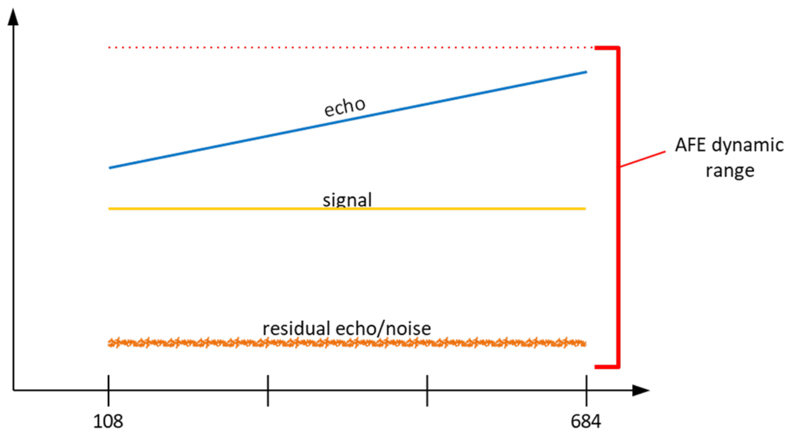


Figure 5 - Upstream Front End Dynamic Range and Residual Downstream Echo/Noise Floor

3. Beyond Node + 0: The FDX Amplifier

A traditional cable system with amplifiers is depicted in Figure 6.

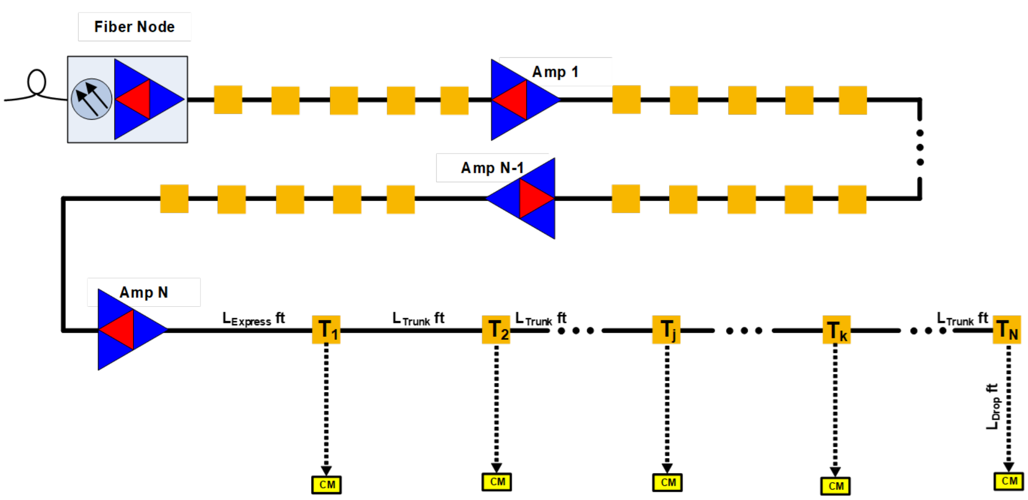


Figure 6 - Node + N amplifier cable system

Upgrading the cable system to FDX by replacing the traditional node with an FDX node and replacing the traditional amplifiers with FDX amplifiers is depicted in Figure 7. Note that the taps are unchanged and the amplifier spacing is maintained.

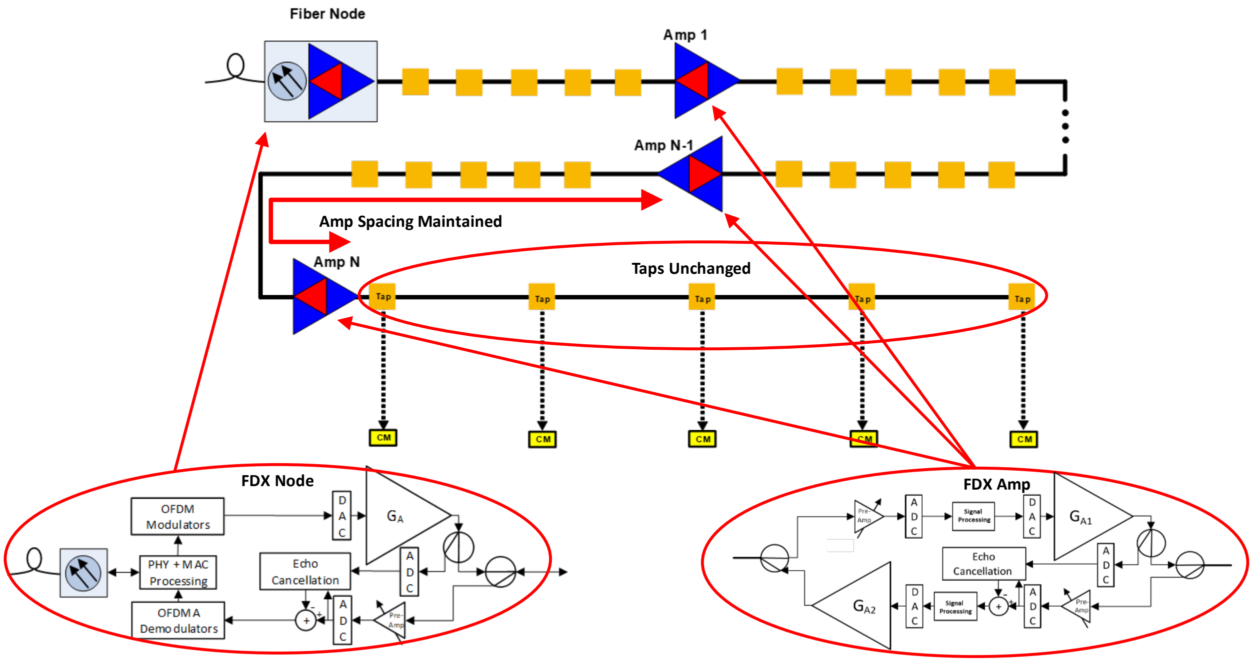


Figure 7 - Node + N amplifier cable system upgrade to support FDX

A similar echo environment found in an FDX node exists for an FDX amplifier. The echo interference paths for an FDX amplifier in a cascade is pictured in Figure 8.

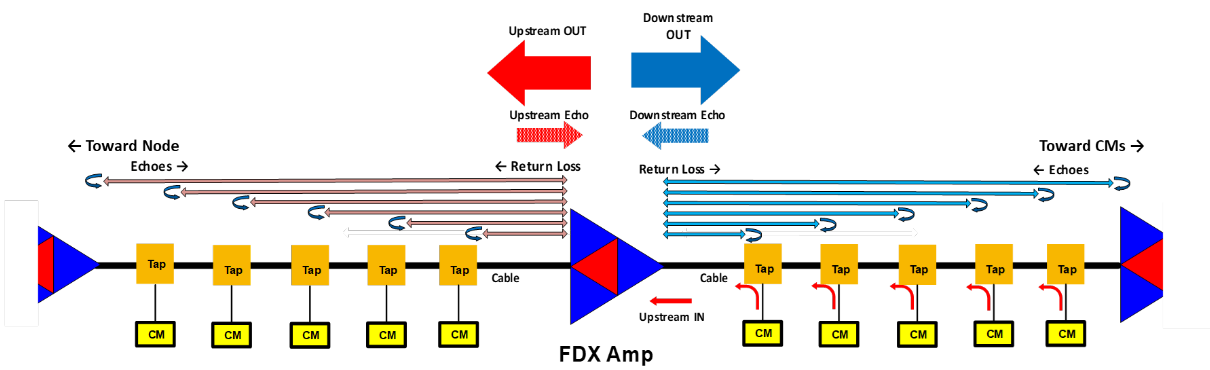


Figure 8 - FDX Amplifier Echo Interference

In the case of a bidirectional amplifier, the downstream transmission level is like that of the node. This results in very similar echo levels in the FDX band. Hence echo cancellation performance required is similar.

The addition of FDX amps requires a different TG grouping of cascaded taps and amps as shown in Figure 9. When a cable modem just upstream of an amp transmits, some of the upstream transmission leaks from the tap port to the output port due to limited tap port-to-output isolation, as depicted in the top amp in the figure. This upstream leakage enters the amp interfering with the intended downstream signal. The SNR is determined by the input downstream-to-upstream leakage ratio. This SNR will propagate downstream of this amp limiting bit-loading (spectral efficiency) thereby lowering downstream capacity. The tap or several taps before the amp and all cascaded taps and amps following the first amp become a single IG. This has been called “IG extension” due to the addition of FDX amps.

To optimize downstream capacity, the entire leg is assigned as a single TG which prevents downstream interference from simultaneous upstream transmission and downstream reception in the same frequency band at the cable modem. Different legs of Figure 9 are combined at the node. Each leg is assigned to a separate TG. The interference from the upstream transmission in one leg into the downstream transmission of the other leg(s) determines the downstream SNR.

Downstream capacity is increased due to the significantly higher isolation between legs of the node splitter/combiner. Traffic engineering of upstream bandwidth grants among the increased number of cable modems in a single TG needs to be considered in long cascades of amplifiers. Also, as explained in the following sections, the degradation of upstream SNR due to the number of amps in a cascade (i.e., Node + x) determines the upstream capacity at the node.

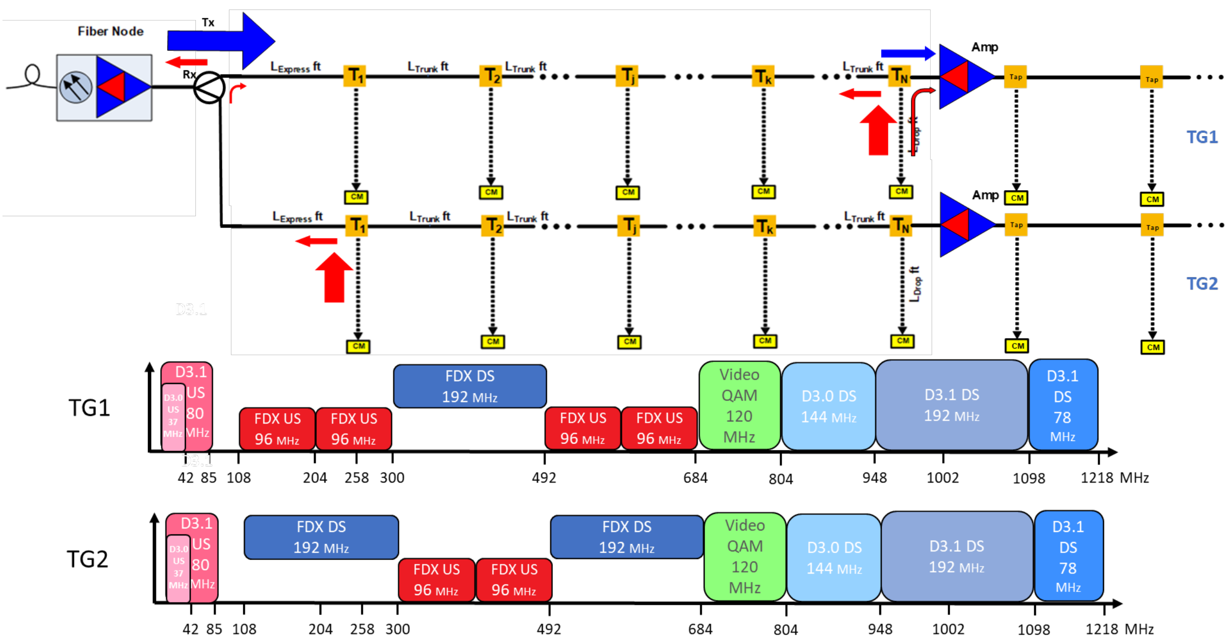


Figure 9 - Node + x cable system with FDX amplifiers

The upstream transmission similarly produces echoes in the received downstream. However, these upstream transmissions negate the reception of the downstream signal in the same band since the signals are in the same transmission group and cannot receive downstream signals in the same band as upstream signals when present from a transmitting modem in that leg of the plant.

The functional diagram for the FDX amplifier is shown in Figure 10. Note the similarity in the EC for the node of Figure 3 on the downstream port of the FDX amplifier. The same EC processing is used here resulting in a similar echo residual after cancelling the echo. This residual is present in the upstream signal. Gain and tilt are applied, and the upstream signal is then launched toward the next amp nearer to the node. Note that this launched upstream signal also produces an echo into the downstream. However, since the upstream transmission is granted in the single TG of the node leg containing the amp (due to IG extension discussed previously), the concurrent downstream signal is not received in the same frequency band.

The same situation applies for a transmitting cable modem producing echo interference in the TG of the node leg containing the amp cascade. This is depicted in Figure 10 where cable modem on the tap before the north port of the amp transmits upstream introducing interfering leakage into the downstream due to limited tap port-to-output isolation.

The cascade of amplifiers each add additional downstream EC residual to the upstream signal. The nature of this EC residual noise buildup in an amplifier cascade and the resultant degradation to the upstream signal arriving at the node is derived in the following section.

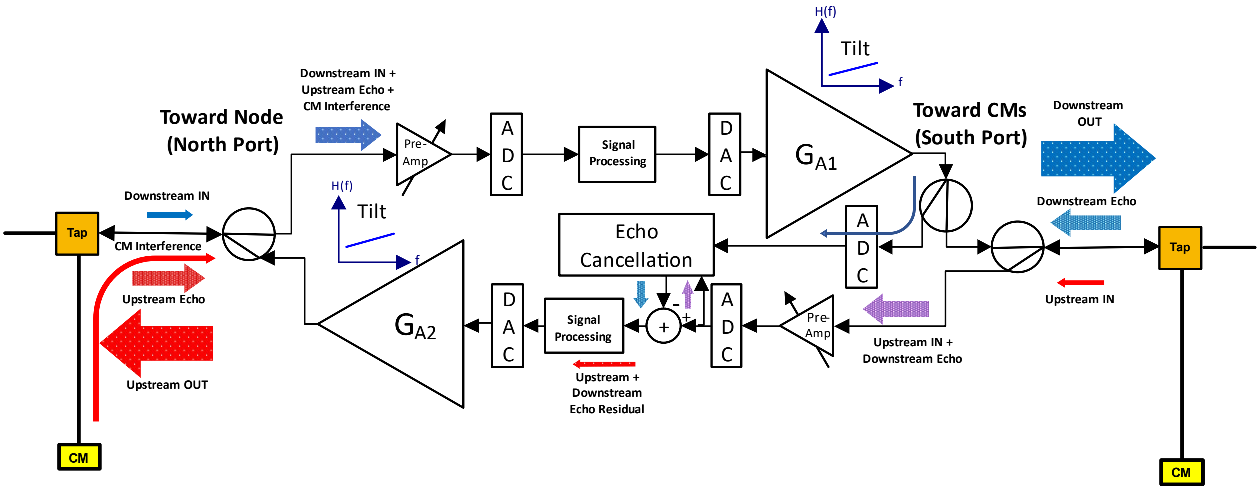


Figure 10 - FDX amplifier with echo cancellation of the downstream echo

4. FDX Amplifier with Echo Cancellation Cascade Analysis

A model for the added noise due to downstream echo interference and the residual noise after echo cancellation is shown in Figure 11.

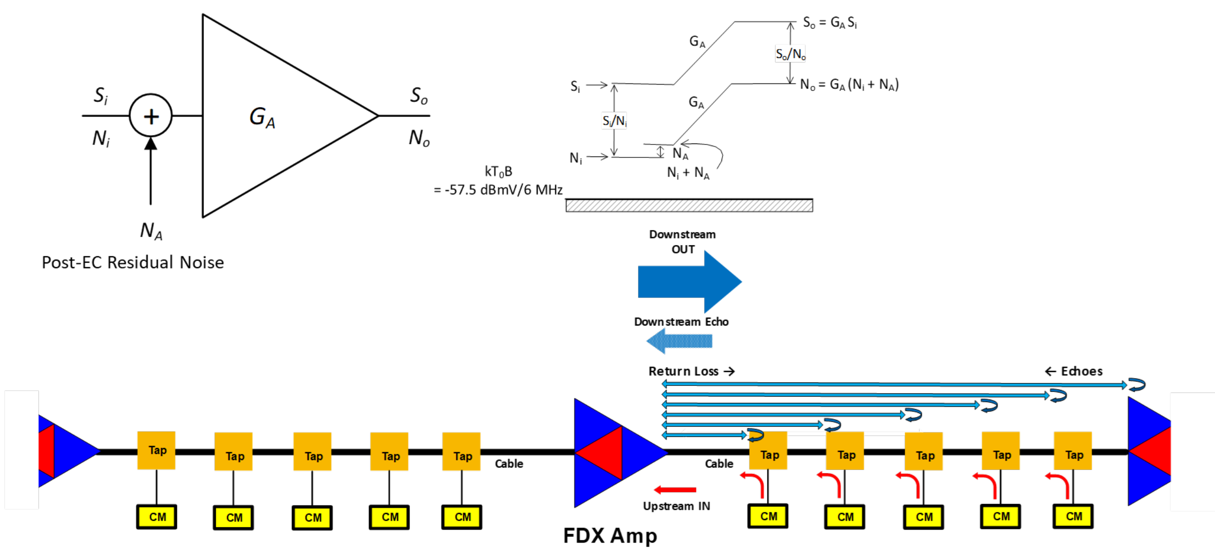


Figure 11 - FDX Amplifier Transmitted Downstream Echo Interference

The upstream input signal S_i to the downstream amplifier is accompanied by input noise N_i with an input SNR of S_i / N_i. Using downstream EC as shown in Figure 10, the EC reduces the echo to a level N_A in

Figure 11 which is substantially above the thermal noise floor. The added downstream echo residual noise N_A is added to the upstream input noise N_i.

The amplifier gain G_A including tilt compensation is applied to the input signal S_i and the combined noise $N_i + N_A$. Thus, the resulting output noise is $G_A (N_i + N_A)$ and the output SNR_o is given by $S_i / (N_i + N_A)$.

This residual EC noise adds for each amp in the cascade as shown in Figure 12.

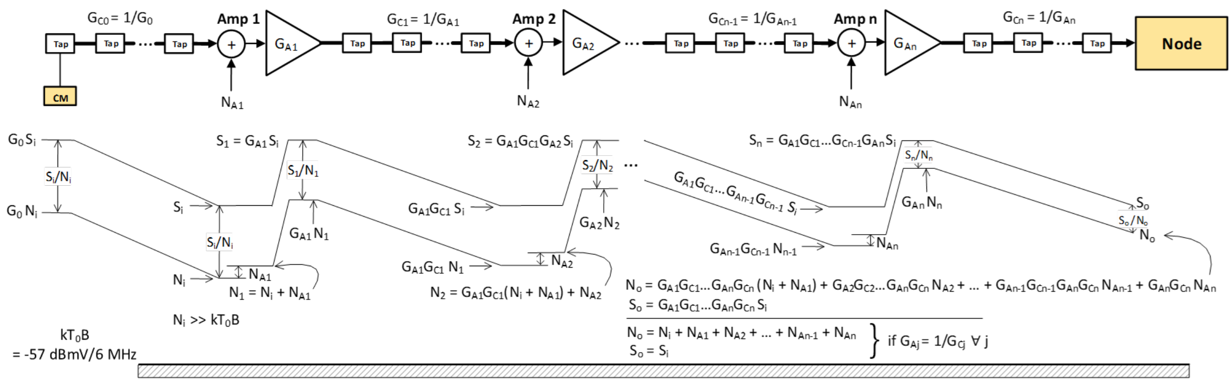


Figure 12 - Cascaded Noise of Amplifier Echo Cancellation Residuals

The node of Figure 4 receives the amplifier cascade upstream signals and accumulated EC residual noise resulting in the signal and noise levels shown at the node port input with an amp cascade CNR of S_o/N_o. This is plotted for a range of values in the bit-loading contour map of Figure 13 below.

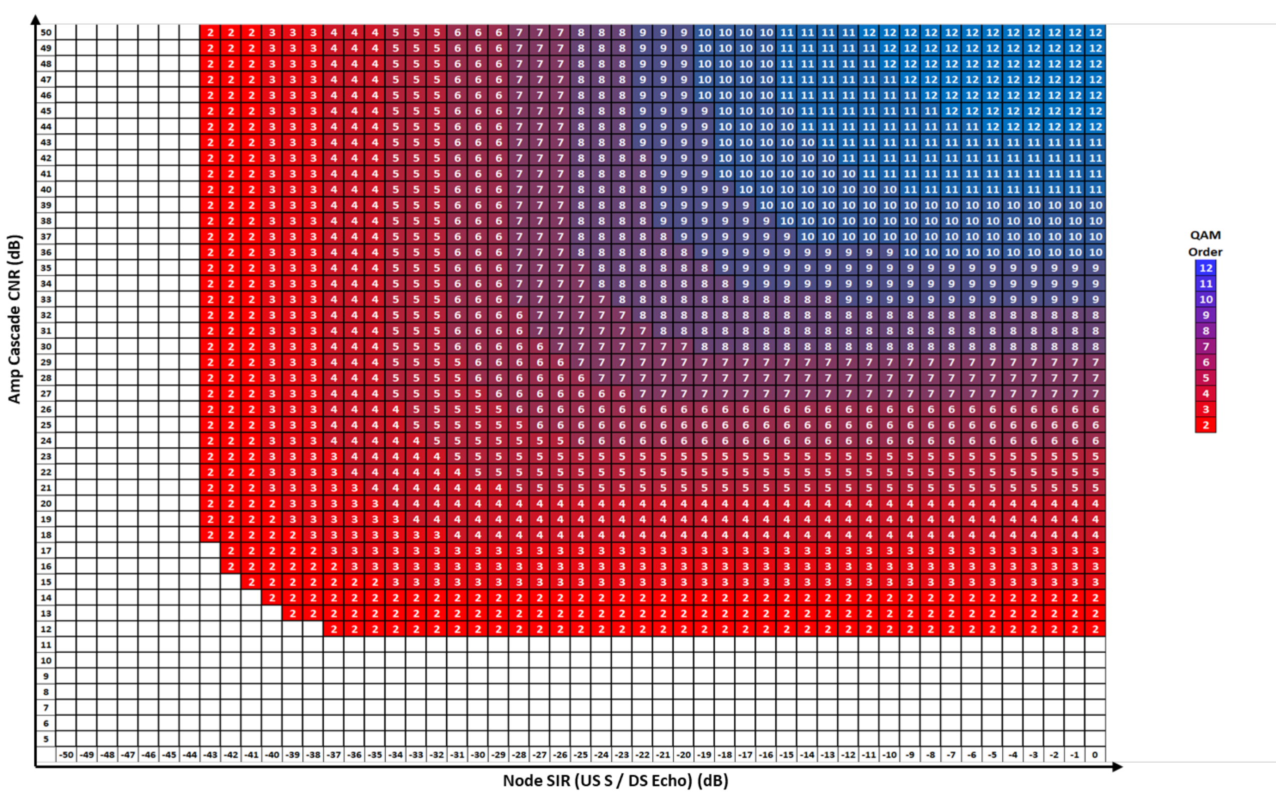


Figure 13 - Bit-Loading Contour Map – Spec Bit-Loading SNR Thresholds

Node Upstream Background CNR vs. Downstream SIR (Signal/Echo Ratio)

The node produces its own downstream echo yielding a node signal/interference ratio (SIR) given by the upstream signal/downstream echo. The node reduces its own downstream echo and the node EC residual adds to the amp cascade EC residual. These two noise sources are uncorrelated and add on a power basis. The resulting bit-loading for the DOCSIS 3.1 spec threshold of the OFDMA receiver is shown in Figure 13 for all combinations of amp cascade CNR vs Node SIR.

Comcast utilized a Profile Management Application (PMA) using lower thresholds from lab and field measurements. Downstream PMA is typically 3 dB lower than spec. Current production OFDM PMA implementation leverages 3 dB of available headroom vs spec in setting downstream OFDM MER thresholds (4k-QAM @ 38 dB vs 41 dB; 2k-QAM @ 34 dB vs 37 dB, etc.).

Upstream is expected to be similar. The result for the bit-loading thresholds using upstream PMA is shown in Figure 14. Using PMA results in higher bit-loading values for the lower PMA thresholds.

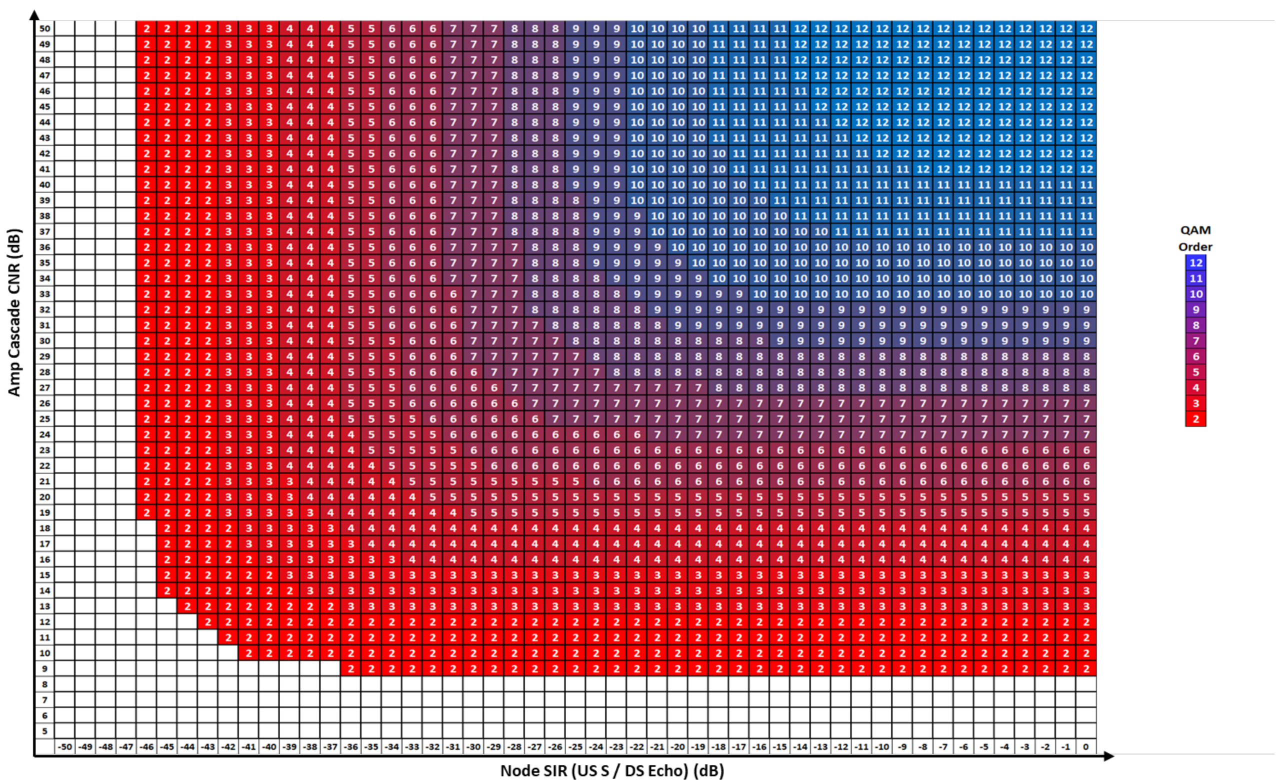


Figure 14 - Bit-Loading Contour Map – PMA Bit-Loading SNR Thresholds
Node Upstream Background CNR vs. Downstream SIR (Signal/Echo Ratio)

5. SNR Calculations for the Node + N FDX Cable System

A representative system for most medium density designs is the single-family unit (SFU). An example of such a system design is shown in Figure 15.

A simulation was performed of the amp cascade upstream signal plus the EC residual accumulation (amp cascade CNR) as depicted in Figure 12 combined with the node EC residual SIR. Echo levels at the downstream port from the tap cascade were modeled using our return loss measurements of the most predominant tap types in our systems. The return loss measurements are shown in Figure 16. A 25 dB average tap return loss in the FDX band was chosen resulting in a 24 dB system return loss in the cable system model of Figure 15.

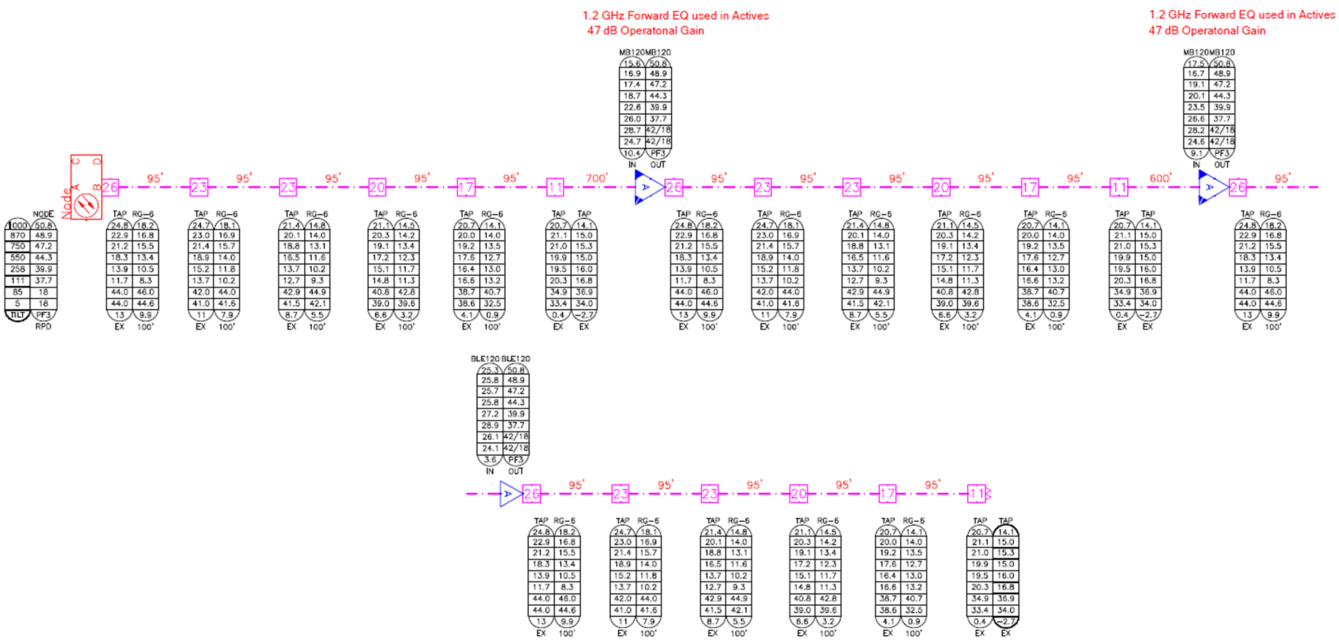


Figure 15 - Single-Family Unit (SFU) Model for N + 6

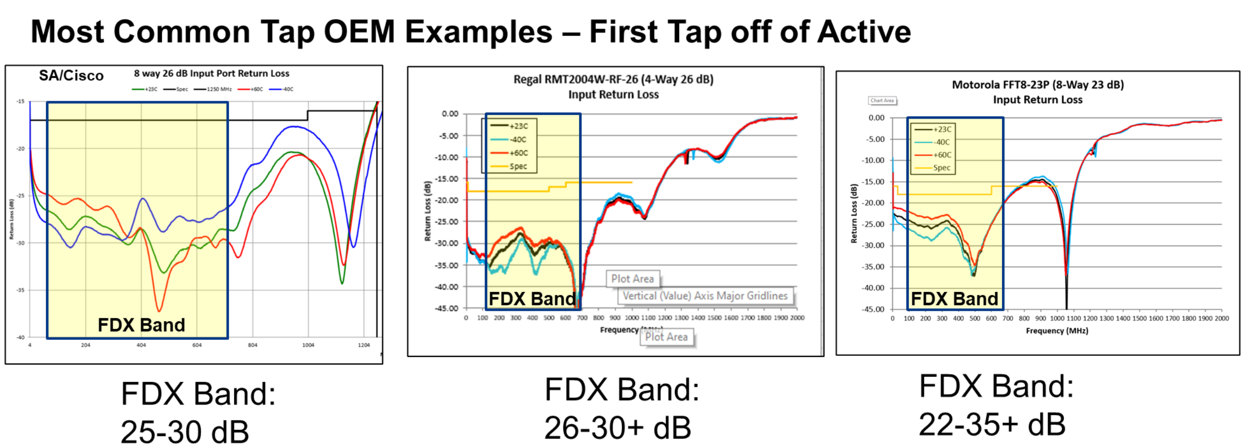
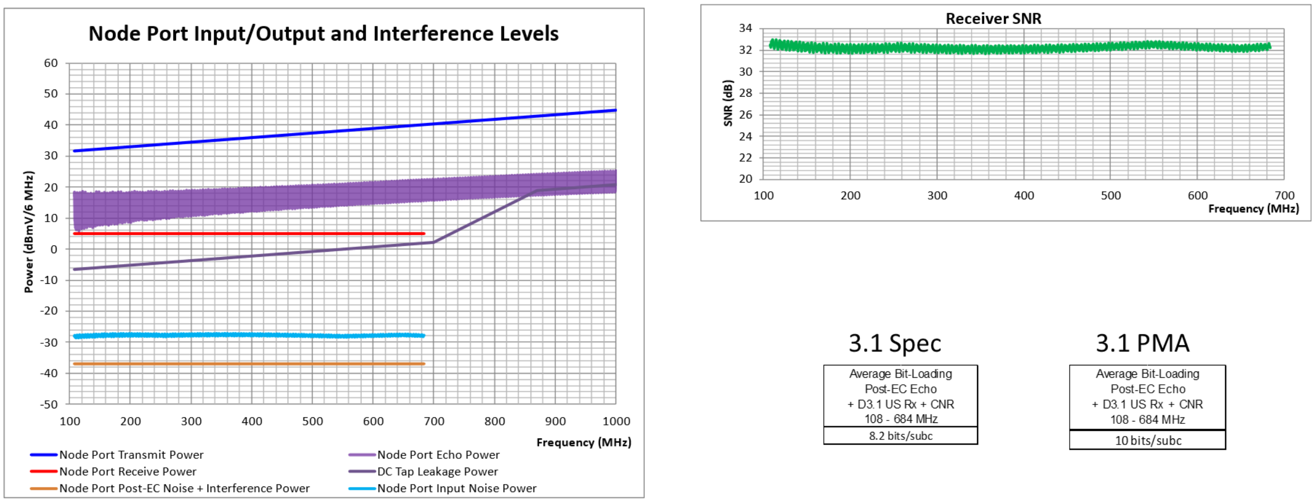


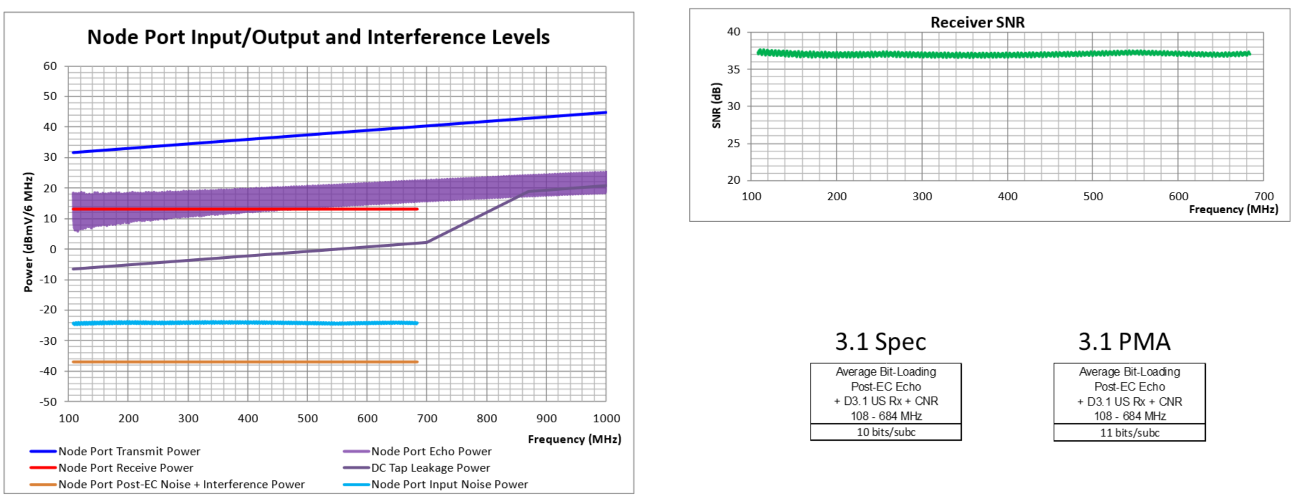
Figure 16 – Return Loss of the Most Common Tap OEM Examples – First Tap from Active

The resultant combined OFDMA demodulator SNR and the bit-loading thresholds as calculated from Figure 13 and Figure 14 are shown in the following figures for different values of upstream input receive power at the node and amp ports. Lower input levels require less output power from transmitting modems. The maximum modem total composite power of 64.5 dBmV corresponds to 13 dBmV/6.4 MHz receive level at the node or amp port. The node port signal and interference levels, OFDMA receiver SNR, and resultant bit-loading for spec and PMA are shown for the Node + 6 cascade depth with 5 and 13 dBmV/6.4 MHz at the node port in Figure 17 and Figure 18 respectively.



Node and Amp Upstream Input Level: 5 dBmV/6.4 MHz
Cable System (Tap Cascade) Return Loss: 24 dB

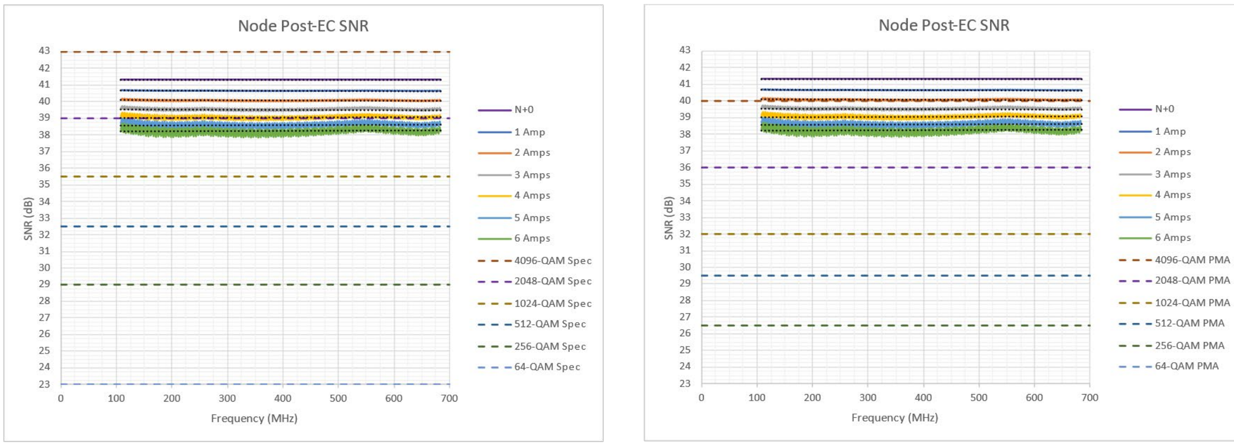
Figure 17 - Node Echo Cancellation and SNR with Node + 6 (5 dBmV/6.4 MHz)



Node and Amp Upstream Input Level: 13 dBmV/6.4 MHz
Cable System (Tap Cascade) Return Loss: 24 dB

Figure 18 - Node Echo Cancellation and SNR with Node + 6 (13 dBmV/6.4 MHz)

A series of 5, 8, 11, and 13 dBmV/6.4 MHz is shown in the following figures:



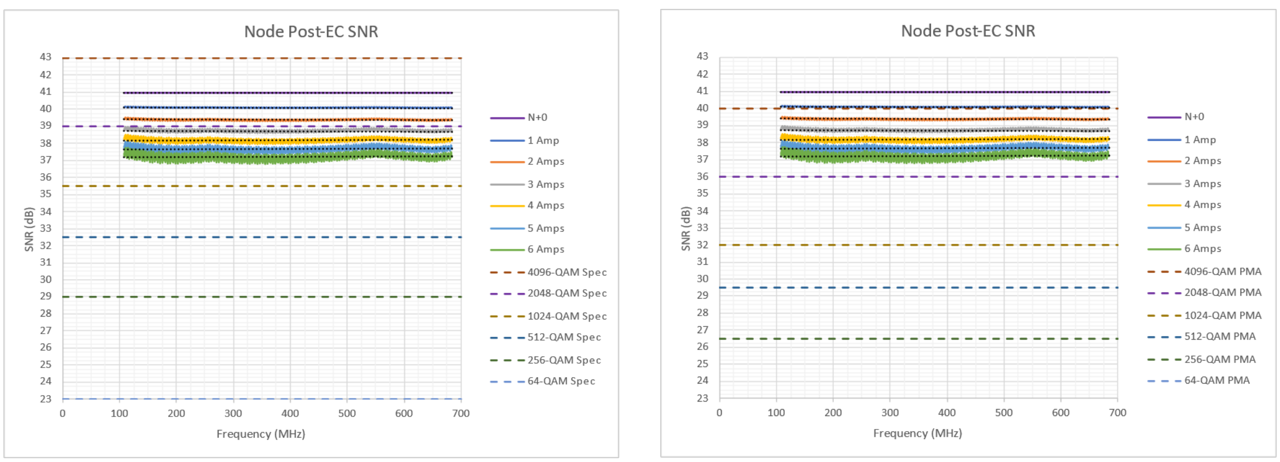
D3.1 Spec OFDMA SNR Thresholds

D3.1 PMA OFDMA SNR Thresholds

Tier 2 SFU with 24 dB tap cascade return loss and 13 dBmV/6.4 MHz upstream input level (node and amps)

Figure 19 - Node Echo Cancellation and SNR with N+1 to 6 Amp Cascade (13 dBmV/6.4 MHz Upstream Input Level)

Node Echo Cancelation and SNR with N+1 to 6 Amp Cascade
(11 dBmV/6.4 MHz Upstream Input Level)

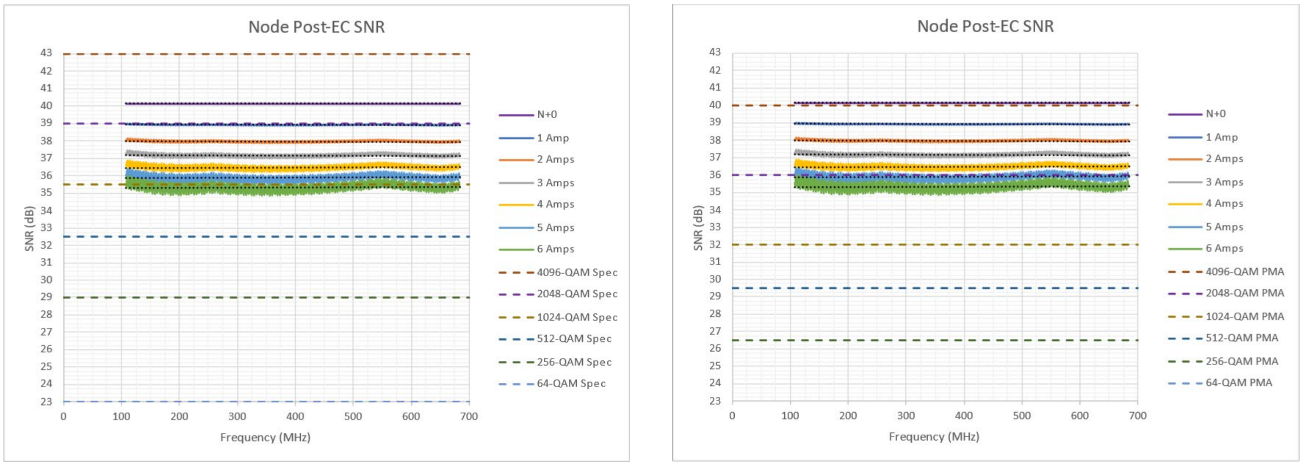


D3.1 Spec OFDMA SNR Thresholds

D3.1 PMA OFDMA SNR Thresholds

Tier 2 SFU with 24 dB tap cascade return loss and 11 dBmV/6.4 MHz upstream input level (node and amps)

Figure 20- Node Echo Cancellation and SNR with N+1 to 6 Amp Cascade (11 dBmV/6.4 MHz Upstream Input Level)

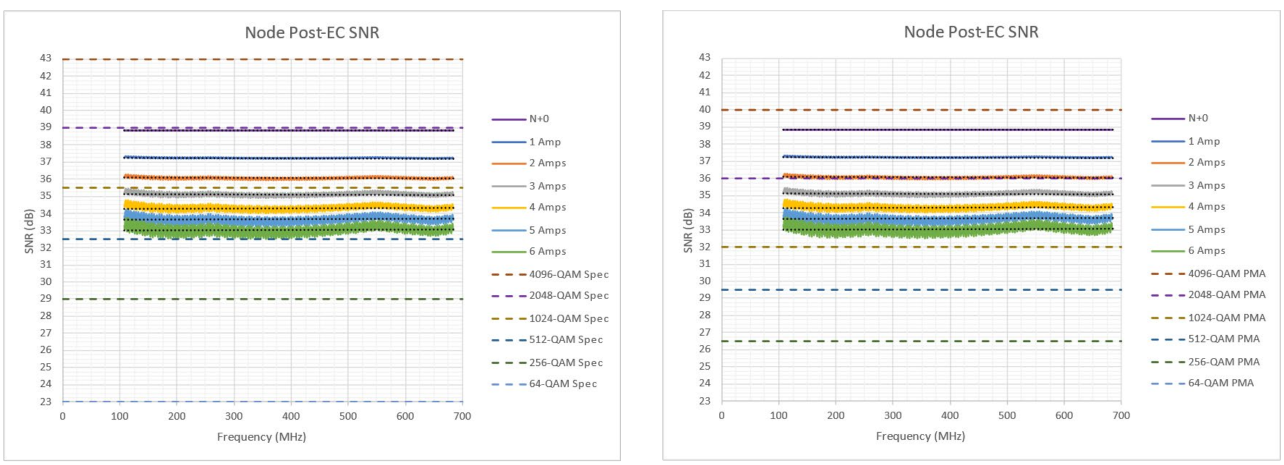


D3.1 Spec OFDMA SNR Thresholds

D3.1 PMA OFDMA SNR Thresholds

Tier 2 SFU with 24 dB tap cascade return loss and 8 dBmV/6.4 MHz upstream input level (node and amps)

Figure 21 - Node Echo Cancellation and SNR with N+1 to 6 Amp Cascade (8 dBmV/6.4 MHz Upstream Input Level)



D3.1 Spec OFDMA SNR Thresholds

D3.1 PMA OFDMA SNR Thresholds

Tier 2 SFU with 24 dB tap cascade return loss and 5 dBmV/6.4 MHz upstream input level (node and amps)

Figure 22 - Node Echo Cancellation and SNR with N+1 to 6 Amp Cascade (5 dBmV/6.4 MHz Upstream Input Level)

The upstream throughput calculations using PMA bit-loading for an upstream receive level of 5, 8, 11, and 13 dBmV/6.4 MHz with an overhead assumption of 25% (75% of PHY Throughput) are shown in Figure 23.

Note that for a six-amp cascade, a minimum 11 dBmV/6.4 MHz upstream receive level across the entire 108 to 684 MHz FDX band (6 upstream channels) is needed for 5 Gbps throughput. Similarly, a minimum 11 dBmV/6.4 MHz upstream receive level across the 108 to 300 MHz FDX band (2 upstream channels) is needed for 2 Gbps throughput. Alternatively, a minimum 5 dBmV/6.4 MHz upstream receive level across the 108 to 396 MHz FDX band (3 upstream channels) is needed for 2 Gbps throughput.

Amp Cascade	96 MHz OFDMA Channels	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
N+1	N+1 OFDMA PHY Rate Mbps	1056	1056	1056	1056	1056	1056
	Total Cumulative NET Mbps	1244	2036	2828	3620	4412	5204
N+3	N+3 OFDMA PHY Rate Mbps	960	960	960	960	960	960
	Total Cumulative NET Mbps	1172	1892	2612	3332	4052	4772
N+6	N+6 OFDMA PHY Rate Mbps	960	960	960	960	960	960
	Total Cumulative NET Mbps	1172	1892	2612	3332	4052	4772

(a) Upstream Rx @ +5 dBmV/6.4 MHz

Amp Cascade	96 MHz OFDMA Channels	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
N+1	N+1 OFDMA PHY Rate Mbps	1056	1056	1056	1056	1056	1056
	Total Cumulative NET Mbps	1244	2036	2828	3620	4412	5204
N+3	N+3 OFDMA PHY Rate Mbps	1056	1056	1056	1056	1056	1056
	Total Cumulative NET Mbps	1244	2036	2828	3620	4412	5204
N+6	N+6 OFDMA PHY Rate Mbps	960	960	960	960	960	960
	Total Cumulative NET Mbps	1172	1892	2612	3332	4052	4772

(b) Upstream Rx @ +8 dBmV/6.4 MHz

Amp Cascade	96 MHz OFDMA Channels	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
N+1	N+1 OFDMA PHY Rate Mbps	1152	1152	1152	1152	1152	1152
	Total Cumulative NET Mbps	1316	2180	3044	3908	4772	5636
N+3	N+3 OFDMA PHY Rate Mbps	1056	1056	1056	1056	1056	1056
	Total Cumulative NET Mbps	1244	2036	2828	3620	4412	5204
N+6	N+6 OFDMA PHY Rate Mbps	1056	1056	1056	1056	1056	1056
	Total Cumulative NET Mbps	1244	2036	2828	3620	4412	5204

(c) Upstream Rx @ +11 dBmV/6.4 MHz

Amp Cascade	96 MHz OFDMA Channels	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
N+1	N+1 OFDMA PHY Rate Mbps	1152	1152	1152	1152	1152	1152
	Total Cumulative NET Mbps	1316	2180	3044	3908	4772	5636
N+3	N+3 OFDMA PHY Rate Mbps	1056	1056	1056	1056	1056	1056
	Total Cumulative NET Mbps	1244	2036	2828	3620	4412	5204
N+6	N+6 OFDMA PHY Rate Mbps	1056	1056	1056	1056	1056	1056
	Total Cumulative NET Mbps	1244	2036	2828	3620	4412	5204

(d) Upstream Rx @ +13 dBmV/6.4 MHz

Upstream Receive @ (a)+5 dBmV/6.4 MHz, (b)+8 dBmV/6.4 MHz, (c)+11 dBmV/6.4 MHz, (d)+13 dBmV/6.4 MHz

Figure 23 - Net Upstream Throughput by Bandwidth Allocation and Cascade Depth vs Receive Level

6. FDX Moves into the Field

A prototype FDX node reference design in a Node + 0 multiple tap cable system was demonstrated in our labs last year. Echo cancellation technology in the FDX node was evaluated with results exceeding expectations [2]. Following the FDX node demonstration, multiple cable modems were evaluated in the Node + 0 FDX proof of concept cable system with a cable modem reference design in each of two transmission groups (complementary upstream transmit, downstream receive Resource Blocks). This included:

2021: Full End-to-End Proof of Concept of 10G FDX

DOCSIS 4.0 vCMTS - Software Upgrade
FDX Node Reference Design
FDX CM Reference Design

Plans for this year include FDX amplifier development and several trials in the field, including:

2022: Move to the Field and Introduce FDX Amps (N+x)

Ongoing: Addition of FDX features per DOCSIS 4.0 spec into the vCMTS code

Now: First full FDX RPD Node

Q2: First Comcast FDX MTA

Q3: Prototype FDX Amplifier
Multi-Gig symmetric over N+x

Q4: Qualification of FDX Node Hardware and Software

Q1 2023 and beyond: Trials
Tech Trial Multi-Gig Symmetric N+0
Tech Trial FDX over N+x

7. Conclusion

The successfully demonstrated echo cancellation (EC) technology developed for the FDX node enables the extension to FDX amplifiers. An EC noise model for FDX amplifiers has been developed to calculate the achievable bit-loading and resultant capacity for varying numbers of cascaded amplifiers.

Sufficient fidelity in reasonable amp cascades can ensure multi-gigabit symmetric speeds up to Node + 6. A powerful PMA engine enables true, adaptive bandwidth/capacity optimization. Straightforward RF guidelines for allocations of FDX upstream OFDMA spectrum can deliver Speed Tier objectives for 2 to 5 Gbit/second symmetric peak throughput.

A Full End-to-End Proof of Concept of 10G FDX cable system was demonstrated in 2021. A prototype FDX amplifier (Node + x) will be introduced in 2022. An FDX Node + 0 trial and Node + x amp trial is planned in 2023.

Abbreviations

ASIC	Application Specific Integrated Circuit
BER	Bit Error Ratio
CM	Cable Modem
CMTS	Cable Modem Termination System
CNR	Carrier-to-Noise Ratio
dBmV	Decibel millivolts
EC	Echo Cancellation
FDX	Full Duplex DOCSIS
Gbit	gigabit
Gbps	Gigabit per second
IC	Integrated Circuit
IG	Interference Group
MER	Modulation Error Ratio
MHz	Megahertz
MTA	Multimedia Terminal Adapter
N + x	Node + x amplifiers
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
PHY	Physical Layer
PMA	Profile Management Application
RPD	Remote PHY Device
R-PHY	Remote PHY
SFU	Single Family Unit
SIR	Signal-to-Interference Ratio
SNR	Signal-to-Noise Ratio
TG	Transmission Group
vCMTS	Virtual CMTS

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[2] R.S. Prodan, *10G Full Duplex DOCSIS Implementation Exceeds Expectations*, SCTE 2021 Cable-Tec Expo