FDX Amplifier for Supporting N+M Network

A Technical Paper prepared for SCTE•ISBE by

Hang Jin
Distinquished Engineer
Cisco System
3700 Cisco Way, San Jose, CA 95134
(214) 538-6245
hangjin@cisco.com

John T Chapman
CTO Cable Access and Fellow
Cisco Systems
3700 Cisco Way, San Jose, CA 95134
408-526-7651
jchapman@cisco.com

Table of Contents

List of Figures

Title **Page Number**

List of Tables

Title **Page Number**

Introduction

Full duplex (FDX) DOCSIS is one of the latest innovations in Cable industry. It allows the downstream and upstream to use the same spectrum at the same time, leading to ~100% increase on spectrum efficiency, and drastic increase on US capacity without scarifying DS capacity. FDX DOCSIS has been adopted into Cablelabs DOCSIS 3.1 specification release I12 on Oct 2017, and MSOs/vendors have conducted numerous successful lab and field trials since. FDX DOCSIS is one of the key technologies that enable HFC to deliver 10Gbps symmetric services.

Current FDX D3.1 standard specifies FDX operation for N+0 coaxial network. Today's networks are mainly N+M (M>0) network; migrating from N+M (M>0) network to N+0 network requires substantial network re-planning effort and CAPEX. There is a strong interest in cable industry to remove this N+0 network deployment constraint and allow FDX technology to be deployed in N+M(M>0) network.

Deploying FDX in N+M (M>0) network requires FDX amplifier. This paper explains the working principle of FDX amplifier, the design considerations and challenges, as well as its impacts on the field deployment and the overall FDX system operation.

Content

1. What is FDX amplifier

Like conventional RF amplifier, FDX amplifier boosts DS/US RF signal levels to extend the node coverage. The prefix 'FDX' means the amplifier supports FDX operation in FDX band 108MHz-684MHz. To support FDX operation, the FDX amplifier needs to implement echo cancellation (EC) function and adopt a new architecture to accommodate this new EC function.

FDX operation introduces co-channel interferences from transmitter to receiver (i.e. echoes), thus requires implementing EC. FDX amplifier needs to implement echo cancellations (EC) on both input and output ports. The EC on the input port suppresses the echo of US transmitted signal on DS receiver, and the EC on the output port suppresses the echo of DS transmitted signal on US receiver. FDX amplifier hardware/system architecture needs to accommodate this new EC functions.

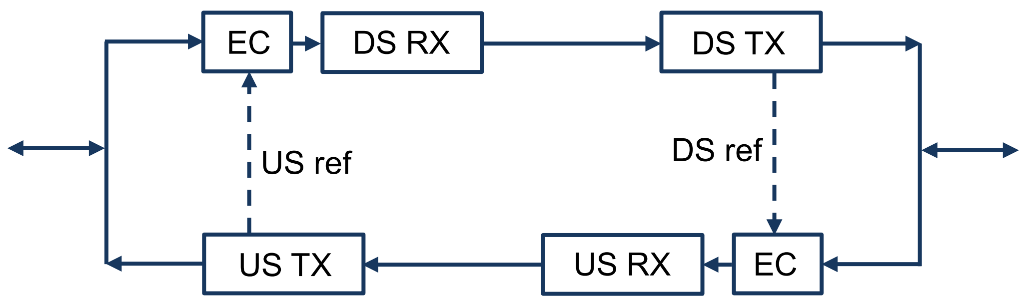

Figure 1 - The high level system architecture of FDX amplifier

2. How FDX amplifier works

Given in Fig.1 is the high level FDX amp architecture. FDX amplifier boosts both DS and US RF signal levels. For legacy spectrum (US 5MHz – 85MHz, DS 684MHz-1218MHz), FDX amplifier operates the same way as the conventional amplifier. However, for the signals in the FDX band (108MHz-684MHz) where DS and US RF signals overlap, FDX amplifier needs to implement EC. The EC needs be implemented on both input and output ports, sitting in front of the receivers. EC requires the reference signal to generate the cancelling signal. The reference signals are the transmitted signals coupled from the transmitters.

Apparently, the design challenge with FDX amplifier is the EC. As the DS and US signals overlap in FDX band 108MHz-684MHz, DS and US signals in FDX band have a close loop amplification within FDX amplifier, the EC needs to provide sufficient echo suppression to ensure the net loop gain is less than zero to prevent the FDX amplifier from self oscillation. Moreover, the echoes need be suppressed way below the desired received signal level to ensure good MER for the received signal. The exact echo suppression required largely depends on the power level of the transmitted signal (echo power coupld to the receiver is linearly proportional to the power level of the transmitted signal) and the level of the desired signal that is expected to be received at the receiver, which will be examined in the following sections.

3. FDX amplifier specifications

Given the channel condition (reflection and coupling), the required echo suppression depends on the transmitted power/tilt of the transmitted signal and the expected received signal level. FDX amplifier RF specification should match with the legacy's, so when the FDX operation is enabled and the legacy amplifier is swapped out with FDX amplifier, the system link budget remains the same.

3.1. Legacy Amp specification

Cisco Systems amplifier (Gainmaker) will be used as the reference to define FDX amplifier specifications.

Table 1 - Cisco Systems amplifier (Gainmaker) RF specification (middle frequency split)

DS	
Frequency range	108MHz - 1218MHz
TCP	72 dBmV
Up tilt	19dB
Gain	48dB max
US	
Frequency range	5MHz - 85MHz
TCP	41dBm
Up tilt	0
Gain	27dB max

For DS, FDX amplifier specification should match exactly with the legacy amplifier's. For US, it is more involved. FDX operation adds extra US spectrum from 108MHz to 684MHz (FDX band). As the FDX US spectrum occupies total 576MHz spectrum, we cannot ignore the path loss variation cross FDX spectrum. Up-tilt needs be specified for FDX US signal in the FDX band.

3.2. US up-tilt in FDX band

Per FDX DOCSIS3.1 specification, CM US signal needs to have 12dB up-tilt at CM output to compensate the path loss variation cross the FDX frequencies, so it will have a relatively flat spectrum when the US signal arrives at RPD receiver. FDX DOCSIS 3.1 defines N+0 network with an assumption that there always is a 100 ft drop cable connecting the tap and the CM. The complete path from CM to RPD include 100 ft drop cable and the multiple segments of taps and trunk cables. In the case of N+M (M>0), the US signal coming out of FDX amplifier input port will not see the drop cable. It needs to overcome the path loss of taps and trunk cables, which has roughly 8dB path loss variation cross 108MHz -684MHz. This 8dB path loss variation can be also derived as follows: taking 12dB up-tilt for the completed path, and then subtracting out 4dB up-tilt due to 100ft drop cable (100ft drop has roughly 4dB loss variation cross 108MHz-684MHz (6dB@684MHz vs 2dB@108MHz)) (See Fig.2 and Fig.3)

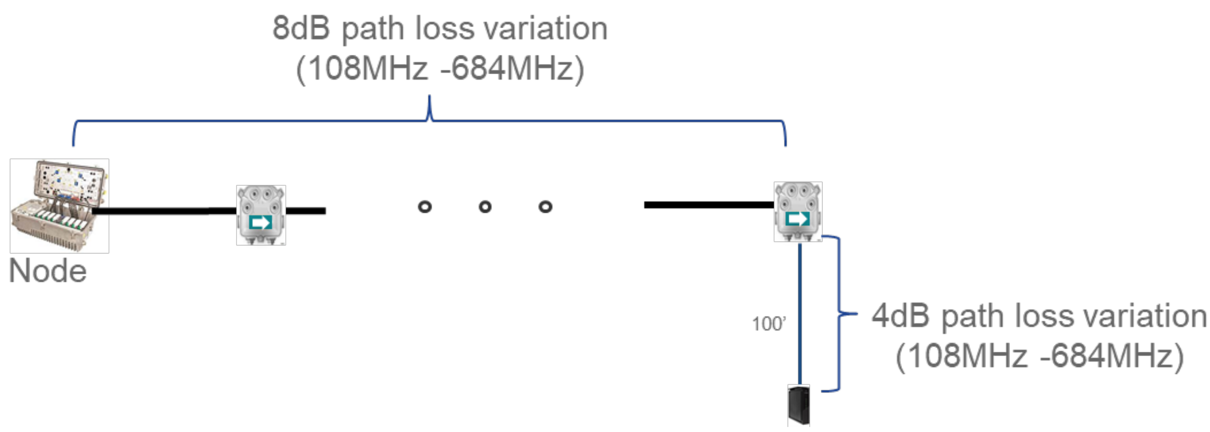

Figure 2 - N+0 network. The total path loss variation is 12 dB (4 dB for 100 ft drop cable, and 8dB for the rest of the path).

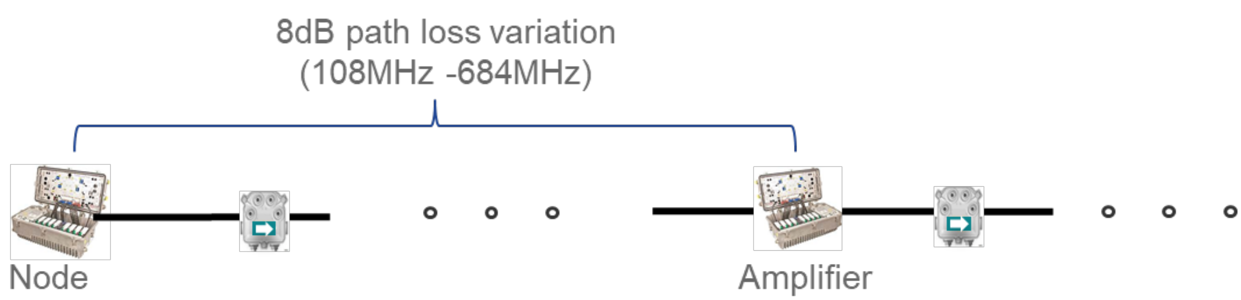

Figure 3 - N+M network. US signal coming out of the input port of FDX amplifier overcomes the path loss of taps and trunk cables, which has 8dB variation in the FDX band (108MHz-684MHz)

3.3. FDX US transmitted power

The US signal channel power is designed as follows:

- The channel power at 108MHz will be the same as the channel power at 85MHz.
- 8 dB up tilt from 108MHz to 684MHz
- Has 35dB max gain (27dB gain to match the legacy system, plus 8dB for the up tilt)

Table 2 - FDX Amplifier RF specification

	DS	
Frequency range	108MHz - 1218MHz	
TCP	72 dBmV	
Up tilt	19dB	
Gain	48dB max	
	US (lagacy band)	**US (FDX band)**
Frequency range	5MHz - 85MHz	108MHz-684MHz
TCP	41dBm	54.1dBm
Up tilt	0	8dB
Gain	27dB max	35dB

The total TCP for US signal is 54.3dBmV, of them, 41dBmV comes from the legacy US spectrum, and 54.1dBmV comes from the FDX band (108MHz-684MHz). US channel power is plotted in Fig.4.

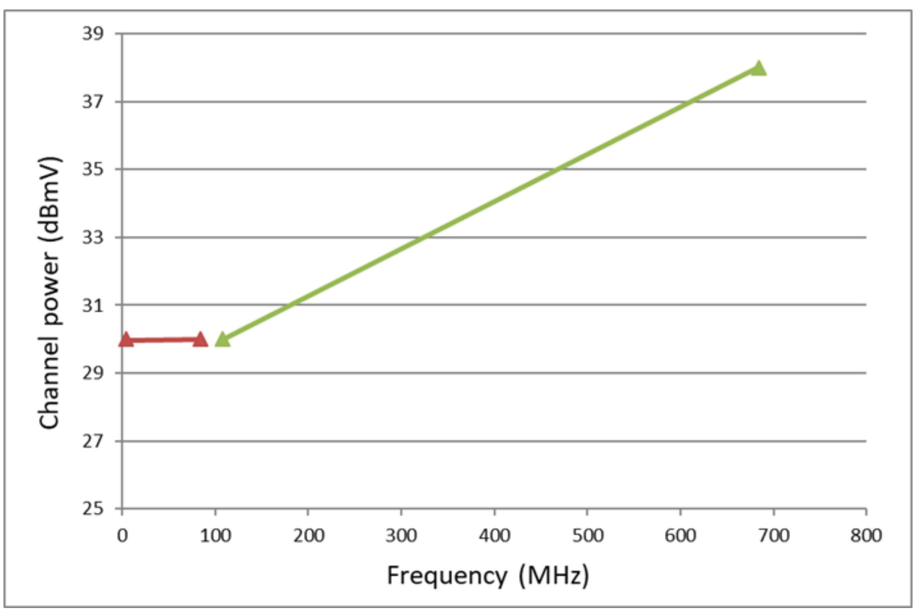

Figure 4 - US channel power (dBmV/6.4MHz)

4. The input power level of the desired signal

Echo cancellation suppresses the echo power at the receiver. The suppression is defined as EC gain and given in dB. Given an echo power and EC gain that can be achieved, the final signal SNR depends on the power level of the desired signal at the receiver input. The input power level of desired signal varies, depending on the network topology and size of the node coverage. For the purpose of the analysis in this paper, the input power level of the desired signal is assumed 5dBmV/ch, where ch=6MHz for DS, and ch=6.4MHz for US.

5. Echo cancellation requirements

The EC gain required depends on the power levels of the desired signal and the echo, which, in turn, depends on the transmitted power (TCP), and the targeted post-EC SNR:

$C_0 - I_0 + EC\_gain = SNR\_req$ Eq.1

Where C_0 is the received power level of the desired signal, I_0 is the power level of the echo, SNR_req is the required post-EC SNR for target modulator order.

From Eq.1, we have:

$EC\_gain = SNR\_req - C_0 + I_0$ Eq.2

With the amplifier RF specification given in the previous section, we can now compute the EC gain required.

5.1. EC gain for US receiver at output port

Assume the input power level of US desired signal is 5dBmV/6.4MHz, the total US power will be 24.5dBmV over 108MHz-684MHz. The total power of the DS echo at the amplifier output port is 52dBmV, assuming 20dB reflection and 72dBmV DS TCP (see Table 2 for FDX amplifier RF specification). The total echo power over 108MHz-684mHz is 42dBmV. In order to support 512QAM, minimum 36dB post-EC SNR is required. So, the EC gain is 36-24.5+42=53.5dB.

The detailed calculations for the signal levels at various points in the receiver chain and EC gain required are given in Fig.5

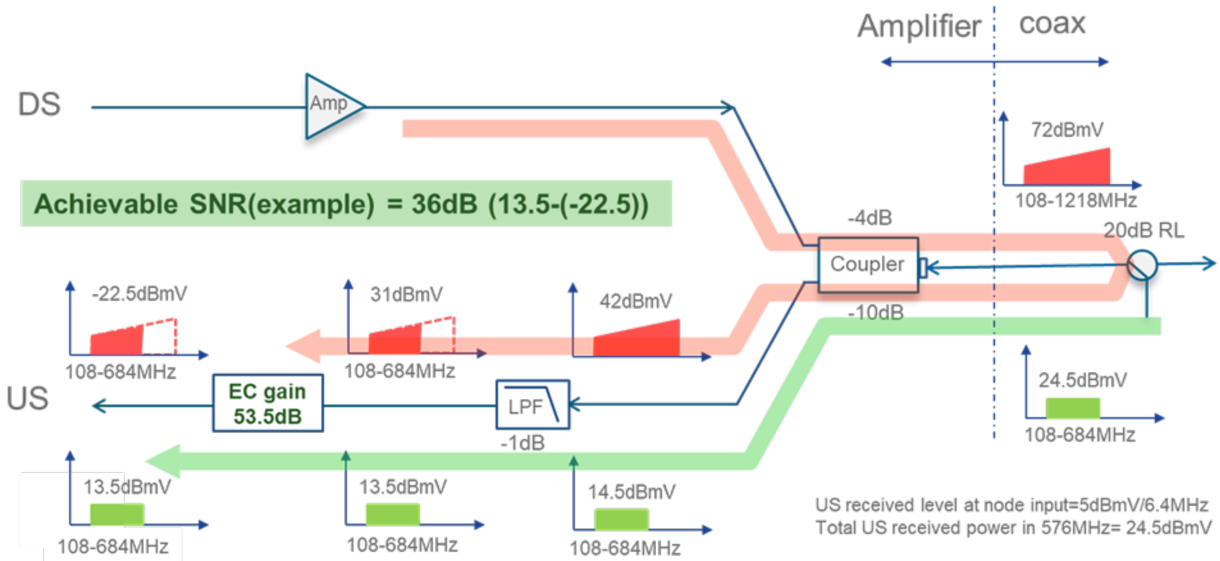

Figure 5 - The signal levels at various points in US receiver chain and EC gain required

The calculation is illustrated with one output port. The calculation methodology and procedure are the same for multiple output ports, just use the aggregated echo powers contributed from all the ports to define the EC gain required.

5.2. EC gain for DS receiver at input port

Similarly, one can calculate EC gain required for DS receiver at input port. Assume the input power level of DS desired signal is 5dBmV/6MHz, the total DS power is 24.8dBmV over 108MHz-684MHz. The total power of the US echo at the amplifier input port is 34.1dBmV, assuming 20dB reflection and 54.1dBmV US TCP in frequencies 108MHz-684MHz. In order to support 4kQAM for DS, minimum 43dB post-EC SNR is required. So, the EC gain required is 43-24.8+34.1=52.3dB (Fig.6)

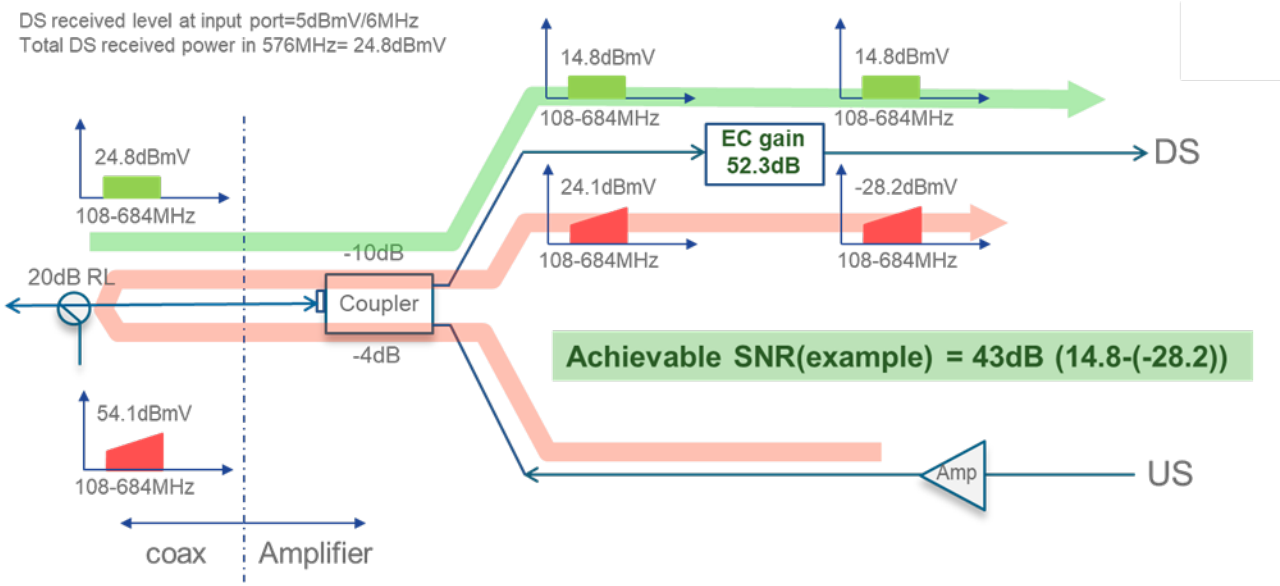

Figure 6 - The signal levels at various points in DS receiver chain and EC gain required

6. EC coefficient training

To cancel out the echo, one needs to genearte the canceling signal. The cancelling isgnal is generated from the reference signal. The cancelling signal needs to have proper magnitude and phase. The magnitude and phases of the cancelling signal are called EC coefficients. The EC coefficients are computed over a time period by comparing/tracking the magnitude and phase differences between the reference signal and echoes. The procedure with which the EC coefficients are computed/tracked is called EC training (ECT), and the time period over which EC is trained is called EC training window (ECTW). During ECTW, the desired received signal is muted so the echoes can be obersved cleanly without 'interference' of desired received signal (Fig.7)

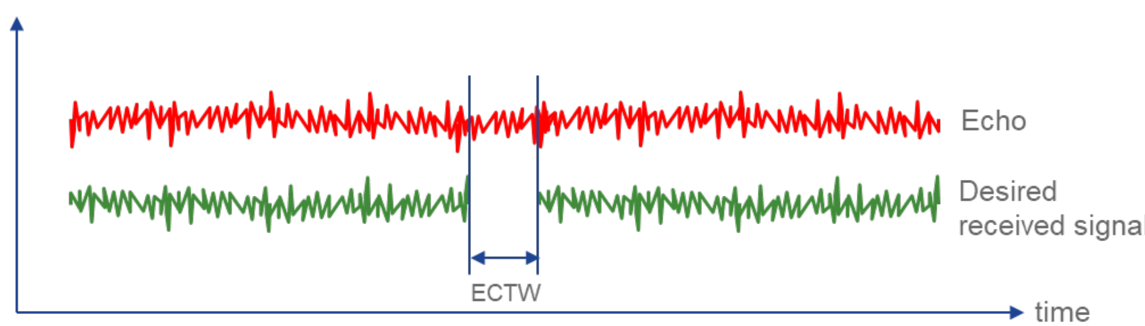

Figure 7 - EC training window (ECTW)

The implementations of EC training are different for input and output ports.

6.1. EC training for output port

EC training requires EC training windows. ECTW is a period of time when no US traffics present in the FDX band (108MHz-684mHz). ECTW allows for clear observation of the echo without the 'interference' of US traffics.

There are two types of ECTW present on the output port.

6.1.1. Explicit ECTW

FDX amp is a part of FDX network. There is always FDX node that supports FDX operation. FDX node requires ECTW for its own EC coef training. FDX amp can use the ECTW that is scheduled for FDX node ECT to train its EC coef for the output port.

6.1.2. Implicit ECTW

FDX node typically has multiple ports. FDX amplifier connects to one of the ports sees only a part of US FDX spectrum used. For example, for a 4 port node, amplifier connecting one of the ports sees 25% of the US mini-slots used on avearge over time. In theory, all the un-used US mini-slots can be used as ECTW.

To utilize the un-used mini-slots for the purpose of ECTW, FDX amplifier needs to know the usage of the mini-slots. This can be done as follows

6.1.2.1. US bandwidth allcoation map (MAP)

The US scheduler allocates the US mini-slots for CMs, and the allocation info is sent down to CMs in MAP. FDX amplifier could listen to the MAP messages and understand if there are any un-used mini-slots or mini-slots that are used by CMs that do not connect to it (those mini-slots are used by CMs whose traffics do not go through it). We define the mini-slots that are used but do not go through the amplifier as non-relevant mini-slots. Apparently, to fully utilize the non-relevant mini-slots for the purpose of ECTW, the amplifier needs to know the information related to the network topology and CM attachment. The amplifier also needs to know the US timing, so it can correlate the US mini-slot allocation timing (US frame) with its local timing. This needs the time/US frame synchronization between CMTS and FDX amplifier.

6.1.2.2. Power detection

Alternatively, the amplifier could simply detect the power of US mini-slot, and if the power of the mini-slot is below certain threshold, the mini-slot can be used for the purpose of ECTW. The threshold can be the global US noise floor with some margin. For example, the threshold value could be N+6 (6dB margin), where N is the US global noise floor. Typically the US needs to support >20dB SNR, so we will see at least 20dB difference in power between used mini-slot or not used. The US global noise floor can be calculated by averaging the power on un-used mini-slots over time.

Both approaches (MAP and power detection) assume the ECT occurs on a per mini-slot base. As the EC is usually done on per sub-carrier base in frequency domain, ECT on a per-mini-slot base works fine. To allow each mini-slot to have the equal ECT opportunity, the scheduler would need to rotate the US mini-slot allocations among the CMs in such a way that each mini-slot has the equal ECT opportunity on each amplifier over time. For example, the FDX node has 4 ports, and each port attaches a group of CMs. Assuming the US traffics are balanced among 4 ports, so each port will see roughly 75% of US mini-slots are un-used over time on average. The scheduler needs to rotate the US allocation among the 4 groups of

CMs so the 75% un-used mini-slots will cover the completed spectrum over time so each mini-slot is given with the equal ECT opportunity on each amplifier.

All the un-used mini-slots can be potentially used for ECT purpose. In practice, depending on the aging of the EC coefficients, some of the un-used mini-slots may be skipped for ECT purpose.

When a mini-slot is detected un-used, regardless if it is used for ECT purpose or not, its energy will be suppressed at the input of IFFT. This will avoid to add its energy to the active mini-slots in the later stage (US noise funneling effect).

6.2. EC training for input port

As explained in the previous sections, ECT is the period of time when the echo can be observed cleanly at the receiver without the 'interference' of the desired received signal. In the case of the input port, the echo comes from US transmitter, and needs be observed, characterized and canceled out at DS receiver. For this purpose, a period of time without DS signal (aka DS EC training window) is required. Unfortunately, there are no known mechanisms (also it is not permitted) to mute DS signal as DS signal is continuous in time and always present regardless of DS traffics. In other words, we can't generate DS EC training window by muting DS signal.

Thus one needs to generate an 'effective' ECTW for the input port that allows the echoes of US to be observed and characterized accurately at the DS receiver without muting DS signal. In other words, ECT for input port must be blind and done with the presence of the DS traffics.

Per FDX standard, only DOCSIS 3.1 (OFDM/OFDMA) are allowed in FDX spectrum. For DOCSIS 3.1 DS, there are scattered pilots on each subc, the scattered pilots are BPSK modulated with known bits, and are on fixed locations with 128 symbol interval. One can leverage DS scattered pilots to create an 'effective' ECTW:

- Generate a staircase 2-dimensional DS EC training window by subtracting out the DS scattered pilots from DS signal (see Fig.8);
- Observes and characterizes US echoes on the locations of the DS scattered pilots where the signals of scattered pilots have been subtracted out.

The ECT for the input port will be done on each subcarrier as follows:

- At each scattered pilot location, extract the US echo by subtracting the scattered pilot out of the total DS signal:
  US_echo=S-Hp*Sp; Eq.3
  Where S is the total DS signal observed at scattered pilot location in 2-dimensional (subc x symbol) space, Sp is the symbol of the scattered pilot (known), Hp is the channel coefficient of the scattered pilot, and US_echo is the US echo extracted.
- Scattered pilot channel Hp can be readily computed through moving averaging:
  - Hp=E{hp}, where hp is the channel coefficient observed at each instance. E{ } stands for averaging with pre-defined length.
  - EC coef is then computed as follows:
  - Cec= US_echo/S0;
  - Where S0 is the US signal (reference signal used in EC), and US_echo is the echo extracted using Eq.3
  - Once the EC coefficients on subc are computed, the EC at the input port is done through simple subtractions.

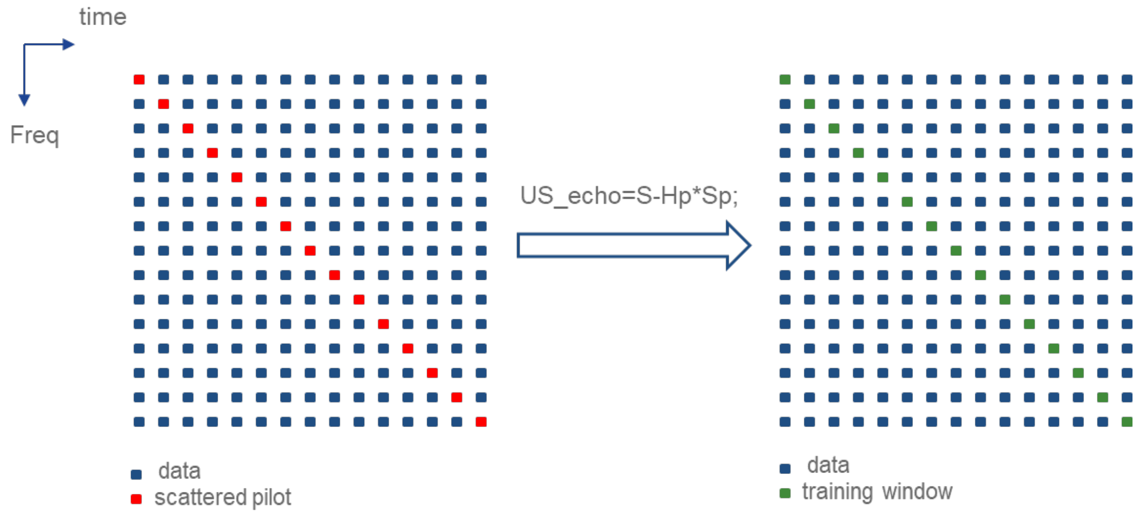

Figure 8 - By subtracting out the scattered pilots, a 2-dimensional staircase EC training window is generated on DS receiver (4k FFT)

The scattered pilots are asserted only on active subcarriers outside of PLC. EC training on subc within PLC will be done on PLC preambles. PLC preambles are BPSK modulated with known bits. The EC training on subc on PLM preambles follows exactly the same procedure as on scattered pilots.

7. EC system architecture

Fig.9 illustrates the system architecture of FDX amplifier. It can be considered as two EC circuitries that put back-on-back: one EC for the output ports, and the other for the input port. While there are some commonalities, EC circuitries for input and output ports are considerably different due to the differences on input and output RF characteristics.

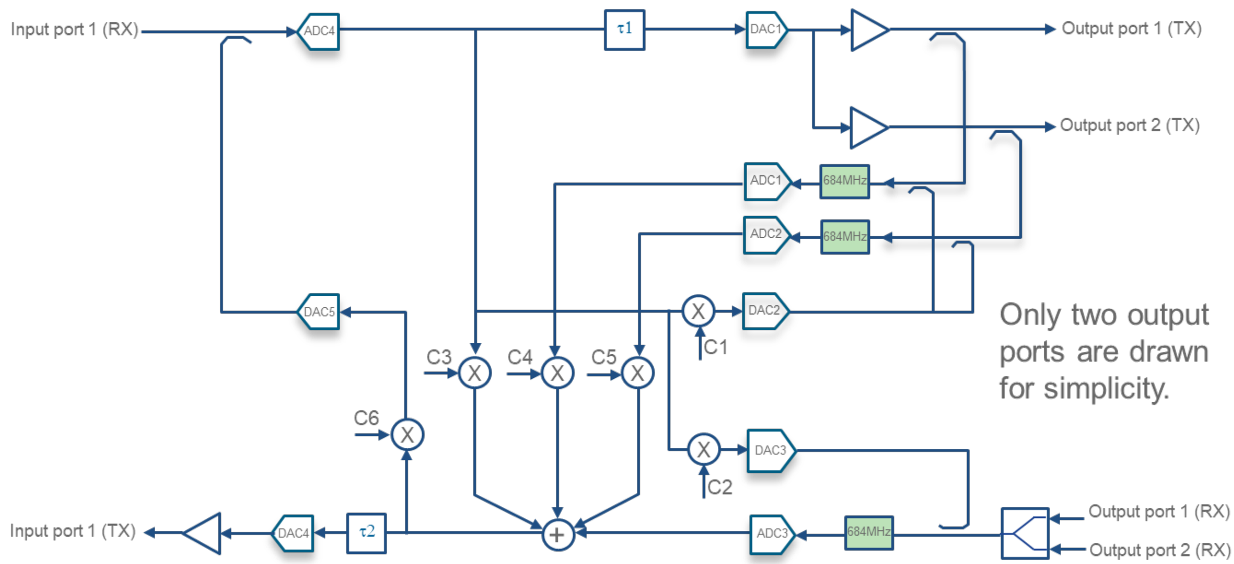

Figure 9 - EC system architecture

7.1. Output port:

The output port contains both analog EC and digital EC. The purpose of the analog EC is to suppress the echo power to a level that is below the US desired signal to avoid any loss to the dynamic range of the US receiver ADC (ADC3). The analog echo cancelling signal is generated from the DS reference signal and converted to analog signal via a DAC (DAC3) and added to the US receiver data path in analog domain. To ensure the causality, the reference signal needs be taken from the DS signal in digital domain (before DAC1). Digital EC is implemented at output ports primarily for cancelling the noises of output launching amplifiers. At digital EC, the noises from launching amplifier, as well as the residue of the DS signal from the analog EC, will be cancelled out. The reference signals for digital EC will be the feedback signals from the output ports (ADC1 and ADC2), which contain the noises of the launch amplifiers, and the DS signal.

7.2. Input port

The input port contains the analog EC only. There are a couple of reasons that input port implements analog EC only:

1. As we recalled, the primary purpose of the digital EC at output port is to cancel out the noises from the output port launch amplifiers. The launch amplifier at the input port requires to deliver much less TCP and occupies half the spectrum compared to the output ports (57.2dBmV vs 72.dBmV, 684MHz vs 1218MHz), thus one can design/select proper launch amplifier at the input port to ensure its in-band noise will not cause adverse effect on DS receiver. Since we need 52dB EC gain for the input port (section 5.2), which implies the in-band noise of US transmitter needs be 52dB below the signal.
2. To enable digital EC, one needs to extract the DS signal in FDX band, and cancel out the echoes in the extracted DS signal, and add the cleaned DS signal in FDX band back into the DS signal. This process requires a very sharp filtering, say, 50dBdB, at the upper edge of the FDX band (684MHz). FDX band occupies from 108MHz to 684MHz, above 684MHz, there could be

QAM/video signals, the guard band between FDX and QAM/video signal is only 2MHz. Achieving 50dB filtering with 2MHz guard band at 684MHz is difficulty and requires lots of DSP processing if even possible.

The analog EC at input port operates the same way as the analog EC at output ports.

The EC circuitries contains lots of ADCs and DACs. Their functions are as follows:

- DAC1: The DAC for the DS transmitted signal (108MHz -1218MHz)
- DAC2: The DAC used to generate the canceling signal for the feedback signals. It suppresses the DS signal in the feedback signals so the majority of the feedback signals will be the noises of the launching amplifiers. This scheme allows better use of the dynamic range of ADC1 and ADC2 for the launch amplifier noises.
- DAC3: The DAC used to generate the cancelling signal for analog EC at output port
- DAC4: The DAC for the US transmitted signal
- DAC5: The DAC used to generate the cancelling signal for analog EC at the input port
- ADC1: The ADC used for the feedback signal of port 1
- ADC2: The ADC used for the feedback signal of port 2
- ADC3: The ADC used for the US received signal
- ADC4: The ADC used for the DS received signal
- C1: The EC coefficients for the cancelling signal for the feedback signals of the output ports
- C2: The EC coefficients for the cancelling signal for the analog EC for the output ports
- C3, C4 and C5: The EC coefficients for the cancelling signals for the digital EC for the output ports
- C6: The EC coefficients for the cancelling signal for the analog EC for the input port

$\tau 1$: The delay added in the forward path to ensure the symbol alignments among all the signals for the purpose of EC at the output ports

$\tau 2$: The delay added in the reverse path to ensure the symbol alignments among all the signals for the purpose of EC at the input port. Other purpose of $\tau 2$ is to match the delays of DS and US signals within FDX amplifier to ensure the delay symmetry of DS and US traffics.

The architecture and the list of the devices are illustrated for two output ports. In the case of three or four output ports, the architecture and DSP functions remain the same , but the number of devices need be updated accordingly.

8. The impacts of FDX amp on overall FDX operation

FDX amplifier allows FDX operation in N+M (M>0) network. FDX operation relies on the sounding scheme for IG discovery, and the FDX gain is realized through multiple IGs. N+0 network was assumed when FDX operation was originally defined and specified. Since N+M (M>0) differs considerably from N+0 in terms of topology and how the signals are distributed cross the network, we need to exam if any limitations/implications are introduced to the FDX operation when FDX operation is extended from N+0 to N+M (M>0).

8.1. Sounding

The purpose of sounding is to sort out the interferences among CMs. There are two sounding methods specified in FDX DOCSIS:

1. Sounding with OFDMA Upstream Data Profile (OUDP) test bursts;
2. Sounding with narrow band CW tone test signals

During the sounding, one or multiple CMs, the test CMs, send the sounding signals, and other CMs, the measuring CMs, will measure the DS signal quality RxMER and report back the measured MER to the MAC in the headend. Based on the reported RxMER, the scheduler can sort out the interferences among CMs, and define proper interference groups (IGs).

The function of FDX amplifier is to enhance the power levels of the bi-directional RF signals with fixed gains, and once configured, the gains are fixed regardless of physcial attributes of the RF signals (power level, wide band OFDM/OFDMA signals or narrow tones). FDX amplifier has no impacts on the sounding procedure defined in the current FDX DOCSIS specifications.

8.2. Interferences among CMs cross FDX amplifier

There are interferences among CMs cross the FDX amplifier. To illustrate this, lets define two groups of CM as illustrated in Fig.10: the CMs before FDX amplifier denoted as a green bubble, and CMs after FDX amplifier denoted as a blue bubble.

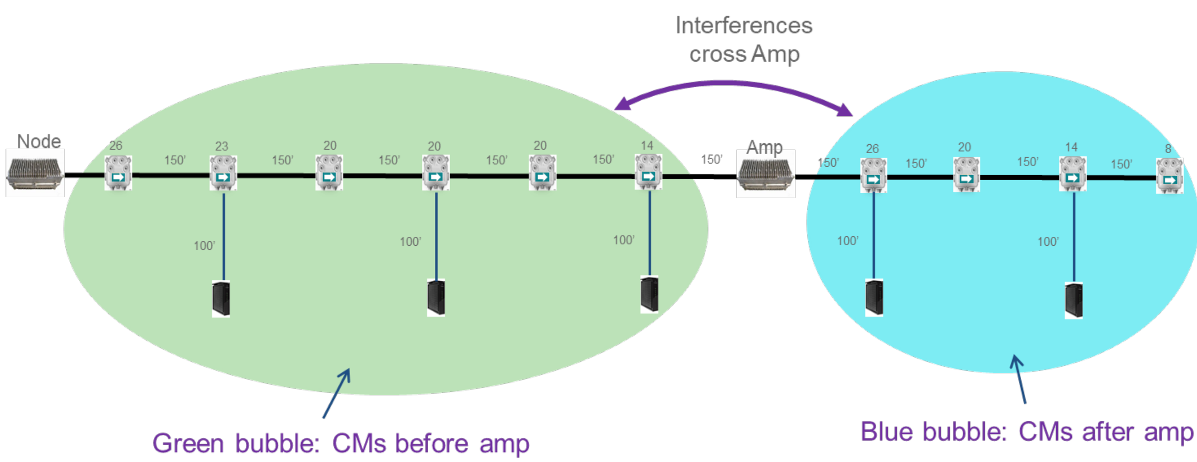

Figure 10 - Interferences among CMs cross FDX amplifier

When we look at the interferences among CM cross the amplifier, we could replace the amplifier with a tap and construct a corresponding N+0 network (see Fig.11). By design, the power levels of all the US signal at the input port of the amplifier should be the same as those in the corresponding N+0 network. In a sense, as far as the interferences between the blue and the green bubbles are concerned, all the CMs in blue bubble appear connecting to the last tap of the corresponding N+0. As the last few taps in a N+0 network need be in the same interference group due to the interferences among them, the CMs in the blue bubble after amplifier need be in the same IG of the last few CMs in the green bubble before amplifier.

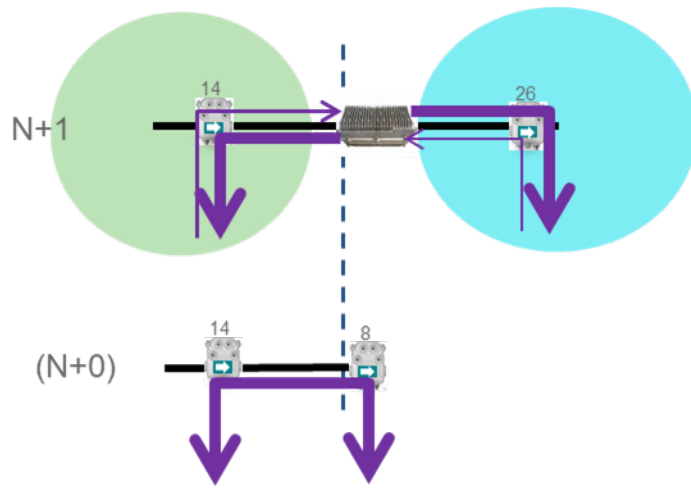

Figure 11 - The N+1 network and its corresponding N+0 network

This leads to the IG expansion: as all the CMs after FDX amplifier (the blue bubble) will interfere with the last few CMs before FDX amplifier (the green bubble), they need be in the same IG. The size of the last IG before the amplifier is expanded to include all the CMs after amplifier (Fig.12).

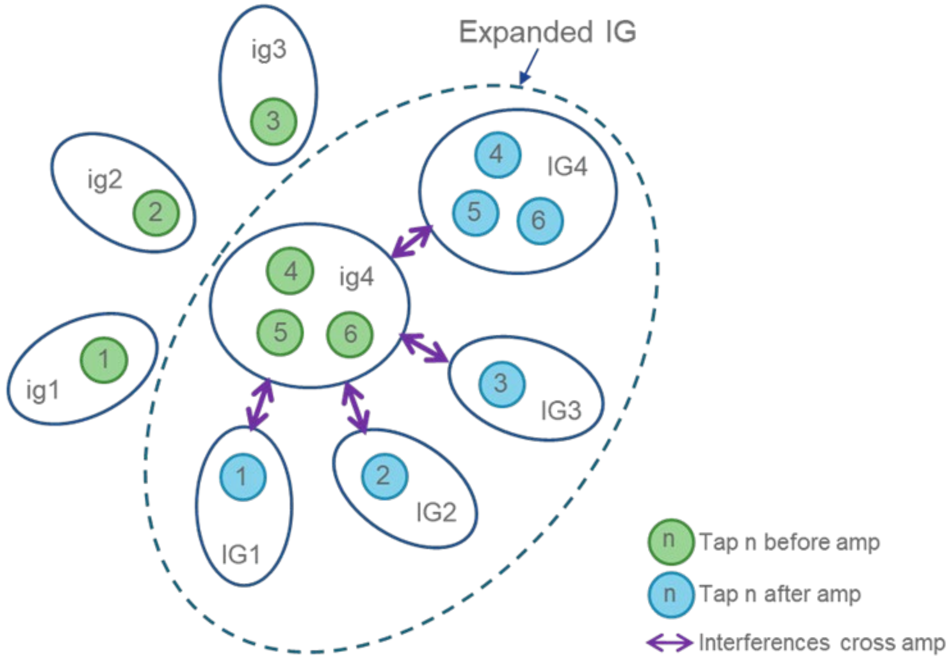

Figure 12 - IG expansion due to the interferences among CMs after the FDX amplifier and the last few CMs before the FDX amplifier

The IG expansion goes further with the layers of FDX amplifier. In the case of N+M(M>0), all the CMs after the first amplifier (amplifiers are indexed from node toward CM) will be in the same IG of the last few taps before the first amplifier (Fig.13)

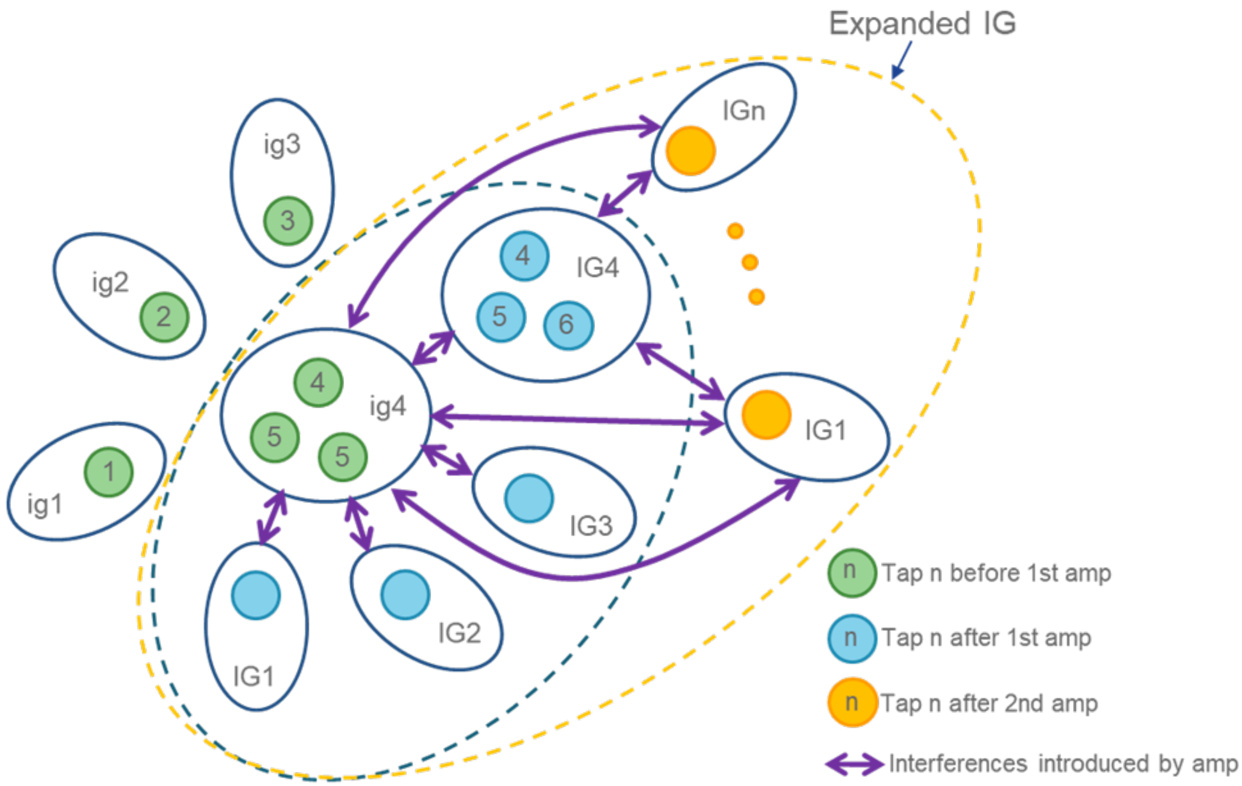

Figure 13 - IG expansions cross multiple layers of FDX amplifiers.

8.3. IG Expansion Termination

The last IG before the amplifier acts like connecting IG that merges the last IG before amp and all the IGs after amplifier into a single IG → IG expansion. IG expansion may be terminated if the taps/coupler before amp are not present, un-used or muted (reference 1). For example, in the case of N+1, the RBA can be set up in such a way that no data are sent or received on sub-band 1 and 2 for the last IG before amplifier (sub-band 1 and 2 are muted for the last IG before amplifier). This will alleviate the interference issues between the last IG before amp and all the IGs after amp on sub-band 1 and 2, and allow all the CMs after the amplifier to use sub-band 1 and 2 for FDX operation (Fig.14).

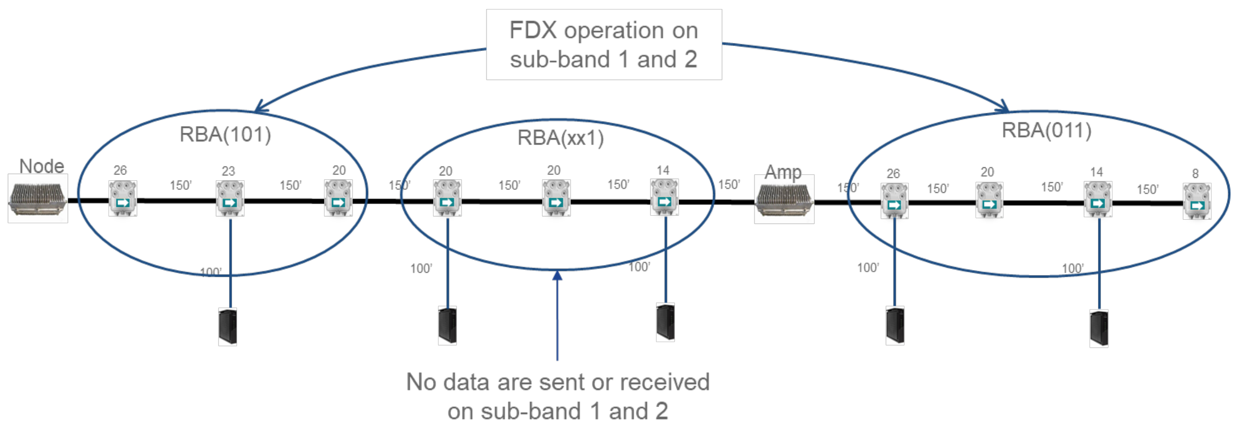

Figure 14 - An example of IG expansion termination: muting sub-band 1 and 2 of CMs before amplifier

8.4. FDX gain in N+M network

Please note: the IG expansion does not cross node ports, so the easiest way to realize FDX gain in N+M network is through CMs on multiple ports of node: CMs on different port of the node will be on different IG regardless of network topology, whether there are amplifiers or not. Typical node has 3 or 4 ports, thus allows at least three IGs; and FDX gain can be realized through three IGs.

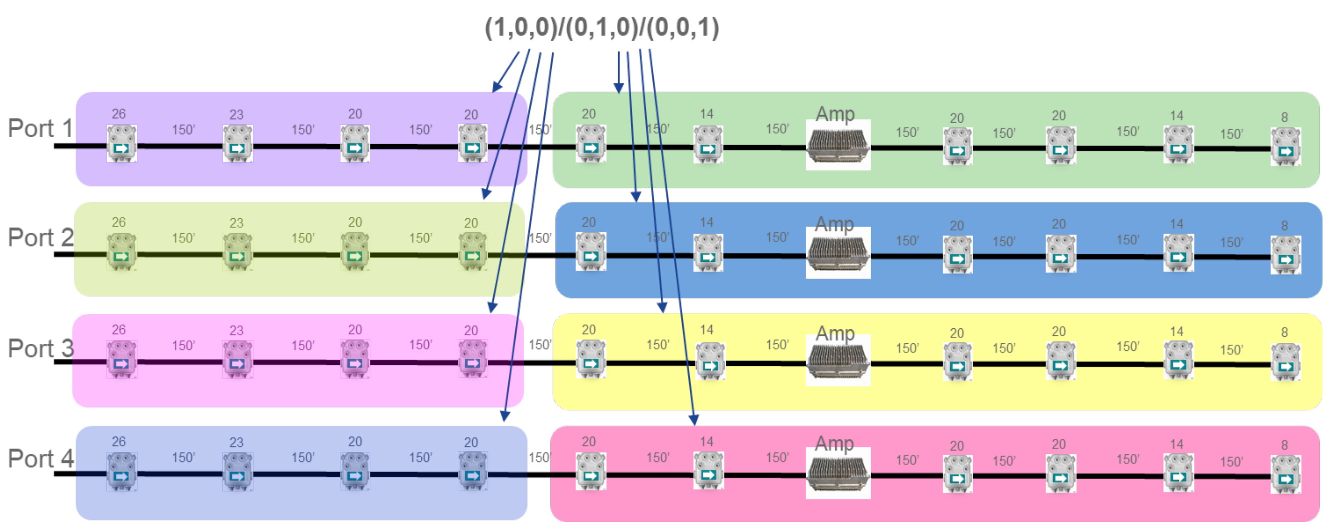

Figure 15 - FDX gain realized through multiple ports of a node

IG expansion does add some limitations on IG/TG and RBA assignment in N+M network. However, these limitations can be largely alleviated through node multiple ports and by muting IG connectors on some sub-bands. Simulations illustrate the performance of FDX operation (FDX gain) in N+M is almost the same as N+0 (reference 2).

9. Static FDX/FDD without Guard-band

In a FDX network, there may be cases where the US and DS are on the different channels/frequencies without any overlapping spectrum. For example, there may be nodes with a single output port, all the CMs attached to a single port node need be grouped into a single IG due to the IG expansion described in the previous section, the US and DS channels assignments for that IG will be on different channels. We define these cases as static FDX mode or FDD without guard-band mode (Fig.16)

Figure 16 - Static FDX/FDD without guard-band

Static FDX has no FDX gain (no spectrum re-use), but it has some benefits: static FDX allows flexible DS/US channel assignments with flexible DS/US cutover frequencies, and there is no spectrum overhead related to DS/US guard-band as static FDX does not require guard-band between DS and US.

With static FDX mode, where DS and US are on different channels, there aren't co-channel interferences. However, EC is still required to suppress the adjacent channel interferences (ACI) and adjacent channel leakage interferences (ALI). By definition, ACI is the interference caused by interferences on adjacent channel, it erodes the dynamic range of ADC by forcing ADC to leave extra headroom to accommodate the interferences on the adjacent channel (Fig.17)

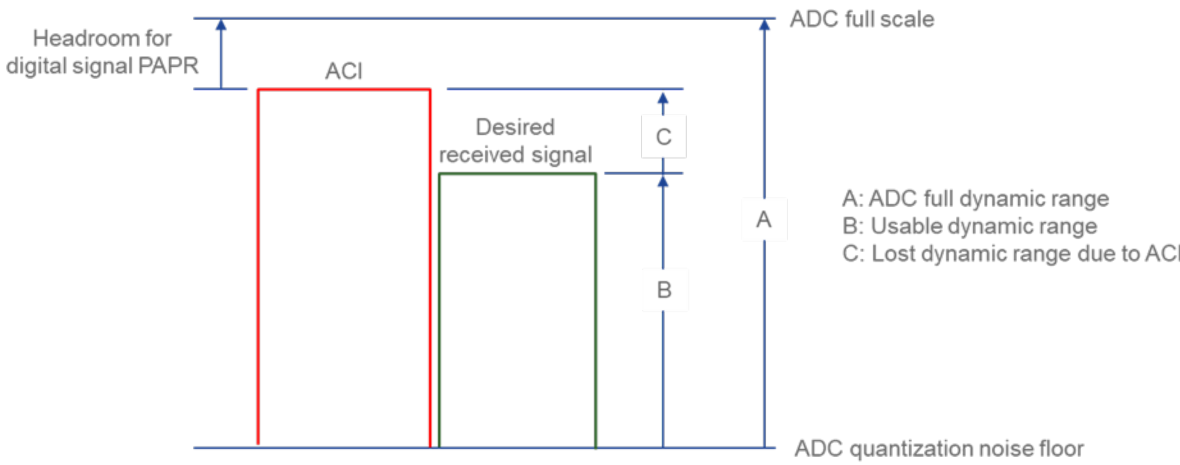

Figure 17 - ADC dynamic range reduction due to ACI

ALI results from the out-of-band leakage from the interference on the adjacent channel into the in-band signal. ALI will add the in-band noise to the received signal and degrade the signal in-band SNR. The added noise depends on the signal level of the out-of-band emission of the interference on the adjacent channels (Fig.18).

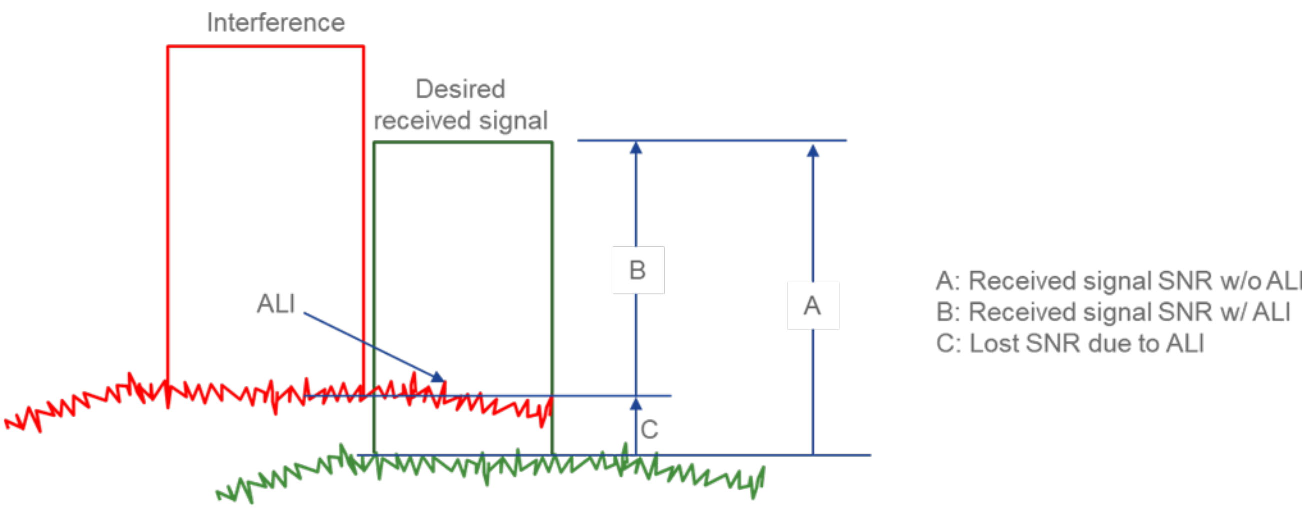

Figure 18 - In-band SNR degradation due to ALI

10. EC gains required in static FDX

To fully utilize ADC dynamic range and protect received signal in-band SNR, EC are required to suppress the ACI and ALI. In the case of ACI suppression, the interferences on adjacent channels need be reduced in power by EC so they have little impacts on the ADC dynamic range. Typically, the power level of the interference needs be 6dB below the received signal level. For ALI suppression, the out-of-band emission that is leaked from the interference on the adjacent channel needs be suppressed so the targeted in-band SNR is met for the received signal.

10.1. EC gain for US receiver at output port

We could estimate the EC gains based on FDX amplifier RF specification given in Table 2. Consider the following static FDX channel assignments (worst case): US traffics on sub-band 1 & 2, and DS traffics on sub-band 3. The DS power level varies from 43.4dBmV on 492MHz to 46.7dBmV on 684MHz, all given in 6MHz channel bandwidth. Assume the echo power is 20dB down from the transmitted power (-20dB reflection), the echo power at the US receiver is 23.4dBmV to 26.7dBmV, in 6MHz. If the US received power is assumed 5dBmV/6.4MHz, the echo on sub-band 3 needs be suppressed by ~25dB so its adverse effect on ADC can be largely eliminated. This leads to 25dB EC gain required for ACI suppression.

For EC gain required for ALI suppression, we use the same channel configuration described above (worst case) and assume the out-of-band emission leaked from DS transmitted signal on sub-band 3 is least 43dB below the echo power itself. In this case, 25dB suppression to ALI should push the power level of the leaked interference 48dB below the US received signal (5dBmV vs -43dBmV). 25dB EC gain is adequate for ALI suppression.

10.1. EC gain for DS receiver at input port

A similar methodology is used to estimate the EC for the DS receiver at the input port for the case of static FDX/FDD without guard-band. Use the following static channel configuration (worst case): US on sub-band 1&2, and DS on sub-band 3. The FDX amp RF specification given in Table 2 are used for echo power estimation. The US power level varies from 30dBmV on 108MHz to 35.3dBmV on 492MHz, all given in 6.4MHz channel bandwidth. Assume the echo power is 20dB down from the transmitted power (-20dB reflection), the echo power at the DS receiver is 10dBmV to 15.3dBmV, in 6.4MHz. if the DS received power is assumed 5dBmV/6MHz, the echo on sub-band 1&2 needs be suppressed by ~15dB so its adverse effect on ADC dynamic range can be eliminated. This leads to 15dB EC gain required for ACI suppression on the input port.

As the US transmitted TCP is 54.3dBmV (Table 2), a linear class-A amplifier can be used as the US launch amplifier to achieve >55dB in-band SNR. In this case, the out-of-band emission leaked from US transmitted signal into DS will be at least 45dB below the DS signal in the worst case. It is not necessary to implement EC at the input port for ALI suppression.

11. EC System architecture for Static FDX

The EC DSP architecture in the static FDX/FDD without guard-band mode looks similar to but has different performance requirements than the full FDX mode. For output ports, both analog EC and digital EC are implemented. The analog EC is used to suppress the ACI, and ACI suppression needs be >25dB. The digital EC is used to suppress the ALI, and ALI suppression needs be >25dB. As the digital EC is intended to suppress the noise of the transmitter, the DS signal reference in digital EC is an optional (Fig.19). It is needed only in the case where the feedback signal contains some residue of DS signal. For input port, only analog EC is required to suppress ACI. The ALI is avoided by using a linear class-A amplifier for the US launch amplifier so its out-of-band emission on adjacent channels is at least 55dB below its transmitted signal.

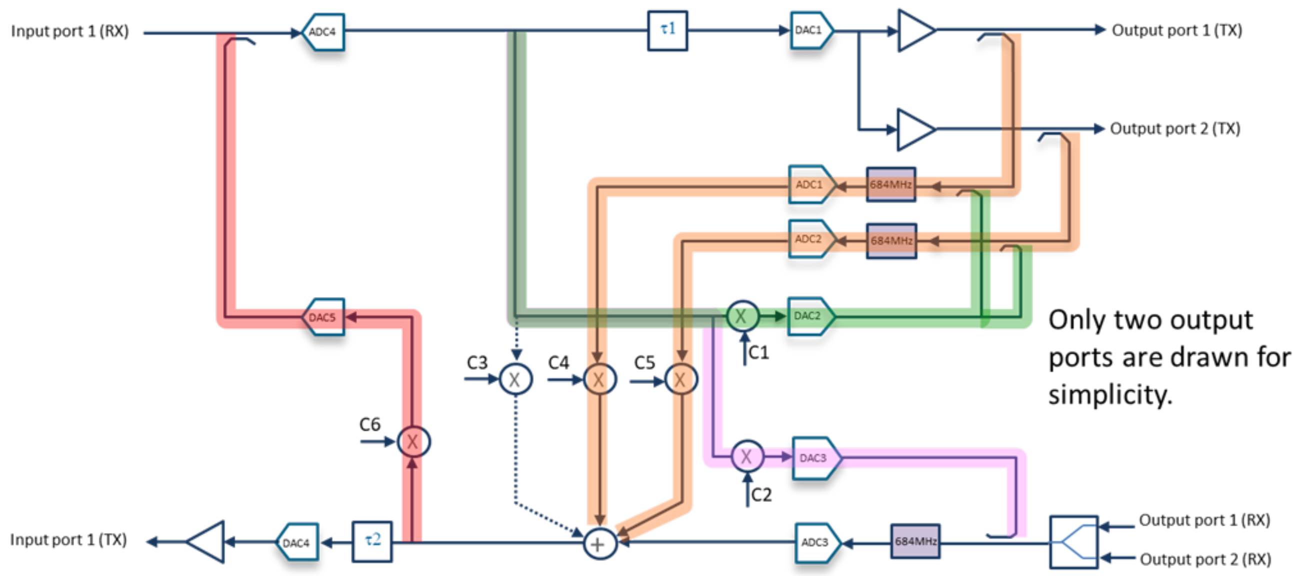

Figure 19 - FDX amplifier DSP architecture in static FDX/FDD without guard-band mode

.

Conclusion

Both full FDX and static FDX/FDD without guardband amplifier require to implement back-on-back EC and share a similar DSP/hardware architecture.

But the required EC gains are substantially relaxed when FDX amplifier operates in static FDX/FDD without guardband mode.

In full FDX mode, DS/US traffics are overlapping, EC in FDX amplifier is used to suppress CCI. The required EC gains are >50dB.

In static FDX/FDD without guardband mode., DS/US traffics are on adjacent channels, no overlapping, EC is used to suppress ACI and ALI. The required EC gains are 25dB for output ports and 15dB for input port, respectively.

Abbreviations

ADC	analog to digital converter
CM	cable modem
CMTS	cable modem termination system
DAC	digital to analog converter
dB	decibel
DOCSIS	Data Over Cable System Interface Specification
DS	downstream
EC	echo canceller
ERL	echo return loss
ERLE	Echo return loss enhancement
FDD	frequency division duplex
FDX	full duplex
Gbps	gigabits per second
HFC	hybrid fiber-coax
HPF	high pass filter
Hz	Hertz
IG	interference groups (used in FDX DOCSIS)
ISBE	International Society of Broadband Experts
LE	line extender (one port HFC amplifier)
LPF	low pass filter
Mbps	Megabits per second
N+0	node plus zero amplifiers
N+M	node plus amplifiers with a depth of M
NF	noise factor
OFDM	orthogonal frequency division multiplexing
PMA	Profile management application (used in DOCSIS 3.1)
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying
RPD	Remote PHY Device
SCTE	Society of Cable Telecommunications Engineers
SNR	signal to noise ratio
TCP	total composite power
TG	transmission groups (used in FDX DOCSIS)
US	upstream

References

Reference 1: IG in N+M FDX Network, Hang Jin, May 22nd, 2019 (presentation in Cablelabs FDX Amplifier Working Group)

Reference 2: Impact of IG Expnasion In N+M Network, Tong Liu and Hang Jin, June 5th, 2019 (presentation in Cablelabs FDX Amplifier Working Group)