Echo Cancellation Techniques for Supporting Full Duplex DOCSIS

A Technical Paper Prepared for SCTE/ISBE by

Hang Jin
Distinguished Engineer
Cisco Systems
2200 E Pres. George Bush Turnpike, Richardson, TX75082
469-255-2666
hangjin@cisco.com

John Chapman
CTO, Fellow
Cisco Systems
3700 Cisco Way, SAN JOSE, CA 95134
408-526-7651
jchapman@cisco.com

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Introduction

Full duplex (FDX) DOCSIS® allows the downstream and upstream to use the same radio frequency (RF) spectrum at the same time, leading to ~100% increase of spectral efficiency. With FDX DOCSIS, the upper band edge of the upstream spectrum can be extended beyond 204 MHz, leading to five to10 times increase in upstream throughput. The downstream throughput is also increased as the use of FDX DOCSIS can eliminate the crossover band of current frequency division duplex (FDD) systems and push the low band edge of the downstream below 258 MHz. Using the 10 MHz to 1.2 GHz spectrum, full duplex DOCSIS has the capability to provide 10 Gbps throughput for the downstream and 5 Gbps throughput for the upstream.

As the downstream and upstream spectrums overlap in FDX DOCSIS, interference occurs between transmission and reception. Thus, interference mitigation is a key enabler for supporting FDX DOCSIS. Echo cancellation (EC) is required in FDX systems to suppress the interference that is coupled or leaked from the transmitter to the receiver as they operate on the same frequencies. Cisco invented and prototyped FDX DOCSIS echo cancellation algorithms, and demonstrated them in August 2016 at the CableLabs Summer Conference.

This paper explains the types of interference that occurs in FDX DOCSIS operation and the corresponding echo cancellation techniques required. The paper is organized as follows. Section 1 explains the basics of FDX DOCSIS operation. Section 2 explains the challenges with FDX DOCSIS operation: the interference from transmitter to receivers and the interference among cable modems (CMs). Interference cancellation must be implemented for supporting FDX DOCSIS operation. Section 3 explains the network topology for supporting FDX DOCSIS. The details on the interference types and the corresponding echo cancellation techniques are given in 4-7. Section 8 explains the echo cancellation lab prototype system and test results, and Section 9 explains the live FDX DOCSIS proof of concept (PoC) demonstration system.

Content

1. FDX DOCSIS: The Continuing Innovation

Today cable access (DOCSIS) employs frequency division duplex. With FDD, the usable frequency spectrum is divided into non-overlapping downstream (DS) and upstream (US) spectrums and a crossover spectrum in between (Fig. 1).

Figure 1 - FDD frequency split

There are three frequency divisions, so called frequency splits, in use today: low split, mid split and high split (see Table 1). DS traffic from the cable modem termination system (CMTS) to CMs is sent in the DS spectrum, and US traffic from CMs to the CMTS is sent in the US spectrum. This FDD DS and US frequency division is completely overthrown in FDX DOCSIS: Both DS and US traffic can use the same spectrum at the same time, resulting in doubling the spectrum usage efficiency as the same spectrum is used simultaneously for DS and US traffic. (Fig. 2).

Table 1 - Frequency splits

	US Spectrum	crossover	DS spectrum
Low split	5 MHz-42 MHz	42 MHz-54 MHz	54 MHz-1218 MHz
Mid split	5 MHz-85 MHz	85 MHz-108 MHz	108 MHz-1218 MHz
High split	5 MHz-204 MHz	204 MHz-258 MHz	258 MHz-1218 MHz

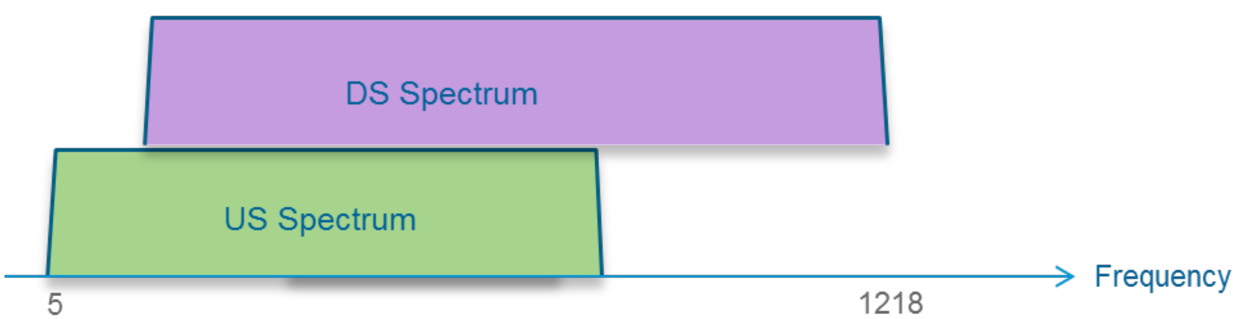

Figure 2 - FDX concept

Compared to today's FDD DOCSIS, FDX DOCSIS has a clear advantage: It 'creates' frequency spectrum for US traffic without sacrificing the frequency spectrum for DS traffic. Today's coaxial network has roughly 1.2 GHz of usable spectrum (limited by the attenuation of the taps installed in the field, which have a sharp roll off around 1.2 GHz). Given this fixed 1.2 GHz of usable spectrum in the coax network, increasing the US spectrum will reduce the DS spectrum if FDD is used. FDX DOCSIS allows DS and US traffic overlap on frequencies, effectively doubling the usable spectrum of the coax network to 2.4 GHz.

Cable operators have been working on increasing the US spectrum in order to keep up with user data demands and stay ahead of the competition. Most of the networks deployed today are either low split, which has 37 MHz total US spectrum, or mid split, which has total 80 MHz US spectrum. 37 MHz or 80 MHz US spectrum is definitely not enough to provide acceptable user experiences given the US spectrum needs be shared among dozens or even hundreds of users. Migrating the frequency plan to high split will increase the US spectrum to ~200 MHz, which may ease some of the US data congestion, but migrating to high split not only results in CAPEX, but also the obstacles of 75 MHz/107 MHz out-of-band (OOB) signals: one needs to creates a "jumper" in the middle of the US spectrum at every active device to allow the DS OOB signals to propagate from the headend to customer premises equipment (CPE) (Fig. 3).

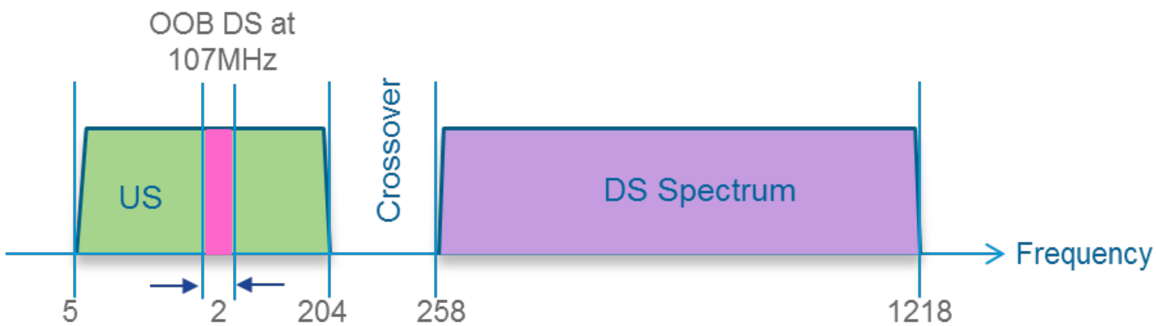

Figure 3 - OOB issue with high split

FDX DOCSIS has a completely new paradigm to solve the US spectrum shortage: it extends the upper edge of US spectrum to as high as 1.2 GHz without taking away any spectrum from the DS. As FDX DOCSIS still operates in the frequency range of 5 MHz to 1.2 GHz, no taps in the field need be replaced. US spectrum in FDX operation can be allocated as high as 1.2 GHz, the OOB signal can still be present at 75 MHz/107 MHz as a part of a guard-band, so no changes are required for supporting OOB signal.

2. Challenges with FDX DOCSIS

While it provides all the benefits, FDX DOCSIS presents many implications and design challenges. The biggest challenge among them is the interference from transmitter to receiver at the CMTS (RPD node) and among CMs.

2.1. Interference from transmitter to receiver at RPD node

Since both DS and US signals use the same spectrum in full duplex operation, the transmitted and received signals will overlap in frequency and time. The transmitted DS signal has a much higher signal level than the received US signal, and the leakage or coupling from the transmitter to the receiver will become co-channel interference and may completely wipe out the received US signal if there is not sufficient isolation between the transmitter and the receiver. The co-channel interference from transmitter to receiver is one of the hurdles that needs be overcome to make full duplex work in the coaxial network.

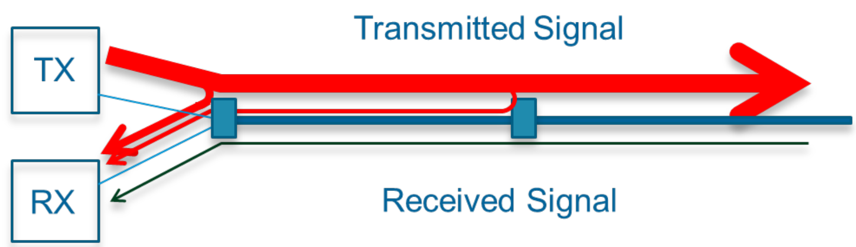

Figure 4 - Interference from transmitter to receiver

Interference from transmitter to receiver at RPD-equipped nodes needs be cancelled out through echo cancellation for supporting FDX operation.

2.2. Interference at CM

In FDX DOCSIS, the CM still works in FDD mode. Although the CM transmits and receives on different channels, there is still interference occurring at the CM. There are two types of interference at the CM: self-interference and interference among CMs (neighboring CMs).

2.2.1. CM self-interference

Although the CM transmits and receives on difference channels, CM self-interference can occur when a CM transmits and receives at the same time. The out-of-band spurious emissions of the transmitted channel may couple and leak into the received channel and become co-channel interference, thus increasing the noise floor of the received signal. Also, the transmitted signal coupled into the receiver may have much higher power than the desired DS signal and saturate the receiver front end.

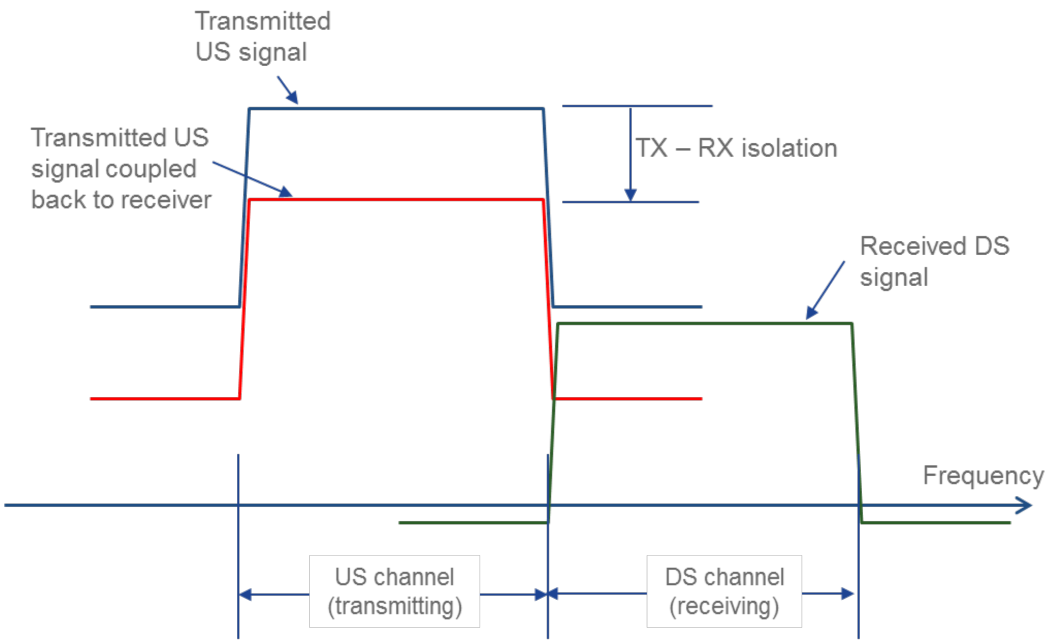

Figure 5 - Interference at CM (CM self-interference)

CM self-interference needs be cancelled out through echo cancellation.

2.2.2. Interference among CMs

Interference could occur among CMs. For example, CM1 is on tap 1 and transmitting on channel 1, and CM2 is on tap 2, receiving on the same channel (channel 1). The transmitted signal from CM1 on channel 1 may leak into CM2 and impair CM2's reception on channel 1, if there is not sufficient isolation between CM1 and CM2.

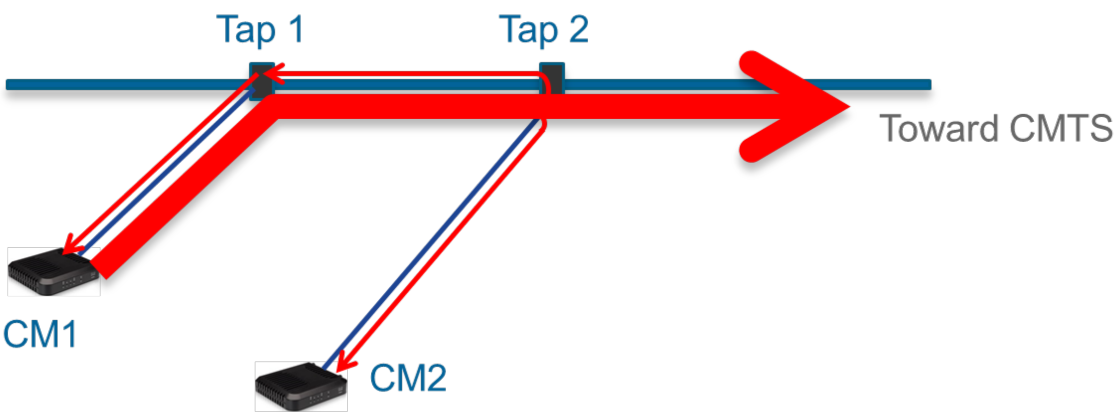

Figure 6 - Interference among CMs

Interference among CMs is mitigated through smart scheduling: schedule the DS and US channel allocations among CMs in such a way to better leverage the isolation among CMs so there is no or little interference among CMs that are transmitting and receiving on the same channel. The nutshell of this smart scheduling is to avoid allocating overlapping DS and US channels to CMs that may interfere with each other. For details on this interference avoidance scheduling, please see reference [1].

3. Network topology for FDX DOCSIS

Technically, FDX DOCSIS could work with any network topology as long as one could develop FDX nodes as well as FDX bi-directional amplifiers. Bi-directional amplification of FDX signals results in bi-directional interference: the output of the DS transmitter will interfere with the reception of the US receiver, and similarly, the output of the US transmitter will interfere with the reception of the DS receiver. This will require bi-directional echo cancellation on both DS and US paths, and ensure the total interference cancellation of the complete loop will be greater than the closed loop gain of the amplifier. Designing FDX amplifiers presents a great challenge on an echo cancellation scheme and RF design.

The assumption today is that N+0 network topology is required for supporting FDX operation to avoid the implications related to FDX amplifiers (design challenges, active amplifiers in the field).

3.1. N+0 network topology

N+0 means there are no active amplifiers between the R-PHY node and CMs. The coax and taps between the R-PHY node and CMs are all passive RF components and can support bi-directional RF signal transmission according to Lorentz reciprocity theorem. The only changes required for supporting FDX are in the R-PHY node and CM. This will avoid expensive upgrade or replacement of the coax and taps already deployed in the field.

4. Interference in FDX operation

In this section, we list and discuss all the interference sources and their power levels in a FDX DOCSIS system.

The interference sources and their power levels are different in the RPD node and CM.

4.1. Interference sources at RPD node

With FDX operation, the DS and US are overlapped in time and frequency, so at the RPD node, the DS traffic may couple from the transmitter into receiver and become co-channel interference to the received signal. This co-channel interference may come from multiple sources (Fig. 7)

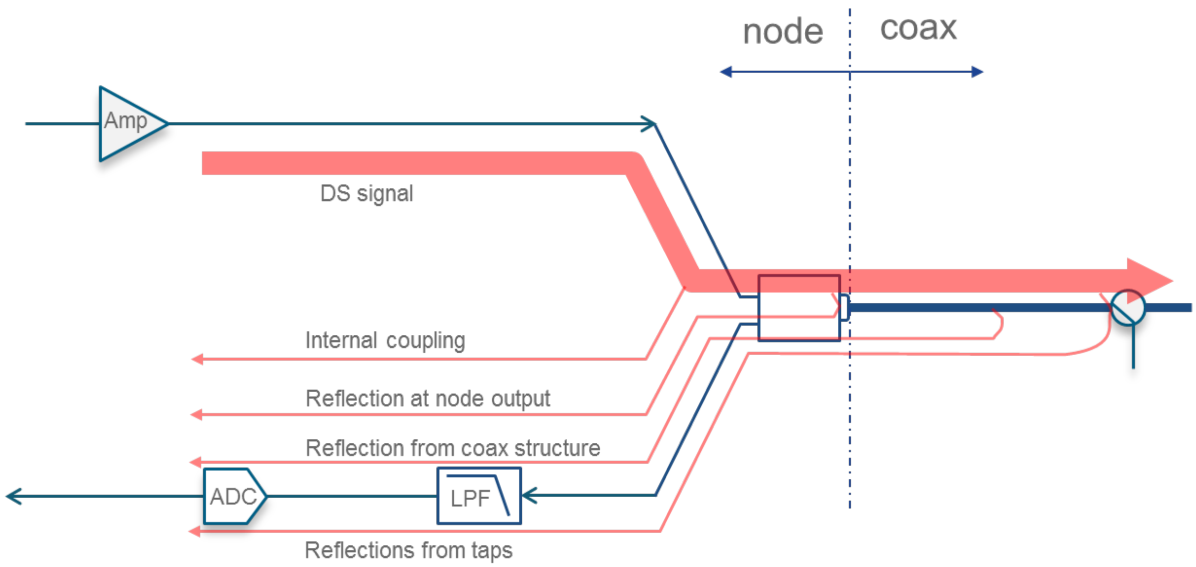

Figure 7 - Interferences in FDX node

4.1.1. RPD internal coupling

The internal coupling is caused by limited isolation between the transmitter and receiver paths. This also includes the coupling between the transmitter and receiver ports of the three port device used to connect the transmitter and receiver to the coax (the common port). Typically this is a directional coupler with limited isolation between the input and coupled ports.

4.1.2. Reflection at node output

The node output has a limited return loss, depending on the type of connector and its quality. Any reflection of the DS signal at the node output will become co-channel interference at the receiver.

4.1.3. Reflection from the taps

Each tap has a limited return loss. All the taps deployed in the field have >23 dB return loss, per published tap specs. Reflections of the DS signal at taps will go toward the US direction, experience the path loss between the taps where the reflections occur and the node input port, and become co-channel interference to the receiver. A long cable between the tap and the node will help reduce the power level of the tap reflection received at the node receiver.

4.1.4. Reflection from coax discontinuities (coax structure reflection)

There are reflections caused by discontinuities in the coaxial cable itself: the coaxial cable structure imperfections cause reflections. The structure imperfections could be the inhomogeneous nature of the dielectric or the inner conductors and outside shields. The reflections resulting from the coax structure imperfections are small in power compared to the reflections from other sources, but they spread over much large time intervals.

4.2. Interference power levels

The interference power levels are different for different sources. The reference point used for interference level is the node input port (node interface D)

4.2.1. RPD internal coupling

This is the internal coupling within RPD. The general design guidance is to reduce the interference due to internal coupling to a negligible level compared to that of the interference from other sources. The dominant interference occuring within the RPD may result from coupling between the transmitter and receiver ports of the three port device used to connect the transmitter and receiver to the coax (the common port). A minimum of 40 dB isolation between the transmitter and receiver ports is preferred.

4.2.2. Reflection at node output

This is the internal reflection at the node output. The same principle is applied here: to reduce the internal reflection from the output port to a negligible level compared to that of interference from other sources.

One may sum up all the interference from all the internal sources (internal coupling and internal reflection) and specify its level to be X dB below the DS output power. With 72 dBmV total composite power (TCP) node output power, the interference level from internal coupling and reflection will be 72 - X dBmV (208 MHz to 1218 MHz). X>35 is preferred.

4.2.3. Reflection from the taps

Assuming 23 dB tap return loss, the reflection from the tap will be 23 dB below the DS transmit signal in power. Assuming 2 dB loss each way in the initial feeder (~100 ft express cable), and 72 dBmV TCP node output power, the reflection at the node input will be 72 – 23 – 2 x 2 = 45 dBmV (108 MHz to 1218 MHz).

4.2.4. Reflection from coax discontinuities (coax structure reflection)

The reflection from coax discontinuities (structure reflections) are much lower than other sources. Its magnitude is much lower than the reflection from the tap as illustrated in Fig. 8. Fig. 8 is the measurement data of all the reflection sources from an actual N+0 network.

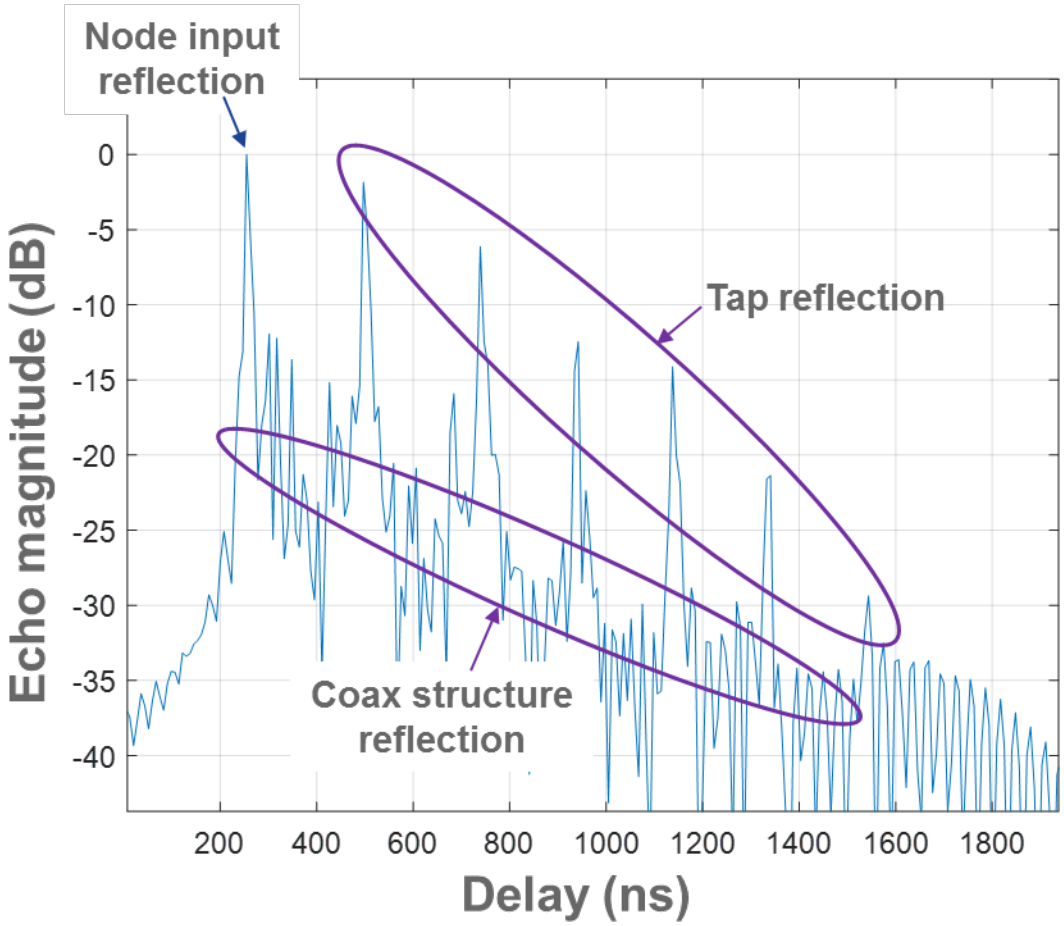

Figure 8 - Lab measured results on the reflection from passive coax network

Although the reflections from the coax discontinuities are lower in power, they can't be ignored. As indicated in Fig. 8, the reflections caused by coax discontinuities are ~20 dB below the tap reflections in magnitude, equivalently having a return loss 43 dB. Given 72 dBmV TCP node output power, with -43 dBc reflection, the reflections at the node input is about 29 dBmV (108 MHz to 1218 MHz), significantly above the thermal noise level (thermal noise power within 108 MHz – 1218 MHz ~= -30 dBmV, assuming 5 dB noise figure). The reflections from coax discontinuities must be cancelled out to ensure proper FDX operation.

4.3. Interference power level in FDX frequency spectrum

The interefrence levels computed in the previous sections are for the frequency range of 108 MHz to 1218 MHz. As the FDX frequency spectrum covers only 108 MHz to 684 MHz, a filter with a cutoff frequency at 684 MHz will be put in the receiver path to suppress the interference power above 684 MHz. Because the DS signal has a 21 dB uptilt from 108 MHz to 1218 MHz, filtering out the power in the frequencies above 684 MHz will significantly reduce the total power of the interference seen by the receiver. There is roughly 10 dB power reduction if the interference above 684 MHz is filtered out. Using the same assumptions in 4.2.3, the total power of the reflection received at the node input in the frequency range 108 MHz to 684 MHz will be 35 dBmV.

4.4. Impacts of DS uptilt

The actual reflection power level varies with the frequency as the DS transmitted signal power level varies with frequency. The power density of DS transmitted signal is not flat over the frequency spectrum, it has 21 dB linear uptilt from 108 MHz to 1218 MHz. This is because the loss of the plant at 1.218 GHz is roughly 21 dB higher than that at 108 MHz, so in order to compensate for this un-equal loss of the plant, the power density of the DS signal is pre-emphasized by uptilting the power density of the DS signal at the transmitter to make the received DS signal power density at the CM relatively flat over the spectrum.

This 21 dB uptilt of DS power density implicates the power density of the reflections received at the RPD-equipped node receiver. As in most of the cases, the dominate reflections come from the node output and first a couple of taps, the total loss does not have 21 dB of downtilt, thus the reflection received at the node receiver is still largely uptilt. This means most of the interference power is concentrated at higher frequencies. Per the FDX DOCSIS 3.1 specification, the FDX operating spectrum is from 108 MHz to 684 MHz, and three DS OFDM channels overlap with six US OFDMA channels. The interference level observed on the last OFDMA channel will be much higher than that on the first OFDMA channel, and in an extreme case (most of the reflection comes from the node output), the interference observed on the last FDX OFDMA channel could be 10 dB higher than that of the first FDX OFDMA channel as indicated in Fig. 9. To achieve the same post-EC performance, the EC must achieve 10 dB better performance on the last FDX OFDMA channel than the first FDX OFDMA channel.

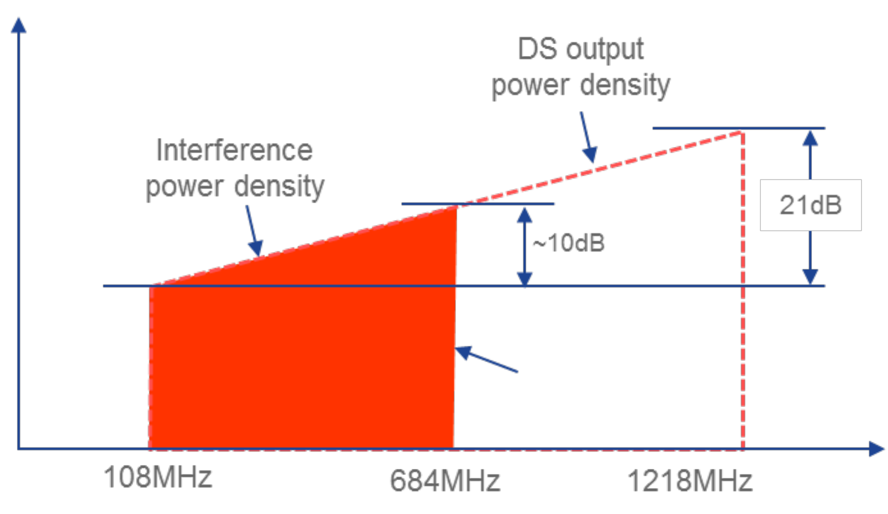

Figure 9 - The interference power density. FDX US channel 6 could see the interference power density 10 dB higher than channel 1 due to the DS signal uptilt.

4.5. Impact of interference on node receiver

The impact of the interference on the node receiver are twofold, as discussed in the next two sections.

4.5.1. Receiver dynamic range

The receiver has a limited dynamic range. The dynamic range of the receiver is mainly limited by the analog-to-digital converter (ADC). For a FDX RPD node, the frequency range of the US is from 108 MHz to 684 MHz. For this range of frequencies, a state-of-the-art ADC can achieve ~50 dB in-band modulation error ratio (MER) for an OFDMA signal with a flat power density. As indicated in Section 4.3, the power level of the reflections in the FDX frequency spectrum 108 MHz to 684 MHz can be as high as 35 dBmV. In FDX operation, the desired US signal power density is around 0 dBmV/6.4 MHz , or ~20 dBmV in the frequency range of 108 MHz to 684 MHz (all six OFDMA channels), indicating the reflection can be 15 dB higher than desired US signal in power. The receiver ADC needs to leave sufficient head room to accommodate the high reflection power level. Leaving head room for reflections will directly impact the effective MER that can be achieved with the ADC, and the achievable MER is reduced dB by dB with the head room reserved, as indicated in Fig. 10

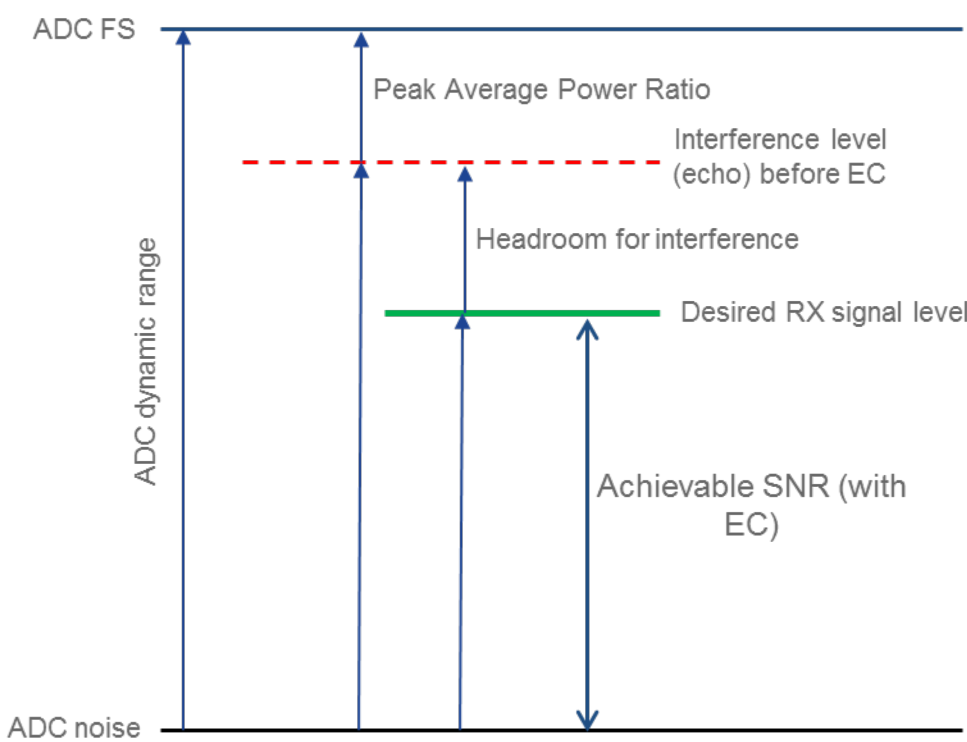

Figure 10 - ADC dynamic range, and the impact of the interference on achievable SNR

One technique to reduce the impact of the reflection on ADC dynamic range is to incorporate analog echo cancellation before the ADC. More details on this are given in Section 5.1

4.5.2. Co-channel interference

Another impact of the reflection on US receiver performance is co-channel interference. As DS and US share the same spectrum at the same time, the reflection of the DS will become co-channel interference to the US. Co-channel interference must be suppressed to a level that the targeted US MER can be met. Co-channel interference will be cancelled through a combination of analog EC and digital EC.

5. Echo cancellation

To ensure proper operation of FDX, the interference resulting from FDX operation must be suppresssed/cancelled. As the interference always occur in the form of reflection, or echoes, the interference in FDX operation will be considered as echoes, and interference suppression/cancellation will be called echo cancellation.

Two types of EC techniques can be implemented in a RPD node to cancel or suppress the echoes.

5.1. Analog EC

Analog EC cancels out the echoes in the analog domain before the ADC. Conventionally analog EC will take a copy of the DS signal, and manipulate its phase and magnitude to generate a canceling signal that has the same magnitude but 180 degrees out-of-phase from the echo. This canceling signal is then added to the receiver path to cancel out the echo. As there will be multiple echoes coming from multiple sources (node output, first tap, second tap, etc.), multiple cancelling signals need be generated, one for each echo. All these need to be done in the analog domain.

As the echoes may come from taps that are located a few hundred feet away from the node, delays are needed to add into the cancelling signals. In coax, 1 ft. distance corresponds to ~1.2 ns delay in time, to cover the actual delay of all the echoes, a delay line with a variable delay of 1 ns~500 ns is required. Also, the bandwidth of this delay line needs to be >684 MHz. Such a delay line doesn’t exist today.

The analog EC used in FDX DOCSIS is actually a hybrid solution. The cancelling is still in the analog domain before the ADC to enable the benefits of analog EC, but the cancelling signal is generated in digital domain first and then converted into analog domain through a digital-to-analog converter (DAC) (Fig. 11). All the delays and magnitudes are computed and set in the digital domain through EC digital signal precessing (DSP).

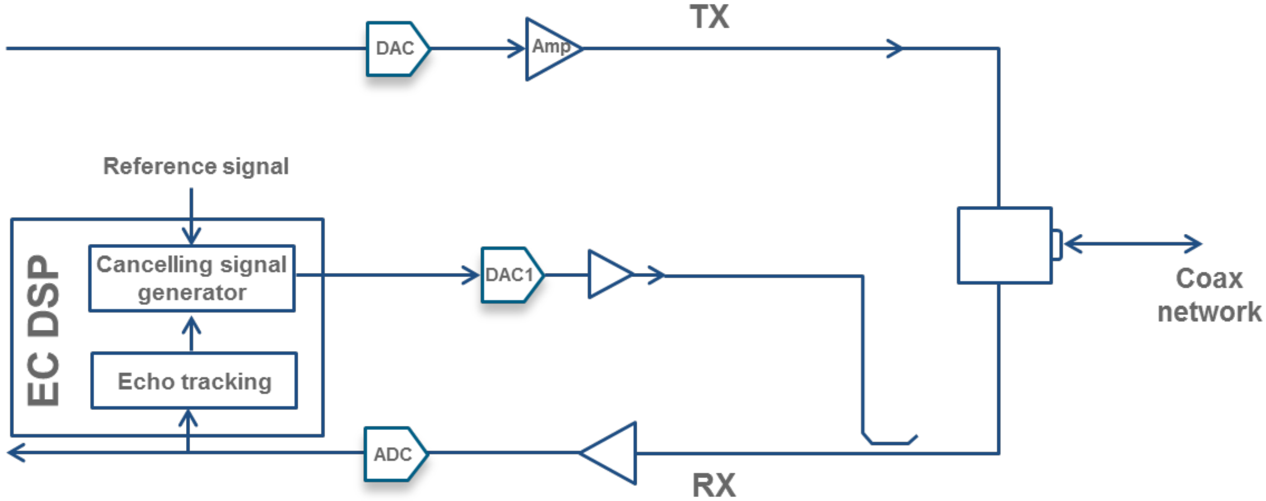

Figure 11 - Analog EC hardware architecture

5.2. Digital EC

Digital EC cancels out the echoes in the digital domain after ADC. After the echoes pass through the ADC and are converted into bits in digital domain, their magnitude and phase can be computed, and the cancelling signal can be generated from the DS reference signal with the proper magnitude and phase and subtracted from the received signal. Unlike analog EC which must be implemented in time domain, digital EC can be implemented in either time domain or frequency domain or combination of both.

5.3. Reference signal for EC

The cancelling signal is generated from the DS signal with the proper magnitude and phase computed from the echoes embedded in the received signal. The DS signal used to generate the cancelling signal is called the EC reference signal. The theoretic base of the EC (both analog and digital EC) is that all the reflections are true copies of the same DS signal, just with various magnitudes and phases, depending on how the echoes are generated. The reference signal can be taken from DS data path in the digital domain, or taken from the output of the last stage amplifier if the noise generated from node launch amplifiers needs to be taken into account in the EC algorithm.

5.4. EC performance target

Analog EC and digital EC complement each other. One can partition the total EC performance target between analog EC and digital EC. For example, the analog EC can be designed to cancel out the echoes to the extent that the ADC dynamic range is not impaired, that is, the echoes are suppressed to a level that is below the desired US signal level, and the digital EC will cancel out all the echo residue to meet the final requirements on in-band MER. As indicated in Section 4.5.1, the echo could be 15 dB higher than the US desired signal in power, one could target the analog EC to have 15 dB echo cancellation, and so that the echo after analog EC will have the same power level as the desired US signal to minimize the impact of the echo on receiver dynamic range. The digital EC then has 40 dB echo cancellation to further suppress the echo to 40 dB below the desired US signal to reach 40 dB inband MER.

5.5. EC coefficient training

To cancel out the echo, the canceling signal 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 difference between the reference and echoes embedded in the received signal. The procedure with which the EC coefficients are computed/tracked is called EC training, and the time period over which the EC is trained is called EC training period. There are two type of EC training: explicit training and implicit training.

5.5.1. Explicit training

Explicit training means there is a dedicated period of time when the EC is training. Normal system operation may be altered to facilitate the EC training. For example, the US traffic may be halted so the received signals are 100% echoes. This will help the EC coefficient computation/tracking algorithm to better compute the magnitude and phase differences between the reference signal and received echo without 'interference' by the US desired signal. Generally speaking, explicit training could lead to a simpler EC training algorithm and more accurate EC coefficients, but may impair normal system operation (for example, halt US traffic from all CMs)

5.5.2. Implicit training

Implicit training means the training is carried out without any explicit training period. With implicit training, the EC coefficient is computed/tracking in the background without impacting system operation. Implicit EC training has no impact on system operation. Implicit EC training needs to deal with the 'interference' of US traffic and usually involves a more sophisticated EC training algorithm and long training time to achieve the accuracy required.

6. Echo cancellation at CM

While most of the EC techniques explained in the previous sections can be used at both the RPD and CM, some changes or improvements to the EC techniques may be required when they are used at CM. At the node, all the echoes present as co-channel interference, while at the CM all the echoes present in a form of adjacent channel interference. This is because the RPD node the true FDX operation, that is, DS and US are completely overlapped at the RPD input/output port, but the CM still operates with frequency division duplex: its DS and US are not overlapped in frequency (ref [1]). The main reason behind this is to reduce the complexity of the CM. To support true full duplex operation, the CM receiver would need to have very high dynamic range, much higher than the RPD's, as the echo would be much higher in power at the CM than RPD. The return loss of a CM F-connector is only 6 dB per specs vs. 23 dB return loss at the tap. Supporting such a high dynamic range results in a very expensive receiver and is cost prohibitive for CMs.

Although the CM supports only FDD, there is still interference that the CM needs to cancel out. It is the interference coming from adjacent channels. More specifically, there are two types of interference at the CM: adjacent leakage interference (ALI) and adjacent channel interference (ACI).

6.1. Adjacent leakage interference

ALI occurs when a CM transmits on one channel and receives on an adjacent channel. The out-of-band spurious emission of the transmitting channel leaks into the receiving channel and cause degradation of the received signal quality (Fig. 12).

6.2. Adjacent channel interference

ACI occurs when a CM transmits on one channel and receives on an adjacent channel. The power of the transmitting channel coupled back to the receiver and causes overload/saturation of the receiver front end.

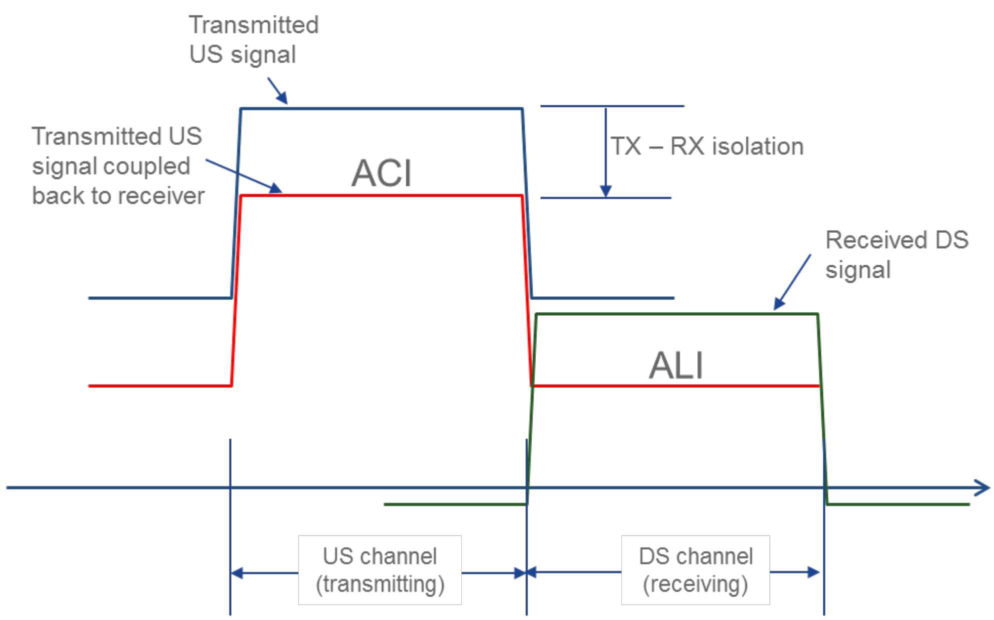

Figure 12 - Adjacent leakage interference and adjacent channel interference at CM

6.3. EC for ALI and ACI

As explained in Section 5.3, the theoretical base for EC is that all the echoes are true copies of a reference signal. The echoes can be expressed by the reference with EC coefficients in a linear space. The core algorithm of the EC is to find these coefficients, which is the same for EC used at the RPD and CM. However, as the echoes at CM all come in a form of adjacent channel interference, there are some unique requirements for EC at CM:

6.3.1. EC for ALI

To cancel out ALI at the CM, the reference used in EC must be the spurious noise generated by the transmitted signal on adjacent channels. This requires either using a reference from the output of the transmitter or predict the noise through an amplifier nonlinear model.

6.3.2. EC for ACI

As the ACI impacts on the receiver front end, the EC for ACI needs be implemented in the analog domain before the front end receiver AGC.

7. Summary on EC

In summary, EC is required at the RPD node to cancel out co-channel interference, and the EC can be implemented in the analog or digital domain or combination of both. While the analog EC must be implemented in the time domain, the digital EC can be implemented in the time domain or frequency domain or combination of both. EC is also required at the CM to cancel out ALI and ACI. The EC technique for ALI is similar to that used at the RPD node, but the difference is that the reference used to cancel out ALI at CM is the spurious emission of CM transmitter. EC for ACI needs be implement in the analog domain before receiver front end AGC.

8. Full duplex EC lab prototype system

A full duplex EC lab prototype system was built to validate the EC algorithm at the RPD node for supporting full duplex operation.

The system consists of three main components (Fig. 13):

1. The transceiver that emulates the RPD node:
   a) It transmits three OFDM channels in the frequency range 108 MHz to 684 MHz
   b) It receives six OFDMA channels in the frequency range 108 MHz to 684 MHz (overlap with the three DS OFDM channels)
   c) It contains an EC function block sitting in front of the receiver demodulator

2. The transmitters that emulate CMs (CM1 and CM2, transmitting only)
   a) CM1 transmits three OFDMA channels in the frequency range 108 MHz to 396 MHz
   b) CM2 transmits three OFDMA channels in the frequency range 396 MHz to 684 MHz

3. The coax network between the emulated RPD and CMs.
   a) Three sections of Series 6 cables, each section 100 ft. long.
   b) The tap values are 26 dB (first tap), 14 dB (second tap) and 8 dB (last tap)
   c) The CMs are connected to the last tap
   d) The total loss between node and CM is ~35 dB.

DS traffic conforms to DOCSIS 3.1 DS frame, but the payload is random data. US traffic conforms to DOCSIS 3.1 US frame but the payload is random data.

The RPD node continuously transmits DS traffic with output TCP = 73.8 dBmV (63 dBmV between 108 MHz and 684 MHz), and at the same time receives US traffic from the CMs. US MER is computed from the constellation after the EC and channel estimation. For all six US OFDMA channels, >37 dB post-EC MER is achieved.

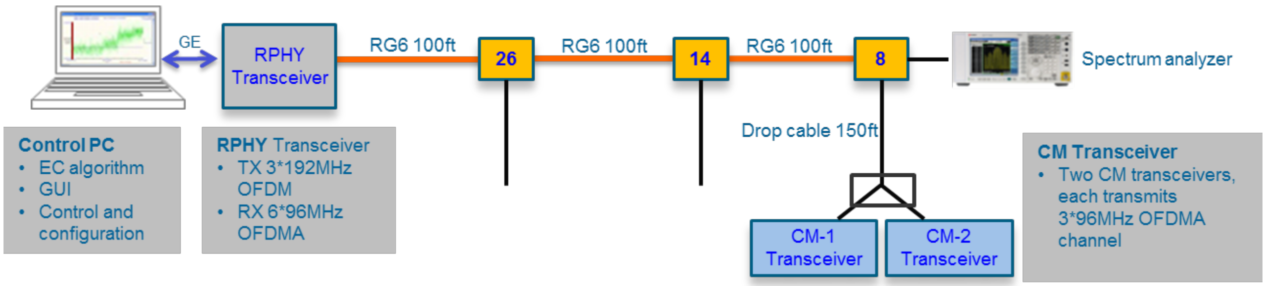

Figure 13 - FDX EC lab prototype system (block diagram)

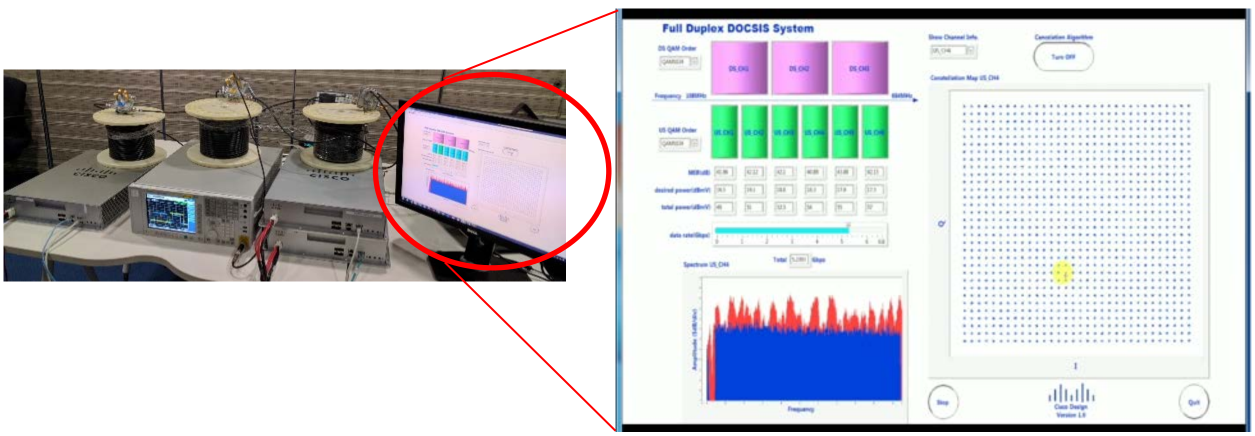

Figure 14 - FDX EC lab prototype system (Actual hardware)

9. FDX DOCSIS live demo system

Cisco partners with Intel and conducted a live demo of FDX DOCSIS at ANGAearlier this year. The system consisted of all essential boxes required in a real system: CMTS (cBR-8), R-PHY node, CMs and coax network to emulate N+0 network. The FDX operation used frequencies between 108 MHz and 204 MHz (one 96 MHz channel). CMs used in the demo were normal DOCSIS 3.1 CMs, and their US transmission frequency was limited to 204 MHz. One of the CMs was configured as low split, receiving DS traffic on 108 MHz to 204 MHz, and the other was configured as high split, transmitting US traffic on 108 MHz to 204 MHz. There was also one DS QAM channel at 300 MHz as the primary DS channel, and one US QAM channel at 8 MHz as the primary US channel.

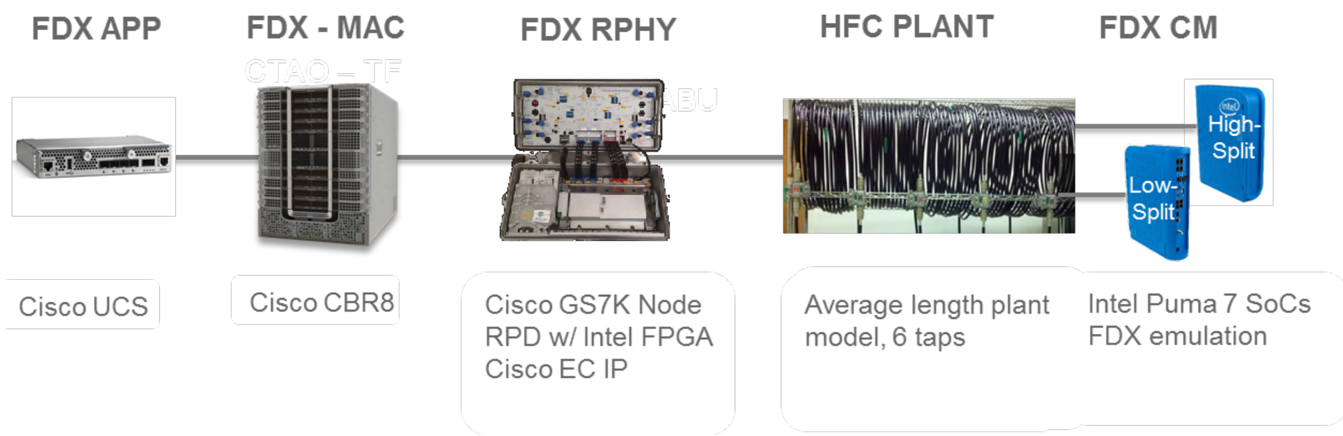

Figure 15 - FDX DOCSIS live demonstration system

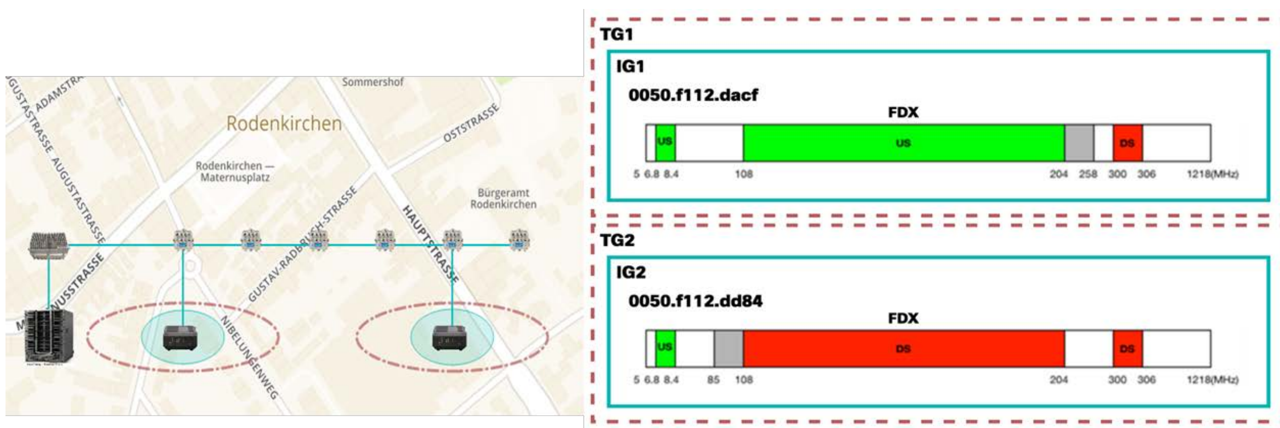

Figure 16 - FDX DOCSIS live demonstration system – network and channel configurations

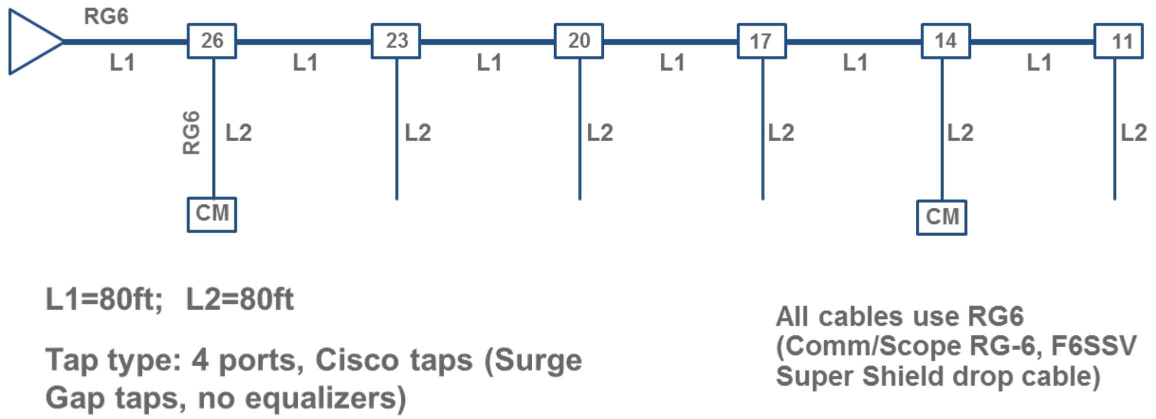

Figure 17 - FDX DOCSIS live demonstration system – plant model

The DS supported 4096-QAM and the US supported 1024-QAM. The US pre-EC MER is -2 dB, and post-EC MER is 37 dB. With a 96 MHz FDX channel, DS throughput achieved ~940 Mbps, and US throughput achieved ~620 Mbps.

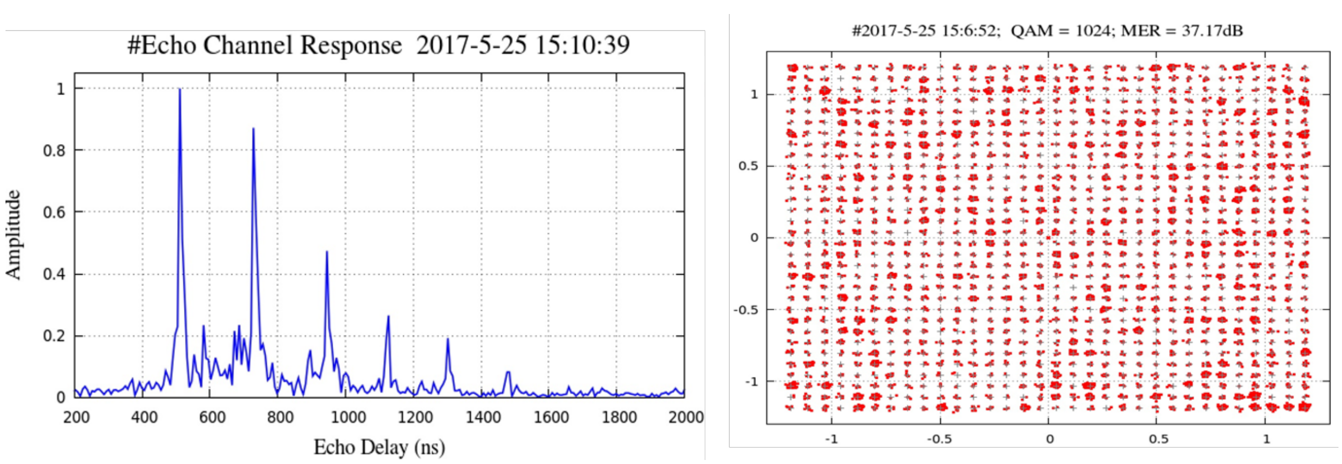

Figure 18 - FDX DOCSIS live demonstration system - measured echoes and post-EC constellation and MER.

Conclusion

Full duplex operation allows DS and US traffic to use the same RF spectrum at the same time, leading to ~100% increase in spectral efficiency and five to 10 times increase in US capacity. The key enabler for full duplex DOCSIS is echo cancellation. Echo cancellation can be implemented in time and/or frequency domains, and in analog and/or digital domain, depending on the system performance targets, hardware limitations and vendor preferences.

A full duplex EC lab prototype system was built in Cisco's lab to validate the EC algorithm at the RPD node for supporting full duplex operation. The system supported full duplex operation of three DS OFDM channels and six US OFDMA channels, for a total of 576 MHz of overlapping FDX spectrum. Over 45 dB echo suppression and >35 dB post-EC were achieved.

A live FDX DCOSIS PoC system was demonstrated at ANGA. The live demo system consisted of all essential boxes required in a real system: CMTS (cBR-8), R-PHY node, CMs and a coax network to emulate N+0 network. The FDX operation was running between 108 MHz and 204 MHz (one 96 MHz channel). 37 dB post-EC MER was achieved. The DS supported 4096-QAM and the US supported 1024-QAM. With a 96 MHz FDX channel, DS throughput achieved ~940 Mbps, and US throughput achieved ~620 Mbps.

Abbreviations

ACI	adjacent channel interference
ADC	analog-to-digital converter
ALI	adjacent leakage interference
CM	cable modem
CMTS	cable modem termination system
DAC	digital-to-analog converter
dB	decibel
dBmV	decibel millivolt
DOCSIS	Data-Over-Cable Service Interface Specifications
DS	downstream
DSP	digital signal processing
EC	echo cancellation
FDD	frequency division duplex
FDX	full duplex
Gbps	gigabits per second
GHz	gigahertz
HFC	hybrid fiber/coax
ISBE	International Society of Broadband Experts
LPF	low pass filter
Mbps	megabits per second
MER	modulation error ratio
MHz	megahertz
ns	nanosecond

OFDM	orthogonal frequency division multiplex
OFDMA	orthogonal frequency division multiple access
OOB	out-of-band
PoC	proof-of-concept
QAM	quadrature amplitude modulation
RPD	remote PHY device
R-PHY	remote PHY
RX	1) receiver; 2) receive
SCTE	Society of Cable Telecommunications Engineers
SNR	signal-to-noise ratio
TCP	total composite power
TX	1) transmitter; 2) transmit
US	upstream

Bibliography & References

Full Duplex DOCSIS, John Chapman and Hang Jin, Spring Technical Forum, May 16-20, 2016, Internet and Television Expo (INTX), Cable Labs/NCTA/SCTE.

