Full Duplex DOCSIS PHY Layer Design and Analysis for the Fiber Deep Architecture

A Technical Paper prepared for SCTE/ISBE by

Richard S. Prodan, Ph.D.
Broadcom Fellow
Set-Top Box and Cable Modem Group
Broadcom Limited
1811 Pike Road, Suite 2C
Longmont, CO 80501
720-864-4227
rich.prodan@broadcom.com

Table of Contents

List of Figures

List of Tables

Introduction

DOCSIS 3.1 has significantly increased the bandwidth utilization and capacity flexibility of cable data service through the use of new physical layer modulation based on OFDM/OFDMA, as well as extending bandwidth in both upstream and downstream transmission bands. DOCSIS 3.1 and prior versions were concerned with forward and reverse path loss and minimum power levels to achieve acceptable signal-to-noise ratio (SNR) for good spectral efficiency. Only unidirectional frequency response limits need be considered and reflected signals back toward the source can be reasonably ignored.

The addition of full duplex (FDX) simultaneous transmission and reception within the same spectrum introduces numerous additional considerations that can be neglected in prior DOCSIS frequency division duplex (FDD) versions. Such concurrent full duplex transmit/receive operation in the same spectrum introduces interference into and reflections back toward the transmission source that must be effectively canceled for simultaneous reception of signals traveling in the opposite direction within the same frequency band.

This paper analyzes the additional considerations for full duplex operation within a fiber deep (passive node plus zero amplifier) required cable system architecture and the resulting expected SNR and spectral efficiency impacts both at the node and the cable modem. These include:

- Signal levels and path loss over the fiber deep coax plant and within the node and modem
- Tap signal conditioning (equalization) over wide bandwidths (up to 1218 MHz)
- Noise and interference sources and levels both across different taps and across ports on the same tap including co-channel interference, adjacent channel interference, and adjacent channel leakage interference from transmitter noise and spurious emissions
- Transmitted signal reflection levels impacting received signals within the same or adjacent frequency bands
- Interference due to limited isolation between transmitted and received signals both at the fiber node and the cable modem
- The segmentation of cable modems into “interference groups”
- SNR and spectral efficiency (bit-loading) achievable within such cable modem groupings.

The Fiber Deep Cable Architecture

1. Cable Network Characteristics and Design

Traditional hybrid fiber/coax (HFC) cable distribution networks have been built as tree and branch networks consisting of a fiber node connecting multiple cascaded amplifier coax cable sections. Each section connects to a series of multiport taps transmitting signal to and receiving signals from drop cables to customer premise equipment. An example of one coax branch of a conventional Node + N HFC architecture shown in Figure 1. The node span contains multiple amplifier spans, each with multiple taps between amplifiers.

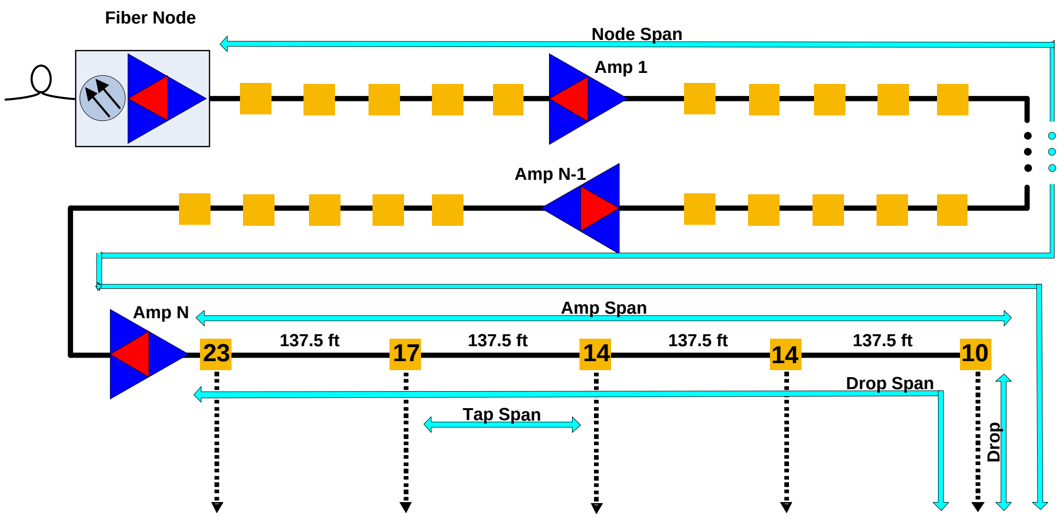


Figure 1 - Conventional node plus N network architecture

This conventional architecture provides two-way signal transmission on separate spectral bands using frequency division duplex operation. Each amplifier section uses diplex filtering to separate upstream transmissions toward the node in the narrower lower frequency band (typically 85 MHz or less) from downstream transmissions from the node in the much wider upper frequency band (up to 1 GHz). Such diplex filtering prevents two-way transmission within the same bandwidth. Each multiport tap contains a directional coupler that diverts a portion of the downstream signal to the drops connected to the tap ports and injects the upstream signals present on the tap ports toward the node. The directivity of the directional coupler prevents upstream signals from propagating in the downstream direction or from diverting to other drops upstream from that tap port.

The full duplex architecture provides two-way signal transmission within the same spectral band. This requires a passive architecture without amplifiers. In this case, the fiber node connects to a single series of multiport taps. Without any amplifiers that require diplex filtering, both upstream and downstream signals can share the part of the same spectrum but with the same directivity of the conventional architecture. The bandwidth supported in this passive fiber deep architecture can be wider than the conventional cascaded amplifier architecture (1218 MHz or more). An example of one coaxial branch of a fiber deep node + 0 architecture is shown in Figure 2.

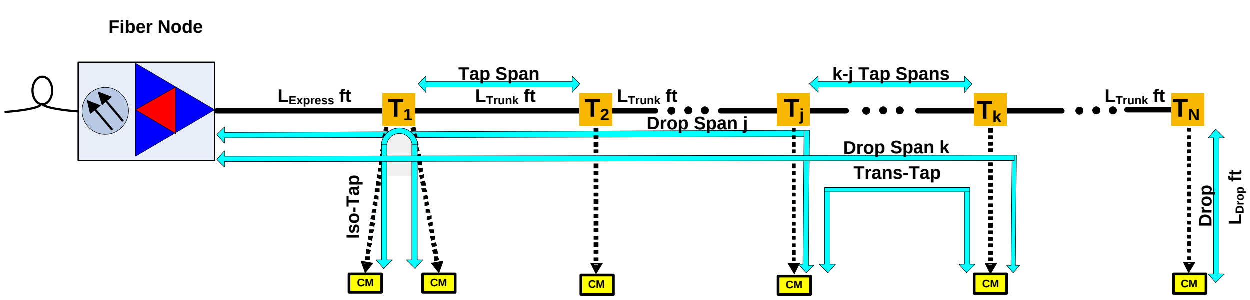


Figure 2 - The fiber deep node + 0 architecture

The design of a conventional or fiber deep network requires specifying the individual components and their values to obtain consistent signal levels across all the subscriber drops. These include:

- hardline cable (trunk and express feeder) and drop cable type and parameters
- tap parameters (insertion loss, tap loss, return loss, isolation)
- downstream and upstream node and tap equalization type, frequency range, and tilt value
- tap spacing
- drop cable length
- amplifier output (level and tilt)

Typical hardline and drop cable specifications include attenuation per length versus frequency and velocity of propagation are shown in Table 1.

Frequency (MHz)	Cable Attenuation (dB/100 ft)
5	0.14
55	0.48
83	0.58
85	0.59
204	0.93
211	0.95
250	1.03
300	1.13
350	1.23
400	1.32
450	1.40
500	1.49
550	1.56
600	1.64
750	1.85
865	2.00
1000	2.17
1002	2.16
1218	2.41

Velocity of Propagation:	0.87
Cable Span Delay (µsec):	0.2045093
Linear Regression Parameters	
Slope	0.1219285
Intercept	-0.0991351

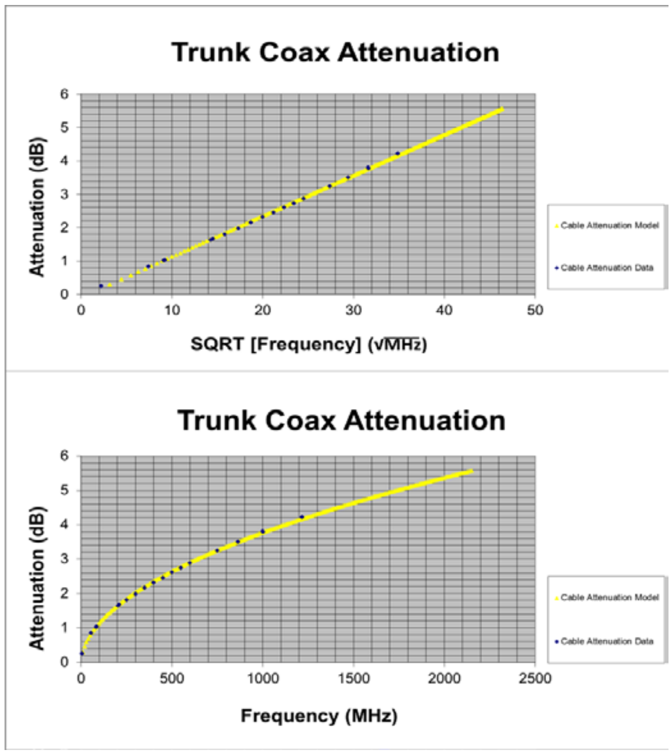


Table 1 - QR 540 hardline cable parameters

Note the linear attenuation versus square root frequency characteristic typical of coaxial cable. This useful property simplifies modeling the behavior of signal attenuation of the interconnecting hardline cable between taps or between a tap port and the terminating device on the drop cable (see Appendix 0).

Tap parameters including insertion loss, tap loss, return loss, and tap-to-output isolation are also specified as attenuation versus frequency. Table 2 shows an example of such tap specifications.

2-Way Maximum Insertion Loss (dB) Number of Ports (#-Way),Tap Value (dB)										
Frequency ≤(MHz)	2,4	2,7	2,10	2,12	2,14	2,17	2,20	2,23	2,26	2,29
5		3.9	2	1.8	1.3	1.2	1	0.7	0.7	0.7
10		3.6	1.8	1.6	1.2	1.1	0.9	0.6	0.6	0.6
50		3.5	1.8	1.6	1.2	1.1	0.9	0.7	0.7	0.7
100		3.6	2	1.8	1.3	1.2	1	0.8	0.8	0.8
450		4.2	2.4	2.1	1.6	1.5	1.3	1.1	1.1	1.1
550		4.2	2.4	2.3	1.8	1.5	1.4	1.2	1.2	1.2
750		4.2	2.4	2.4	1.8	1.6	1.5	1.3	1.3	1.3
870		4.3	2.7	2.7	2	1.6	1.6	1.4	1.4	1.4
1000		4.3	3	3	2.3	1.6	1.6	1.6	1.6	1.6
1218		5.2	3.6	3.6	2.7	2.2	2	2	2	2

Minimum Return Loss (dB) For ALL Tap Values		
Frequency ≤(MHz)	Minimum Return Loss In-Out (dB)	Minimum Return Loss Tap (dB)
5	16	16
10	16	17
750	16	17
1000	16	17
1218	16	16

2-Way Nominal Tap Value (dB) Number of Ports (#-Way),Tap Value (dB)											Tap Value Tolerance ±(dB) Number of Ports (#-Way)		
Frequency ≤(MHz)	2,4	2,7	2,10	2,12	2,14	2,17	2,20	2,23	2,26	2,29	2	4	8
5	4	7	10	12	14	17	20	23	26	29	2	2	3
1000	4	7	10	12	14	17	20	23	26	29	2	2	3
1218	4	7	10	12	14	17	20	23	26	29	2.5	2.5	3.5

2-Way Tap-to-Output Isolation (dB) Number of Ports (#-Way),Tap Value (dB)										
Frequency ≤(MHz)	2,4	2,7	2,10	2,12	2,14	2,17	2,20	2,23	2,26	2,29
5		20	20	22	22	26	29	32	35	38
10		20	20	22	22	26	29	32	35	38
85		25	25	25	26	30	33	36	38	40
300		21	22	23	26	30	33	36	38	40
750		22	22	23	26	30	31	34	36	39
900		20	20	22	23	28	30	33	35	37
1218		20	20	20	22	25	29	31	33	35

Tap-to-Tap Isolation (dB) For ALL Tap Values	
Frequency ≤(MHz)	Isolation (dB)
5	20
10	25
85	27
300	27
750	23
1218	20

Table 2 - Tap specifications for insertion loss, tap value loss, return loss, and tap-to-output isolation versus frequency for each tap value

An important consideration for supporting the wider bandwidth on the passive fiber deep plant is the use of tap plug-in equalizers. Such equalizers provide either upward or downward attenuation (tilt) with increasing frequency. The amount for each tap is determined to provide approximately the same output levels versus frequency at all tap ports. An example of tap equalizer magnitude frequency (amplitude) responses is shown in Figure 3.

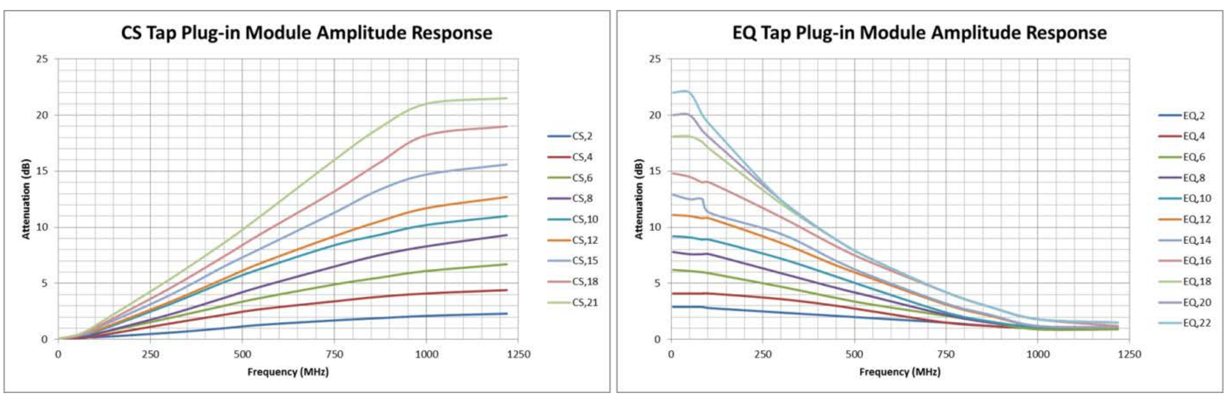


Figure 3 - Tap equalization ("signal conditioning") plug-in characteristics

The design of the fiber deep coaxial cable plant requires specification of signal levels versus frequency, selection of cable lengths and types, and tap values including equalization appropriate for the inter-tap spacing and drop cable length to provide uniform signal levels across all tap ports. An example of fiber deep signal levels and limits is given in Table 3.

Node Signal Levels (21 dB linear up-tilt from 111 to 1215 MHz)	
Transmit Power/6 MHz	Receive Power/6.4 MHz
37 dBmV (111 MHz)	8 dBmV (5 to 85 MHz@node;
58 dBmV (1215 MHz)	≤32 dB loss@85 MHz to tap port)

Subscriber Signal Levels	
Transmit Power/6.4 MHz	Receive Power/6 MHz
40 dBmV (5 to 85 MHz@tap max)	-6 dBmV (min@4 outlets)
	4 dBmV (111 MHz@tap min)*
	6 dBmV (111 MHz@tap max)*
	12 dBmV (1218 MHz@tap min)*
	19 dBmV (1218 MHz@tap max)*

*Absolute limit but actual tap port level depends on drop length

Tap Specifications	0' to 50' RG-6 short drop model for 256-QAM		
Minimum Level Low Frequency	4 dBmV@111 MHz		
Minimum Level High Frequency	12 dBmV@1218 MHz		
Maximum Tilt	10 dB	Minimum Tilt	6 dB
Maximum Return at Tap Port	40 dBmV@85 MHz		

Tap Specifications	51' to 100' RG-6 standard drop model for 256-QAM		
Minimum Level Low Frequency	5 dBmV@111 MHz		
Minimum Level High Frequency	15.5 dBmV@1218 MHz		
Maximum Tilt	12 dB	Minimum Tilt	8 dB
Maximum Return at Tap Port	40 dBmV@85 MHz		

Tap Specifications	101' to 150' RG-6 long drop model for 256-QAM		
Minimum Level Low Frequency	6 dBmV@111 MHz		
Minimum Level High Frequency	19 dBmV@1218 MHz		
Maximum Tilt	15 dB	Minimum Tilt	11 dB
Maximum Return at Tap Port	40 dBmV@85 MHz		

Tap Specifications	151' to 200' RG-11 extra-long drop model for 256-QAM		
Minimum Level Low Frequency	6 dBmV@111 MHz		
Minimum Level High Frequency	18 dBmV@1218 MHz		
Maximum Tilt	14 dB	Minimum Tilt	10 dB
Maximum Return at Tap Port	40 dBmV@85 MHz		

Table 3 - Fiber deep node, tap, and subscriber RF signal levels and limits

Analysis of Fiber Deep Networks

2. Fiber Deep Transmission Model and Analysis

An approach to modeling signal transmission through the various elements of the fiber deep network is discussed in this section. Analysis of the frequency response including signal levels transmitted from the node and received by the cable modem or vice versa is described. This approach allows the use of log magnitude values versus frequency from component spec sheets to model the transfer function of each section of transmission line (i.e., cable) terminated at either end with an impedance (i.e., a tap, node, or cable modem) characterized by its magnitude return loss versus frequency.

Consider the fiber deep architecture model depicted in Figure 4. The fundamental transmission transfer function block is denoted by the tap span shown in this figure.

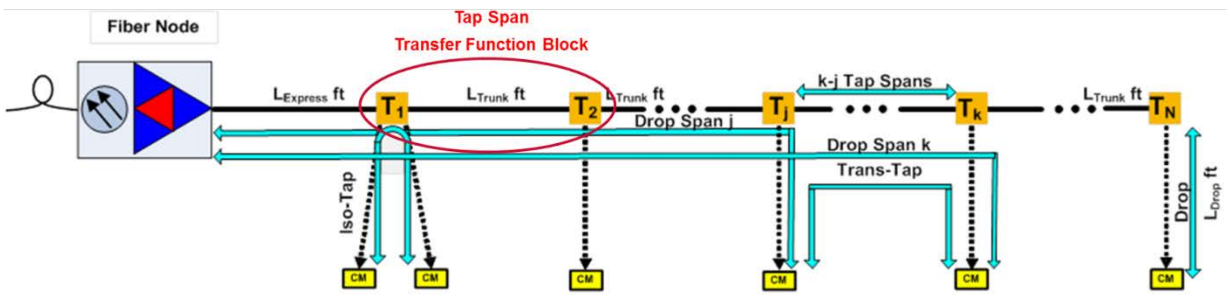


Figure 4 - Fiber Deep model for Full Duplex operation

It is shown in Appendix 1 for a length of trunk cable with cable propagation delay T, cable amplitude response A(f), and tap input/output port return loss RL = -10 Log(ρ) where ρ = reflection coefficient, that the transfer function H(f) for the tap span cable transmission line is given by:

$$H(f) = \frac{A(f)}{1 - A^2(f)\, 10^{-\frac{(\mathrm{RLi+RLo})}{20}} e^{-j4\pi fT}}$$

Note that this formulation provides the complex frequency response with only the scalar amplitude versus frequency of the cable transmission line and the magnitude return loss versus frequency of the tap terminating impedances. This avoids the need to measure complex valued s-parameters versus frequency for each component and convert to t-parameters for transmission frequency responses that can be cascaded to compute the end-to-end transfer function between any two points in the network.

The same analysis applies to a drop cable section between tap port and the cable modem where the attenuation model and propagation delay are specified for the drop cable instead of the hardline cable and the input and output return losses are specified for the tap port and cable modem F-connector port respectively.

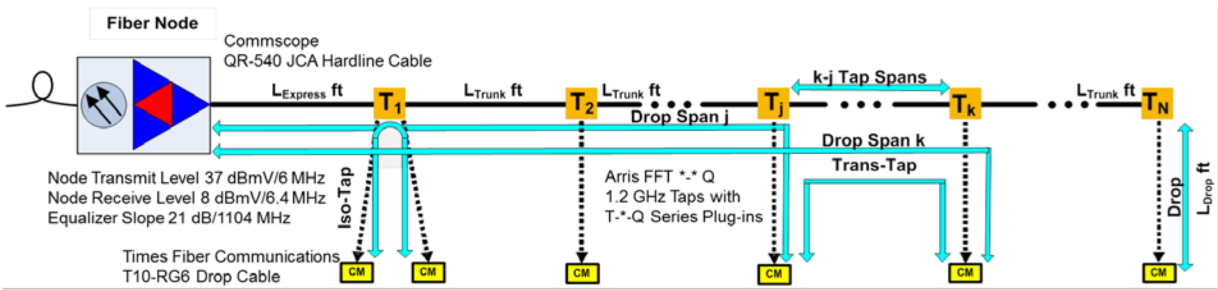
Denote the drop frequency response as $H_{drop}(f)$ and the hardline trunk feeder section frequency response by $H_{trunk}(f)$. The return path frequency response $H_n(f)$ for a drop on the nth tap after the amplifier with tap loss value T_n and insertion losses $I_{n-1}, I_{n-2}, \dots, I_1$ (all tap loss amplitudes are a nearly constant function of frequency by design) is simply the product of the frequency responses of each section given by:

$$H_n(f) = T_n\, I_{n-1}\, I_{n-2} \dots\, I_1\, H_{drop}(f)\, [H_{trunk}(f)]^{n-1}$$

This approach is used to model the transfer function between the node and any cable modem or between cable modems on the same or different taps.

3. Fiber Deep Network Example Design

An example design of suburban cable plant with standard 100 foot length drops is analyzed next using the approach described in the previous section. The plant model (Model 1) is shown in Figure 5.



Express Coax Span (ft):	175
Trunk Coax Span (ft):	175
Drop Coax Span (ft):	100

Tap Specifications	51′ to 100′ RG-6 standard drop model for 256-QAM		
Minimum Level Low Frequency	5 dBmV@111 MHz		
Minimum Level High Frequency	15.5 dBmV@1218 MHz		
Maximum Tilt	12 dB	Minimum Tilt	8 dB
Maximum Return at Tap Port	40 dBmV@85 MHz		

Tap Position (Highest to Lowest):	Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
Tap Type (Number of Ports):	4	4	4	4	4	4
Tap Value (dB):	29	29	26	20	14	7
Tap Conditioner Type (CS or EQ):	CS	CS		EQ	EQ	EQ
Tap Conditioner Value (dB):	6	2		6	10	16

Figure 5 - Model 1 – suburban plant and standard drops with fiber deep signal levels

An analysis of received downstream signal levels at the tap ports and cable modems attached to the drops is provided in this section with the methodology described previously using the node signal launch levels and up-tilt, tap and plug-in equalizer characteristics, and cable attenuation versus frequency for the hardline and drop cable types. The resulting tap port received levels are plotted in Figure 6.

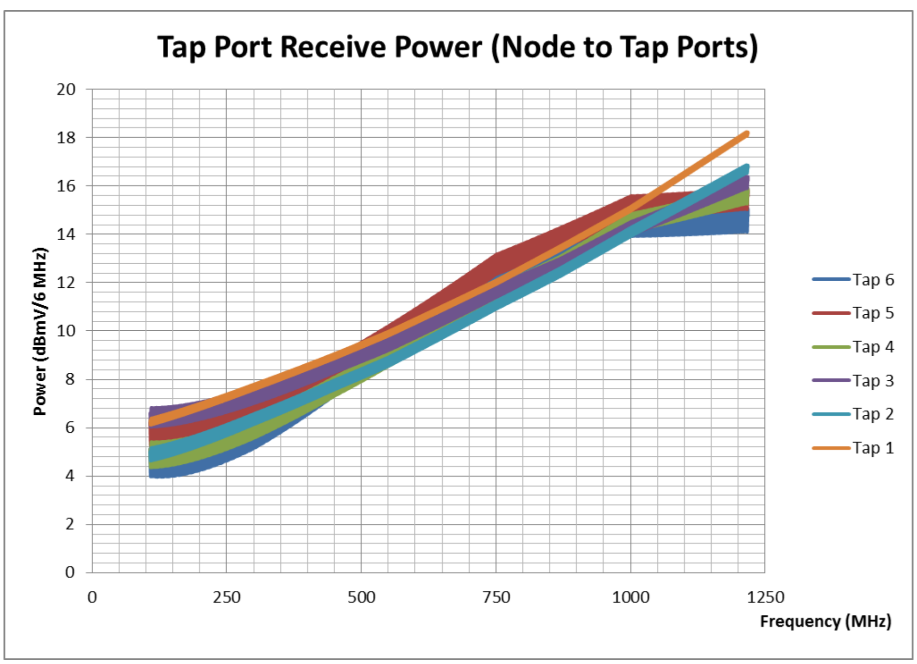


Figure 6 - Receive power levels for all taps in Model 1

Note that the tap port levels for each tap are approximately the same and compliant within a dB with the fiber deep signal levels and limits given in Table 3 for standard length 100 foot drops. This is the result of design selection of appropriate tap values and tap plug-in equalizers for the cable lengths and types.

The resulting cable modem received levels at the end of the drops from each tap are plotted in Figure 7. An expanded view of the received power of the cable modem on tap 1 shows the detailed amplitude response due to micro-reflections from finite return losses in the tap ports and cable modem F-connector.

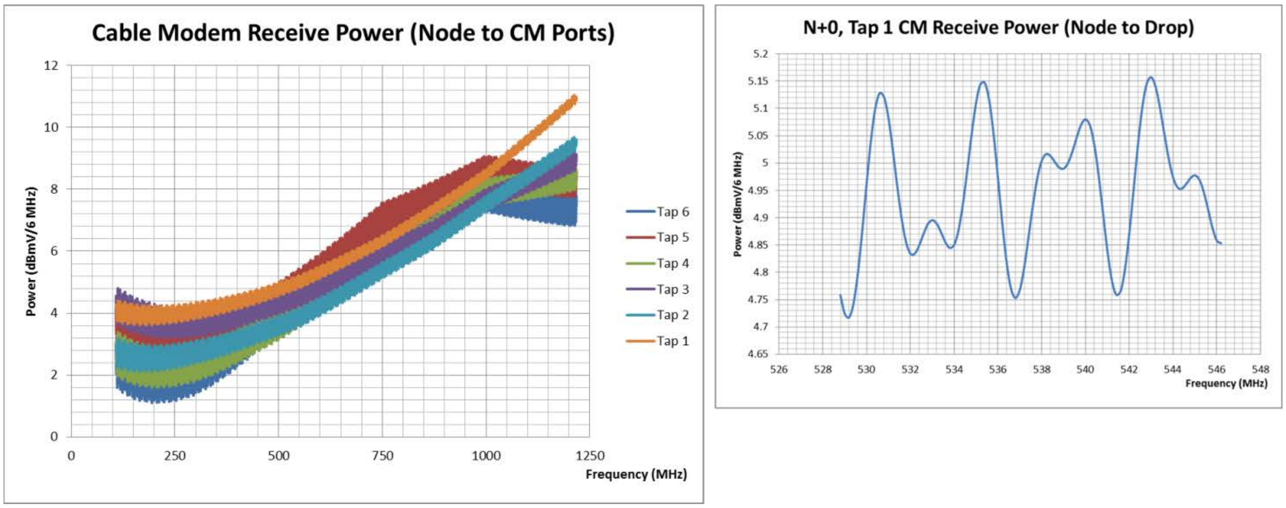


Figure 7 - Receive power levels for modems on each tap drop

Due to the symmetry of the passive cable plant, the same calculated frequency responses from the node to each tap port can be used to evaluate the cable modem transmit levels at each tap drop. However, the received level at the node port is specified to be a flat power spectral density across the 108 MHz to 684 MHz full-duplex band. The value of that power spectral density level is determined such that the total composite power transmitted in the full-duplex band by any cable modem in the network does not exceed 64.5 dBmV. In this design example, it will be shown later in the node port analysis that received upstream power spectral density level is approximately 5 dBmV/6.4 MHz. The resulting cable modem transmit levels for each tap are shown in Figure 8.

Note that the transmitted signal levels are approximately the same for all cable modems across all taps. As will be shown later for the node, the tilt in the upstream transmissions from each cable modem results in the received flat power spectral density level at the node port noted previously.

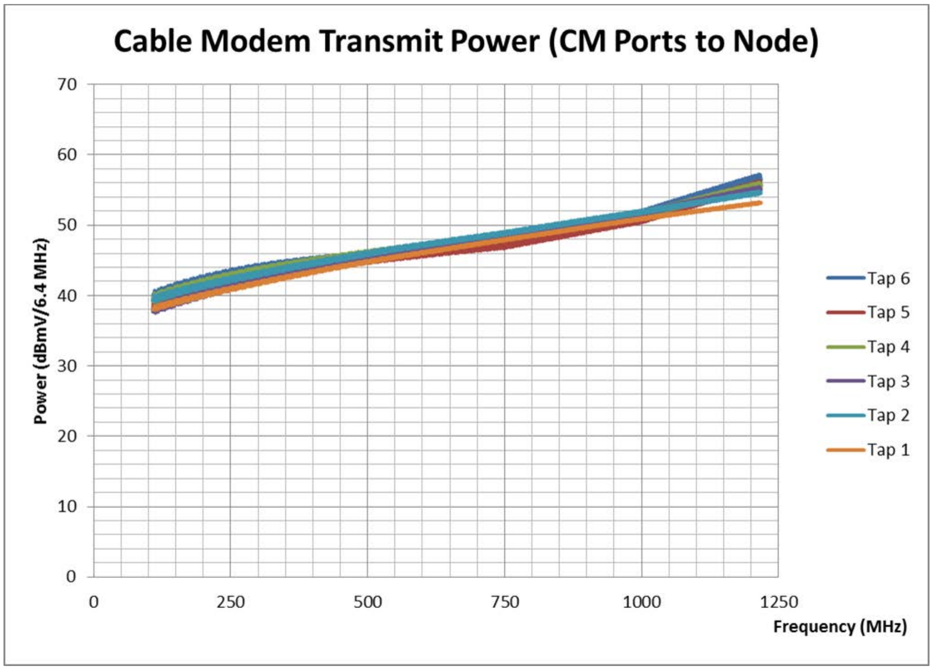


Figure 8 - Modem port transmit levels at the drop for each tap

Full Duplex Network Operation

4. Full Duplex Interference Groups

Simultaneous true full duplex transmission and reception within the same frequency band only occurs at the node. Each cable modem utilizes 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 a given 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 different tap ports of the same tap or different taps. Thus, the downstream receiving cable modem has no reference for the upstream transmitting cable modem signal making cancellation within the same frequency band impossible.

It will be shown that cable modems on the same tap in this situation can only either transmit or receive in a given channel, but never simultaneously. However, if the transmitting and receiving modems are separated across different taps, then simultaneous transmission by one modem and reception by another modem on a different tap with sufficient separation to provide isolation between the signals sharing the same frequencies in a given channel is possible. This segregating of each modem into a group where modems in each individual group mutually interfere while other modems in a different group do not mutually interfere significantly is known as an interference group (IG).

Figure 9 shows the dynamic FDD upstream transmit and downstream receive channel allocations within a single IG.

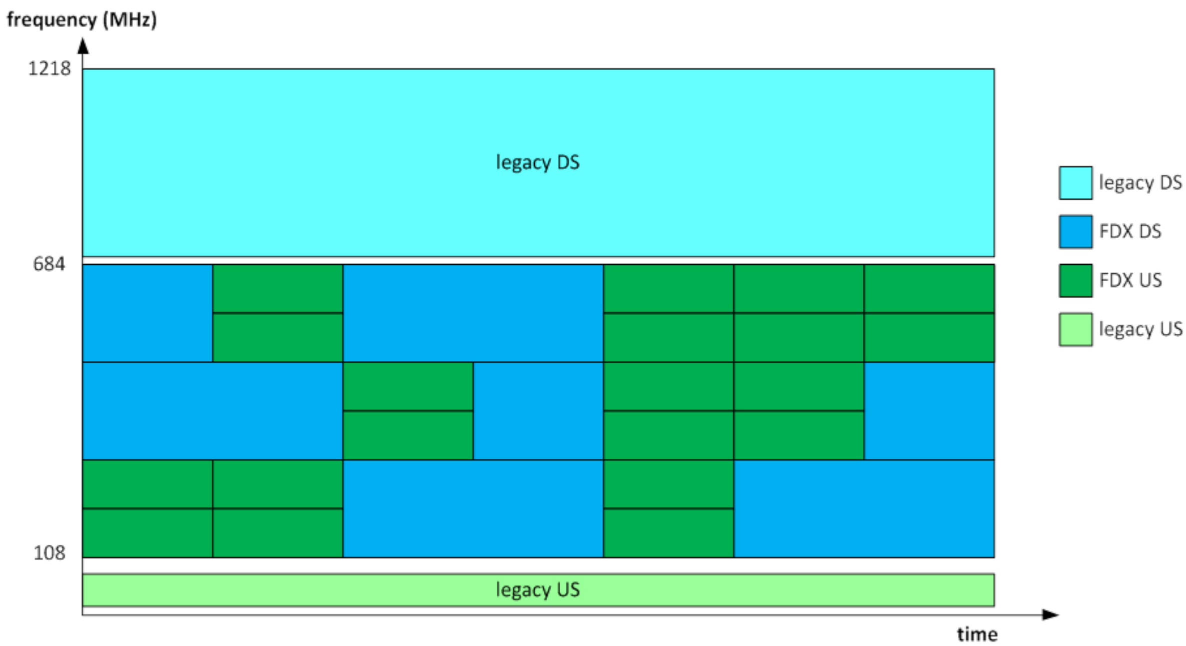


Figure 9 - Time variability of FDD transmission and reception in the FDX spectrum for a single interference group

All modems in the same IG see the same up/down resource block assignments (RBA) which are the fixed channel assignments to upstream transmission or downstream reception. Modems in different IG's may get the same or (usually) different RBAs. The collection of all IG's within the shared full-duplex spectrum is known as a transmission group (TG).

The TG at the node receives signals from all modems across all channels in every IG resulting in true full-duplex spectral utilization at the node. However, each modem uses dynamic FDD as shown in the example of Figure 9. Several interference mechanisms and their impact on spectral efficiency (bit-loading) is examined next.

5. Full Duplex Interference Group Analysis of Co-channel Interference

Referring to the fiber deep architecture of Model 1 in Figure 5, modem-to-modem co-channel interference (CCI) is examined in the following. Consider a modem on tap j which transmits in each FDX channel. The worst case interference seen at the receiver of a modem on tap k relative to its downstream receive signal level on each FDX channel is shown in the green line of Figure 10.

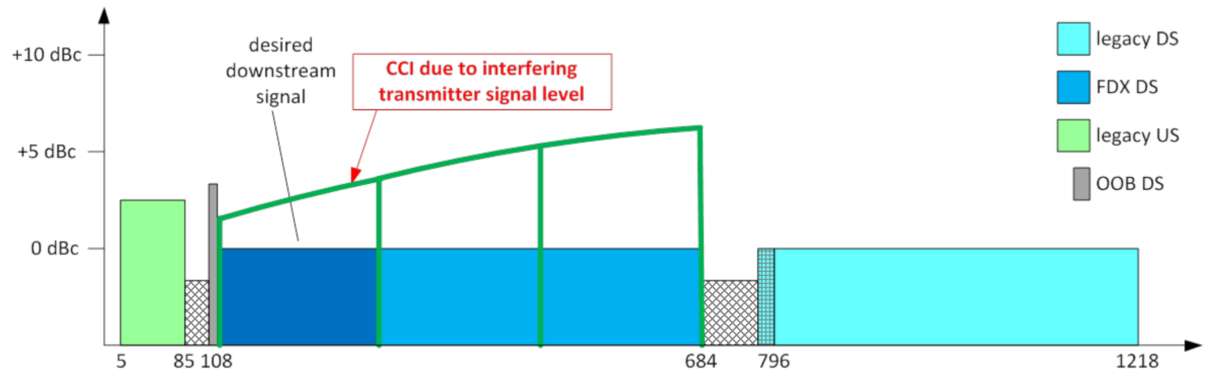


Figure 10 - Modem-to-modem co-channel interference

The interference level depicted in this figure is representative of modems on the same tap or when j equals k. Modems that are more widely separated across different taps will experience considerably lower levels of CCI. The downstream signal to upstream CCI SNR versus frequency between two modems with the widest separation of taps is shown in Figure 11 using the calculation method of Appendix 3: SNR Calculations of CCI.

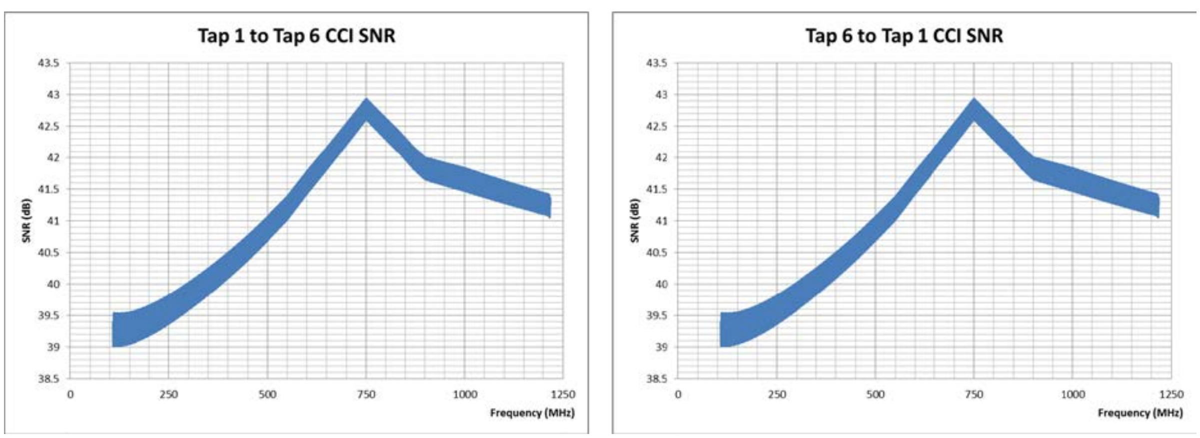


Figure 11 - Example of modem CCI SNR across interference groups

Note the symmetry in either transmission direction due to the symmetric frequency response of the passive coaxial network. The SNR at each frequency can be compared to the threshold value for DOCSIS 3.1 OFDM modulation efficiency (bits/subcarrier) to determine the QAM order that can be supported in a given FDX channel as shown in Table 4.

QAM Order	Modulation Efficiency (bits/subc)	Spectral Efficiency (bits/subc)	FEC SNR Threshold (dB)	CNR Threshold (dB)	Channel Capacity (bits/subc)
0	0.0	0.00	-100.0	-100.0	0.00
QPSK	2.0	1.76	7.5	9.0	2.73
16-QAM	4.0	3.51	13.0	15.0	4.39
64-QAM	6.0	5.27	18.6	21.0	6.20
64/128-QAM	6.5	5.71	20.4	22.5	6.79
128-QAM	7.0	6.15	21.4	24.0	7.12
128/256-QAM	7.5	6.59	23.3	25.5	7.75
256-QAM	8.0	7.03	24.2	27.0	8.04
256/512-QAM	8.5	7.47	26.0	28.7	8.64
512-QAM	9.0	7.91	26.9	30.5	8.94
512/1024-QAM	9.5	8.35	28.7	32.2	9.54
1024-QAM	10.0	8.79	29.7	34.0	9.87
1024/2048-QAM	10.5	9.22	31.6	35.5	10.50
2048-QAM	11.0	9.66	32.4	37.0	10.76
2048/4096-QAM	11.5	10.10	34.2	39.0	11.36
4096-QAM	12.0	10.54	35.2	41.0	11.69

Table 4 - Downstream bit-loading table for calculation of modulation efficiency

Modulation efficiency represents the OFDM subcarrier bit-loading as a function of CNR threshold. Calculate bit-loading using Table 4 of modulation efficiency vs. CNR at each frequency and average bit-loading per frequency over a frequency band for calculating average bit-loading in a channel. The results for average CCI SNR and bit loading for Model 1 is shown in Table 5. Note that a modem transmitting on the same tap as other receiving modems on the same tap results in a negative CCI SNR. Downstream reception in the same channel as the upstream transmission is not possible in this case.

		SNR in Total Channel (108 MHz to 684 MHz)					
	SNR	TRANSMIT					
	(dB)	Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
RECEIVE	Tap 1	-4.7	40.4	40.4	40.4	40.4	40.4
	Tap 2	40.4	-7.2	36.2	36.2	36.2	36.2
	Tap 3	40.4	36.2	-5.4	32.2	32.2	32.2
	Tap 4	40.4	36.2	32.2	-7.3	24.0	24.0
	Tap 5	40.4	36.2	32.2	24.0	-5.7	13.7
	Tap 6	40.4	36.2	32.2	24.0	13.7	-7.2

		Bit-Loading in Total Channel (108 MHz to 684 MHz)					
	Bit-Loading	TRANSMIT					
	(bits/subc)	Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
RECEIVE	Tap 1	0.0	11.6	11.6	11.6	11.6	11.6
	Tap 2	11.6	0.0	10.5	10.5	10.5	10.5
	Tap 3	11.6	10.5	0.0	9.3	9.3	9.3
	Tap 4	11.6	10.5	9.3	0.0	6.8	6.8
	Tap 5	11.6	10.5	9.3	6.8	0.0	2.4
	Tap 6	11.6	10.5	9.3	6.8	2.4	0.0

Table 5 - Average CCI SNR and bit loading for Model 1

The SNR table values are estimated in the “sounding” process. A modem transmits a reference signal (CW tones or an upstream data profile testing burst within an OFDMA Upstream Data Profile (OUDP) interval usage code (IUC) grant). All other modems receive the reference signal plus the downstream signal containing zero bit-loaded (ZBL) subcarriers or symbols depending on the reference signal chosen. The modulation error ratio (MER) is measured over a sufficient number of OFDM symbols. Each modem is assigned to an IG determined by the sounding MER results (“IG discovery”).

An example of using this sounding table to assign modems on different taps to interference groups is shown in Table 6.

RECEIVE	SNR (dB)	SNR in Total Channel (108 MHz to 684 MHz) TRANSMIT Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
	Tap 1	-4.7	40.4	40.4	40.4	40.4	40.4
	Tap 2	40.4	-7.2	36.2	36.2	36.2	36.2
	Tap 3	40.4	36.2	-5.4	32.2	32.2	32.2
	Tap 4	40.4	36.2	32.2	-7.3	24.0	24.0
	Tap 5	40.4	36.2	32.2	24.0	-5.7	13.7
	Tap 6	40.4	36.2	32.2	24.0	13.7	-7.2

RECEIVE	Bit-Loading (bits/subc)	Bit-Loading in Total Channel (108 MHz to 684 MHz) TRANSMIT Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
	Tap 1	0.0	11.6	11.6	11.6	11.6	11.6
	Tap 2	11.6	0.0	10.5	10.5	10.5	10.5
	Tap 3	11.6	10.5	0.0	9.3	9.3	9.3
	Tap 4	11.6	10.5	9.3	0.0	6.8	6.8
	Tap 5	11.6	10.5	9.3	6.8	0.0	2.4
	Tap 6	11.6	10.5	9.3	6.8	2.4	0.0

OFDM Modulation:	4096-QAM	2048-QAM	1024-QAM	512-QAM
SNR Threshold:	41 dB	37 dB	34 dB	30.5 dB

Interference Group partitioning:

- **IG 0** SNR ≥ 41 dB ↔ (no Taps)
- **IG 1** SNR > 37 dB ↔ (Tap 1)
- **IG 2** SNR > 34 dB ↔ (Tap 2)
- **IG 3** SNR > 30.5 dB ↔ (Tap 3)
- **IG 4** SNR ≤ 30.5 dB ↔ (Taps 4, 5, 6)

Interference Group resulting bit-loading:

IG 0 (no Taps) receive 4096-QAM (12 bits/subcarrier)

IG 1 (Tap 1) receives 2048-QAM (11 bits/subcarrier) when IG 2, 3, or 4 transmit

IG 2 (Tap 2) receives 1024-QAM (10 bits/subcarrier) when IG 1, 3, or 4 transmit

IG 3 (Tap 3) receives 512-QAM (9 bits/subcarrier) when IG 1, 2, or 4 transmit

IG 4 (Taps 4, 5, 6) receives 512-QAM (9 bits/subcarrier) when IG 1, 2, or 3 transmit

Table 6 - CCI interference group possible assignments for Model 1

Assignment of a modem to an IG can be done by successively checking to see if the measured MER is above a threshold SNR for a given bit loading starting at the highest SNR threshold. If so, then the modem is assigned to this highest IG associated with that threshold SNR (IG 5). If not, then the measured MER is checked to be above the next lower threshold SNR. If so, then the modem is assigned to this next highest IG associated with that next lower threshold. If not, this process continues until the MER is above the given threshold for an IG. Finally if the MER is below the SNR for the lowest IG, then the CM is assigned to this lowest IG.

The results of this sorting process of cable modems into IG's is shown in Table 6. No modems were found to be above the threshold for the 4096-QAM IG. The modems on tap 1 are above the threshold for 2048-QAM when modems on taps 2 through 6 transmit and are therefore assigned to this next highest IG 4. The modems on tap 2 are above the threshold for 1024-QAM when modems on taps 3 through 6 transmit and are therefore assigned to this next highest IG 3. The modems on tap 3 are above the threshold for 512-QAM when modems on taps 4 through 6 transmit and are therefore assigned to this next highest IG 2. The modems on taps 4 through 6 are below the lowest threshold for 512-QAM when modems on taps 4 through 6 transmit and are therefore assigned to this lowest IG.

In summary, modem-to-modem CCI is the primary impairment that limits spectral efficiency (i.e., maximum throughput) for a full duplex modem. CCI between different taps increases with increasing distance from the node and decreasing proximity between transmitting and receiving modems. SNR is reduced for modems further from the node. SNR is reduced with decreasing distance (fewer number of intervening taps) between transmitting and receiving modems. CMs on the same tap will have negative CCI SNR and will be in the same interference group.

6. Full Duplex Interference Group Analysis of Adjacent Leakage Interference

Again, referring to the fiber deep architecture of Model 1 in Figure 5, modem-to-modem adjacent leakage interference (ALI) will be examined in the following. Consider a modem on tap j which transmits in the two highest frequency FDX channels. The worst case interference due to out-of-band noise and spurious emissions seen at the receiver of a modem on tap k relative to its downstream receive signal level on the lowest frequency FDX channel is shown in the red line of Figure 12.

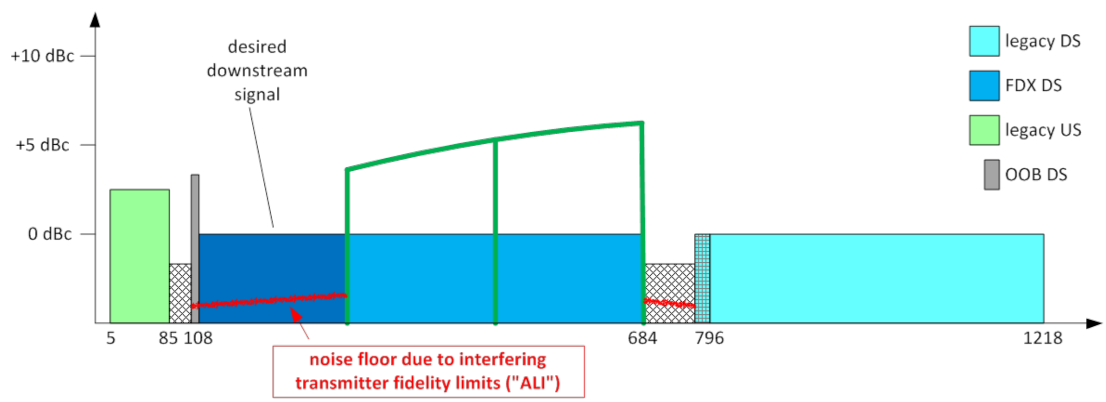


Figure 12 - Cable modem-to-modem adjacent leakage interference

The interference level depicted in this figure is representative of modems on the same tap or when j equals k. Modems that are more widely separated across different taps will experience considerably lower levels of ALI. It will be shown that ALI from modems across different taps is insignificant.

The modem spurious emissions transmit mask for the FDX spectrum is shown in Figure 13.

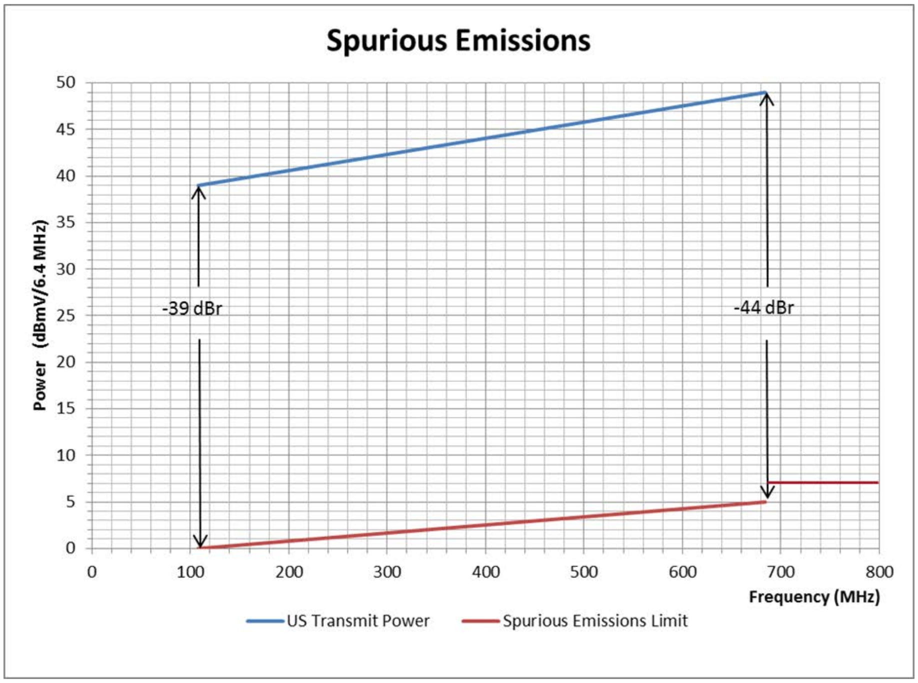


Figure 13 - Modem spurious emissions with 570 MHz FDX active spectrum

The upstream transmit signal is shown for the maximum 576 MHz grant and 10 dB up-tilt with the maximum 64.5 dBmV total composite power. The spurious emissions limit has a linear taper from -39 dBr at 108 MHz to -44 dBr at 684 MHz. Spurious emissions level at modem port with this transmit up-tilt is adjusted by $10*\log_{10}$(upstream grant power/ total composite power) for grants less than the full FDX band down to the under grant hold bandwidth of $1/6^{th}$ of the modulated spectrum width.

The above spurious emissions mask is used to calculate ALI power adjusted by the grant size. The modem SNR is then calculated with the ALI power that migrates across ports of the same tap using the calculation method of Appendix 4: SNR Calculations of ALI. The results are shown in Figure 14 for the first and last tap.

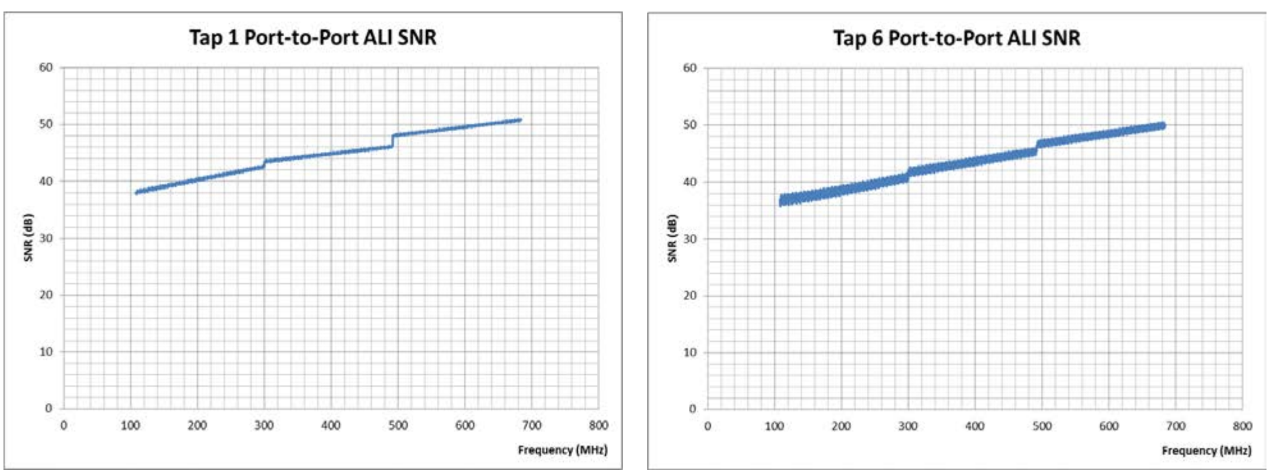


Figure 14 - ALI SNR at modems across ports of the same tap

	SNR (dB)	SNR in Total Channel (108 MHz to 684 MHz) TRANSMIT Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
RECEIVE	Tap 1	43.3	87.8	86.6	88.0	87.2	88.2
	Tap 2	86.5	42.0	83.0	84.4	83.6	84.6
	Tap 3	86.5	84.2	43.1	81.2	80.4	81.3
	Tap 4	86.6	84.3	79.9	41.8	72.4	73.3
	Tap 5	86.6	84.3	79.9	73.2	42.6	63.6
	Tap 6	86.6	84.3	80.0	73.3	62.7	41.7

	Bit-Loading (bits/subc)	Bit-Loading in Total Channel (108 MHz to 684 MHz) TRANSMIT Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
RECEIVE	Tap 1	11.9	12.0	12.0	12.0	12.0	12.0
	Tap 2	12.0	11.8	12.0	12.0	12.0	12.0
	Tap 3	12.0	12.0	11.9	12.0	12.0	12.0
	Tap 4	12.0	12.0	12.0	11.7	12.0	12.0
	Tap 5	12.0	12.0	12.0	12.0	11.8	12.0
	Tap 6	12.0	12.0	12.0	12.0	12.0	11.7

Table 7 - average ALI SNR and bit loading for Model 1

The average ALI SNR and bit loading for model one is tabulated in Table 7. Comparing to the average CCI SNR and bit loading in Table 5, it can be seen that iso-tap ALI degradation of SNR given along the diagonal of the table is comparable in the lowest frequency channel and several dB lower on average over all FDX channels. Also note that ALI SNR across different taps given by the off diagonal table entries is negligible. The SNR impact on combining these impairments is calculated in the next section.

7. Full Duplex Interference Group Analysis of Combined Interference

The combined trans-tap CCI plus iso-tap ALI SNR at modems across interference groups is plotted in Figure 15.

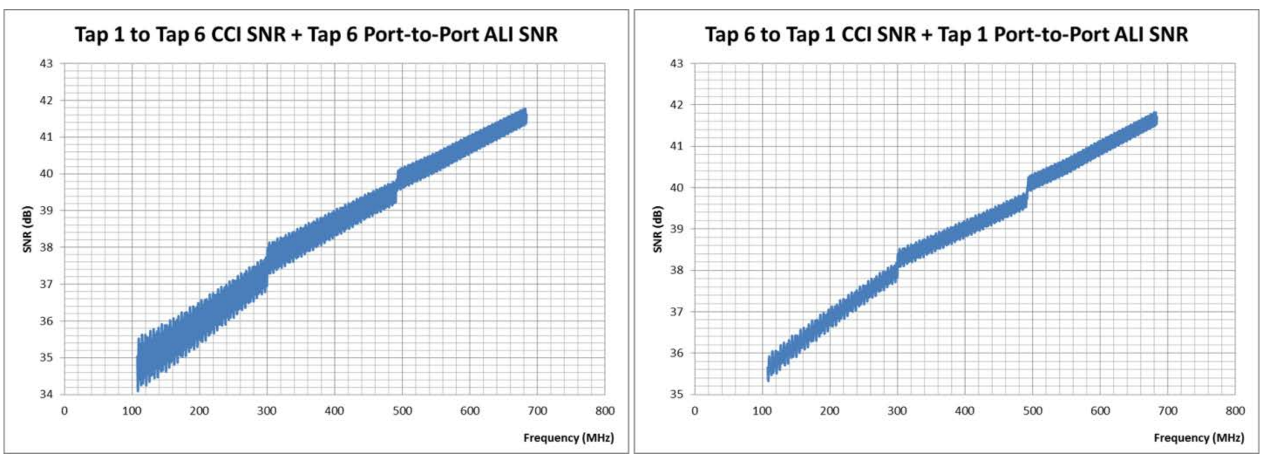


Figure 15 - Trans-tap CCI plus iso-tap ALI SNR that modems across interference groups

The average trans-tap CCI plus iso-tap ALI SNR and bit loading for Model 1 are tabulated in Table 8.

	SNR (dB)	SNR in Total Channel (108 MHz to 684 MHz) TRANSMIT Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
RECEIVE	Tap 1	-4.7	38.6	38.6	38.6	38.6	38.6
	Tap 2	38.1	-7.2	35.2	35.2	35.2	35.2
	Tap 3	38.5	35.4	-5.4	31.9	31.9	31.9
	Tap 4	38.0	35.2	31.8	-7.3	23.9	23.9
	Tap 5	38.3	35.3	31.8	23.9	-5.7	13.7
	Tap 6	38.0	35.1	31.7	23.9	13.7	-7.2

	Bit-Loading (bits/subc)	Bit-Loading in Total Channel (108 MHz to 684 MHz) TRANSMIT Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
RECEIVE	Tap 1	0.0	11.2	11.2	11.2	11.2	11.2
	Tap 2	11.1	0.0	10.2	10.2	10.2	10.2
	Tap 3	11.2	10.2	0.0	9.1	9.1	9.1
	Tap 4	11.1	10.2	9.1	0.0	6.8	6.8
	Tap 5	11.2	10.2	9.1	6.8	0.0	2.4
	Tap 6	11.1	10.2	9.1	6.8	2.4	0.0

Table 8 - Average trans-tap CCI plus iso-tap ALI SNR and bit loading for Model 1

This table of combined interference shows about a 2 dB degradation in SNR. This is less than 1 bit/subcarrier spectral efficiency loss if the resulting SNR crosses the CNR threshold for an interference group. The combined average trans-tap CCI plus iso-tap ALI interference groups are recalculated in Table 9. Note that the additional impact of iso-tap ALI on interference group SNR is typically less than 2 dB or less than 0.5 bits/subcarrier bit loading.

RECEIVE / SNR (dB)	SNR in Total Channel (108 MHz to 684 MHz) TRANSMIT					
	Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
Tap 1	-4.7	38.6	38.6	38.6	38.6	38.6
Tap 2	38.1	-7.2	35.2	35.2	35.2	35.2
Tap 3	38.5	35.4	-5.4	31.9	31.9	31.9
Tap 4	38.0	35.2	31.8	-7.3	23.9	23.9
Tap 5	38.3	35.3	31.8	23.9	-5.7	13.7
Tap 6	38.0	35.1	31.7	23.9	13.7	-7.2

RECEIVE / Bit-Loading (bits/subc)	Bit-Loading in Total Channel (108 MHz to 684 MHz) TRANSMIT					
	Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
Tap 1	0.0	11.2	11.2	11.2	11.2	11.2
Tap 2	11.1	0.0	10.2	10.2	10.2	10.2
Tap 3	11.2	10.2	0.0	9.1	9.1	9.1
Tap 4	11.1	10.2	9.1	0.0	6.8	6.8
Tap 5	11.2	10.2	9.1	6.8	0.0	2.4
Tap 6	11.1	10.2	9.1	6.8	2.4	0.0

OFDM Modulation:	4096-QAM	2048-QAM	1024-QAM	512-QAM
SNR Threshold:	41 dB	37 dB	34 dB	30.5 dB

Interference Group partitioning:

- **IG 0** SNR ≥ 41 dB ↔ (no Taps)
- **IG 1** SNR > 37 dB ↔ (Tap 1)
- **IG 2** SNR > 34 dB ↔ (Tap 2)
- **IG 3** SNR > 30.5 dB ↔ (Tap 3)
- **IG 4** SNR ≤ 30.5 dB ↔ (Taps 4, 5, 6)

Interference Group resulting bit-loading:

IG 0 (no Taps) receive 4096-QAM (12 bits/subcarrier)

IG 1 (Tap 1) receives 2048-QAM (11 bits/subcarrier) when IG 2, 3, or 4 transmit

IG 2 (Tap 2) receives 1024-QAM (10 bits/subcarrier) when IG 1, 3, or 4 transmit

IG 3 (Tap 3) receives 512-QAM (9 bits/subcarrier) when IG 1, 2, or 4 transmit

IG 4 (Taps 4, 5, 6) receives 512-QAM (9 bits/subcarrier) when IG 1, 2, or 3 transmit

Table 9 - Combined trans-tap CCI plus iso-tap ALI interference groups for Model 1

In summary, analysis for the increased degradation of trans-tap average CCI by iso-tap average ALI shows the following trends:

- Iso-tap ALI across ports of same tap adds slight degradation to trans-tap CCI across IGs
- Iso-tap ALI across ports of same tap adds slight degradation to trans-tap CCI across IGs

For the highest capacity interference group (Tap 1) receiving and the lowest capacity interference group (Taps 4, 5, and 6) transmitting: ALI bit-loading impact is ~0.5 bits/subcarrier in across the FDX band (108 MHz to 684 MHz).

For the next highest capacity interference group (Tap 2) receiving and the lowest capacity interference group (Taps 4, 5, and 6) transmitting: ALI bit-loading impact is about half the previous case.

For the next highest capacity interference group (Tap 3) receiving and the lowest capacity interference group (Taps 4, 5, and 6) transmitting: ALI bit-loading impact is again about half the previous case.

The ALI impact in further division into more interference groups would be negligible. For example (Tap 4) receiving and the lowest capacity interference group (Taps 5 and 6) transmitting.

Full Duplex Echo and Self-Interference Analysis

8. Full Duplex Echo Model and Analysis

An approach to modeling signal reflection from the various elements of the fiber deep network is discussed in this section. Analysis of the echo response including transmitted signal levels reflected back toward the node and received by the node and similarly for the cable modem is described. This approach allows the use of log magnitude values versus frequency from component spec sheets to model the reflections of each section of transmission line (i.e., cable) terminated at either end with an impedance (i.e., a tap, node, or cable modem) characterized by its magnitude return loss versus frequency.

Consider the fiber deep architecture model depicted previously in Figure 4. The fundamental reflection model function block is again denoted by the tap span shown in this figure. It is shown in Appendix 2 for a length of trunk cable with cable propagation delay T, cable amplitude response A(f), and tap input/output port return loss RL = -10 Log(ρ) where ρ = reflection coefficient that the echo response E(f) for the tap span cable transmission line is given by:

$$E(f) = \frac{A^2(f)\,10^{-\frac{(\mathrm{RLi})}{20}}e^{-j4\pi fT}}{1 - A^2(f)\,10^{-\frac{(\mathrm{RLi+RLo})}{20}}e^{-j4\pi fT}}$$

Note that this formulation provides the complex frequency response with only the scalar amplitude versus frequency of the cable transmission line and the magnitude return loss versus frequency of the tap terminating impedances. This avoids the need to measure complex valued s-parameters versus frequency for each component in the network.

The same analysis applies to a drop cable section between tap port and the cable modem where the attenuation model and propagation delay are specified for the drop cable instead of the hardline cable and the input and output return losses are specified for the tap port and cable modem F-connector port respectively.

The echo response $E_n(f)$ for a reflection from the n^{th} tap from the node port with tap insertion losses $I_{n-1}, I_{n-2}, \ldots, I_1$ (all tap loss amplitudes in linear magnitude as a function of frequency) is given as the echo response $E(f)$ above with the length of the echo path delay from the node to the n^{th} tap being n times the tap span delay T and with the square of the linear magnitude cable attenuation $A^2(f)$ being multiplied by product of all tap insertion loss responses in the echo path squared (two passes through the tap for each reflection).

The echo response from the node to the n^{th} tap in the echo path is given by:

$$E_n(f) = \frac{A^2(f)(I_{n-1}\,I_{n-2}\ldots\,I_1)^2\,10^{-\frac{(\mathrm{RLi})}{20}}e^{-j4\pi fnT}}{1 - A^2(f)(I_{n-1}\,I_{n-2}\ldots\,I_1)^2\,10^{-\frac{(\mathrm{RLi+RLo})}{20}}e^{-j4\pi fnT}}$$

Denote the node total echo response as $E_{node}(f)$. The sum of all node echoes from all N taps is the sum of each echo path depicted in Figure 16 and given by:

$$E_{node}(f) = \sum_{i=1}^{N} E_i(f)$$

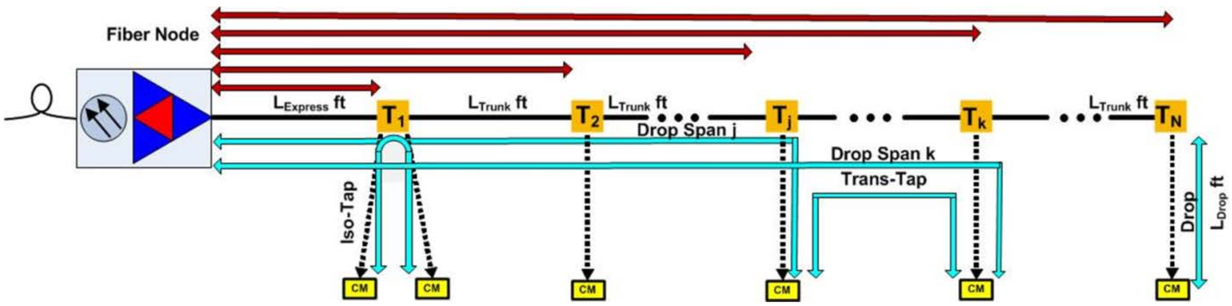


Figure 16 - Node principal echo paths

This approach is used to model the echo response between the node and all taps. The Fourier transform of the echo response in the frequency domain yields the impulse response in the time domain. The node port impulse response so obtained is shown in Figure 17.

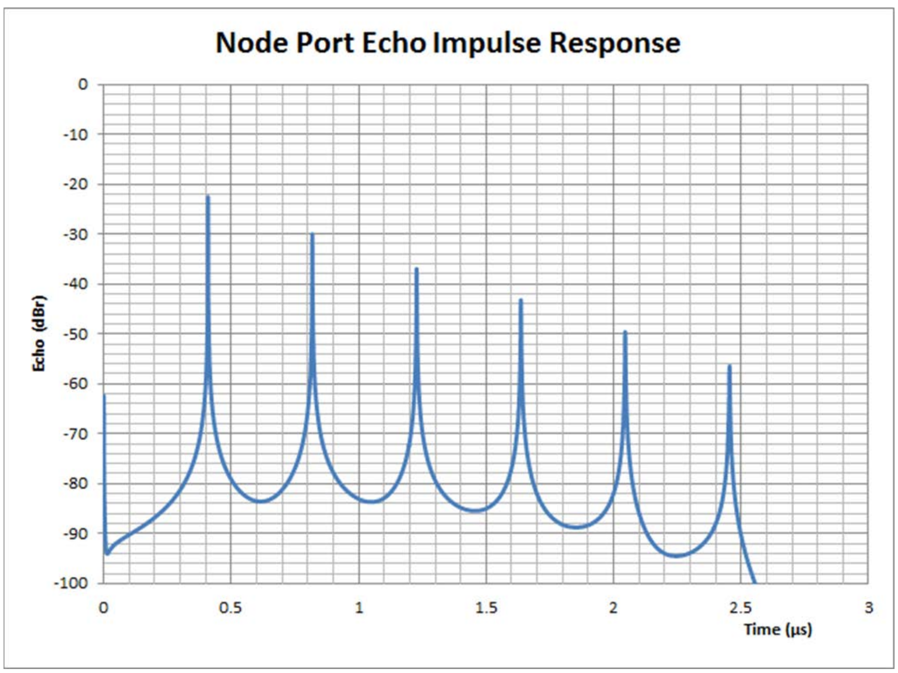


Figure 17 - Node port echo impulse response

The principal echo from each equidistant tap is evident in the delayed peaks of the impulse response at multiples of twice the electrical delay path length to each tap which is equal to 2*175'*1'/ns/0.87=0.41 µs for a 175 foot inter-tap cable spacing with a velocity of propagation of 0.87 times the speed of light.

A similar formulation is used to model the echo response from any cable modem attached to the n^{th} tap with two echo paths, one through the tap toward the node and the other through the tap-to-output isolation toward the last tap as shown in Figure 18.

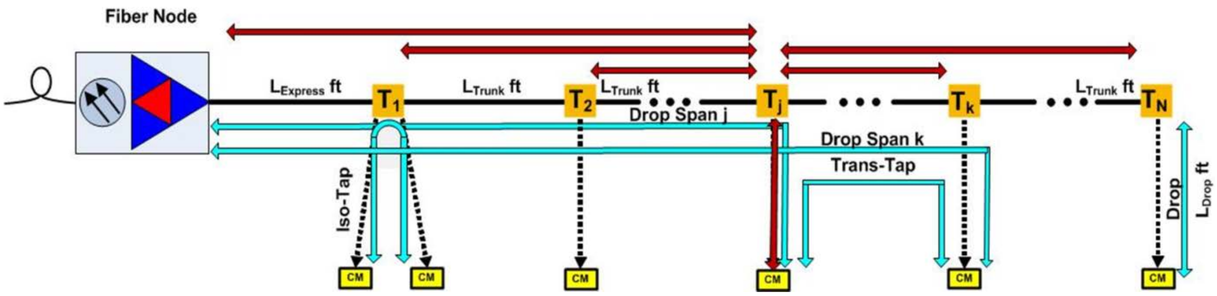


Figure 18 - Modem principal echo paths on the drop from tap j

This similar approach is used to model the echo response between the modem and all taps both upstream and downstream from the transmitting modem. The Fourier transform of the echo response in the frequency domain yields the impulse response in the time domain and is shown in Figure 19 for modems connected to the first tap 1 and the last tap 6 from the node.

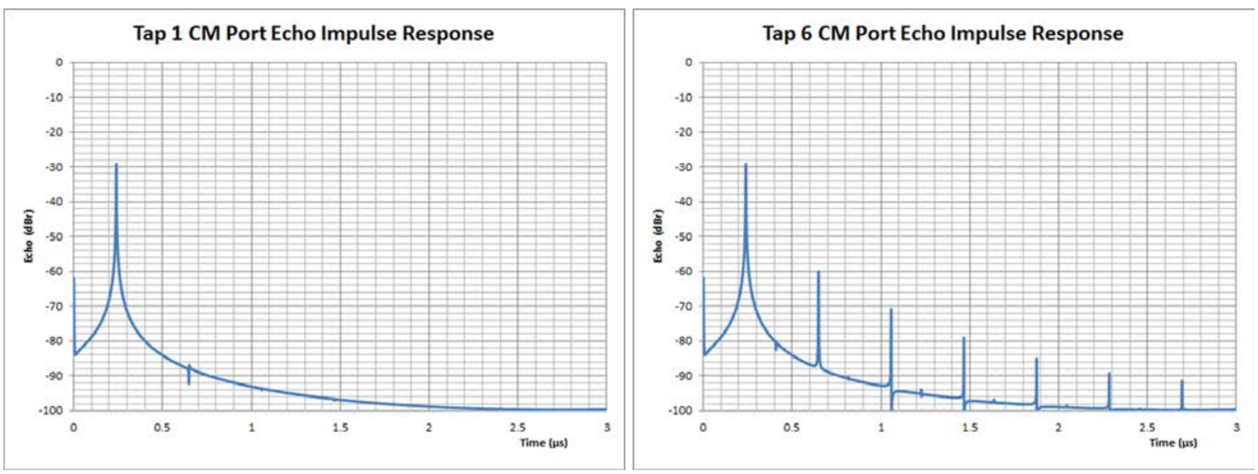


Figure 19 - Modem port echo impulse responses connected at the first and last tap

Note that the impulse response of a modem connected with 100 feet of drop cable to the first tap exhibits a single reflection from that tap. Twice the electrical delay drop length to the tap is equal to 2*100'*1'/ns/0.85 = 0.24 µs for a 100 foot Series 6 ("RG-6") cable. The very small echo at 0.41 + 0.24 = 0.65 µs is the primary reflection from the node.

Also note that the impulse response of a modem connected with 100 feet of drop cable to the last tap exhibits a multiple reflections from the drop plus all other taps and the node. The echo path delays are given by the drop delay plus multiple inter-tap delays at 0.24 + N*0.41 µs for N = 0, 1, …, 6.

9. Full Duplex Echo, Adjacent Leakage Interference, and Adjacent Channel Interference

Consider first the simultaneous full-duplex transmission and reception at the node. A high level functional block diagram of the node is shown in Figure 20.

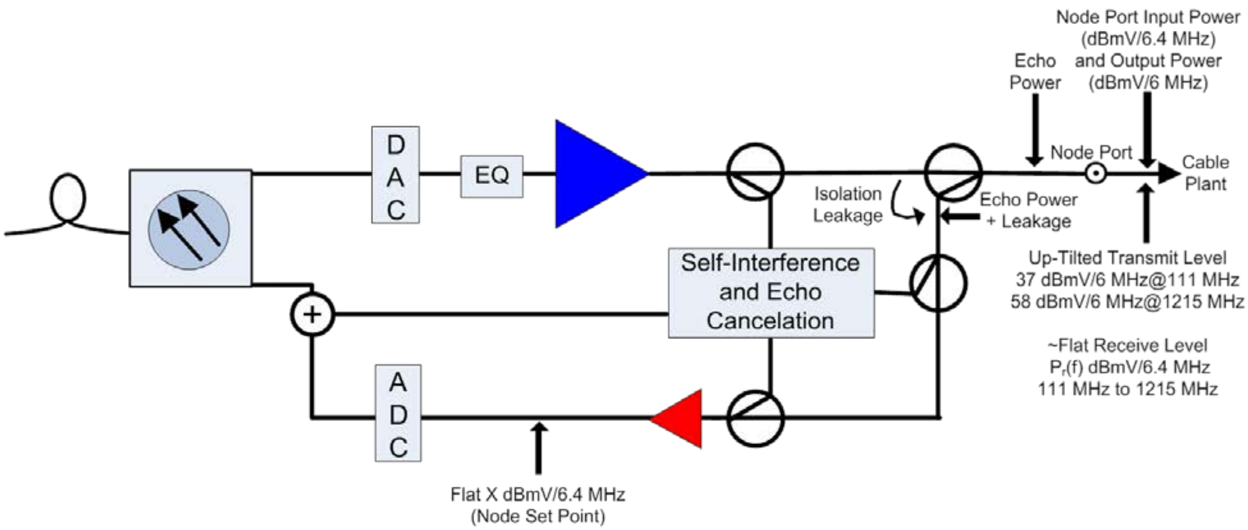


Figure 20 - Node functional block diagram for self-interference and echo cancellation

A directional coupler connected to the node port replaces the diplex filter in a conventional DOCSIS 3.1 FDD system. The directional coupler is needed to separate the upstream received signal from the downstream transmitted signal respectively entering and leaving the node port and occupying the same true full-duplex spectrum. Two sources of interference corrupt the reception of the upstream signal. The first is self-leakage of the downstream high power transmitted signal from the directional coupler output port to the tap port of the where the upstream signal is received. The second is the downstream high power echo returning from the cable plant through the node port and into the received signal path through the directional coupler tap port.

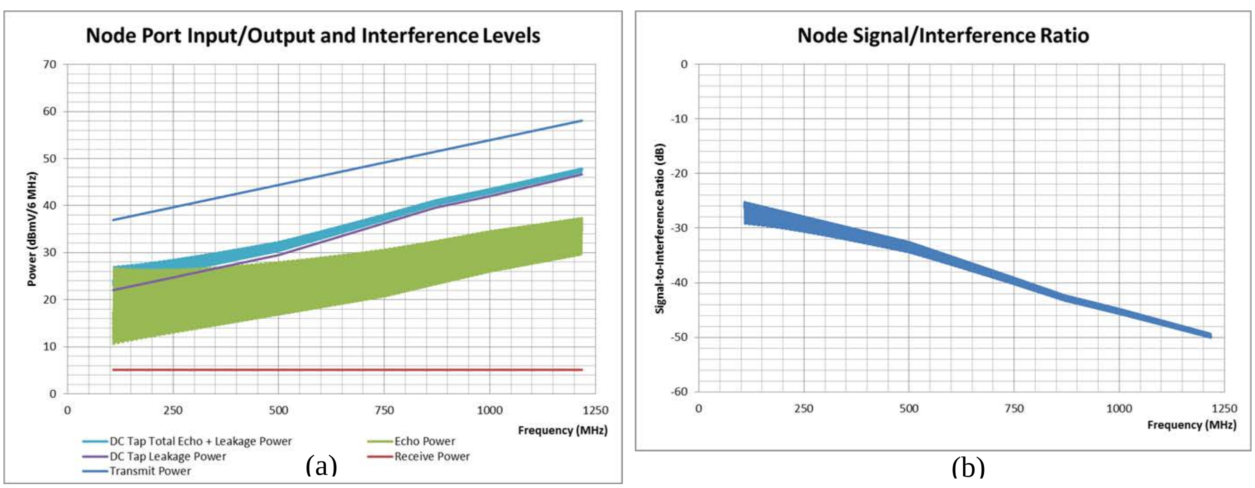


Figure 21 - Node echo plus leakage interference and signal-to-interference ratio

The downstream transmit power out of the node port has a 21 dB up tilt from 37 dBmV/6 MHz at 111 MHz to 58 dBmV/6 MHz at 1215 MHz as shown in Figure 21a. The received level at the node port is specified to be a flat power spectral density across the 108 MHz to 684 MHz full-duplex band. The value of that power spectral density level is determined such that the total composite power transmitted in the full-duplex band by any cable modem in the network does not exceed 64.5 dBmV. In this design example, the received upstream power spectral density level meeting this modem transmit power limit is approximately 5 dBmV/6.4 MHz.

The node downstream echo power increases from an average 20 dBmV/6 MHz to 25 dBmV/6 MHz in the FDX band. The echo power level closely tracks the transmit power level attenuated by approximately 20 dB. The variation in echo power is over 10 dB peak-to-peak about the average. This is due to the multiple echoes with different path lengths that add on a voltage basis with rapidly varying group delay versus frequency causing both maximum constructive and destructive interference at various frequencies.

The self-leakage power from the directional coupler through port isolation to the tap port is seen to be higher average power than the echo average power. Again comprising attenuated and delayed versions of the same signal, the self-leakage power and echo power add coherently on a voltage basis at the directional coupler tap port as shown in Figure 21a. The node upstream signal to total echo plus self-leakage interference ratio is highly negative from -32 dB to -40 dB as shown in Figure 21b. Thus at least 60 dB to 70 dB of self-interference plus echo cancellation and/or suppression is required to obtain a positive signal to interference ratio that can support 1024-QAM upstream signal reception in the node.

Consider next the simultaneous FDD transmission and reception at the modem. A high level functional block diagram of the modem is shown in Figure 22.

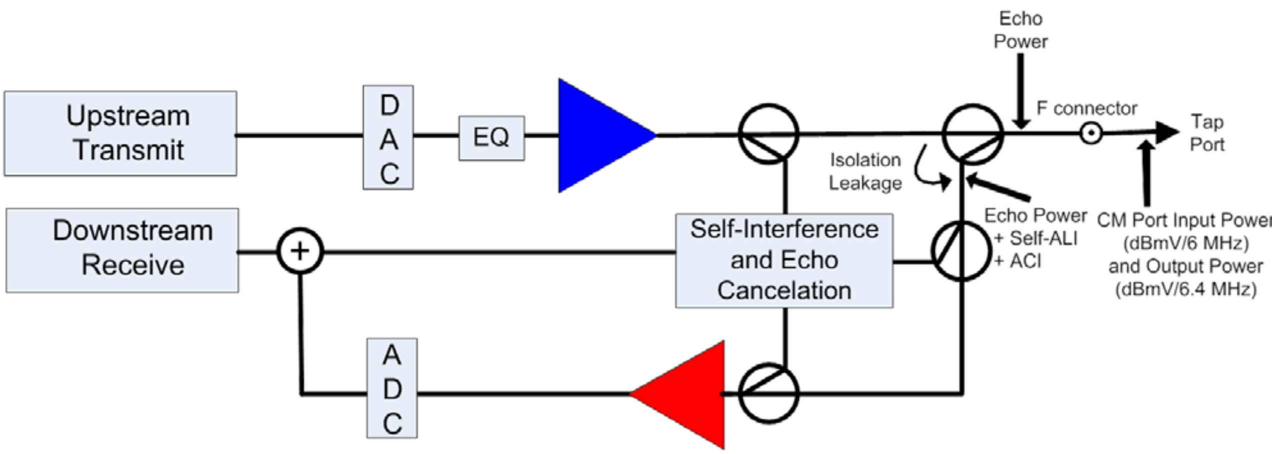


Figure 22 - Modem functional block diagram for self-interference and echo cancellation

A directional coupler connected to the modem port replaces the fixed diplex filter in a conventional DOCSIS 3.1 FDD modem. The directional coupler is needed to both separate the downstream received signal entering the modem port and combine the dynamically allocated spectrum of the upstream transmitted signal leaving the modem port. However, the coupler does not offer the isolation of the fixed-frequency diplex filter between the upstream transmitted and downstream received frequency bands.

The reason for separating transmission and reception within different channels is to obviate the need for echo and leakage interference cancelation in the same received downstream channel as the upstream transmission in a modem. If the modem transmits in a given channel, then both the echo and the leakage of the transmitted upstream signal can be canceled in that modem since the transmitted signal is known. Other modems in the same IG (e.g., on the same tap) will experience large co-channel interference from the transmitting modem. Unlike the situation at the node, these modems do not have knowledge of the transmitted signal and therefore have no reference with which to cancel the transmission leakage and echoes from a different modem. Thus true full-duplex operation within the same channel in the modem is precluded.

Even by separating transmission and reception dynamically within different channels in the modem, two sources of in-band interference can still corrupt the reception of the downstream signal in a transmitting modem. Referring to Figure 22, the first is isolation leakage of self-adjacent channel interference from the upstream high power transmitted signal (i.e., self-ALI from transmitter out-of-band spurious emissions) across the directional coupler output port into the tap port where the downstream signal is received. The second is the echo of this self-ALI returning from the cable plant through the modem port and into the received signal path through the directional coupler tap port.

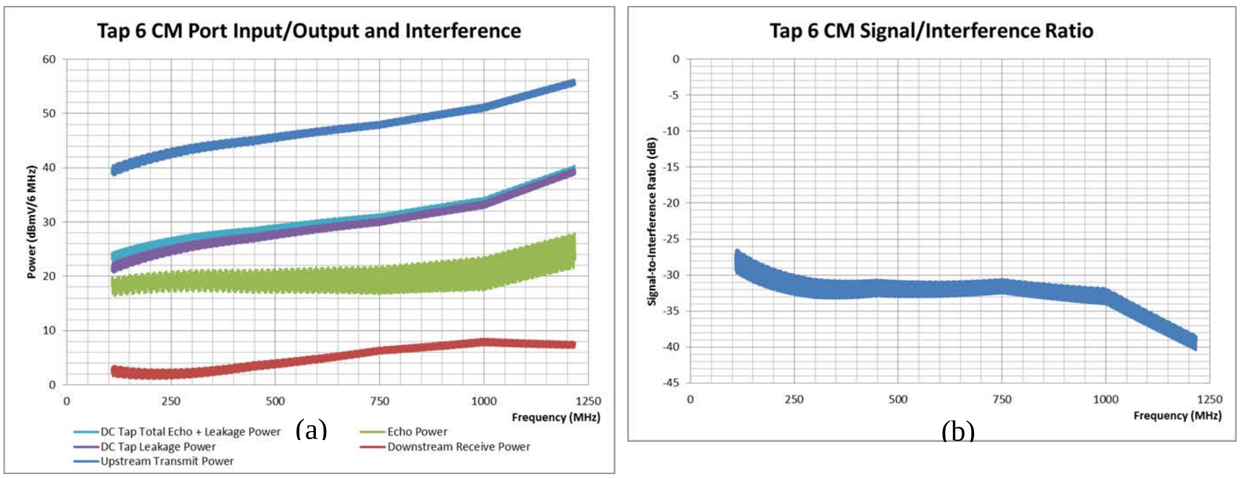


Figure 23 - Modem echo plus leakage interference and signal-to-interference ratio

The echo plus leakage interference and signal-to-interference ratio for a modem attached to a drop from tap 6 is shown in Figure 23a and Figure 23b respectively. This figure shows the interference across the entire downstream band. However, the upstream and downstream signals must occupy non-overlapping spectrum as explained previously. This is depicted in Figure 24.

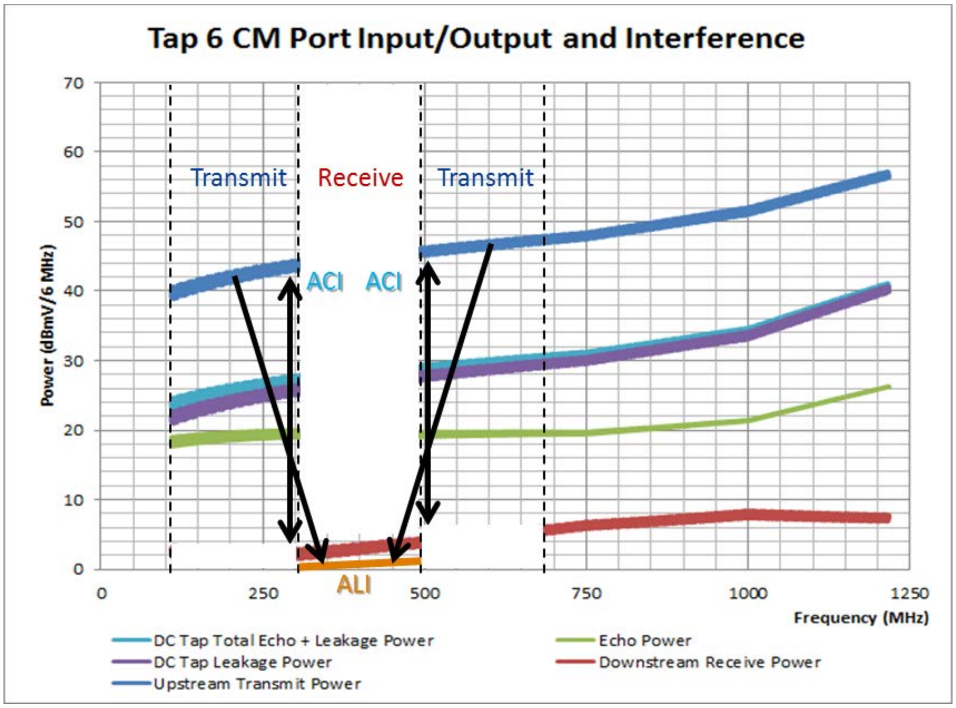


Figure 24 - Modem adjacent channel echo and self-adjacent leakage interference

The received level at the node port is specified to be a flat power spectral density across the 108 MHz to 684 MHz full-duplex band. The value of that power spectral density level is determined such that the total composite power transmitted in the full-duplex band by any cable modem in the network does not exceed 64.5 dBmV. In this design example, the received upstream power spectral density level meeting this modem transmit power limit is approximately 5 dBmV/6.4 MHz as shown previously in Figure 21a.

The modem upstream echo power in the adjacent channels to the downstream receive channel is approximately 20 dB higher than the received downstream signal both measured at the modem port as shown in Figure 24. This echo power, although not in the downstream receive band, is a significant adjacent channel interference source that may impair the operation of the downstream receiver.

The high level upstream transmitted signal in the 40 to 50 dBmV/6.4 MHz range will contribute self-adjacent leakage interference due to the limited output-to-tap isolation of the directional coupler.

Consider the situation for dynamic self-interference mechanisms in the modem. Figure 25 shows time varying self-interference of FDD transmission and reception in the FDX spectrum for a single interference group. Each modem in the same IG receives in all channels except the transmitting CM channel in that IG. As shown in the figure, the transmitting CM in an IG is subject to both self-ACI and iso-tap ACI (from modems on other ports of the same tap) adjacent to its received bands, and self-ALI within all received bands.

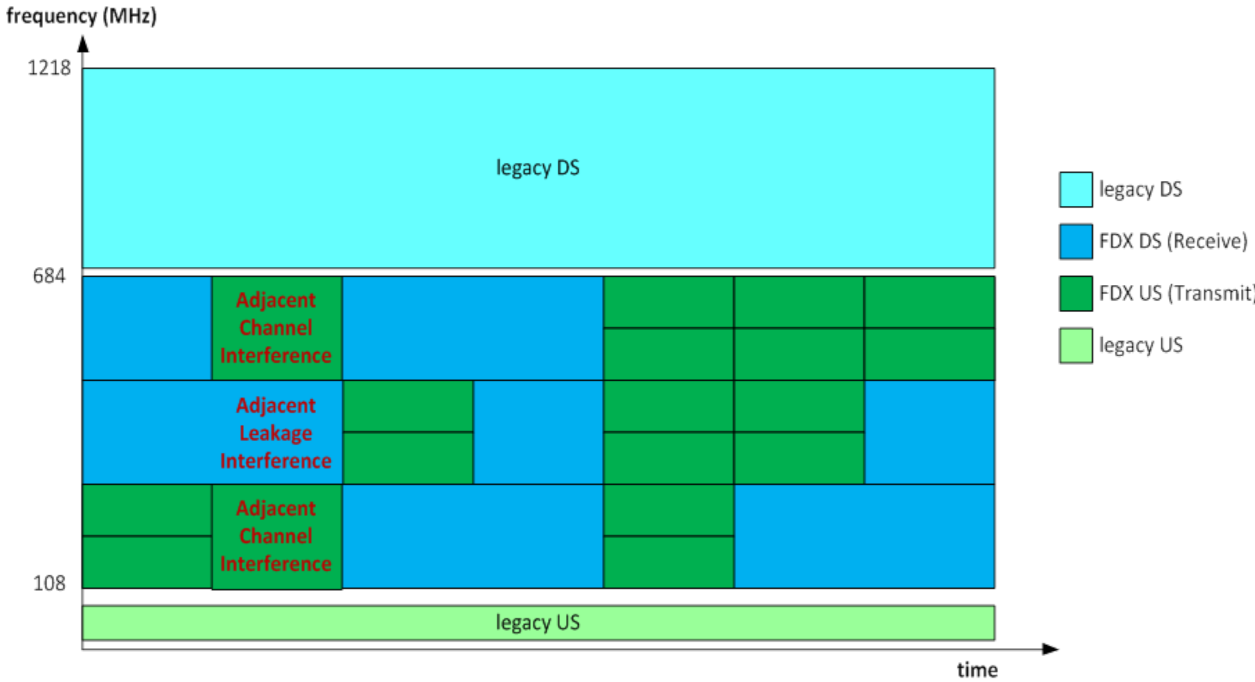


Figure 25 - Time varying self-interference of FDD transmission and reception in the FDX spectrum for a single interference group

Figure 26 shows one possible scenario for modem adjacent channel interference. The modem transmits upstream in the two highest FDX channels. The green line shows worst-case self-adjacent channel interference seen at the receiver of the same modem relative to its downstream receive level on the lowest FDX channel.

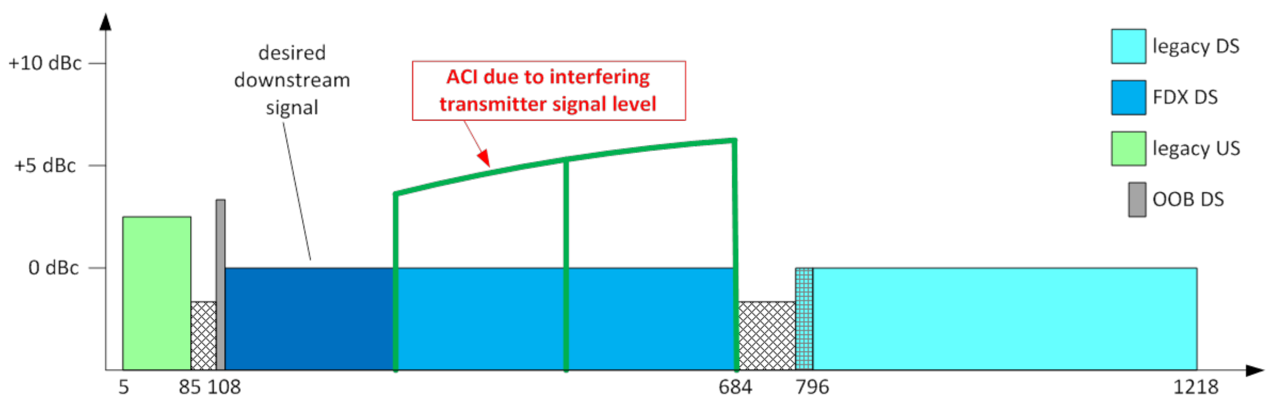
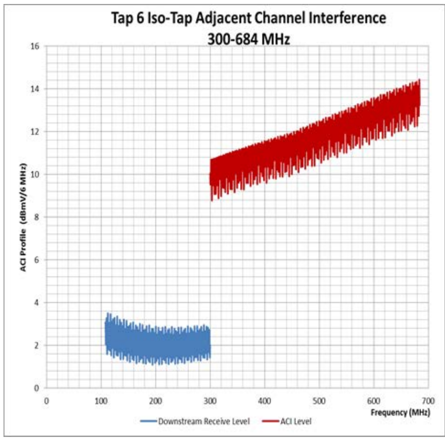
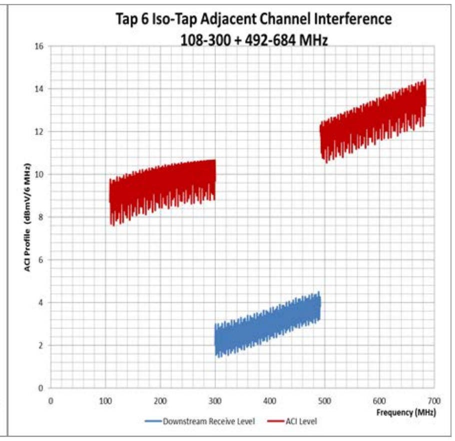


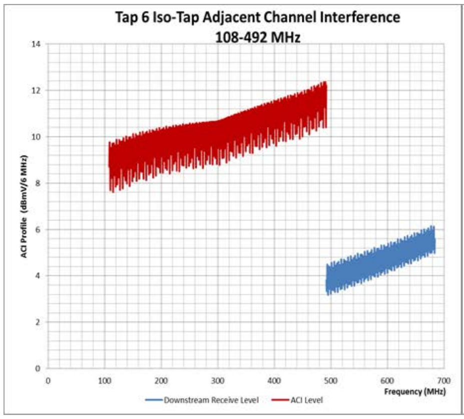
Figure 26 - Modem adjacent channel interference

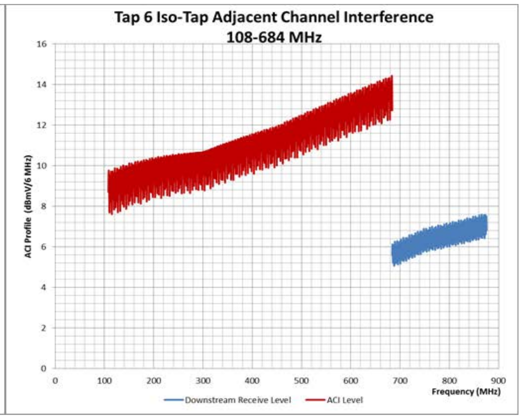
Iso-tap ACI power at the receiving modem port is calculated as the power at the transmitting modem port less the drop losses and tap port-to-port isolation. The iso-tap signal-to-adjacent channel interference ratio is calculated for a modem on tap 6 of Model 1 using the calculation method of Appendix 5: SIR Calculation of ACI and plotted in Figure 27. Note that the ACI arising from a different modem on the same tap cannot be canceled since the receiving modem has no transmitted signal reference from a different modem.





RBA = 011 RBA = 101





RBA = 110 RBA = 111

Figure 27 - Modem iso-tap adjacent channel interference for Model 1, tap 6

Self-ACI power is calculated as the transmit power plus the coupler insertion loss less the coupler isolation. The signal-to-self- adjacent channel interference ratio is calculated for a modem on tap 6 of Model 1 and plotted in Figure 28. This power will vary and may be mitigated in the transmitting modem based on the performance of the directional coupler chosen and the addition of self-ACI cancelation.

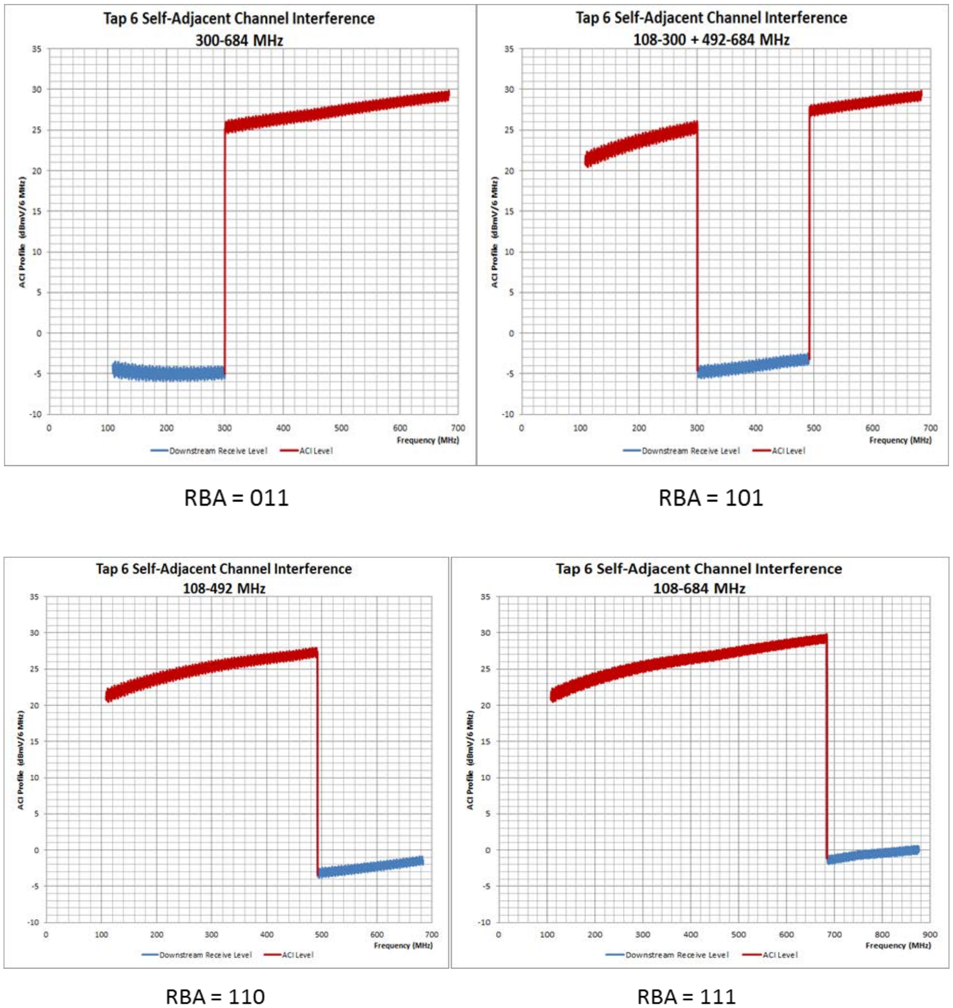


Figure 28 - Modem self-adjacent channel interference for Model 1, tap 6

Modem self-adjacent leakage interference will be considered next. Figure 29 shows one possible scenario for modem self-adjacent leakage interference. The modem transmits upstream in the two highest FDX channels. The red line shows worst-case self-adjacent leakage interference seen at the receiver of the same modem relative to its downstream receive level on the lowest FDX channel.

The self-adjacent leakage interference at the modem port in each sub-band with all other sub-bands transmitting is calculated for a modem on tap 6 of Model 1 and plotted in Figure 30. Self-ALI power in an FDX band receive channel arises from both other channels transmitting in two of the three sub-band channels that contribute interference. Self-ALI power in a receive channel in the legacy downstream band above the FDX band arises from all three FDX channels transmitting. Such high self-interference levels will require self-ALI mitigation to maintain high bit-loading in the FDX band. A traditional low pass filter plus a transition band would be an alternative approach instead of self-ALI cancelation above 684 MHz in the legacy downstream band.

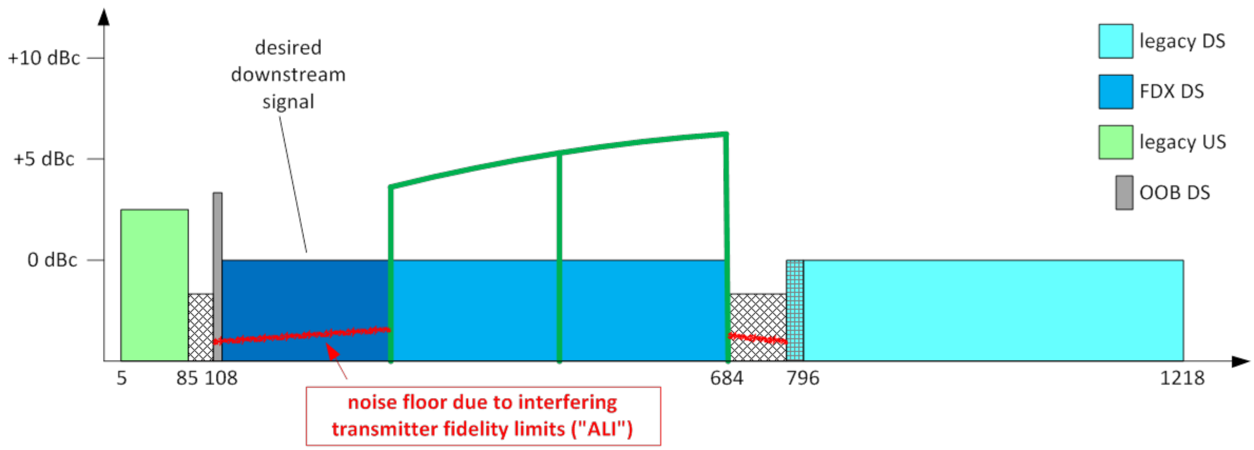


Figure 29 - Modem self-adjacent leakage interference

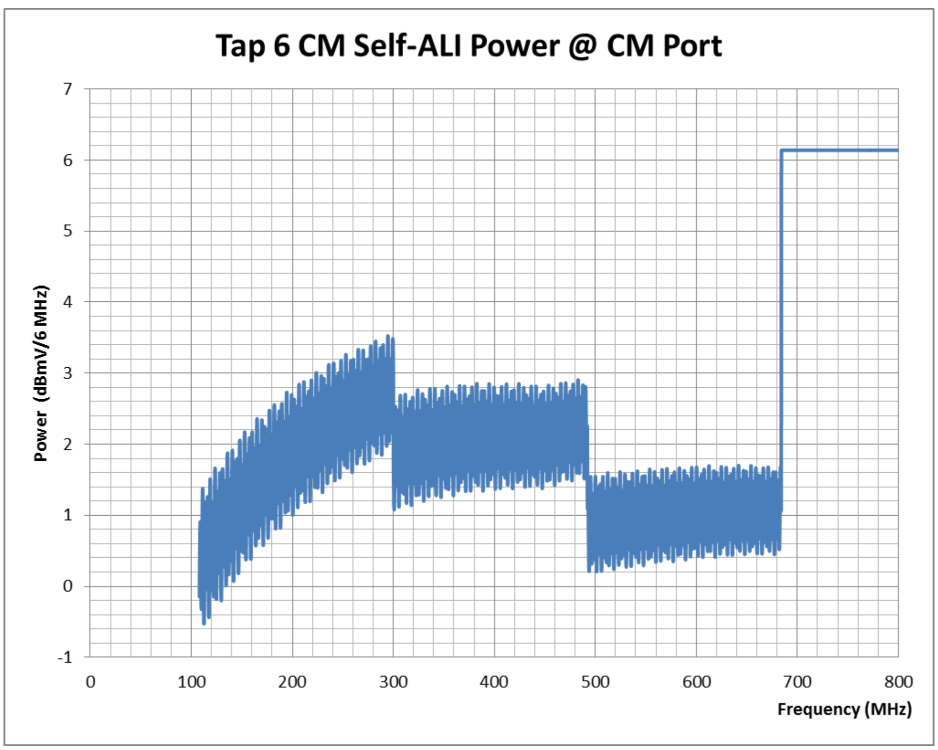


Figure 30 - Modem self-adjacent leakage interference for Model 1, tap 6

Conclusion

The fiber deep architecture is designed for uniform spectral efficiency both downstream and upstream in frequency division duplex systems such as DOCSIS 3.0 and 3.1. Fiber deep specified transmitted and received levels are designed with enough margin to provide 4096-QAM spectral efficiency downstream with up to a 200 foot drop cable plus a 4-way splitter and additional in-home wiring to the customer premise equipment.

Full duplex systems based on DOCSIS 3.1 over the fiber deep architecture lower the spectral efficiency of the downstream progressively in interference groups as a function of tap distance from the node. Simultaneous transmission and reception within the same frequencies in different interference groups introduces co-channel interference lowering spectral efficiency. Simultaneous transmission and reception within the different frequencies in the same interference group introduces adjacent leakage interference lowering spectral efficiency. Both these interferences can occur concurrently and add destructively impairing downstream reception.

Impaired receivers due to self-interference and transmitter echoes in both the node and the cable modem require self-interference and echo cancellation.

Operation in the full duplex band lowers overall downstream capacity while greatly increasing overall upstream capacity (which is the primary objective) at the expense of substantially increased complexity.

Appendix 0: Cable Attenuation Model

It will be shown that the signal level attenuation solely due to frequency dependent passive cable attenuation (or "tilt") can be reliably calculated from the measurement of actual cable attenuation characteristics such that the minimum mean squared error of the measured amplitude variations is achieved. This results in a simple model for the frequency dependent attenuation characteristic of a coaxial cable.

The coaxial cable produces signal attenuation per unit length that is frequency dependent whereby the higher frequency signals are subjected to greater attenuation than the lower frequency signals over the same length of cable. The attenuation in dB is proportional to the square root of frequency.

Specifically, for the cable attenuation A_1 dB at frequency f_1 and A_2 dB at frequency f_2, the ratio of attenuations is equal to the cable loss ratio:

$$A_1/A_2 = \sqrt{f_1/f_2}$$

Define:

$A_H \equiv$ signal attenuation at the highest carrier frequency f_H

$A_L \equiv$ signal attenuation at the lowest carrier frequency f_L

Tilt $\equiv$ the difference in signal attenuation between f_L and f_H is given by

$$Tilt = A_H - A_L = A_H - A_H\sqrt{f_L/f_H} \quad \text{(dB)}$$

Therefore the signal attenuation at the highest carrier frequency is given by

$$A_H = \frac{Tilt}{1-\sqrt{f_L/f_H}} \quad \text{(dB)}$$

The signal attenuation at the lowest carrier frequency is given by

$$A_L = A_H\sqrt{f_L/f_H} \quad \text{(dB)}$$

Therefore, the *relative* signal attenuation at a frequency f where $f_L \le f \le f_H$ is given by

$$\mathrm{A}(f) = \mathrm{A}_H \sqrt{f / f_H} - \mathrm{A}_L \text{ (dB)}, \text{ where } 0 \le \mathrm{A}(f) \le Tilt.$$

Substituting $x = \sqrt{f}$ above yields

$$\mathrm{A}(x) = \frac{\mathrm{A}_H}{\sqrt{f_H}} x - \mathrm{A}_L$$

which is a linear function of attenuation versus the square root of frequency.

Suppose one wants to estimate the cable attenuation at any frequency using the above attenuation model derived from some measured frequency vs. attenuation data pairs.

The attenuation model at any frequency could be derived from the measured data pairs in a least squares fit using linear regression (i.e., the line F(x) = mx + b with slope m and intercept b) on the set of attenuation levels versus the square root of frequency.

Using the method of least squares for determining the best linear fit for the attenuation y vs. the square root of frequency x yields

$$m = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

$$b = \bar{y} - m\bar{x}$$

where $\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$ and $\bar{y} = \frac{1}{N}\sum_{i=1}^{N} y_i$ are the means of x and y respectively.

An example of this method for determining the attenuation vs. frequency characteristics from measured Series 11 (“RG-11”) drop cable attenuation at multiple frequencies is shown in the following figures. Figure 31 shows the linear fit as a function of the square root of the frequency and Figure 32 shows the attenuation as a function of frequency by straightforward independent variable substitution. The actual measured data points from the manufacturer’s data sheet are shown in blue and the estimated cable attenuation model calculated with a least squares linear regression are shown in yellow. Note the close correlation between the actual and the estimated attenuation levels (typically within less than 1 dB).

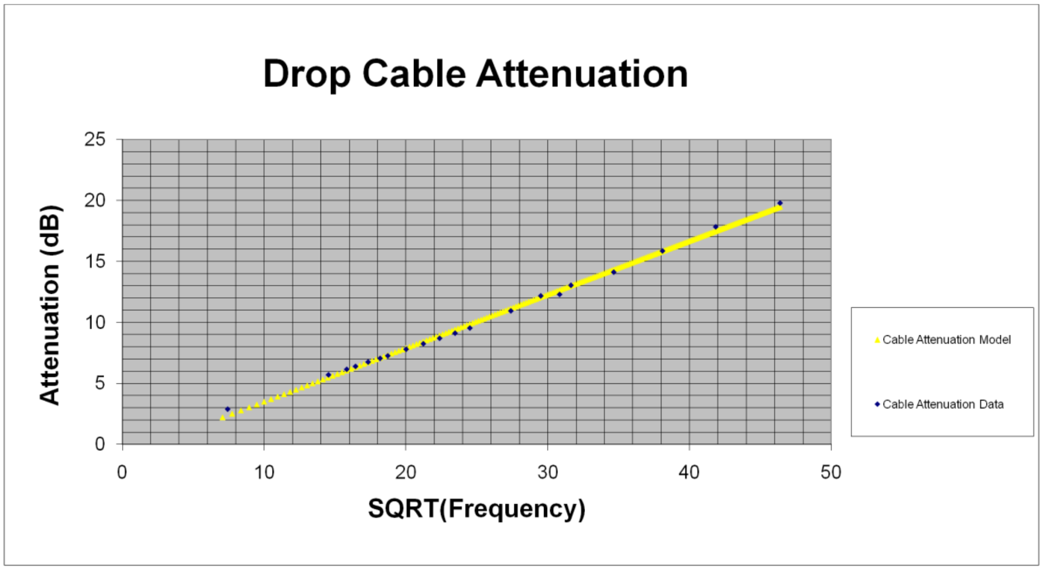


Figure 31 - Series 11 cable attenuation as a (straight line) function of $\sqrt{f}$

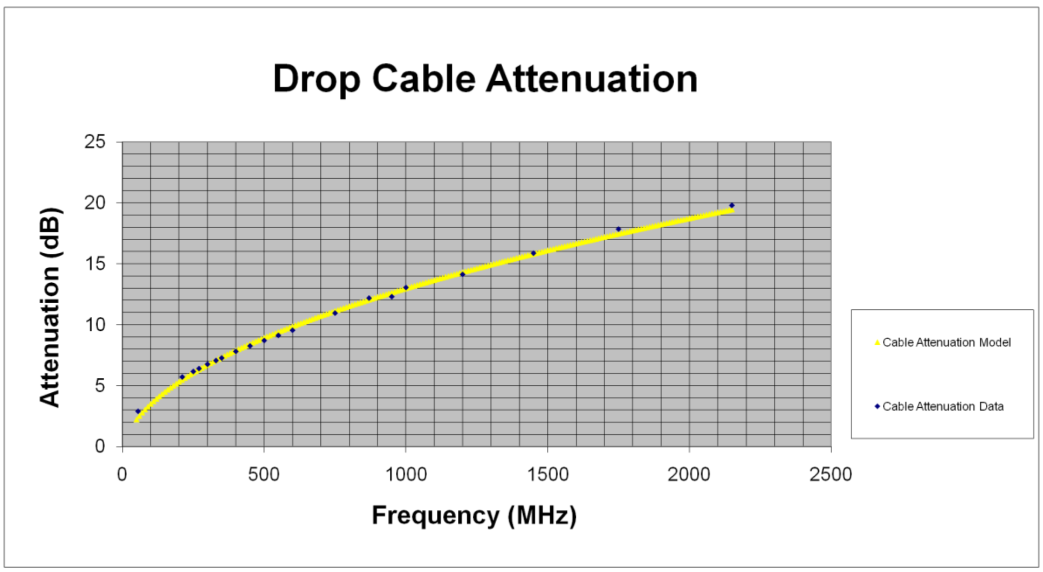


Figure 32 - Series 11 cable attenuation as a function of frequency

Appendix 1: Transmission Transfer Function

Consider a signal transmitted downstream from a tap output to the adjacent tap input as shown in Figure 33 with amplitude response $A(f)$ and linear phase response which has the corresponding impulse response of the cable denoted by $a(t)$. The transmitter at the signal source has (nearly) matched impedance to the drop cable but with a return loss RL_o (dB). The signal traverses the cable to the tap with propagation delay T which has a (nearly) matched impedance to the cable with return loss RL_i (dB). A portion of the signal equal to the reflection coefficient $10^{-RLi/20}$ is reflected back to the source, which in turn a portion of the reflected signal equal to the reflection coefficient $10^{-RLo/20}$ is re-reflected back toward the tap, and so on ad infinitum. This can be represented as a sum of the incident signal x(t) and the infinite series of reflections each delayed by the round trip (i.e. twice) the propagation delay T of the cable.

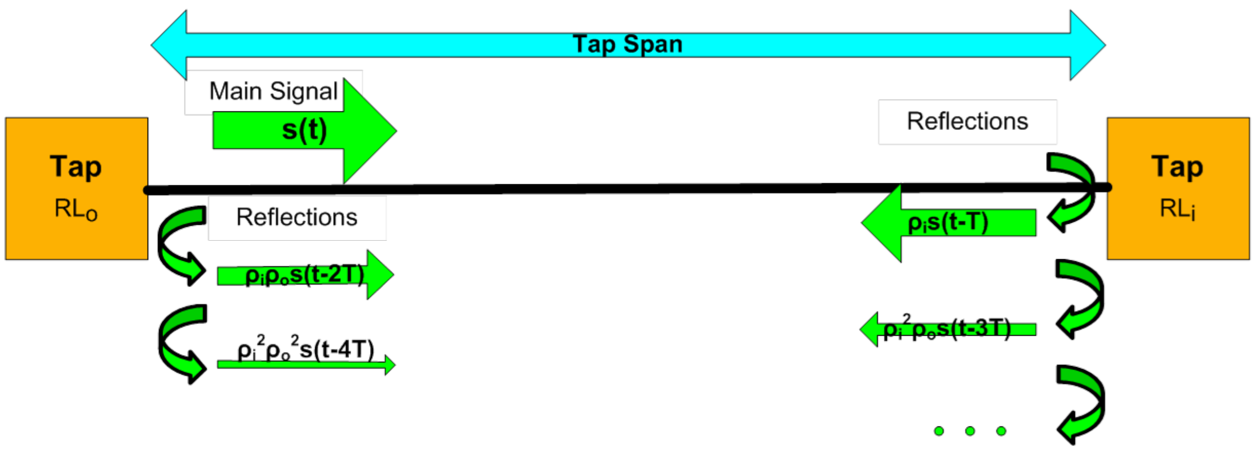


Figure 33 - Signal reflections in a cable between adjacent taps

Thus, the tap input consisting of the incident signal plus the discrete delays of each round trip reflected signal is given by:

$$y(t) = x(t) \circledast a(t) + 10^{-\frac{(\mathrm{RLi+RLo})}{20}} \mathrm{x(t-2T)} \circledast a(t) \circledast a(t) \circledast a(t) + 10^{-\frac{2(\mathrm{RLi+RLo})}{20}} \mathrm{x(t-4T)}$$

$$\circledast a(t) \circledast a(t) \circledast a(t) \circledast a(t) \circledast a(t) + \ldots$$

where $\circledast$ denotes convolution. Taking the Fourier transform results in:

$$Y(f) = A(f)X(f) + A^3(f)\, 10^{-\frac{(\mathrm{RLi+RLo})}{20}} e^{-j4\pi fT} X(f) + A^5(f)\, 10^{-\frac{2(\mathrm{RLi+RLo})}{20}} e^{-j8\pi fT} X(f) + \ldots$$

The transmitted signal transfer function $H(f)$ is given by:

$$H(f) = Y(f)/X(f)$$

$$= A(f)\,[1 + A^2(f)\, 10^{-\frac{(\mathrm{RLi+RLo})}{20}} e^{-j4\pi fT} + A^4(f)\, 10^{-\frac{2(\mathrm{RLi+RLo})}{20}} e^{-j8\pi fT} + \ldots]$$

or

$$H(f) = A(f)\ \sum_{k=0}^{\infty} A^{2k}(f)\, 10^{-\frac{\mathrm{k(RLi+RLo)}}{20}}\ e^{-j4\pi fTk}$$

Using the relationship

$$1 + r + r^2 + r^3 + \ \dots = \frac{1}{1-r};\ |r| < 1$$

yields the closed form transfer function $H(f)$ as

$$H(f) = \frac{A(f)}{1 - A^2(f)\, 10^{-\frac{\mathrm{(RLi+RLo)}}{20}} e^{-j4\pi fT}}$$

The same analysis applies to a feeder cable section between taps where the attenuation model and propagation delay are specified for the hard-line cable instead of the drop cable and the input and output return losses are specified for the through ports of the taps.

Appendix 2: Echo (Reflection) Transfer Function

Consider a signal transmitted downstream from a tap output to the adjacent tap input as shown in Figure 33 with amplitude response $A(f)$ and linear phase response which has the corresponding impulse response of the cable denoted by $a(t)$. The transmitter at the signal source has (nearly) matched impedance to the drop cable but with a return loss RL_o (dB). The signal traverses the cable to the tap with propagation delay T which has a (nearly) matched impedance to the cable with return loss RL_i (dB). A portion of the signal equal to the reflection coefficient $10^{-RLi/20}$ is reflected back to the source, which in turn a portion of the reflected signal equal to the reflection coefficient $10^{-RLo/20}$ is re-reflected back toward the tap, and so on ad infinitum. This reflected signal can be represented as a sum of the infinite series of reflections each delayed by the propagation delay T plus multiples of the round trip time (i.e. twice the propagation delay or 2T) of the cable.

Thus, the tap output reflections consisting of the discrete delays of each round trip reflected signal is given by:

$$y(t) = 10^{-\frac{(\mathrm{RLi})}{20}} \mathrm{x}(\mathrm{t}-2\mathrm{T}) \circledast a(t) \circledast a(t) + 10^{-\frac{2(\mathrm{RLi})+(\mathrm{RLo})}{20}} \mathrm{x}(\mathrm{t}-4\mathrm{T})$$

$$\circledast a(t) \circledast a(t) \circledast a(t) \circledast a(t) + \ldots$$

where $\circledast$ denotes convolution. Taking the Fourier transform results in:

$$Y(f) = A^2(f)\, 10^{-\frac{(\mathrm{RLi})}{20}} e^{-j4\pi f T} X(f) + A^4(f)\, 10^{-\frac{2(\mathrm{RLi})+(\mathrm{RLo})}{20}} e^{-j8\pi f T} X(f) + \ldots$$

The reflected signal transfer function $E(f)$ is given by:

$$E(f) = Y(f)/X(f)$$

$$= A^2(f)\, 10^{-\frac{(\mathrm{RLi})}{20}} e^{-j4\pi f T} \left[1 + A^2(f)\, 10^{-\frac{(\mathrm{RLi+RLo})}{20}} e^{-j4\pi f T} + A^4(f)\, 10^{-\frac{2(\mathrm{RLi+RLo})}{20}} e^{-j8\pi f T} + \ldots\right]$$

or

$$E(f) = A^2(f)\, 10^{-\frac{(\mathrm{RLi})}{20}} e^{-j4\pi f T} \sum_{k=0}^{\infty} A^{2k}(f)\, 10^{-\frac{\mathrm{k(RLi+RLo)}}{20}} e^{-j4\pi f T k}$$

Using the relationship

$$1 + r + r^2 + r^3 + \ldots = \frac{1}{1-r};\ |r| < 1$$

yields the closed form transfer function $E(f)$ as

$$E(f) = \frac{A^2(f)\, 10^{-\frac{(\mathrm{RLi})}{20}} e^{-j4\pi f T}}{1 - A^2(f)\, 10^{-\frac{(\mathrm{RLi+RLo})}{20}} e^{-j4\pi f T}}$$

Appendix 3: SNR Calculations of CCI

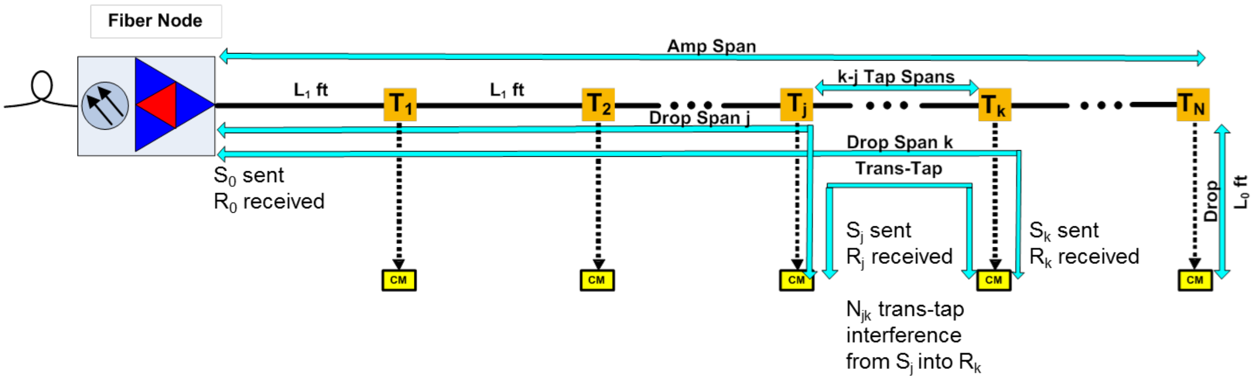


Figure 34 - Modem trans-tap interference in a coax cable system

Denote the transfer function *H*(f) between a modem on tap j and a modem on tap k in Figure 34 as:

$H_{jk} \equiv$ *H*(f) from tap j to tap k

where the node is defined as position 0. The received signal R_k is related to the node transmitted signal S_0 by:

$$R_k = S_0 H_{0k}$$

The trans-tap CCI N_{jk} by the transmitted signal from tap j to the received signal into tap k is:

$$N_{jk} = \{S_j | R_0\} H_{jk}$$

Noting that

$$R_0 = S_j H_{0j}$$

so $\{S_j | R_0\} = R_0 / H_{0j}$

Therefore

$$N_{jk} = R_0 H_{jk} / H_{0j}$$

and the SNR caused by the transmitted signal from tap j to the received signal into tap k is:

$$SNR_{jk} \equiv 20 \log \frac{R_k}{N_{jk}} = 20 \log \frac{S_0}{R_0} \frac{H_{0j} H_{0k}}{H_{jk}} (dB)$$

SNR_{jk} is a function of frequency f_i

Average over f_i; $0 \leq i < n$ for n frequency points to obtain:

$$\overline{SNR}_{jk} = S_{0dB} - R_{0dB} - 20\ \log \frac{1}{n} \sum_{i=0}^{n-1} \frac{H_{jk}(i)}{H_{0j}(i) H_{k0}(i)} (dB)$$

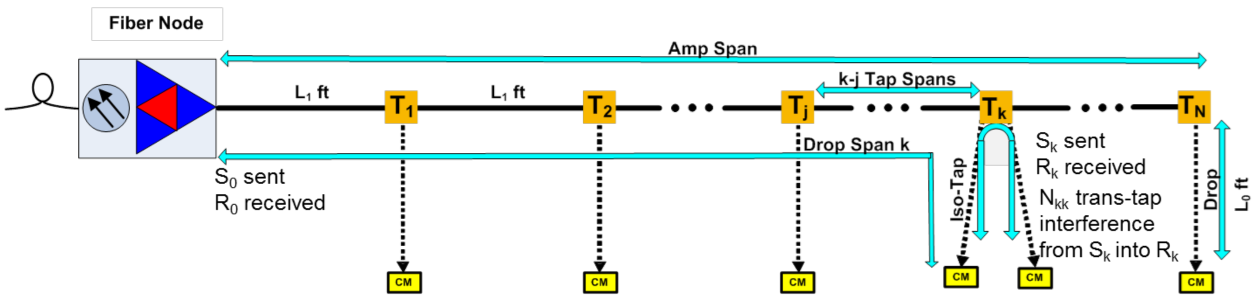


Figure 35 - Modem iso-tap interference in a coax cable system

Denote the transfer function *H*(f) between a modem on a drop of tap k and a modem on another drop of the same tap k in Figure 35 as:

$H_{kk} \equiv\ H$(f) between different drops on tap k

where the node is defined as position 0. The received signal R_k is related to the node transmitted signal S_0 by:

$$R_k = S_0 H_{0k}$$

The iso-tap interference N_{kk} by the transmitted signal between drops on tap k is:

$$N_{kk} = \{S_k | R_0\}\ H_{kk}$$

Noting that

$$R_0 = S_k H_{0k}$$

so $\{S_k | R_0\} = R_0 / H_{0k}$

Therefore

$$N_{kk} = R_0\ H_{kk} / H_{0k}$$

and the SNR caused by the transmitted signal on a drop from tap k to the received signal into another drop on the same tap k is:

$$SNR_{kk} \equiv 20 \log \frac{R_k}{N_{kk}} = 20\ \log \frac{S_0}{R_0} \frac{H_{0k}\ H_{0k}}{H_{kk}} (dB)$$

SNR_{kk} is a function of frequency f_i

Average over f_i; $0 \leq i < n$ for n frequency points to obtain:

$$\overline{SNR}_{kk} = S_{0dB} - R_{0dB} - 20\ \log\frac{1}{n}\sum_{i=0}^{n-1}\frac{H_{kk}(i)}{H_{0k}(i)H_{k0}(i)}(dB)$$

Appendix 4: SNR Calculations of ALI

Denote the transfer function H(f) between a modem on tap j and a modem on tap k in Figure 34 as:

$H_{jk} \equiv H$(f) from tap j to tap k

where the node is defined as position 0. The ALI from the modem port into tap j is defined as A_j which is a function f(·) of the modem transmitted signal S_j. Noting that

$R_0 = S_j H_{0j}$

so $\{S_j | R_0\} = R_0 / H_{0j}$

Therefore

$\{A_j | S_j\} = \mathrm{f}(S_j) = \mathrm{f}(R_0 / H_{0j}) = A_j$

The trans-tap ALI N_{jk} by the transmitted signal from tap j to the received signal into tap k is:

$N_{jk} = A_j H_{jk}$

and the SNR caused by the transmitted signal from tap j to the received signal into tap k is:

$$SNR_{jk} \equiv 20 \log \frac{R_k}{N_{jk}} = 20 \ \log \frac{S_0}{A_j} \frac{H_{0k}}{H_{jk}} (dB)$$

SNR_{jk} is a function of frequency f_i

Average over f_i; $0 \le i < n$ for n frequency points to obtain:

$$\overline{SNR}_{jk} = S_{0dB} - A_{jdB} - 20 \ \log \frac{1}{n} \sum_{i=0}^{n-1} \frac{H_{jk}(i)}{H_{0k}(i)} (dB)$$

Denote the transfer function H(f) between a modem on a drop of tap k and a modem on another drop of the same tap k in Figure 35 as:

$H_{kk} \equiv H$(f) between different drops on tap k

where the node is defined as position 0. The ALI from the modem port into tap k is defined as A_k which is a function f(·) of the modem transmitted signal S_k. Noting that

$R_0 = S_k H_{0k}$

so $\{S_k | R_0\} = R_0 / H_{0k}$

Therefore

$\{A_k|S_k\} = \mathrm{f}(S_k) = \mathrm{f}(R_0/H_{0k}) = A_k$

The iso-tap ALI N_{kk} by the transmitted signal on a drop of tap k into the received signal of a modem on another drop of the same tap k is:

$$N_{kk} = A_k H_{kk}$$

and the SNR caused by the transmitted signal on a drop from tap k to the received signal into another drop on the same tap k is:

$$SNR_{kk} \equiv 20 \log \frac{R_k}{N_{kk}} = 20 \log \frac{S_0}{A_k} \frac{H_{0k}}{H_{kk}} (dB)$$

SNR_{kk} is a function of frequency f_i

Average over f_i; $0 \leq i < n$ for n frequency points to obtain:

$$\overline{SNR}_{kk} = S_{0dB} - A_{kdB} - 20 \log \frac{1}{n} \sum_{i=0}^{n-1} \frac{H_{kk}(i)}{H_{0k}(i)} (dB)$$

Appendix 5: SIR Calculation of ACI

Denote the transfer function H(f) between a modem on tap j and a modem on tap k in Figure 34 as:

$H_{jk} \equiv H$(f) from tap j to tap k

where the node is defined as position 0. The received signal R_k is related to the node transmitted signal S_0 by:

$$R_k = S_0 H_{0k}$$

The trans-tap ACI N_{jk} by the transmitted signal in adjacent bands from tap j to the received signal into tap k is:

$$N_{jk} = \{S_j | R_0\} H_{jk}$$

Noting that

$$R_0 = S_j H_{0j}$$

so $\{S_j | R_0\} = R_0 / H_{0j}$

Therefore

$$N_{jk} = R_0 H_{jk} / H_{0j}$$

and the signal-to-interference ratio (SIR) from the ACI of the adjacent channel transmitted signal from tap j to the received signal into tap k is:

$$S/ACI_{jk} \equiv 20 \log \frac{R_k}{N_{jk}} = 20 \log \frac{S_0}{R_0} \frac{H_{0j} H_{0k}}{H_{jk}} (dB)$$

S/ACI_{jk} is a function of frequency f_i

Average over f_i; $0 \le i < n$ for n frequency points to obtain:

$$\overline{S/ACI}_{jk} = S_{0dB} - R_{0dB} - 20 \log \left[\frac{\frac{1}{m} \sum_{i=0}^{m-1} H_{jk}(i) / H_{0k}(i)}{\frac{1}{n} \sum_{i=0}^{n-1} H_{0j}(i)} \right] (dB)$$

with n points in-band and m points in the interfering adjacent band.

Denote the transfer function H(f) between a modem on a drop of tap k and a modem on another drop of the same tap k in Figure 35 as:

$H_{kk} \equiv H$(f) between different drops on tap k where the node is defined as position 0. The received signal R_k is related to the node transmitted signal S_0 by:

$$R_k = S_0 H_{0k}$$

The iso-tap ACI N_{kk} by the transmitted signal in adjacent bands to the received signal between drops on tap k is:

$$N_{kk} = \{S_k|R_0\}\ H_{kk}$$

Noting that

$$R_0 = S_k H_{0k}$$

so $\{S_k|R_0\} = R_0/H_{0k}$

Therefore

$$N_{kk} = R_0\ H_{kk}/H_{0k}$$

and the signal-to-interference ratio from the ACI of the adjacent channel transmitted signal from a drop on tap k to the received signal on another drop of the same tap k is:

$$S/ACI_{kk} \equiv 20\log\frac{R_k}{N_{kk}} = 20\ \log\frac{S_0}{R_0}\frac{H_{0k}\ H_{0k}}{H_{kk}}\,(dB)$$

S/ACI_{kk} is a function of frequency f_i

Average over f_i; $0 \le i < n$ for n frequency points to obtain:

$$\overline{S/ACI}_{kk} = S_{0dB} - R_{0dB} - 20\log\left[\frac{\frac{1}{m}\sum_{i=0}^{m-1} H_{kk}(i)/\ H_{0k}(i)}{\frac{1}{n}\sum_{i=0}^{n-1} H_{0k}(i)}\right](dB)$$

with n points in-band and m points in the interfering adjacent band.

Abbreviations

ACI	adjacent channel interference
ALI	adjacent leakage interference
CCI	co-channel interference
CNR	carrier-to-noise ratio
CW	continuous wave
dB	decibel
dBmV	decibel millivolt
dBr	decibel reference (sometimes decibel relative)
DOCSIS	Data-Over-Cable Service Interface Specifications
FDD	frequency division duplex
FDX	full duplex
FEC	forward error correction
GHz	gigahertz
HFC	hybrid fiber-coax
IG	interference group
ISBE	International Society of Broadband Experts
IUC	interval usage code
MER	modulation error ratio
MHz	megahertz
OFDM	orthogonal frequency division multiplex
OFDMA	orthogonal frequency division multiple access
OUDP	OFDMA upstream data profile
QAM	quadrature amplitude modulation
QPSK	quadrature frequency shift keying
RBA	resource block assignment
RL	return loss
SCTE	Society of Cable Telecommunications Engineers
SIR	signal-to-interference ratio
SNR	signal-to-noise ratio
TG	transmission group
ZBL	zero bit loaded