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Analysis and related solutions for full duplex interference

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Summary

This Technical Paper describes several primary interferences that will impact the in-band full-duplex cable modem (CM) performance, and also provides interference mitigation solutions.

NOTE – This is an informative ITU-T publication. Mandatory provisions, such as those found in ITU-T Recommendations, are outside the scope of this publication. This publication should only be referenced bibliographically in ITU-T Recommendations.

Keywords

Adjacent channel interference, adjacent leakage interference, co-channel interference, in-band full-duplex, interference group, sounding.

Change log

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Editor: Evan Sun   E-mail: evan.sun@huawei.com
Huawei Technologies Co., Ltd.
China

Tae Kyoon Kim   E-mail: tkkim@etri.re.kr
ETRI
Korea

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Analysis and related solutions for full duplex interference

1   Scope

Several primary interferences will impact the in-band full-duplex CM performance, and the interference mitigation solutions are provided.

2   Abbreviations and acronyms

ALI   Adjacent Leakage Interference

ACI   Adjacent Channel Interference

ADC   Analogue-to-Digital Converter

CCI   Co-Channel Interference

CM   Cable Modem

CMTS   Cable Modem Terminal System

FDX   Full Duplex

IG   Interference Group

MER   Modulation Error Ratio

QAM   Quadrature Amplitude modulation

RxMER   Receiving Modulation Error Ratio

SNR   Signal to Noise Ratio

TG   Transmission Group

3   Introduction

Full duplex (FDX) technology is targeted at significantly increasing the spectrum efficiency by using the same spectrum for simultaneous upstream and downstream transmission. A CM's downstream signal can be impacted by the upstream signal of itself or other CMs. With different upstream transmission and channel, there are five interferences illustrated in Figure 1.
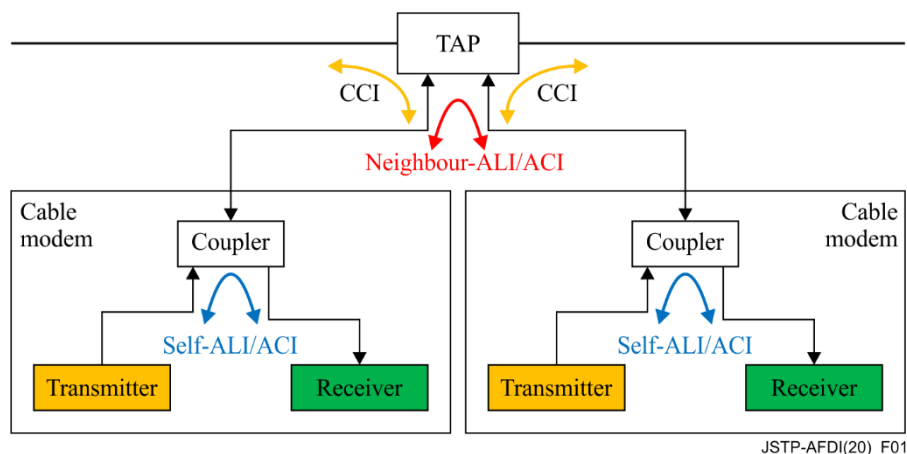

Figure 1 – Cable modem and interferences schematic

There are five primary interferences that can impact the FDX CM performance:

–   Self-adjacent leakage interference (ALI), and self-adjacent channel interference (ACI) resulting from the CM's own upstream transmissions.

–   Neighbour-ALI and neighbour-ACI resulting from upstream transmissions of other CMs in the cable plant, in particular, other CMs in the same interference group (IG).

–   Co-channel interference (CCI) resulting from upstream transmission of other CMs in the cable plant at the same channel.
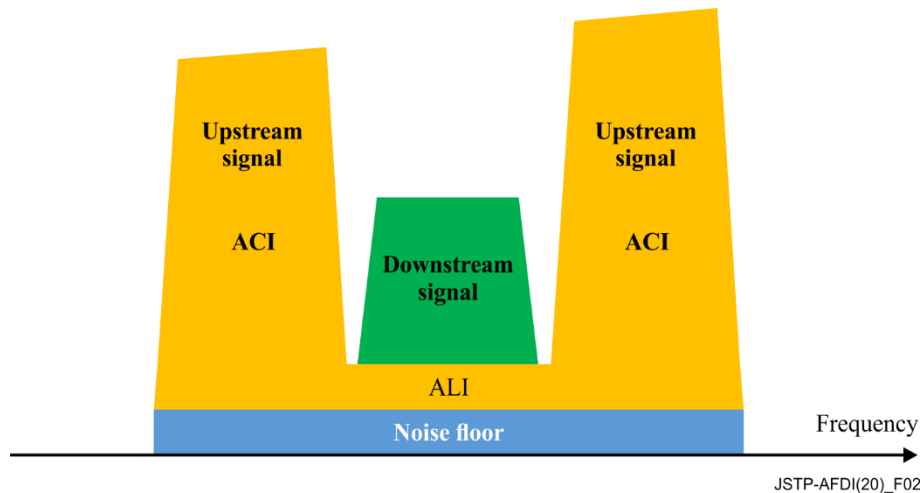

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Figure 2 – ALI and ACI illustrated in the spectral plane

Self-ALI refers to the power that leaks into a downstream channel of a CM from an upstream transmission of the same CM in another part of the FDX spectrum. The CM has to transmit at a relatively high-power level to be received by the FDX node, and as a result the power of the out-of-band components of this upstream transmission are comparable to the power of a downstream signal in an adjacent channel at CM input. Some of this upstream out-of-band power gets coupled into the receiver path through the coupler within the CM, shown in Figure 1. Further out-of-band power gets added to the received signal through reflections in the drop cable and at the connection with the main cable. The sum of all these out-of-band components of the upstream transmission that gets added to the downstream signal is referred to as ALI. This ALI level can be significantly higher than the noise floor of the system displayed in Figure 2 and, therefore, its cancellation is required for the CM to decode data in subcarriers with moderate to high order quadrature amplitude modulation (QAM) constellations.

Self-ACI refers to the power that remains in the same band as the transmitted signal but gets added into the receiver path through the coupler within the CM as well as through reflections in the cable and its taps. This is significantly stronger than ALI, but it is not an in-band interference like ALI. Its main effect is in overloading the receiver circuitry. Therefore, its cancellation is required for the CM to reduce the load on the receiver analogue and analogue-to-digital conversion circuitry.

Neighbour-ALI refers to the power that leaks into a downstream channel of a CM from an upstream transmission of neighbour CM in another part of the FDX spectrum. If the tap to tap isolation is not enough, this ALI level can be higher than the noise floor of the system, meanwhile, neighbour-ALI cannot be cancelled, so it will impact the CM receiver performance.

Neighbour-ACI is similar to the self-ACI, but the power is from upstream transmissions of neighbour CMs through the CM to CM path. This ACI level is normally less than the self-ACI, but cannot be cancelled, it will increase the receiver dynamic range and should be filtered out at receiver.

CCI refers to the power that injects into a downstream channel of a CM from an upstream transmission of other CMs in the same frequency band. To avoid the risk of CCI, the cable modem terminal system (CMTS) schedules transmissions and grants such that a CM does not transmit at the

same time as other CMs that are susceptible to interference from the transmitting CMs. CM to CM interference susceptibility is measured through a sounding process. After measuring CM to CM interference susceptibility, the CMTS creates groups of CMs that are susceptible to interfering with one another, called interference groups and schedules transmissions and grants to CMs to avoid having a CM transmit when other CMs in its IG are receiving.

All the five interferences will impact the FDX network, and should be analysed to meet the FDX CM receiver performance requirements as follows:

– CCI will impact the CM registration, so normally the CM should be registered in the non-FDX channel, or if there is no non-FDX channel, a mechanism to confirm a proper registration should be available. To avoid the risk of CCI, after CM registration, the IG discovery should be completed through the sounding process, and the CM will be assigned to a transmission group (TG).

– Self-ALI can be significantly higher than the noise floor of the CM receiver system, and self-ACI can overload the receiver circuitry, so echo cancellation should be used to improve FDX CM receiver performance by cancelling ALI and ACI resulting from the CM's own upstream transmissions.

– Neighbour-ALI and neighbour-ACI cannot be cancelled, so they should be analysed to find a way to avoid the risk of impacting CM performance.

4   Co-channel interference mitigation

In the previous section it is mentioned that with different upstream transmission channel, there are five primary interferences (self-adjacent leakage interference, self-adjacent channel interference, neighbour-ALI, neighbour-ACI and co-channel interference) which will affect the performance of CMs. This section focuses on the analysis of CCI and the related solutions to mitigate the interference.

CCI to CM downstream receiving is introduced by upstream transmission of other CMs at the same time and at the same frequency band (full duplex mode). Transmitting CMs and receiving CMs can be under the same Tap or under different Taps as shown in Figure 3. CM3 under Tap n transmits signal on FDX frequency band. CM1 and CM2 receive signals at the same band. Then two CCI are generated due to limited isolation among CMs.
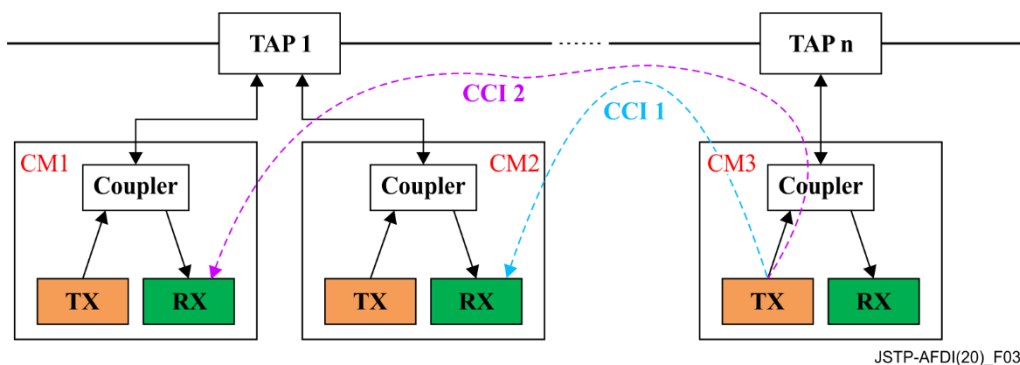
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Figure 3 – CCI introduction in cable network

As previously established, CCI cannot be cancelled because the copy of transmitted signal from CM3 cannot be obtained by CM1 and CM2. However, there is a possibility to mitigate this type of interference CCI 1 is larger than CCI 2, which reveals that the further two CMs are separated, the larger the isolation is.

In order to demonstrate this, a simulation is done with cable network parameters measuring from real devices. Figure 4 describes the cable network model and marks measured parameters for Taps and coax cable. Tap can be related to a three-part device. The loss among the three parts is listed above

each Tap. Loss_12 represents the loss between part 1 and 2. Trunk cable loss at 450 MHz between Taps is measured at 3.4 dB and drop cable loss at 450 MHz between Tap and CM is measured at 5.2 dB. Transmitting power and receiving power for fibre node are 43 dBmV/6 MHz and 10 dBmV/6 MHz when spectrum is centred at 450 MHz. According to these conditions, downstream receiving power and upstream transmitting power for each CM can be calculated as listed in Figure 4 below each CM in dBmV/6 MHz.
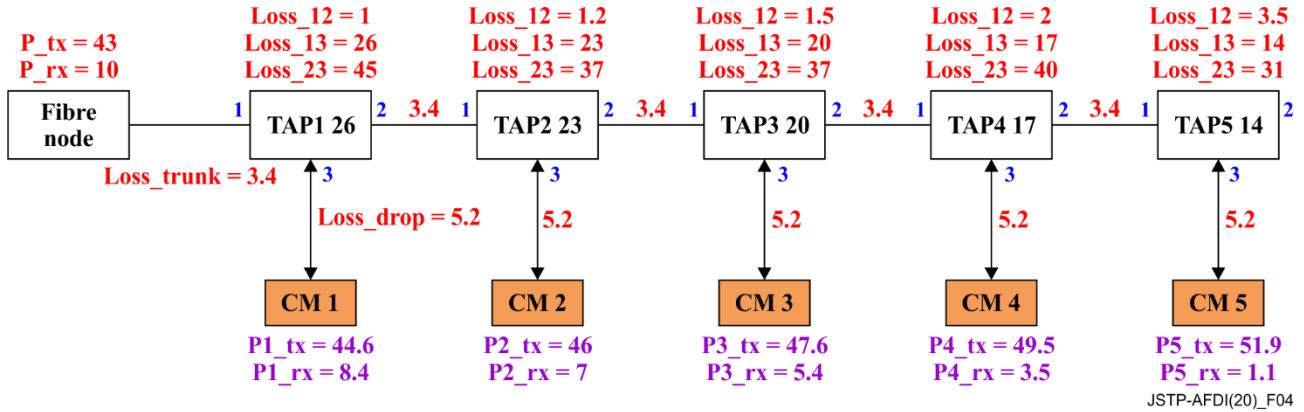

Figure 4 – CCI introduction in cable network at 450 MHz

There is a sounding process to measure the level of CCI. During sounding, the CMTS selects one or more FDX capable CMs as test CMs to transmit test signals on designated spectrum, while directing other FDX capable CMs as measurer CMs to compute and report the received modulation error ratio (MER) on the same spectrum. The CMTS repeats this procedure until the interference levels are tested between all CM combinations.

According to the cable network model and parameters in Figure 4, each combination can be simulated and the MER for each combination can be computed. The following equation is used to compute MER. Receiving MER for CMs under Tap i is denoted as **MER_ij** while CMs under Tap j are transmitting signal at full duplex mode.

$$MER\_ij = Pi\_rx - Pij\_interference$$

Pi_rx represent the power of downstream receiving signal for CMs under Tap i. **Pij_interference** is the power of downstream receiving interference for CMs under Tap i. And the interference comes from CMs under Tap j. The calculation of **MER_12** can be used as an example. **P1_rx** is 8.4 as shown in Figure 4. **P12_interference** is the power of receiving interference for CM1 under Tap1 while CM2 under Tap2 is transmitting signal at full duplex mode. **P12_interference** is equal to the transmitting power of CM2 subtracted by the loss between CM2 and CM1.

$$P12\_interference = P2\_tx - Loss\_drop - Loss2\_13 - Loss\_trunk - Loss1\_23 - Loss\_drop$$

$$=46 - 5.2 - 23 - 3.4 - 45 - 5.2 = -35.8$$

$$MER\_12 = P1\_rx - P12\_interference = 8.4 - (-35.8) = 44.2$$

MER for other combination can refer to the above equation. Table 1 shows the calculated MER data for various combinations at 450 MHz. Just looking at the last column data, it means CM5 under Tap5 transmits signal while other CMs under other Taps receive signal at full duplex mode and measure individual MER.

From Table 1, the following is observed:

–   Low MERs for CMs under the same tap; for example, the MER is –2.2 dB for CMs under Tap1, and the MER is –2.4 dB for CMs under Tap2; as the signal path loss between the CMs under the same tap is much smaller compared to the inter-tap case.

– Low MERs for CMs under the taps close to the last Tap; for example, CMs under Tap3 through Tap5 all have MER below 24 dB, as the bad coupling loss of the lower-value taps.

**Table 1 – Receiving modulation error ratio (RxMER)
measurement data for CCI at 450 MHz**

	MER (dB)	TX				
		TAP1	TAP2	TAP3	TAP4	TAP5
RX	TAP1	−2.2	44.2	44.2	44.2	44.2
	TAP2	44.2	−2.4	30.2	30.2	30.2
	TAP3	44.2	30.2	−2.6	23.7	23.7
	TAP4	44.2	30.2	23.7	−3	19.4
	TAP5	44.2	30.2	23.7	19.4	−3.8

After all MER is obtained, an attempt is made to remove the impact of CCI. It is observed from the first column of MER data that CMs under Tap1 does not affect the receiving performance for CMs under other Taps except itself. All CMs under Tap1 can be made to work at FDD mode but work at FDX mode on CMs under other Tapsand CMs under Tap1 are grouped to IG 1. MER for IG 1 is 44.2 dB. It supports 4096 QAM. CMs under Tap2 have some impact on performance for CMs under other Taps. But CMs under Tap2 can still be grouped to IG 2. MER for IG 2 is 30.2 dB. It supports 256 QAM. IG 3 includes all CMs under Tap3, Tap4 and Tap5. MER for IG3 is 30.2 dB. It also supports 256 QAM.

In order to explore the level of co-channel interference in other frequency band, Figures 5 and 6 give cable model parameters at centre frequency of 200 MHz and 800 MHz individually. Corresponding RxMER is listed in Tables 2 and 3. The value in these tables has the same meaning as that in Table 1. According to RxMER value TAPs can also be grouped into different IGs to mitigate the impact of CCI.
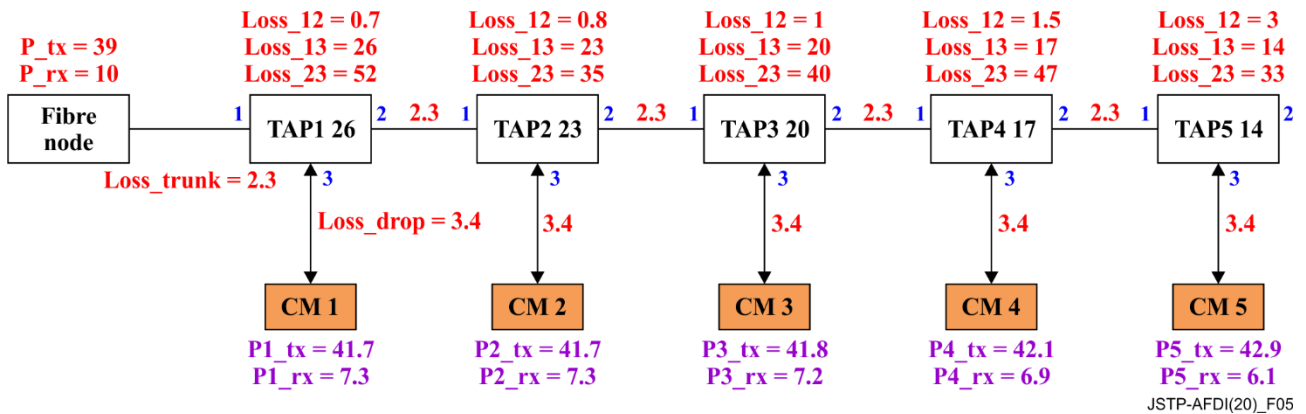

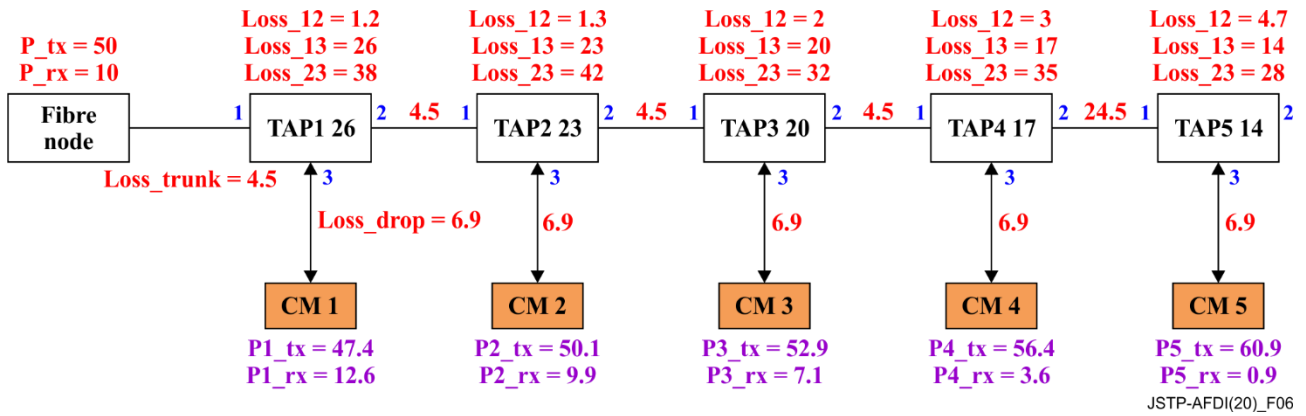**Figure 5 – CCI introduction at 200 MHz in cable network**

Figure 6 – CCI introduction at 800 MHz in cable network

It can be concluded that CMs under the same IG works at FDD mode and CMs under different IG works at FDX mode. By applying this strategy, CCI can be mitigated.

Table 2 – RxMER measurement data for CCI at 200 MHz

	MER (dB)	TX				
		TAP1	TAP2	TAP3	TAP4	TAP5
RX	TAP1	−2.5	49.7	49.7	49.7	49.7
	TAP2	49.7	−2.1	29.6	29.6	29.6
	TAP3	49.7	29.6	−2.2	31.2	31.2
	TAP4	49.7	29.6	31.2	−2.6	34.1
	TAP5	49.7	29.6	31.2	34.1	−3.5

Table 3 – RxMER measurement data for CCI at 800 MHz

	MER (dB)	TX				
		TAP1	TAP2	TAP3	TAP4	TAP5
RX	TAP1	−3	41.8	41.8	41.8	41.8
	TAP2	41.8	−2.8	37.3	37.3	37.3
	TAP3	41.8	37.3	−2.9	18	18
	TAP4	41.8	37.3	18	−3.5	10
	TAP5	41.8	37.3	18	10	−3.9

This section gives a sounding process to measure MER among CMs under all Taps. CMs are grouped to multiple IGs to mitigate the impact of CCI according to measured MER data.

5 Adjacent channel interference and adjacent leakage interference mitigation

In this section, an analysis of the impact of ACI and ALI based on measuring data of real network devices was undertaken and some mitigation solutions were also proposed.

For FDX application, fixed spectrum must be allocated. Normally 108 MHz to 684 MHz is adopted by FDX due to good network parameters. During this band, it can be divided into three 192 MHz downstream channels or six 96 MHz upstream channels or mixed with each other.

Figure 2 illustrates ACI and ALI in the spectral plane. It is supposed that a 192 MHz downstream channel is located in the middle of FDX band. Another spectrum is occupied by upstream signal.

From Figure 2 it is observed that ACI is located outside of the downstream band and it does not affect the signal to noise ratio (SNR) of the downstream signal. However, when CM receives downstream signal, ACI is also captured. As ACI has more power than the downstream receiving signal, the effective dynamic range of analogue-to-digital converter (ADC) will be reduced. ALI is located in the downstream band. It will affect SNR directly.
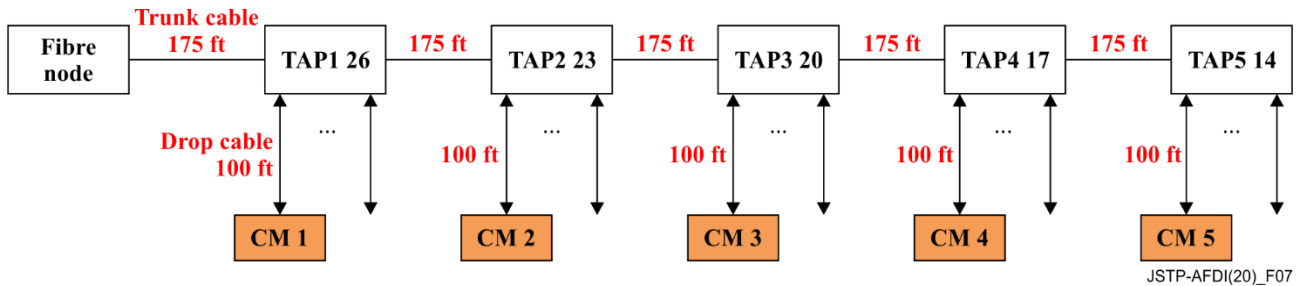

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Figure 7 – FDX model in cable network

Figure 7 shows an FDX model in cable network which includes five TAPs. Trunk cable length is 175 feet and drop cable length is 100 feet. In the following sections, all analysis is done based on this model.

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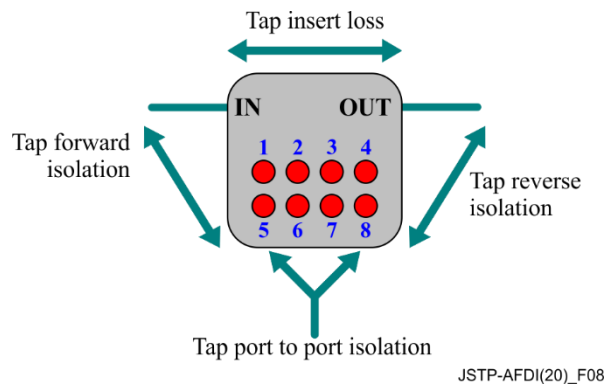
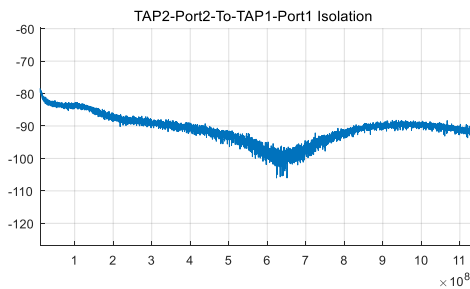**Figure 8 – Various parameters of TAP**

For each TAP, there are multiple network parameters such as insert loss, forward isolation, reverse isolation and port to port isolation as shown in Figure 8.
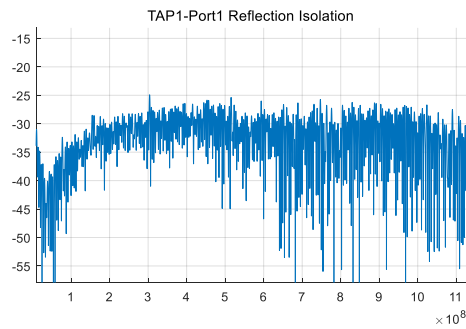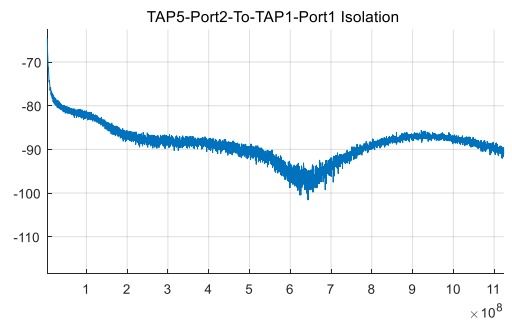
(a) Port1 Reflection Isolation of TAP1
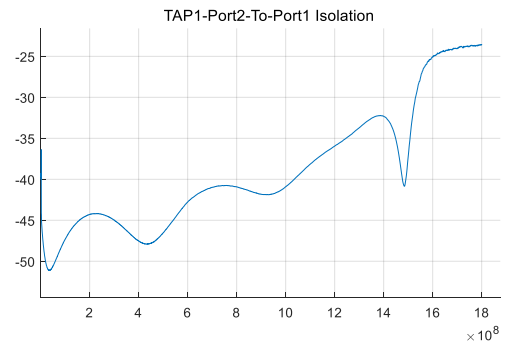
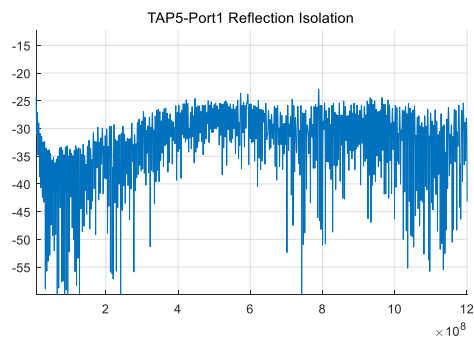(b) Port2 to Port1 Isolation of TAP1
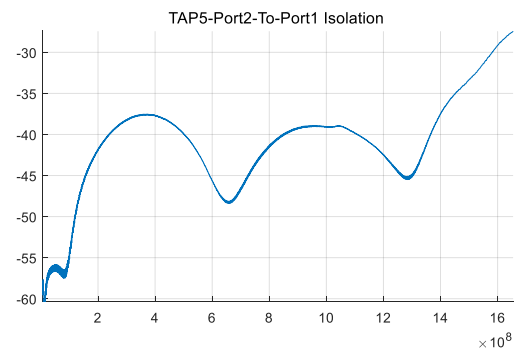
(c) TAP2 Port2 to TAP1 Port1 Isolation
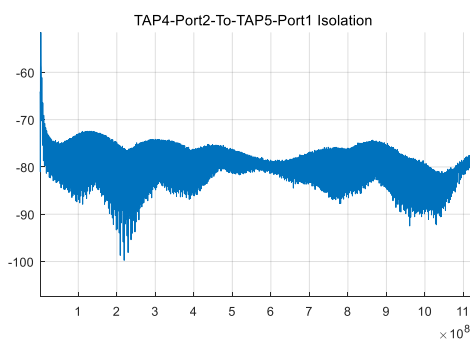
(d) TAP5 Port2 to TAP1 Port1 Isolation

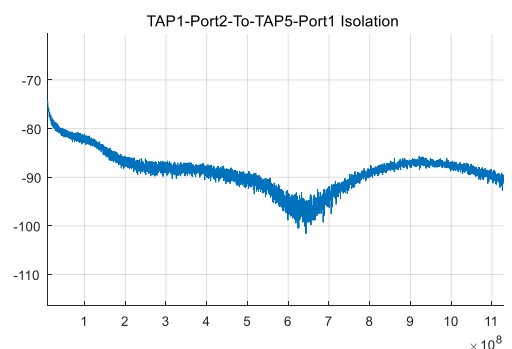**Figure 9 – Real measuring parameters for TAP1**

(a) Port1 Reflection Isolation of TAP5

(b) Port2 to Port1 Isolation of TAP5

(c) TAP4 Port2 to TAP5 Port1 Isolation

(d) TAP1 Port2 to TAP5 Port1 Isolation

Figure 10 – Real measuring parameters for TAP5

In order to understand the impact level of ACI and ALI, the network parameters for all five TAPs were tested; but only the results of the first and the last TAP are listed which are shown in Figures 9

and 10. Other TAPs has similar results. Three types of parameter are the most important for ACI and ALI analysis. One is the reflection isolation for each port of individual TAP. The second is port to port isolation among the same TAP and the third is port to port isolation among different TAPs. From Figures 9 and 10, it is observed that all TAPs have more than 25 dB reflection isolation for total spectrum, more than 35 dB port to port isolation among the same TAP for frequency below 1.2 GHz, and more than 70 dB port to port isolation among different TAPs.

CM5 under TAP5 in Figure 7 can be used as an example to illustrate the impact level of ACI and ALI. Figure 11 described the different level of upstream transmitting signal, self-ACI and ALI, neighbour-ACI and ALI, downstream receiving signal. For each signal, the x axis represents the frequency which is from 108 MHz to 684 MHz. The y axis represents the signal level and the unit is dBmv.
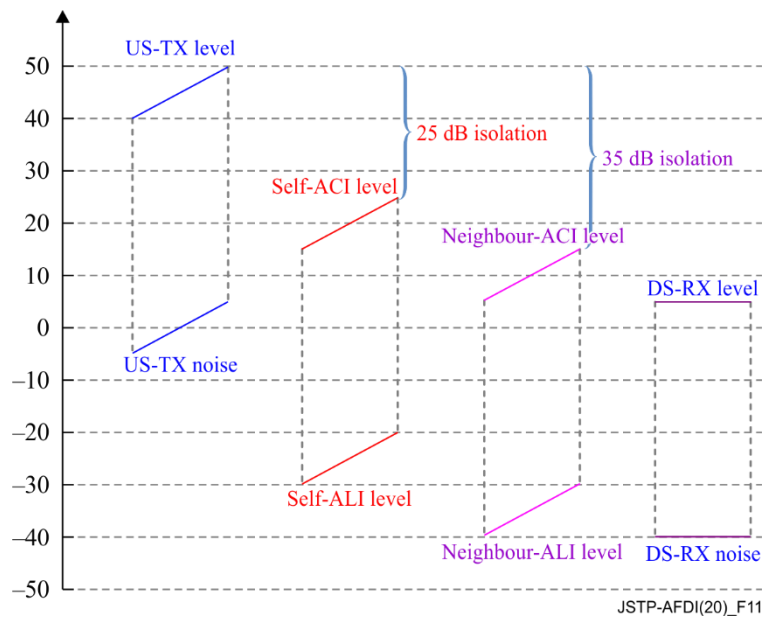

Figure 11 – Self-and-neighbour ACI: Impact into ADC dynamic range; Self-and-neighbour ALI: Impact into SNR performance

It is assumed that the upstream transmitting signal level is 40 dBmv/6 MHz at lower frequency and 50 dBmv/6 MHz at a high frequency. There is 10 dB tilt due to different coax attenuation for different frequency. Downstream receiving signal is assumed to be flat and the level is 5 dBmv/6 MHz. Upstream transmitting SNR and downstream receiving SNR are both 45 dB. Port to port isolation among different TAPs is too large to consider its impact on downstream receiving signal. So only 25 dB port reflection isolation of TAP5 which introduce self-ACI and ALI, 35 dB port to port isolation of TAP5 which introduce neighbour-ACI and ALI need to be considered.

If no action is taken into this interference, then two impacts occur:

1   SNR of downstream receiving signal is deteriorated by 15-20 dB due to self and neighbour ALI.

2   The power level of downstream capturing signal is increased due to self and neighbour ACI.

Several suggestions are proposed to mitigate these interferences:

–   Self-ACI can be reduced by analogue cancellation. CM5 knows the exact reference signal for self-ACI. According to this reference signal and self-ACI, a group of analogue cancellation coefficient can be calculated and can be applied to the analogue cancellation module. From Figure 12, it is observed that 20 dB cancellation capacity is enough to eliminate the impact of self-ACI. Normally, it is easy to obtain the 20 dB capacity.

– Self-ALI can be reduced by digital cancellation. CM5 also knows the exact reference signal for self-ALI. Self-ALI is mixed with downstream receiving signal. Normally pilot symbols will be filled into downstream signal when digital cancellation is training. Then clear self-ALI can be obtained by cancelling downstream receiving signals from the mixed signals when training. According to self-ALI and its reference signal, another group of digital cancellation coefficient can be calculated and can be applied to the digital cancellation module. Because of limitations due to the downstream receiving noise, only 10 dB cancellation capacity can be obtained. Some residual self-ALI still existed.

– Neighbour-ACI cannot be cancelled due to failure to obtain its reference signal as the reference signal is transmitted by other CMs. An ADC with higher dynamic range at the receiver can be used to overcome neighbour-ACI, but this increases hardware cost.

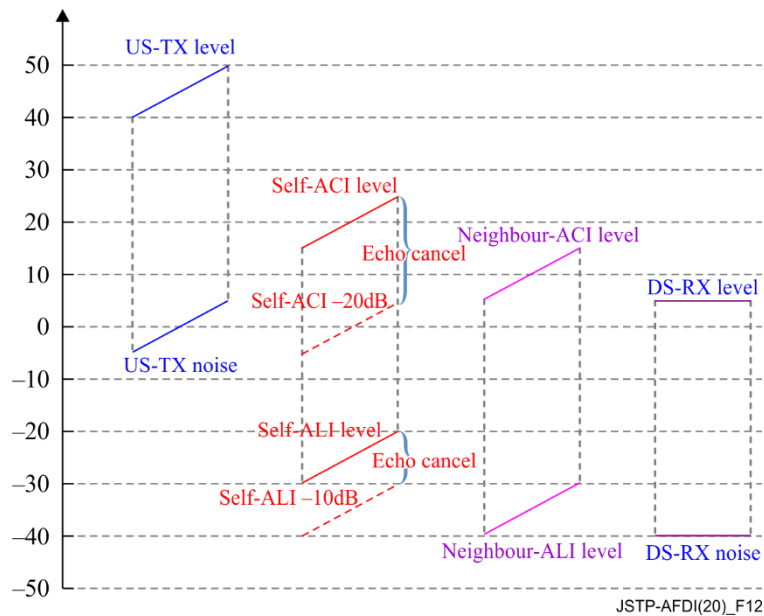– For the same reason as neighbour-ACI, neighbour-ALI cannot be cancelled either.

Figure 12 – Self-and-neighbour ACI: Impact into ADC dynamic range; Self-and-neighbour ALI: Impact into SNR performance

This section analysed the impact level of ACI and ALI to downstream receiving signal based on the measuring data derived from real devices. Several solutions are applied to mitigate these interferences. After cancellation, self-ACI have little impact on the receiving signal, but residual self-ALI will still deteriorate receiving signal by 5~10 dB. With a higher dynamic range ADC, the impact of neighbour-ACI can be eliminated. However, there is no way to remove neighbour-ALI as it will deteriorate receiving SNR by 5~10 dB.

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