Harmonizing FDX and FDD to Minimize ACI Impacts in 10G Networks

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Table of Contents

Title	Page Number
1. Abstract	3
2. Introduction	3
2.1. ACI History	3
2.2. Increased Upstream Bandpass and Incumbant Equipment Coexistence	5
2.2.1. DOCSIS 3.x – Mid-Split and High-Split Coexistence	5
2.2.2. DOCSIS 4.0 Coexistence	6
2.3. ACI Overview	6
3. Legacy Equipment ACI	7
3.1. Legacy ACI Detection	9
3.2. Legacy Device Impact	9
4. DOCSIS 4.0 Equipment ACI	11
4.1. UHS-396 ACI Detection	11
4.2. UHS-396 Device Impacts	12
4.3. FDX ACI Detection	12
4.3.1. Sounding	12
4.4. UHS-684 or FDX Device Impacts	13
4.5. FDX ACI Solutions	14
5. ACI Model Summary for Legacy and DOCSIS 4.0 Devices	15
6. Acknowledgements	16
7. Conclusions and Recommendations	16
Abbreviations	17
Bibliography & References	18

List of Figures

Title	Page Number
Figure 1 - General Instrument Converter	3
Figure 2 - Mandell and Brownstein Converter Block Diagram	4
Figure 3 - ACI Test Topology	8
Figure 4 - CACIR = -20 dB Threshold Measurements	9
Figure 5 - Mid-Split ACI: Maximum Mid-Split TCP and 0 dBmV per 6 MHz Receive Power	10
Figure 6 - Hight-Split ACI: Maximum High-Split TCP and 0 dBmV per 6 MHz Receive Power	11
Figure 7 - UHS-396 ACI: Maximum UHS-396 TCP and 0 dBmV per 6 MHz Receive Power	12
Figure 8 - UHS-684/FDX ACI: Maximum UHS-684/FDX TCP and 0 dBmV per 6 MHz Receive Power	13
Figure 9 - FDX ALI and ACI	14

List of Tables

Title	Page Number
Table 1 - Legacy and DOCSIS 4.0 ACI Susceptible Device Summary	15

1. Abstract

Adjacent Channel Interference (ACI) and its mitigation strategies are well understood for mid-split and high-split deployments as low likelihood interference to legacy services. ACI can be an in-Premises interference problem, mostly affecting tuner-sensitive legacy video set-top boxes (STBs). Increased spectral overlap associated with high-split can overcome port-to-port isolation in taps causing ACI to neighbor equipment. Low tap port return loss can also be troublesome for customers with both a higher speed tier modem and one or more STBs. The newly defined Data Over Cable System Interface Specifications 4.0 (DOCSIS® 4.0) band splits, with added upstream capability, will have even more spectral overlap, compounding the ACI problem further by impacting legacy and newer generation equipment. This paper's first goal is to summarize standards-based features necessary for minimizing the increasing impact of ACI for future 10G networks.

Successful Full Duplex DOCSIS (FDX) operation was based on the expectation that interference conditions would be more challenging and diversified, so mechanisms including interference group (IG) and transmission group (TG) management were included to minimize their impact and maintain DOCSIS fidelity. FDX's echo cancellation (EC) also plays a role in interference minimization. CCI and ALI are FDX interferences that must be managed to enable coexistence between upstream and downstream signaling in either the same or directly adjacent spectrum.

ACI impacts for both mid-split and high-split systems is becoming well understood, but more needs to be learned as overlapping bandwidths increase for both FDX and Frequency Division Duplex (FDD) networks. This paper's second goal will be to summarize and review the current ACI research, adding new data, where necessary to provide a comprehensive overview of ACI as it applies to both FDD and FDX networks. Finally, this paper will conclude with recommendations for the minimization of ACI in future 10G networks.

2. Introduction

2.1. ACI History

In Figure 1 below is a Starcom II, 36-Channel Converter, Model JSX-3, made by General Instrument, circa 1983. Holding the device, one can easily appreciate the long history of community antenna television (CATV) technology and how much it has evolved.

Figure 1 - General Instrument Converter

US Patent 3,333,198, from July 25th, 1967, by inventors, Ronald C. Mandell and George Brownstein, shown in Figure 2, enabled delivery of higher-fidelity video signals. This converter connected the CATV network via a drop cable, 12, fed by distribution cable, 10, which was fed by a headend transmitter, also shown in Figure 2.

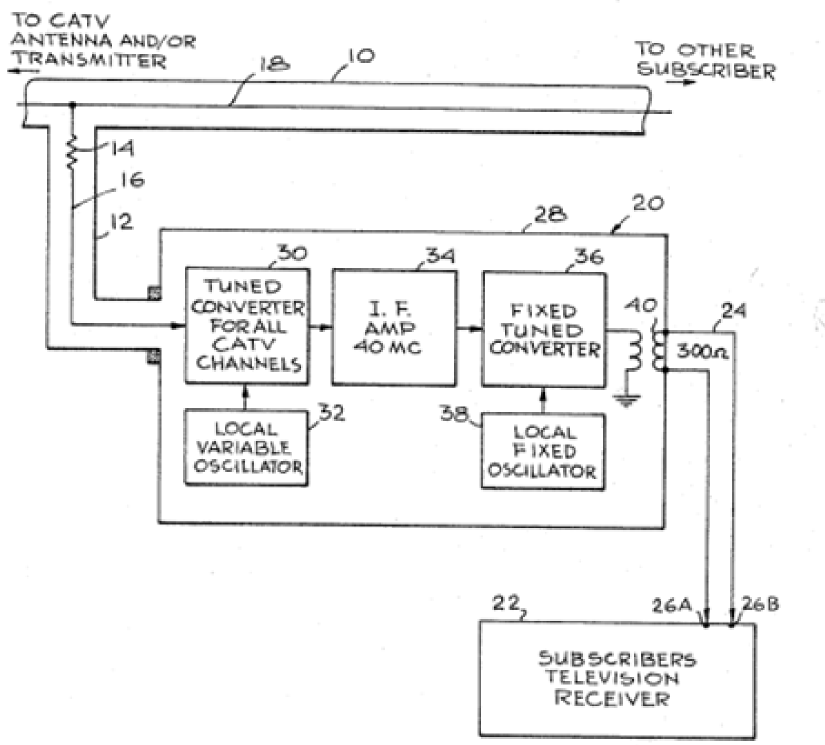

Figure 2 - Mandell and Brownstein Converter Block Diagram

The purpose of this device was to convert a tuned signal to an unused very high frequency (VHF), and condition it for input into the subscriber's television. CATV networks, being isolated systems, increased the fidelity of the video signals, which meant improved video quality over traditional over-the-air-broadcasts of the time.

Note that there was no diplex filter at the converter input. Of course, it wasn't needed at the time. Two-way communications to the subscriber premise equipment wouldn't be designed into CATV networks until the late 1980s. The main concern at that time was enabling more video services from 300 MHz to 550 MHz, and so on, up to 1 GHz.

However, the first installation of the two-way communications was in the video transport, or local insertion, of return television signals from remote locations to the headends. It was in these networks where a few lucky individuals worked out the process for successful use of the upstream band. This information allowed designers of the time to account for upstream signals in CATV networks, all the while knowing return path services were meant for future CATV network growth.

Very limited early cable modem (CM) deployments lead to such terminology as reverse windows for upstream transmit levels and filtering. Of course, the provisioning of this equipment was all worked out manually at the time of each install of the customer premise equipment (CPE) as this was all before automated level provisioning and pre-DOCSIS technology. One missed calculation in the decimal to binary conversions by the installer, which was all done by hand, would cause interference on the adjacent customer converters such as the JSX-3 described above.

Knowing that converters, like the Jerrold JSX-3, were deployed at scale, operators used technology sessions in conferences to share the knowledge learned. Also, operators pushed manufacturers to develop equipment needed to mitigate these issues. These same operators went through great lengths to change their one-way CATV networks into the thriving two-way networks we enjoy today, by building the network, enabling transceiver technology, trialing the new services, and ultimately launching those services at scale.

The ACI would impair these converters if they inadvertently received an upstream signal, intended for a headend receiver. Operators turned to external filters in the plant to resolve the ACI for affected devices. The next advancement was to develop equipment with these filters in the front-end of the device that would minimize the ACI impact. Tuned converters, robust enough to reject appreciably higher upstream energy, protecting intermediate frequency (IF) amplifiers from overload, coexisted well with two-way services. Phasing diplexed devices in over time would enable operators to preserve the downstream video quality of experience over their CATV networks while allowing for new services such as Impulse pay-per-view (IPPV) and high-speed data (HSD) service in the most advanced networks of the time.

During the last 20 years within the CATV industry, there have mostly been networks deployed with diplex filters, separating downstream and upstream payloads. One can imagine what engineering teams must of went through identifying two-way challenges, like ACI, and rolling out fixes, like STBs with diplex filters, for future generations to build on. This paper's authors are grateful to be part of the generation empowered to increase upstream capacity but like those early days of upstream deployments, new challenges involving ACI must also be understood and overcome. There are few old timers that are still working in the industry who worked tirelessly to work through these unknown issues. Today we use technology to solve and limit the issues they used to fight to build the networks into what they are today. Ironically, when it comes to ACI, what is old is new again.

2.2. Increased Upstream Bandpass and Incumbant Equipment Coexistence

Increasing upstream bandpass while maintaining legacy device populations have continued into modern day systems. [18] addressed coexistence between DOCSIS 3.1 signals and Multimedia Over Coax Alliance (MoCA) signals in 2017, which is still relevant today especially considering that extended spectrum passband, with its upper downstream edge at 1,794 MHz, that would overlap with MoCA signaling.

However, this paper is concerned about ACI problems that manifest when the new DOCSIS upstream service bandpass overlaps with the incumbent downstream receivers. Fortunately, our understanding of ACI has continued to grow as well. Mixing mid-split or high-split services in networks with standard-split STBs have been documented well in [15] et al. This section will briefly review what is known about existing mid-split and high-split ACI and then introduce implications for DOCSIS 4.0 equipment being deployed in a similar mixed device population scenario.

2.2.1. DOCSIS 3.x – Mid-Split and High-Split Coexistence

[14] approached the identification of ACI impact in a proactive manner. Essentially leveraging software-based tools, combined with network telemetry, to probe customer homes and predict those cases where the introduction of a new enhanced upstream service would degrade existing video services. The tool discussed in [14] was named in-home health assessment test (iHAT). Armed with information before the deployment of new upstream services, remediation methods could be better integrated into the operational

processes used by the operators, to deliver those new services in a seamless manner via self-install-kits (SIKs) or enhanced delivery processes. Some of the remediation methods needed, included the following:

- Removal of devices that blocked mid-split, typically drop amplifiers (not an ACI problem)
- Swapping of equipment with ACI insensitive gear like Wi-Fi enabled video streamers
- Prescriptively installing filters to suppress upstream energy into ACI sensitive receivers

2.2.2. DOCSIS 4.0 Coexistence

If there are DOCSIS 4.0 cable modem (CM) transmissions in a band that overlaps with incumbent STB/CM downstream receivers, there will be potential for ACI impairment. Fortunately, operators can leverage remediation methods discussed but may have additional options to help. Frequency Division Duplex (FDD) and Full Duplex DOCSIS (FDX) could leverage multi-mode switching capabilities of their CMs to bring entire service group (SG) populations over to the new bandpass via MAC Domain Descriptor (MDD) messaging. Of course, not all legacy CMs will have higher upstream passbands to switch to, but operators who plan future DOCSIS 4.0 deployments that include their switched modes, will be rewarded with more homogenous networks that have a lower risk of ACI problems. This also makes a case against deploying bootfile-controlled modes for managing CM bandpass but may be manageable on a case-by-case basis.

2.3. ACI Overview

There are great resources available to readers wanting to understand the mechanics of how ACI manifests found in [15] et al. for in-home and neighboring cases. The purpose of this section will be to identify the range of technology that may be sensitive to ACI. First, we will define any STB or CM with a lower downstream edge ≤ 258 MHz and DOCSIS 3.1 or older as a legacy device. The legacy definition includes all standard-split, mid-split, and high-split devices and associated band pass.

1. Standard-split STB; 5-42 MHz return, 54-1002 MHz forward
2. Standard-split CM; 5-42 MHz return, 108-1002 MHz forward
3. Mid-split CM; 5-85 MHz return, 108-1002 MHz forward
4. High-split CM; 5-204 MHz return, 258-1221 MHz forward

Second, DOCSIS 4.0 equipment includes all CMs that support either FDD and/or FDX. FDD compliant CMs use internal diplexers for the following Ultra-High-Split (UHS) bands but our paper will only focus on the 2nd and 4th band pass scenarios:

1. UHS-300; 5-300 MHz return, 372-1794 MHz forward
2. UHS-396; 5-396 MHz return, 492-1794 MHz forward
3. UHS-492; 5-492 MHz return, 606-1794 MHz forward
4. UHS-684; 5-684 MHz return, 834-1794 MHz forward

Additionally, FDX compliant CMs may use cascaded mid-split and FDX diplexers to support the following band pass scenarios. Note that nodes and amplifiers may have larger passband to support legacy signaling, like a STB out-of-band (OOB) signal at 102-108 MHz.

- 5-85 MHz return
- 108-684 MHz FDX
- 684-1218 MHz forward

We define Self-ACI as ACI occurring within a device, node, amplifier, or CM, while external-ACI as ACI coming from outside the device. Self-ACI isn't a concern for legacy nodes, amplifiers, and CMs due to design techniques that leverage the use of proper diplex filtering. FDX coupling removes the traditional diplex filtering and leverages echo cancellation (EC) to maintain the upstream and downstream coherency. External-ACI, or just ACI is the primary focus of this paper, covering both in-home and neighboring scenarios. In-home ACI problems occur 1.7% of 2.4M mid-split deployments [15], making it a low probability scenario. In-home, ACI scenarios have mainly occurred between mid-split CMs and standard-split STBs, given 31 MHz of overlapping bandwidth. The scope of in-home, ACI scenarios expand between high-split CMs and the following three devices and corresponding overlapping bandwidth:

1. Standard-Split STBs with 150 MHz of overlapping bandwidth
2. Standard-Split CMs with 96 MHz of overlapping bandwidth
3. Mid-Split CMs with 96 MHz of overlapping bandwidth

Mid-split ACI is not likely strong enough to overcome outdoor tap-port-to-tap-port isolation, so it is mostly viewed as primarily an in-home problem. In-home isolation being approximately 26-27 dB [16]. High-split has both a larger overlapping bandwidth and greater total-channel-power (TCP) within that overlap, which is why it is currently being evaluated as both an in-home and neighboring interference problem. Neighboring isolation being approximately 32-36 dB [16]. The total transmit power capability of a mid-split device is the same as high-split, just less of that power lands in the overlap region. Since the overlap region is <40% of the total transmit spectrum for the mid-split transmitter, but 75% of total transmit spectrum for the high split device. This logic extends to DOCSIS 4.0 devices, since similar conditions of overlapping bandwidth and TCP associated with those devices will be even larger still. This paper evaluates the following cases for ACI susceptibility:

- Standard-Split STB impacted by a Mid-Split/High-Split/UHS-396/UHS-684/FDX CM
- Standard-Split/Mid-Split CM impacted by a High-Split/UHS-396/UHS-684/FDX CM
- High-Split CM impacted by a UHS-396/UHS-684/FDX CM
- UHS-396 CM impacted by a UHS-684 CM
- FDX CM impacted by a FDX CM

3. Legacy Equipment ACI

Managing legacy ACI problems has quickly become business as usual (BAU) for some cable operators. Effectively diagnosing ACI impairments, in the field, requires knowledge of ACI thresholds, and associated levels that are likely to degrade the customer's quality of experience. Figure 3 provides a test topology for assessing ACI thresholds for a CM device under test (DUT).

Carrier-to-ACI-Ratio (CACIR) is one of the ways to measure how much ACI is present in a downstream receiver's payload. CACIR = -20 dB has been documented as the threshold for mid-split CM to standard-split STB ACI susceptibility, meaning that if the ACI level becomes more than 20 dB above downstream receive signal, as measured in a 6 MHz channel bandwidth for both the receive signal and ACI, then the downstream receiver is likely to experience loss in fidelity of its desired signals, in the form of degraded modulation-error-ratio (MER), codeword-error-rate (CER), packet-error-rate (PER) and/or bit-error-rate (BER) [14] et al.

Testers can find these thresholds by baselining error free performance at CACIR = 0 dB, then gradually degrading CACIR, until the DUT begins to experience degraded fidelity and ultimately go offline.

Figure 3 leverages a distributed access architecture (DAA) environment, but it is not required. What's important is that DUTs are configured for upstream channels below any overlapping bands, so as not to interfere with the ACI source, labeled as the "Signal Generator."

The ACI source will be configured for varying duty cycles, like 100% down to 10%, in 15% increments. It's also important that a representative set of downstream channels be included in the threshold evaluation. In this diagram, low, mid and high channel frequencies are used for testing the downstream payload. Testers may want to investigate more strategic channel frequencies or even a larger sampling of channels.

Traffic generation and analysis is used for assessing PER and BER. Ideally, maximum but lossless traffic will be flowing through the system at baseline levels. The DUT will measure downstream fidelity, MER and CER, throughout the test.

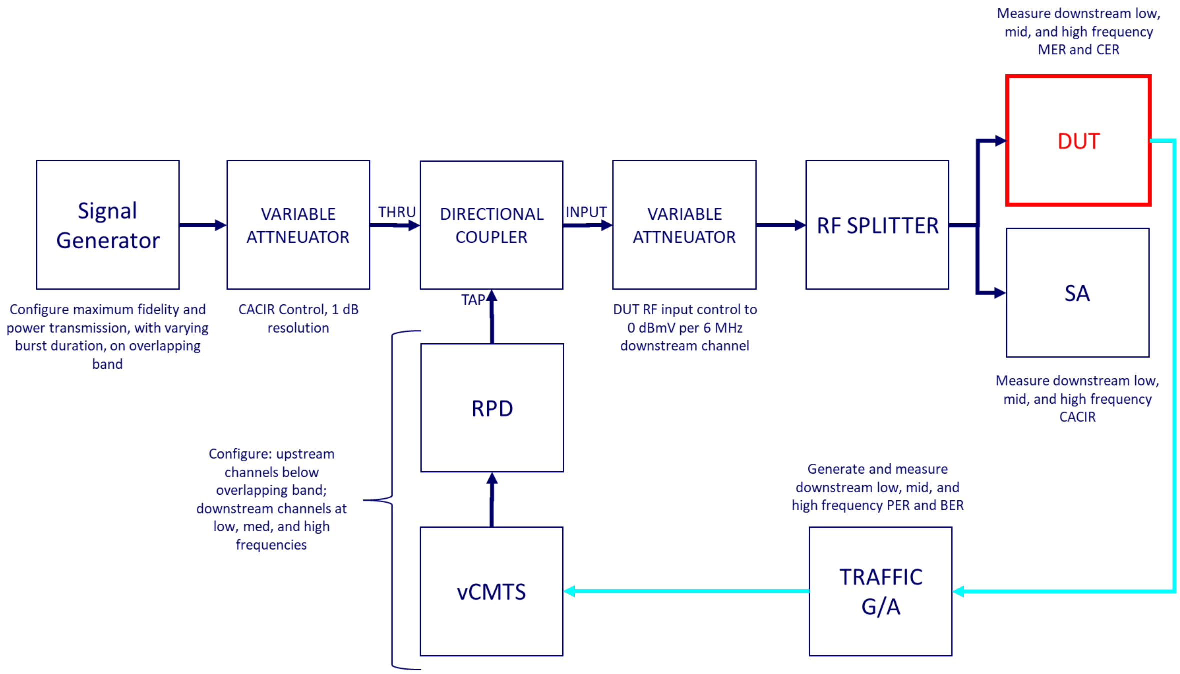

Figure 3 - ACI Test Topology

Figure 4 models the threshold for a standard-split STB, operating in a mid-split environment. The levels shown in Figure 4 are using 100 kHz resolution so that comparison between upstream 6.4 MHz channels can be made with downstream 6 MHz channels. Correcting for bandwidth, one could use $10*\log10(6.0e6/6.4e6) = -0.28$ dB to convert power of an upstream signal power at 6.4 MHz bandwidth to a downstream signal power at 6 MHz bandwidth. The mid-split upstream, in blue as "MS US (dBmV)", overlaps with a standard-split STB downstream receiver, shown in red as "SS STB DS OL (dBmV), results in a CACIR ≈ -20 dB per 6 MHz bandwidth.

The TCP of the overlapping bandwidth is approximately 27 dBmV and spans 31 MHz of bandwidth. The TCP of the downstream bandwidth, in green, is approximately 22 dBmV based on 0 dBmV per 6 MHz channel, which results in a TCP difference of approximately 5 dB. Operators may choose to use both CACIR and TCP-delta measurements together to make their threshold predictions more reliable [15]. TCP deltas may better predict when the receiver's total input power is being dominated by ACI. Note that the red line has been slightly offset to illustrate the overlapping band, but both have equal power per 100 kHz bandwidth as far as the model is concerned.

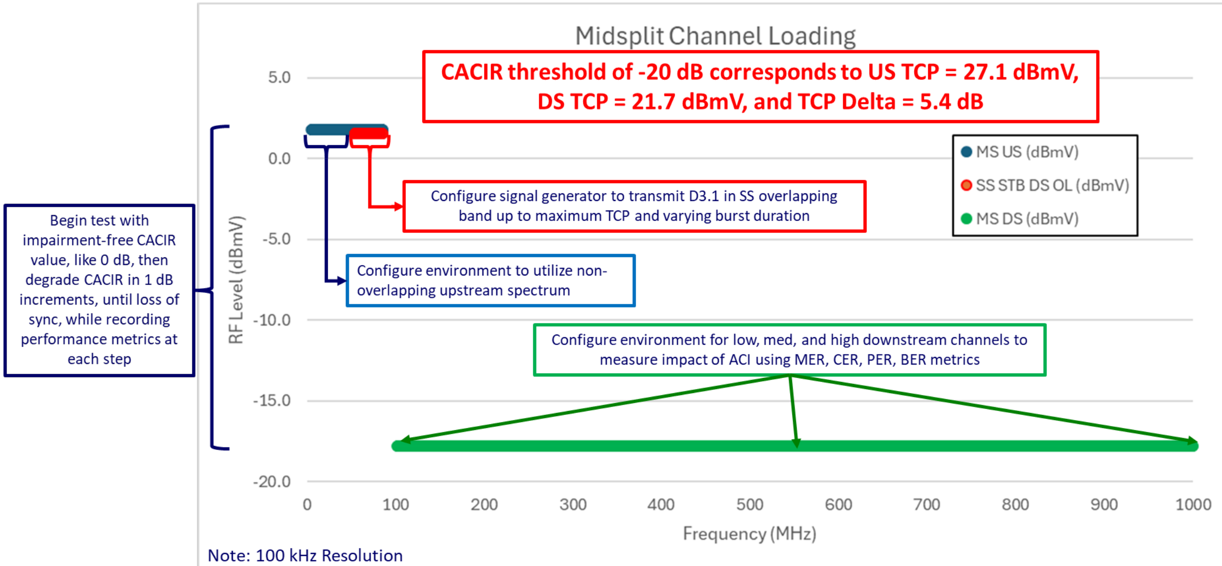

Figure 4 - CACIR = -20 dB Threshold Measurements

3.1. Legacy ACI Detection

With thresholds defined, OFDMA User Data Profile (OUDP) probing can be a remote, proactive and non-service-disrupting way of identifying devices at risk of ACI impairment where methods are still evolving [15]. If a technician is onsite, similar conclusions can be drawn from max-hold spectrum analyzer traces of the input to the suspected, ACI-impaired devices.

3.2. Legacy Device Impact

Simple models like the last figure can be created to understand the maximum amount of overlapping TCP that could be incident on any ACI-susceptible receiver. In Figure 5, a mid-split CM transmits at its highest allowable TCP, 65 dBmV for DOCSIS 3.1, shown as the blue “MS US (dBmV)” line. 60.9 dBmV TCP or 39% of that the maximum TCP, will overlap with a standard-split STB downstream receiver, shown as the red “SS STB DS OL (dBmV) line. This overlapping TCP has the potential to propagate toward an unintended receiver. Accounting for in-home network isolation and cabling, the actual ACI TCP presented to a receiver would be 26-27 dB lower [16]. These estimates of maximum ACI TCP provide a more complete way for operators to assess ACI problems with planned DOCSIS 4.0 CM deployments.

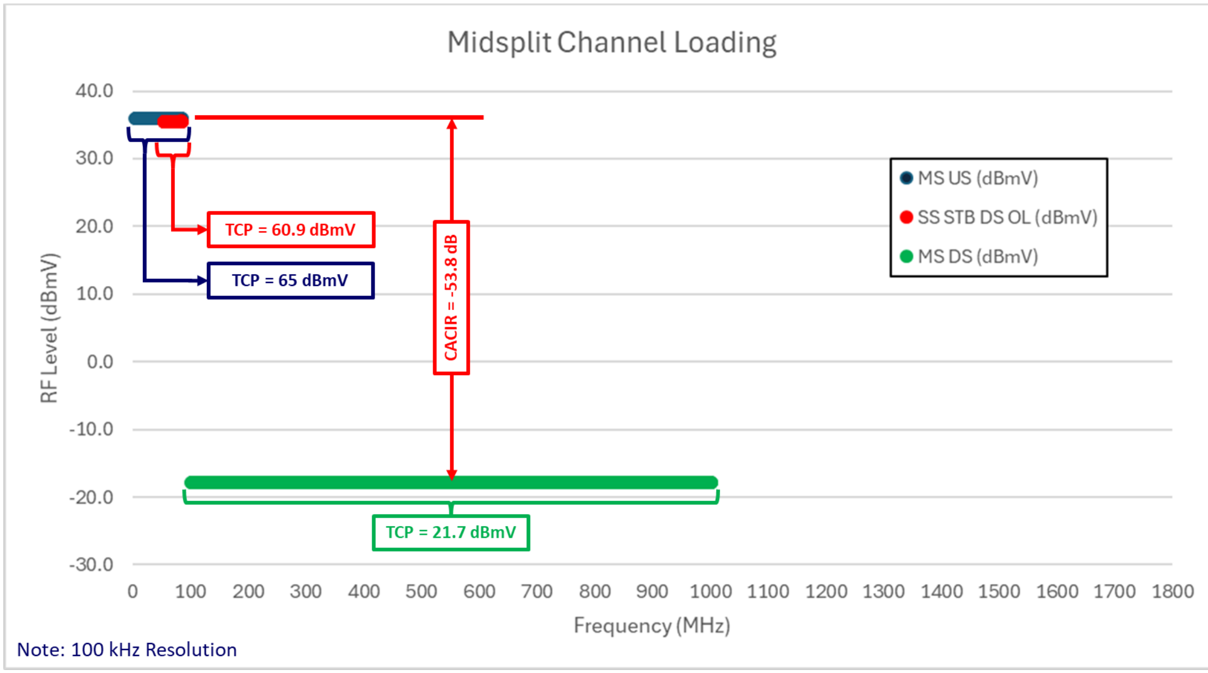

Figure 5 - Mid-Split ACI: Maximum Mid-Split TCP and 0 dBmV per 6 MHz Receive Power

In Figure 6, a high-split CM can overlap it's upstream with either a standard-split STB or a standard-split/mid-split CM by 150 or 96 MHz respectively. The high-split model is an easy extension of the mid-split model, more upstream and less downstream bandwidth. The same 65 dBmV maximum TCP is spread over high-split band, so the power per hertz (Hz) may be lower and the overlapping power changes slightly. The standard-split STB downstream overlap "SS STB DS OL (dBmV)", shown in red, TCP is 63.8 dBmV, which is approximately 3 dB more than standard-split STB in a mid-split environment case. The standard-split or mid-split CM downstream overlap "SS/MS CM DS OL (dBmV)", in yellow, TCP is 61.8 dBmV. Note that equivalent CACIR = 49.8 dB but different overlapping TCPs, 63.8 dB vs. 61.8 dB, making it inadvisable to rely solely on CACIR assessments.

The downstream band, shown in green and labeled "HS DS (dBmV)", covers the 258 to 1221 MHz band. Legacy devices are downstream bandlimited to 1002 MHz, and will have correspondingly lower TCP = 20.9 dBmV.

This model shows a high-split CM presenting 1-3 dB more TCP to an ACI susceptible receiver. The differences between mid-split and high-split transmitter overlap may cause operators to change their strategy for in-home ACI cases. Increased energy may increase the likelihood of service disruption for a STB device coexistence with a high-split CM. Operators may choose to accompany high-split service deployments with video device swaps to Wi-Fi-enabled video equipment to avoid in-home ACI issues altogether. The increased TCP also has the potential for crossing into neighboring homes, where the isolation increases to approximately 32-36 dB [16] and disrupting service for other CMs installed off the same tap. Operators may choose to install protective filters on neighboring tap ports to protect those customers from neighboring ACI.

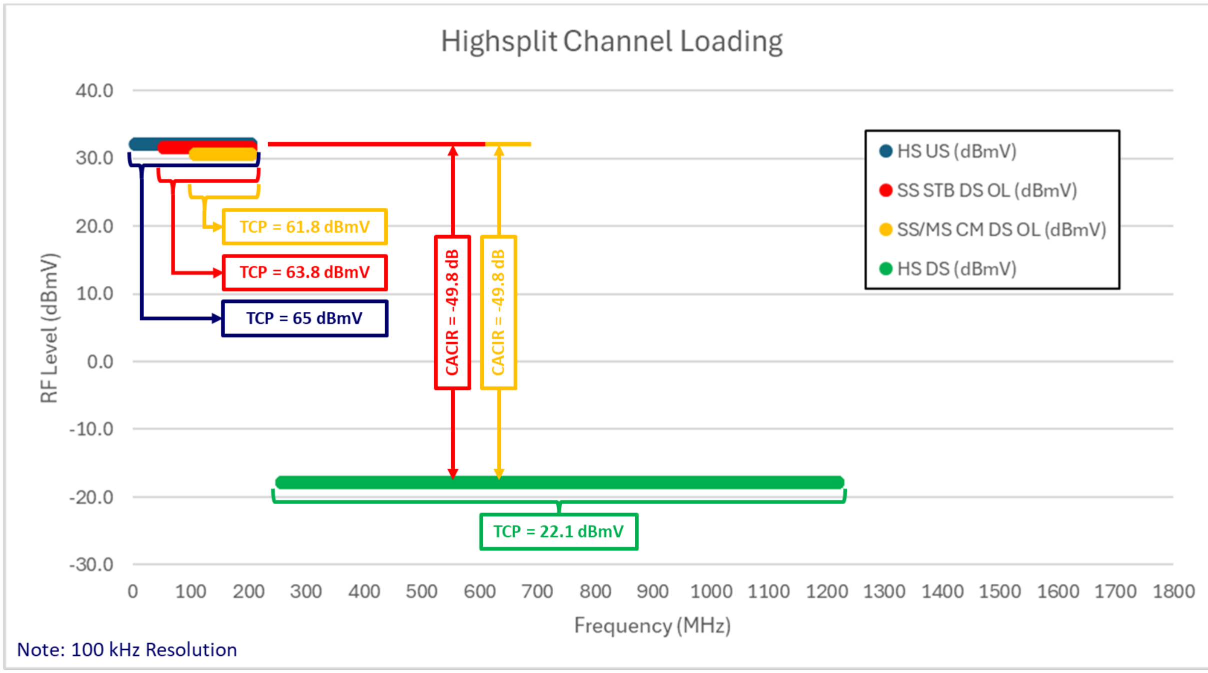

Figure 6 - Hight-Split ACI: Maximum High-Split TCP and 0 dBmV per 6 MHz Receive Power

4. DOCSIS 4.0 Equipment ACI

4.1. UHS-396 ACI Detection

ACI challenges are expected to continue with the deployment of D4 FDD gear. Therefore, existing practices will need to be adapted to accommodate the expanded list of ACI-susceptible devices. The expanded list includes all the ACI-susceptible devices discussed in the previous legacy section plus the high-split CM.

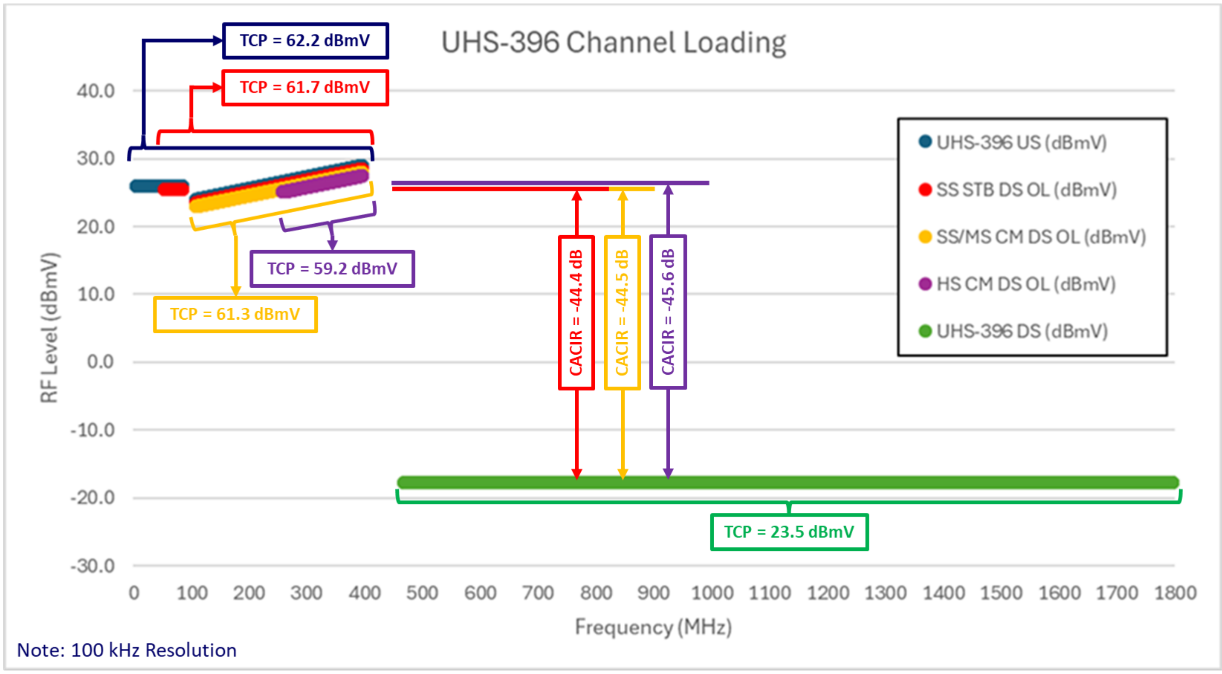

Figure 7 - UHS-396 ACI: Maximum UHS-396 TCP and 0 dBmV per 6 MHz Receive Power

4.2. UHS-396 Device Impacts

Modeling UHS-396 ACI, shown in Figure 7, includes changes that account for the DOCSIS 4.0 specifications. Legacy upstream maximum TCP is now 55 dBmV. UHS-396 maximum TCP is 61.3 dBmV and the output of this CM can be tilted by 5 dB to counter the loss vs. frequency effects of the coaxial cable. The downstream band, shown in green and labeled “UHS-396 DS (dBmV)”, covers the 468 to 1794 MHz band. Legacy devices are downstream bandlimited to either 1002 MHz or 1221 MHz, and will have correspondingly lower TCPs, 19.5 and 21.0 dBmV respectively.

The average upstream power per Hz reduces because of the expanded bandwidth, shown in blue and labeled “UHS-396 US (dBmV)”. The standard-split STB downstream receiver now overlaps with 342 MHz of UHS-396 upstream, and the maximum TCP is 61.7 dBmV, shown in red, labeled “SS STB DS OL (dBmV)”. The standard-split/mid-split CM downstream receiver overlaps with 288 MHz, and a maximum TCP of 61.3 dBmV, shown in yellow, labeled “SS/MS CM DS OL (dBmV)”. The high-split CM downstream receiver overlaps with 138 MHz, and a maximum TCP of 59.2 dBmV, shown in purple, labeled “HS CM DS OL (dBmV)”.

Compared to the high-split model, upstream ACI TCP decreases for the standard-split STB and the standard-split/mid-split CM by a small amount in either case. Existing remediation methods may be extended for the UHS-396 case. Device swaps may continue for in-home ACI cases. Rejection filter bands would need to be increased accordingly to counter the effects of neighboring ACI.

4.3. FDX ACI Detection

4.3.1. Sounding

Sounding was introduced in DOCSIS 4.0 to measure the impact of CCI. It measures the impact on the receiver of other transmitters in the same channel and does not measure the impact of adjacent channels. Sounding is intended for identifying Interference Groups (IGs) and allowing CMs to be grouped into

Transmission Groups (TGs). This is useful for managing external-CCI but doesn't help with external-ACI. It ensures that all CMs in the group are transmitting in the same direction on the same channels, but all devices could, and frequently will, transmit in different directions on different channels (e.g. lowest channel upstream, middle channel downstream, highest channel upstream for RBA 101). Therefore, a nearby neighbor device could still transmit an adjacent channel signal that strongly impacts with the receiver of the current device.

4.4. UHS-684 or FDX Device Impacts

Doubling FDD upstream bandwidth or deploying FDX will impact legacy gear and any earlier generation FDD gear, and this model considers the ACI impact of UHS-684 on an UHS-396 CM, along with all the legacy cases previously discussed.

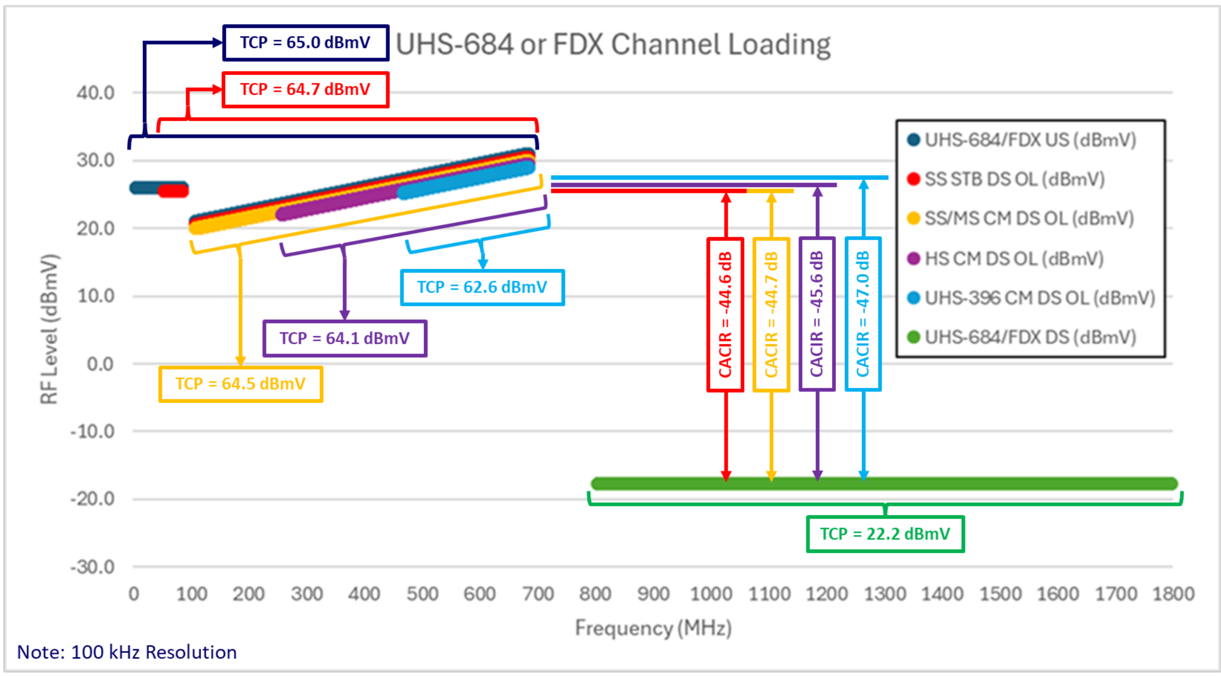

Figure 8 - UHS-684/FDX ACI: Maximum UHS-684/FDX TCP and 0 dBmV per 6 MHz Receive Power

Modeling UHS-684 ACI, shown in Figure 8, includes changes that account for the DOCSIS 4.0 specifications. Legacy upstream maximum TCP is 55 dBmV, as it was for UHS-396 model. UHS-684 maximum TCP is 64.5 dBmV and the output of this CM can be tilted by 10 dB to counter the loss vs. frequency effects of the coaxial cable. The downstream band, shown in green and labeled "UHS-684 DS (dBmV)", covers the 804 to 1794 MHz band and only applies to the UHS-396 CM. Legacy devices are downstream bandlimited to either 1002 MHz or 1221 MHz, and will have correspondingly lower TCPs, 15.2 and 18.4 dBmV respectively.

Compared to the UHS-396 model, the average upstream power per Hz increases because of the expanded bandwidth and tilt, shown in blue and labeled "UHS-684 US (dBmV)". The standard-split STB downstream receiver now overlaps with 630 MHz of UHS-684 upstream, and the maximum TCP is 64.7 dBmV, shown in red, labeled "SS STB DS OL (dBmV)". The standard-split/mid-split CM downstream receiver overlaps with 576 MHz, and a maximum TCP of 64.5 dBmV, shown in yellow, labeled "SS/MS CM DS OL (dBmV)". The high-split CM downstream receiver overlaps with 426 MHz, and a maximum TCP of 64.1 dBmV, shown in purple, labeled "HS CM DS OL (dBmV)". The UHS-396 CM downstream receiver overlaps with 216 MHz and a maximum TCP of 62.6 dBmV, shown in light blue, labeled "UHS-396 CM DS OL (dBmV)". Compared to the UHS-396 model, upstream ACI TCP increases 3 to 5 dB, depending on the legacy device installed, with the high-split CM being the most exposed. Even the DOCSIS 4.0 UHS-396 CM could be exposed to external ACI energy. Existing remediation methods may be extended for the UHS-684 case. Device swaps may continue for in-home ACI cases. Rejection filter bands would need to be increased accordingly to neighboring ACI.

Let's discuss the FDX CM ACI susceptibility, for completeness. The FDX CM will have two dedicated receivers, one for legacy downstream, between 804 and 1794 MHz, and another for the FDX band, between 108 and 684 MHz. The legacy downstream receiver will not be impacted by FDX upstream ACI since it will be protected by a diplex filter.

Figure 9, from the specifications for self-ACI, illustrates the signals reaching the receiver in the FDX band. The specification requires that the echo canceller (EC) tolerate a certain amount of the upstream self ACI TCP while maintaining FDX downstream coherency. For external-ACI, there are no DOCSIS 4.0 specifications, as external-ACI is assumed to be appreciably lower than self-ACI due to plant isolation, and thus not a factor for FDX downstream reception. This assumption may not hold in all real-world circumstances, in which case additional mitigation may be needed.

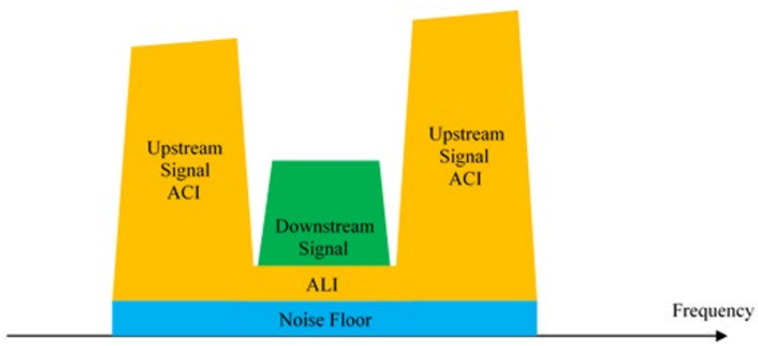

Figure 9 - FDX ALI and ACI

4.5. FDX ACI Solutions

DOCSIS 4.0 FDX does not have any built-in mechanisms either for detecting neighbor ACI or for mitigating it, it only includes echo cancellation (EC) for self-ACI. EC is targeted at eliminating self-interference at a particular device, but it doesn't do anything to address neighbor interference. The CM isn't capable of cancelling neighboring interference, since cancellation requires knowledge of the transmitted signal.

Echo Cancellation (EC) enables bidirectional communication at the node and amplifier, by cancelling the downstream self-CCI, self-ALI, and self-ACI. At the CM, EC cancels upstream self-ALI and self-ACI. In summary, the EC function works to minimize the effects of the following self-interference:

- Self-CCI: receiver overlap of an unknown desired signal with a known undesired signal (FDX node and amplifier only)
- Self-ALI: receiver overlap of unknown desired signal with a known undesired adjacent spurious leakage

- Self-ACI: known adjacent TCP that overwhelms unknown desired reception with a combination of AGC-impacting levels and/or elevated, possibly colored, CIN from overdriven RF front end or analog-to-digital converter (ADC)

An FDX device is tolerant of strong self-interference up to 684 MHz, which may somewhat reduce the number of cases where physical mitigation is needed, relative to, say, a UHS-396 FDD device that must tolerate interference from some future UHS-684 transmitter. However, FDX doesn't inherently solve the problem of neighbor interference, or even provide a means to detect it. And of course, FDX doesn't prevent an FDX CM's transmitter from producing ACI into a nearby DOCSIS 3.1 CM or another legacy receiver.

It would be possible for an operator to develop tools for DOCSIS 4.0 devices to make measurements of neighbor interference to identify problems, just as this is possible for a legacy system shown in [15]. These would be going beyond what is called for in sounding functions of the DOCSIS 4.0 specifications. FDX CM TGs configured to either all downstream or all upstream RBAs (000 or 111) are expected to be most immune to FDX neighboring ACI due to their dual CM receiver architecture for FDX and legacy bands respectively (108-684, and 804-1794 MHz). Limiting FDX to only these RBAs may be acceptable for early deployments of FDX technology to achieve an upstream capacity boost, but in the longer term, ACI will need to be managed to exploit the full potential of DOCSIS 4.0 capacity enhancements.

5. ACI Model Summary for Legacy and DOCSIS 4.0 Devices

Table 1 summarizes the results from all the models discussed in this paper. Columns identify the cable access environment from mid-split to UHS-684/FDX. From a legacy device point of view, UHS-684 and FDX, all upstream resource block allocation (RBA-111) are equivalent in the amount of maximum TCP. From a DOCSIS 4.0 FDD CM point of view, a UHS-396 CM would be susceptible to ACI if it were installed in a UHS-684 network. The DOCSIS 4.0 FDX CM is expected to deal with self-ACI, along with ALI.

Table 1 - Legacy and DOCSIS 4.0 ACI Susceptible Device Summary

ACI Scenario	Cable Access Network Environment					Notes
	Midsplit	Highsplit	UHS-396	UHS-684	FDX	
SS STB RX Overlap TCP (dBmV)	60.9	63.8	61.7	64.7	64.7	54 MHz lower RX edge
CACIR (dB)	-53.8	-49.8	-44.1	-44.5	-44.5	Based on maximum TCP and 0 dBmV per 6 MHz RX PWR
BW Overlap (MHz)	31	150	342	630	630	Corrected by legacy management techniques
SS/MS CM RX Overlap TCP (dBmV)	N/A	61.8	61.3	64.5	64.5	108 MHz lower RX edge
CACIR (dB)	N/A	-49.8	-44.5	-44.7	-44.7	Based on maximum TCP and 0 dBmV per 6 MHz RX PWR
BW Overlap (MHz)	N/A	96	288	576	576	Corrected by legacy management techniques
HS CM RX Overlap TCP (dBmV)	N/A	N/A	59.2	64.1	64.1	258 MHz lower RX edge
CACIR (dB)	N/A	N/A	-45.6	-45.6	-45.6	Based on maximum TCP and 0 dBmV per 6 MHz RX PWR
BW Overlap (MHz)	N/A	N/A	138	426	426	Corrected by legacy management techniques
D4 UHS-396 CM RX Overlap TCP (dBmV)	N/A	N/A	N/A	62.6	N/A	468 MHz lower RX edge
CACIR (dB)	N/A	N/A	N/A	-47.0	N/A	Based on maximum TCP and 0 dBmV per 6 MHz RX PWR
BW Overlap (MHz)	N/A	N/A	N/A	216	N/A	Correction method TBD
D4 FDX CM RX Overlap TCP (dBmV)	N/A	N/A	N/A	N/A	64.5	108 MHz lower RX edge
CACIR (dB)	N/A	N/A	N/A	N/A	-44.7	Based on maximum TCP and 0 dBmV per 6 MHz RX PWR
BW Overlap (MHz)	N/A	N/A	N/A	N/A	576	Corrected by FDX EC and TG/IG management

From this modeling analysis, operators will need to remain diligent in detecting, and mitigating ACI issues that will arise, as their networks continue to evolve to support more upstream capacity. Fortunately, many of the practices that are in use today, like proactive detection, device swaps, and switchable diplexer CMs can continue to help operators minimize ACI.

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7. Conclusions and Recommendations

ACI may be present with DOCSIS CM upstream transmissions overlap into neighboring or in-home CM/STB downstream reception. Overlapping energy increases incrementally with bandwidth, even though the same TCP is used to facilitate DOCSIS 4.0 CM transmissions. CACIR combined with TCP delta are used to understand service impacting thresholds for service impact due to ACI when present. Existing mitigation methods for legacy device ACI, to include focus on assuring all CPE is operating with margin - within your company's specifications, will also be useful to minimize the use of band stop filters. From the early two-way activations to the expanded upstream spectrum of today, we are addressing similar but new ACI, what was old is indeed new.

Abbreviations

ACI	Adjacent Channel Interference
ADC	Analog to Digital Converter
ALI	Adjacent Leakage Interference
BAU	Business As Usual
BER	Bit Error Rate
CACIR	Carrier-to-Adjacent-Channel-Interference Ratio
CATV	Community Antenna Television
CCI	Co-Channel Interference
CER	Codeword Error Rate
CM	Cable Modem
CPE	Customer Premise Equipment
DAA	Distributed Access Architecture
dB	Decibel
dBmV	Decibel Milli-Volt
DOCSIS	Data Over Cable System Interface Specification
DS	Downstream
DUT	Device Under Test
EC	Echo Cancellation
FDD	Frequency Division Duplex
FDX	Full Duplex DOCSIS
HS	High-Split
HSD	High Speed Data
Hz	Hertz
IF	Intermediate Frequency
IG	Interference Group
iHAT	In-Home Health Assessment Test
IPPV	Impulse Pay-Per-View
kHz	Kilohertz
MAC	Media Access Control
MDD	MAC Domain Descriptor
MER	Modulation Error Ratio
MHz	Megahertz
MS	Mid-Split
OFDMA	Orthogonal Frequency Division Multiple Access
OUDP	OFDMA User Data Profile
PER	Packet Error Rate
PHY	Physical Layer
QoE	Quality of Experience
RBA	Resource Block Allocation
RF	Radio Frequency
RPD	Remote PHY Device
SA	Spectrum Analyzer
SG	Serving Group
SIK	Self-Install Kits
SS	Standard-Split
STB	Set Top Box
TCP	Total Channel Power

TG	Transmission Group
UHS	Ultra-High-Split
US	Upstream
vCMTS	Virtual Cable Modem Termination System
VHF	Very High Frequency
Wi-Fi	Wireless Fidelity

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