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# Leakage In A High Split World

## Detecting and Measuring Upstream Leakage Levels in a One Gpbs Symmetrical High Split Hybrid Fiber Coax Network

A Technical Paper prepared for SCTE/ISBE by

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# 1. Introduction

System leakage monitoring is an integral and extremely important aspect of system maintenance. Federal Communications Commission (FCC) leakage requirements, test and mitigation methods for present cable systems with 5-42 MHz and 5-85 MHz return bands are well understood. Leakage signal sources, monitoring equipment, methods and measurement programs are all in place for measurements in the downstream band, 54-1000 MHz, with an emphasis on the aeronautical band of 108-137 MHz. The FCC sets maximum individual signal leakage levels for cable systems, with more stringent limits on cable systems that may interfere with aeronautical and navigation communications.

In a traditional cable system with a 5-42 MHz return band, high level signals in the downstream are present at the headend or node output, and at the home, the downstream signal is at its lowest level. What happens if you increase the upper boundary of the upstream signal path to 204 MHz or higher? The system is essentially turned upside down, with the highest signal levels in the aeronautical band (108-137 MHz) at the home, and the lowest upstream signal levels at the headend or node.

This paper will look at the implications of these inverted plant levels. How do the FCC's cable signal leakage requirements apply to this scenario? Can the same leakage tools and methods be used? What changes and considerations need to be made? These questions not only apply to high split plants with 204 MHz upstream, but also to future full duplex data over cable service interface specification.

(FDX DOCSIS) and extended spectrum DOCSIS (ESD) systems, each with upstream signals well beyond 204 MHz.

This paper will review these considerations and discuss the implications of the "inverted" plant. Different options and scenarios will be examined, and their implementation and feasibility evaluated to help readers ensure a solid leakage measurement program is in place for when these plant upgrades are implemented.

# 2. Capabilities of DOCSIS 3.1

DOCSIS® 3.1 (D3.1) specifications expand the useable frequency spectrum as well as provide a more efficient use of that spectrum compared to its predecessor DOCSIS®3.0 (D3.0.) With downstream operation out to 1218 MHz along with a high-split (204/258 MHz) option, network capacity can be dramatically improved, particularly in the upstream direction. Included in these exceptional capabilities are orthogonal frequency-division multiplexing (OFDM) channels in the downstream and orthogonal frequency-division multiple access (OFDMA) channels in the upstream. OFDM and OFDMA channels permit a wide-ranging encompassed spectrum-improving capacity, while still allowing very small minislots for enhanced bandwidth utilization. With the 204 MHz upstream spectrum available, and with optimal use of the OFDMA technology, 1 Gbps symmetrical services become possible. In addition, higher-order modulations, including 1024 to 4096 QAM downstream and 256 to 2048 QAM upstream, as well as enhanced forward error correction (FEC) methods in both directions, provide another example of how D3.1 can improve overall capacity and customer experience. Modifications to the hybrid fiber coax (HFC) network parameters, as they pertain to a D3.1 upgrade, need to be continuously evaluated for impact on legacy and future FCC compliance.

# 3. The Need for High-Split Hybrid Fiber Coax Networks

The demands of an HFC network, and, in particular network traffic, continue to increase. Downstream traffic has seen tremendous growth, with over-the-top (OTT) video driving most of the surge. With D3.1, the downstream network is more than capable of handling this traffic increase. A typical High-Split D3.1 downstream channel lineup can accommodate over ninety (256 QAM) D3.0 channels and two 192 MHz (4096 QAM) OFDM D3.1 channels, exceeding throughputs of 9 Gbps.

The limited 5-42 MHz signaling spectrum is typically where the bottleneck in the upstream network performance occurs. Applications and hardware are continually being developed that utilize the upstream more frequently, and with higher bandwidth needs. Internet of Things (IOT), video doorbells, security cameras, online gaming and cellphone Wi-Fi handoffs are all taxing the upstream network.

Currently, and even more relevant, is the impact that COVID-19 is having on the network. In three months, from early March to late May, multiple system operators (MSOs) saw a 32% increase in upstream traffic and an 11% increase in downstream traffic. This added growth is due to a sharp rise in video conferencing and video streaming, now that so many employees and students are working/learning from home.

Beyond D3.1 improvements in efficiency, node splits have been the go-to method to increase upstream capacity. While node splits do increase capacity, they do so without increasing the upstream peak data rate. Upgrading to a mid-split (5-85 MHz) will increase the upstream data throughput to ~ 500 Mbps, and upgrading to high-split (5-204 MHz) will allow >1 Gbps upstream throughput, future proofing the network and keeping the DOCSIS network competitive with alternative technologies. Full duplex (FDX) technology further expands the upstream capabilities, enabling multi-Gbps upstream speeds.

High-split D3.1 technology and products are in high demand and readily available. End-to-end solutions from cable modem termination system (CMTS) all of the way through the plant to the customer premise equipment (CPE) can be procured and installed. This allows operators to upgrade to a high-split network quickly, drastically improving upload speeds, while maintaining extraordinary downstream traffic capacity.

## 3.1. Impact on Existing Legacy Customer Premise Equipment

A large majority of cable modems deployed in the field do not support high-split operation and will operate "business as usual" with the channels that reside in their existing spectrum allocations. Moreover, legacy set-top boxes (STBs) are limited to control channel frequencies between 70 and 130 MHz in the downstream direction, so the out-of-band (OOB) channel will not pass through any diplex filters notched at 204/258 MHz that are used in the traditional HFC network. MSOs are faced with two options: Replace all legacy STBs to support high-split systems with DOCSIS set-top gateways (DSGs) (with the OOB control channel carried over DOCSIS) or enable the OOB control channel signal to propagate through the high-split network to the legacy STB in the upstream spectrum band. For the latter solution, signal requirements defined by SCTE 55-1, 55-2 and SCTE 40 must be maintained, and with a broad range of possible OOB frequencies, challenges from a scalability and standardized solution perspective will need to be resolved.

# 4. Federal Communications Commision Requirements

Understanding the FCC requirements for leakage is a daunting task. The FCC requirements are a maze of different related and unrelated requirements. We'll take you through the main requirements as they relate to the CATV network today and as they relate to the high split network.

There are a few main key FCC requirements. **47 CFR § 76.605** Technical Standards defines the CATV signal and signal leakage limits for both analog and digital signals. Leakage limits are defined in § 76.605 and are shown below in Table 1.

**Table 1 - CFR § 76.605 Signal Leakage Limits**

| Frequencies | Signal leakage limit | Distance in meters (m) |
|---|---|---|
| Analog signals less than and including 54 MHz, and over 216 MHz | 15 µV/m | 30 |
| Digital signals less than and including 54 MHz, and over 216 MHz | 13.1 µV/m | 30 |
| Analog signals over 54 MHz up to and including 216 MHz | 20 µV/m | 3 |
| Digital signals over 54 MHz up to and including 216 MHz | 17.4 µV/m | 3 |

The following FCC requirements are applicable to all multichannel video programming distributors (MVPDs): §76.605(d) Technical Standards, § 76.611 Cable television basic signal leakage performance criteria, § 76.612 Cable television frequency separation standards, § 76.613 Interference from a multichannel video programming distributor (MVPD, 76.614 Cable television system regular monitoring, 76.616 Operation near certain Aeronautical and Marine Emergency Radio Frequencies, 76.617 Responsibility for interference, 76.1803 Signal Leakage monitoring and 76.1804 Aeronautical frequencies: leakage monitoring (CLI)

With respect to 47 CFR § 76.610 – Operation in the frequency bands 108-137 MHz and 225-400 MHz - scope of application, this requirement states: The provisions of §§ 76.605(d), 76.611, 76.612, 76.613, 76.614, 76.616, 76.617, 76.1803 and 76.1804 are applicable to all MVPDs (cable and non-cable) transmitting analog carriers or other signal components carried at an average power level equal to or greater than 100 microwatts across a 25 kHz bandwidth in any 160 microsecond period or transmitting digital carriers or other signal components at an average power level of 75.85 microwatts across a 25 kHz bandwidth in any 160 microsecond period at any point in the cable distribution system in the frequency bands 108-137 and 225-400 MHz for any purpose.

The requirements above warrant a look at the upstream levels generated at the cable modem, to determine if the additional sections referenced apply in a High Split system. Take, for example, an upstream channel configuration with four SC-QAM channels in the 5-42 MHz band and two OFDMA channels, each with a bandwidth of 81 MHz, from 42-204 MHz.

Per the D3.1 specifications, the maximum transmit power from a cable modem is 65 dBmV. With 4 SC-QAMs each 6.4 MHz wide and two OFDMA channels from 42-204 MHz, the total upstream utilized bandwidth is 187.6 MHz. This equates to a power per 25 KHz bandwidth of 5.6 uW and a power per 30 KHz bandwidth of 6.7 uW. This transmit power is below the 75.85 uW threshold in 76.610, which triggers applicability to; §§ 76.605(d), 76.611, 76.612, 76.613, 76.614, 76.616, 76.617, 76.1803 and 76.1804. Even though 76.1804 is not applicable, 76.1804 had a different threshold of 10 uW. In this example, the threshold of 10uW in 76.1804 is also not exceeded. 76.616 is also not applicable per the requirements, but the exlusion zones required to avoid any impact to these emergency beacons are supported by D3.1, are minimal in bandwidth impact, and have minimal effect on upstream capacity or peak speeds.

D3.1 has a maximum power limit for OFDMA channels of <= 24 MHz of -9 dBmV/Hz. As another example, consider a single OFDMA channel of 24 MHz, which happens to overlap with the 108-137 MHz aeronautical band. While a deployment that only uses 24 MHz is not a productive use of spectrum and is unlikely to be deployed, it could possibly be done as the worst case power spectral density, per the D3.1 specifications. The power per Hz is constant at -9 dBmV. This equates to a power per 25 KHz bandwidth of 42 uW, and a power per 30 KHz bandwidth of 50.4 uW, which is again below the threshold of 75.85 uW in 76.610, which triggers applicability to §§ 76.605(d), 76.611, 76.612, 76.613, 76.614, 76.616, 76.617, 76.1803 and 76.1804. 76.1804 has a power level requirement of 10 uW in a 30 KHz band. The threshold of 76.1804 is exceeded and FCC notification on form 321 is required. The same comments on 76.716 apply as in the first example.

To help navigate the FCC requirements, Figure 1 shows the majority of requirements and applicable conditions which apply to CATV systems.

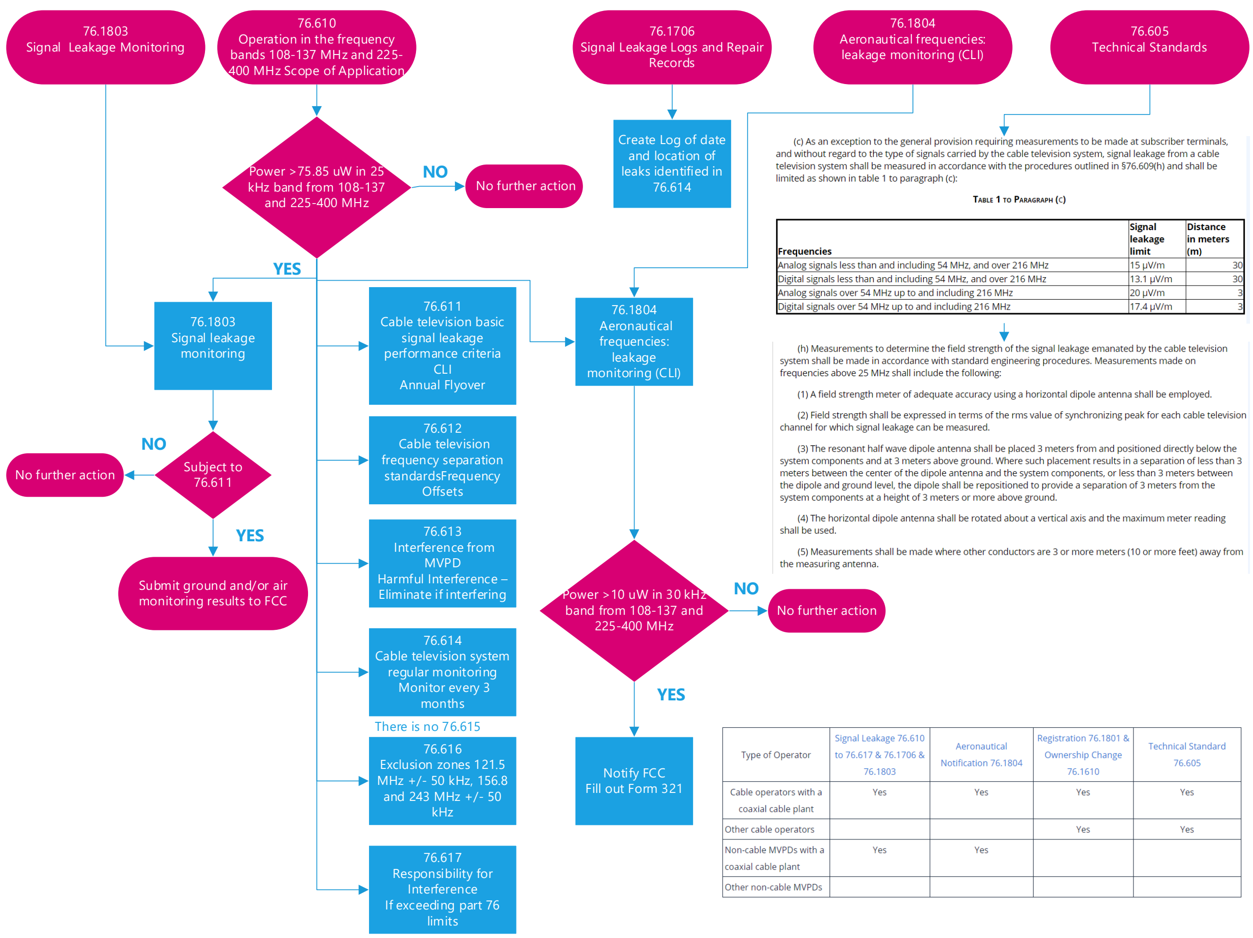



**Figure 1 - FCC Requirements Flow Chart**

## 5. How Leakage Detection is Currently Measured in the Downstream

There are several methods of signal leakage detection utilized by operators in today's HFC network. These can be broadly broken down into three categories: detection of low-level inserted carriers, direct QAM detection using correlation processing, and detection of harmonics of OFDM continuous pilots.

### 5.1. Detection of low-level inserted carriers

With this technique, two CW carriers are inserted into the network, at either the hub or at the R-PHY or MAC-PHY node, and the leakage signal is captured using a fast fourier transform (FFT) detector. The carriers are typically configured to be -30dBc, relative to the SC-QAM digital channel power. Various leakage detection vendors utilize different configurations of CW carrier placement or configuration of the inserted signal. Some examples of widely used signal types are provided in Figure 2 and Figure 3.

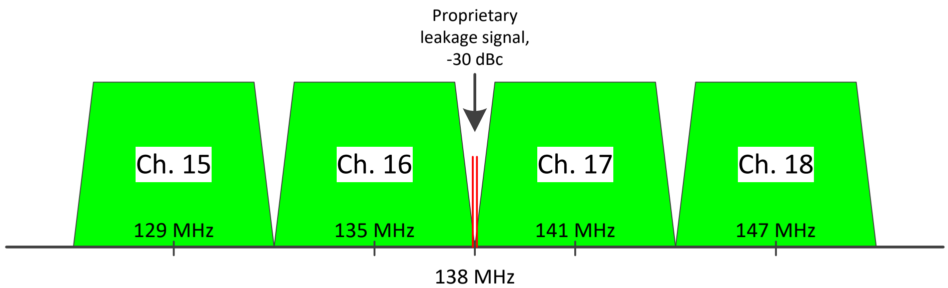



**Figure 2 - Leakage test signal injected at 138 MHz, on the channel boundary between adjacent SC-QAM signals (STD channel plan assumed).**

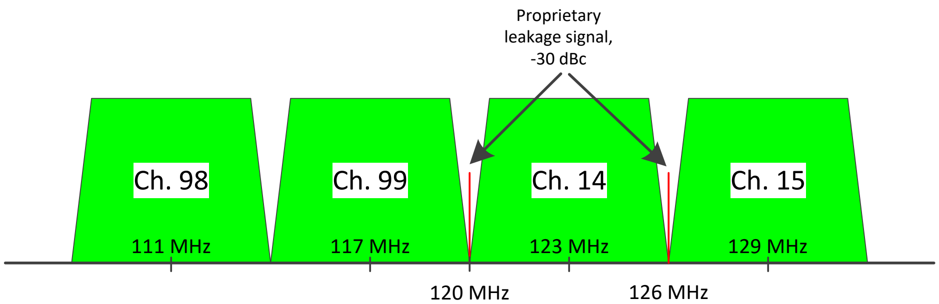



**Figure 3 - Leakage test signal injected at 120 MHz and 126 MHz, on the channel boundaries below and above SC-QAM signal (STD channel plan assumed).**

### 5.2. Direct QAM detection using correlation processing

With this technique, downstream signal samples are captured at the headend at the desired leakage detection frequency. The signal samples are time stamped using a GPS reference clock and transmitted to a leakage detector in the field. The leakage detector receives signals leaking from the HFC network, time stamps the received signals, and then applies a cross-correlation process on the two signal sets to resolve the detected leak.

### 5.3. Detection of harmonics of OFDM continuous pilots

With this technique, an FFT detector is again utilized in the field meter to capture the leakage signal – but with this method no additional tagging or CW signal is inserted into the HFC network. The detected signals are the existing harmonics of the OFDM continuous pilots, as show below in Figure 4.

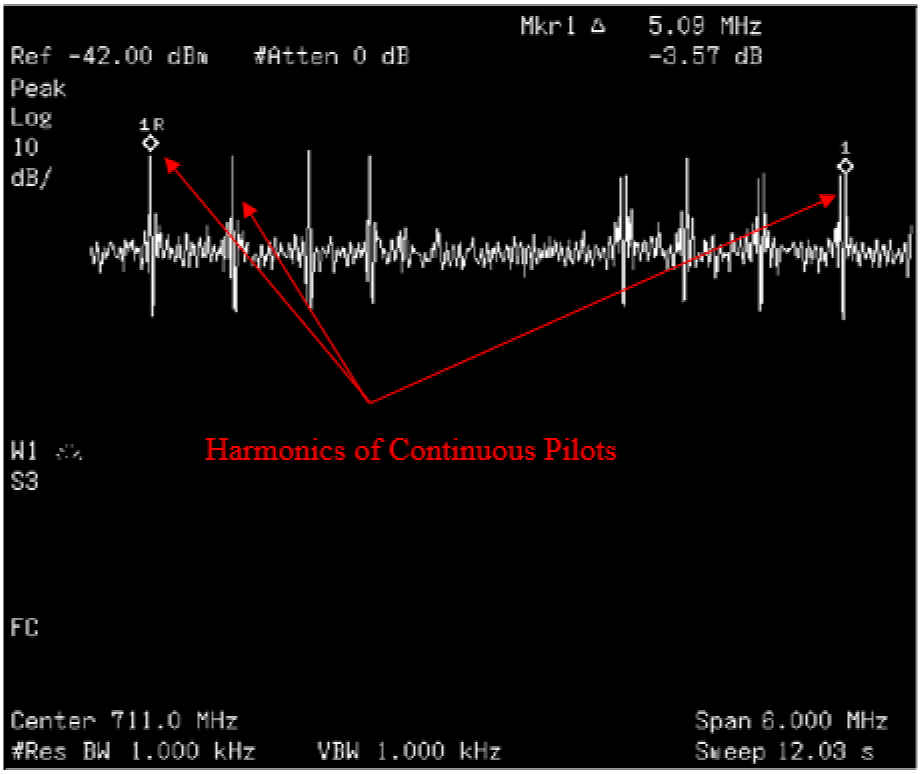



**Figure 4 - Harmonics of OFDM Continuous Pilots**

Unfortunately, none of the status quo approaches are suitable for use in the high-split network. This is mainly because the signals coming from the cable modem (CM) are inherently burst-like in nature, and instead of the leakage detection signal being generated from one source, as is the case with downstream detection, the detection signal is generated from the numerous non-coherent CMs in the upstream network. There are, however, some alternatives, presented below.

## 6. Similarities and Differences between Upstream and Downstream Leakage Detection

For upstream signal generation, the high-split cable modem must be the source of the leakage detection signal. With the majority of the emphasis for downstream leakage detection on the "feed" side of an HFC network, attention now inverts to the "drop" side, including the home -- where upstream signal levels in a high-split network now encompass the aeronautical band and are at much higher levels than the downstream. Cable modems can transmit a maximum power of 65 dBmV for a single 6.4 MHz SC-QAM channel and receive downstream signals within a recommended range of (10 to –10 dBmV, 6 MHz BW.) In this instance, the leakage level delta in terms of uV/m can be over **2000** times higher in the upstream direction versus the downstream, if the leak is on the output of the cable modem. Having multiple cable modems transmitting leakage tones (per the technique described in Section 5.1) at the same time and frequency can cause constructive and destructive signal combining because of the different phases of the signal. This will create a high likelihood of inaccurate leakage detection measurements. Furthermore, upstream leakage detection signals should be in burst mode operation, as opposed to continuous mode downstream tones, to limit the impact on upstream capacity and to protect the upstream power budgets of the optical components. Figure 5 illustrates the inverse relationship of DS to US signal levels between the "feed" and "drop" side of a tap.

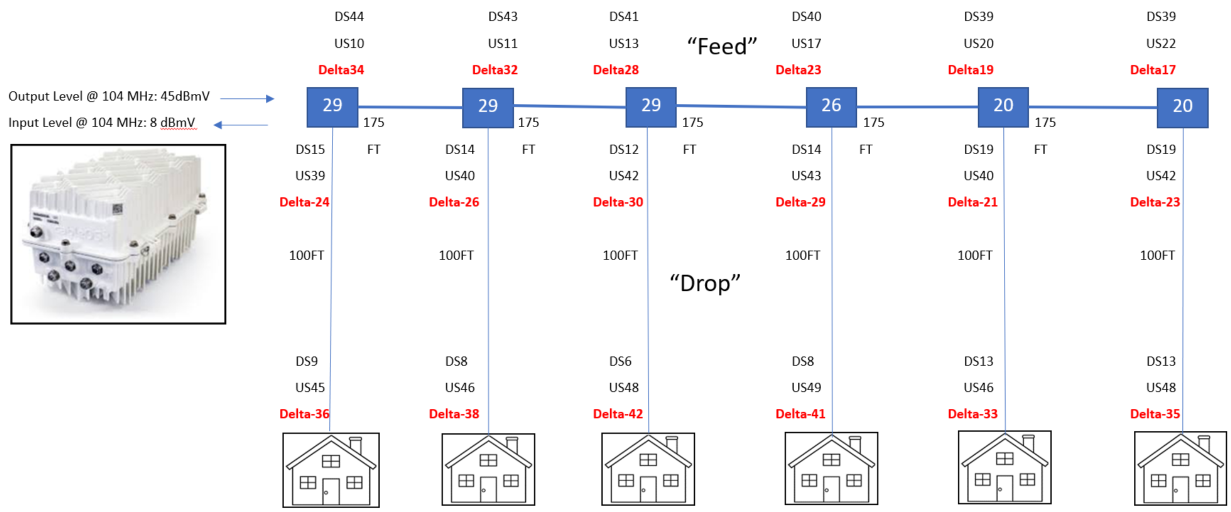



**Figure 5 - Example HFC Network Downstream to Upstream Level Deltas**

# 7. Upstream Leakage Detection Possibilities

## 7.1. Downstream Out of Band (OOB) CW pilots

With millions of legacy set top boxes that utilize SCTE 55-1 and SCTE 55-2 out-of-band data carriers in the forward/downstream, this functionality can be maintained through the distributed access architecture (DAA) node and amplifiers in high split systems. Two of the typical frequencies for the OOB carriers are 75.25 MHz and 104.2 MHz in 5-42 MHz systems. In mid split systems with 5-85 MHz upstream, 104.2 MHz is the typical frequency for the OOB carrier in the downstream.

In a high split system, 104.2 MHz sits in the middle of the upstream band and is also very close to the aeronautical band. To utilize a 104.2 MHz OOB carrier in a high split system, the 104.2 MHz OOB signal is generated in the CMTS or remote physical device (RPD), and via couplers and filtering this signal can be injected onto the plant on the low side of the diplex filter. Notch filters are required in the upstream to prevent the OOB signal from entering the return path receiver of the CMTS or RPD at a level that would cause distortion or interference. See Figure 6 for a simplified OOB implementation example in a high split RPD/node.

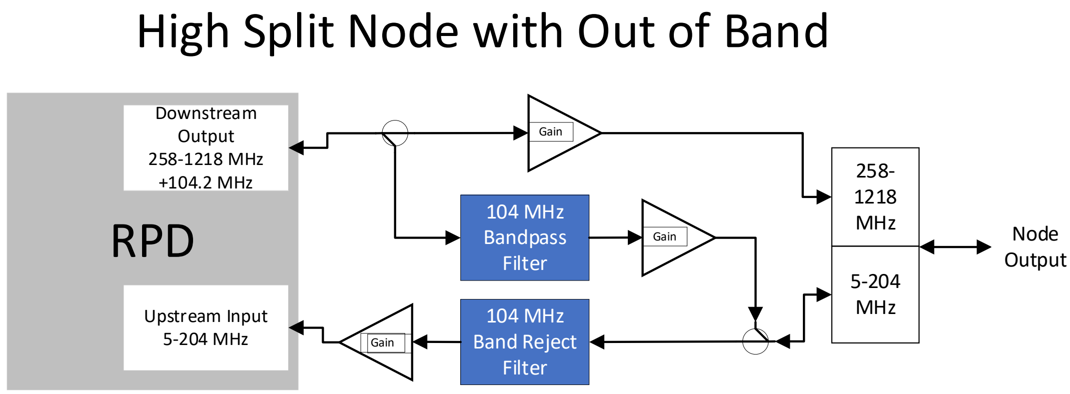



**Figure 6 - High Split RPD/Node with OOB Filtering**

Leakage tones can be generated in the RPD and placed close to the OOB carrier, and still fit within the 104 MHz bandpass filter passband. In a 5-204 MHz upstream, the two OFDMA channels can be placed above and below 104.2 MHz, to create a band gap for the 104.2 MHz OOB carrier. See Figure 7.

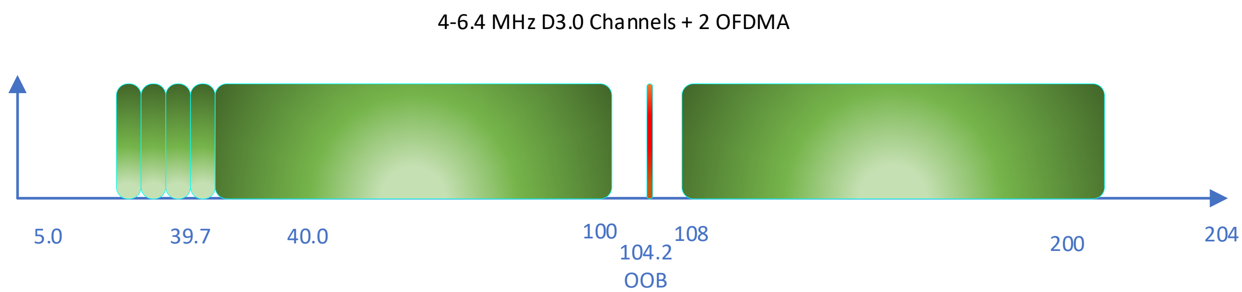



**Figure 7 - High Split Upstream Channel Configuration with OOB**

The 104 MHz bandpass filter can be made wide enough to include both the 104.2 MHz OOB and leakage tones. The leakage tones will then proceed down the plant along with the OOB carrier. See Figure 8.

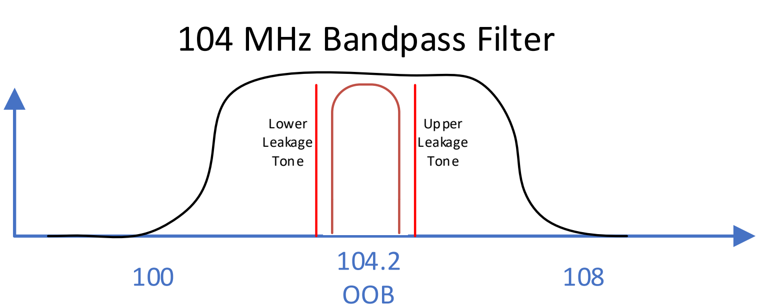



**Figure 8 - Out of Band Band Pass Filter Response with OOB Signal and Leakage Tones**

Although the leakage tones can be generated close to the lower edge of the aeronautical band, all the difficulties of the inverted plant and level differences between the downstream and upstream levels will make it difficult to correlate leakage measurements. Looking at Figure 5, the downstream-to-upstream signal level delta is a positive 37 dB, and slowly decreases as you travel down the hard line plant, to a delta of 17 dB at the input to the last tap. Once you move to the drop side of the tap, the downstream-to-upstream delta decreases dramatically, with the largest negative delta at the premises. A method could be developed, based on plant maps and GPS coordinates, as leakage is measured along the plant. The maximum CM transmit level of 65 dBmV could be assumed, or additional information on CM transmit levels could also be determined from monitoring tools.

High Split devices will be introduced into the plant incrementally, as needed. Using the leakage tones generated at the RPD or CMTS could generate false readings, as the leakage tones are distributed to the whole plant and all homes. In most instances, using the default transmit value of 65 dBmV will be higher than the actual CM transmit values, and potentially create false high leakage readings. With the extensive mapping and software updates required, and the difficulty in correlating downstream-to-upstream levels, the other approaches described in this paper are likely more practical to implement. The goal is to be able to measure leakage events as reliably as possible, to meet regulatory requirements, without unnecessary increases in operational expense, or unnecessary risks for compliance issues.

## 7.2. Continuous Waveform Upstream Test Signal

One of the possibilities for upstream leakage detection is for the CM to generate continuous wave (CW) carriers. The CW carriers generated by the CMs cannot be continuously and simultaneously present at any one frequency, because the numerous out-of-phase signals would combine randomly and, as a direct result, yield random detection results. As an alternative, two CW approaches are presented below -- one with the CW burst controlled in time by the CMTS, and the second where each CM in a node transmits at a unique frequency. One important obstacle that will need to be overcome in these two approaches involves the fact that both are outside of the existing D3.1 specification. Also, current CMs are not able to generate the required CW carriers without updated firmware, and face constraints without updated hardware.

### *7.2.1. CW Time-Division Multiple Access (TDMA)*

In this scenario, there is continuous cyclical generation of two CW test bursts by CMs, under CMTS control, in an exclusion segment of bandwidth of the OFDMA spectrum within the aeronautical band. Detection of the leakage signal is provided by advanced FFT overlap processing, with leak signal validation accomplished by measuring the frequency offset between CW test tones, and by verifying the time sync and duration of the CW bursts. Figure 9 and Figure 10 below describe the burst schema and carrier placement.

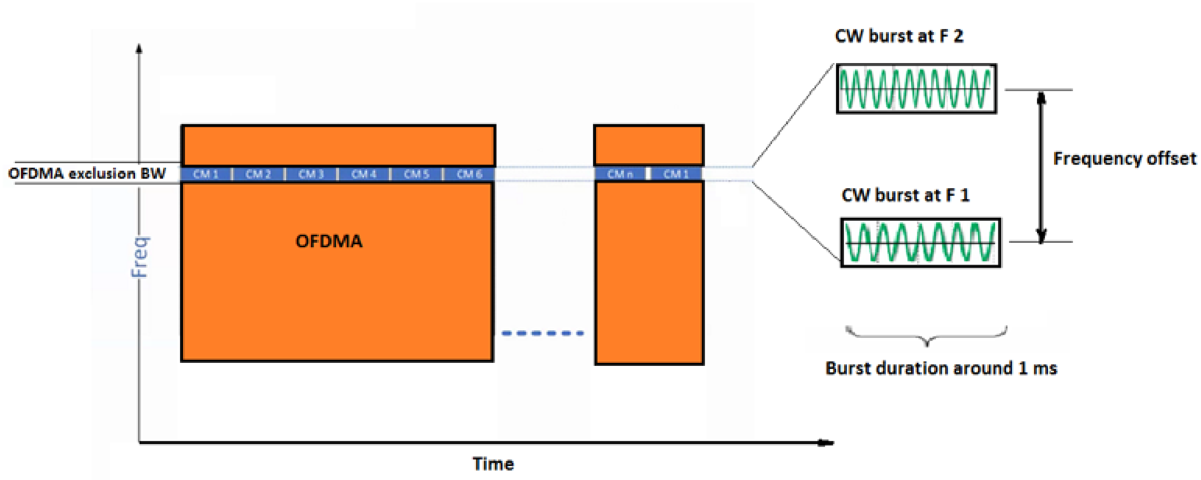



**Figure 9 - Illustration of permanent generation of CW test bursts by CM**

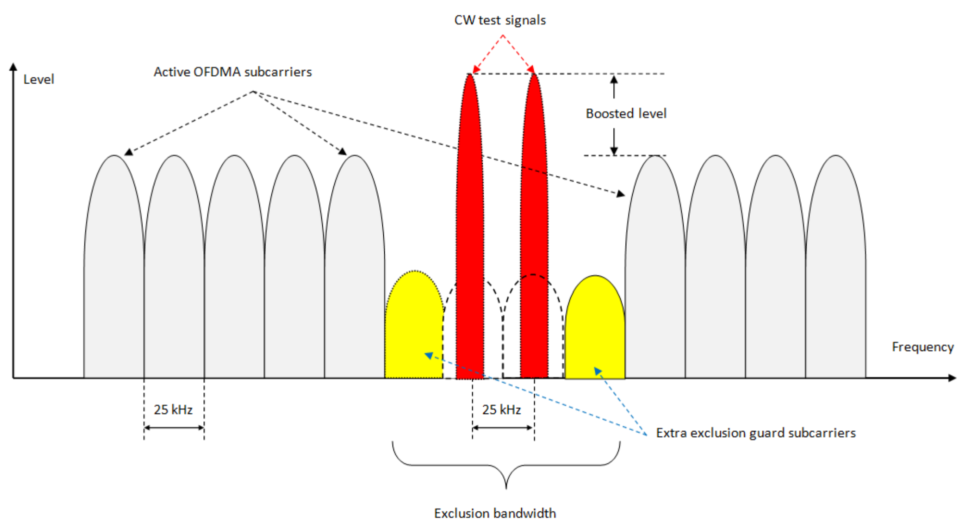



**Figure 10 - Illustration of CW test signals within exclusion BW of OFDMA signal (4k FFT mode)**

### *7.2.1.1.* Analysis of the parameters of the CW test signal*:*

The following parameters of the CW test signal are relevant for leakage detection and for compatibility with HFC data transmission:

- Frequency location of the CW test signal;
- Duration of the CW burst;
- Frequency offset between the CW bursts central frequencies;
- Level of the CW test signal relative to the level of the OFDMA subcarriers;

- **The frequency location of the CW test signal** should be within or very close to aeronautical band 108 - 137 MHz for accurate CLI reporting. Given that 108 MHz is the edge frequency for FDX, it makes sense to assume that high split HFC upstream OFDMA spectrum also will also occupy the 108 MHz to 204 MHz band. This means the CW test signal could be placed near or within the OFDMA spectrum, in an exclusion bandwidth (BW), or below the edge frequency of 108 MHz, at a guard bandwidth within the lower adjacent OFDMA upstream signal.

- **The duration of the CW test** burst should be as long as possible, to provide improved sensitivity of leakage detection. On the other hand, the duration of the CW test burst is limited by the condition that each CM in a node serving group should be granted a transmit (Tx) test burst at least two times during the 1 second leak measuring session. Therefore, for a typical number of CMs in node, from 100 to 500 CMs, the maximum duration of the CW test burst is limited to around 1 ms.

- **The frequency offset between CW tones** should be as low as possible, to minimize the exclusion BW area of the OFDMA spectrum. On the other hand, the frequency offset needs to be sufficient to provide the FFT analyzer with enough resolution for correct leak signal validation. The bandwidth of a CW burst with a duration of 1 ms is a few kHz. Therefore, the minimum frequency offset should be around 10 kHz or more. To provide the minimum interfering effect, when receiving the OFDMA signal at the CMTS, it makes sense to establish the central frequencies of the CW bursts equally to the central frequencies of OFDMA subcarriers. In this case, the frequency offset between CW bursts will be 25 kHz (4k FFT) or 50 kHz (for 2k FFT) mode. The minimal exclusion bandwidth for placing CW test signals will be two subcarriers, however additional guard band carriers may be required for the exclusion area.

- **The level of each CW test signal** should be boosted as much as possible, relative to the OFDMA subcarriers level, to provide better sensitivity of leak detection. On the other hand, the level of the CW test burst must be below the possible interfering threshold at the receive (Rx) side of CMTS. According to the D3.1 specifications, OFDMA pilots could be boosted by at least 4.7 dB:[1]

  > The CM MUST boost pilots and complementary pilots by a factor of 3 in power (about 4.7 dB).

  Another approach to boosting the gain could be to increase the exclusion BW in the OFDMA spectrum and add the energy of the excluded subcarriers to the CW test signal. For example, in case of exclusion BW = 1.6 MHz, the boosting gain could be increased to +15 dBc. In this scenario, by placing the CW test signal outside the OFDMA spectrum (for example, below 108 MHz), the boosting gain could be increased up to + 20 dBc, where the power of CW test signal will be equal to the energy of one upstream SC-QAM. As a rule of thumb, the larger the spectrum exclusion, the more lost capacity for user data. Capacity calculation and OFDMA testing indicates that the goal of a 1 Gbps US product capability will require precise attention to spectral efficiency.

### 7.2.2. CW Frequency-Division Multiple Access (FDMA)

This approach requires continuous generation of a pair of CW tones by each CM. The frequency offset between CW tones is the same at all CMs used for leak signal validation. The central frequencies of the CW tone pairs at different CMs within one node will have a specific frequency offset, with each CM in a node transmitting at a unique frequency. This frequency offset is required for frequency resolution of signals from different CMs in the leak detector, and for correct measurement of the leak level, such as in the scenario where there is combining of CW tones from many CMs in the trunk line. All CW tones are located within the exclusion bandwidth of the OFDMA spectrum within the aeronautical band. The level of CW tones is suppressed relative to the level of the OFDMA subcarriers, to prevent interfering with the CMTS Rx side. Detection of the leak signal is provided by FFT processing. This is the same technology as is currently used for detection of DS harmonics of OFDM continuous pilots, and for pilots inserted between SC-QAM channels.

With this approach, permanent control from the CMTS side is not required, as is the case of CW time division multiple access (TDMA) burst or OFDMA upstream data profile (OUDP) approaches. The generation of CW tones can be activated at the CMs during initial provisioning by using direct access via telnet, simple network management protocol (SNMP) or the web. This provisioning of tone frequency, and the frequency accuracy, calibration to OFDMA power levels, and fidelity is not supported in current standards and would need to be agreed upon by all high split CM vendors, through the CableLabs specification and certification process. Figure 11 describes this concept.

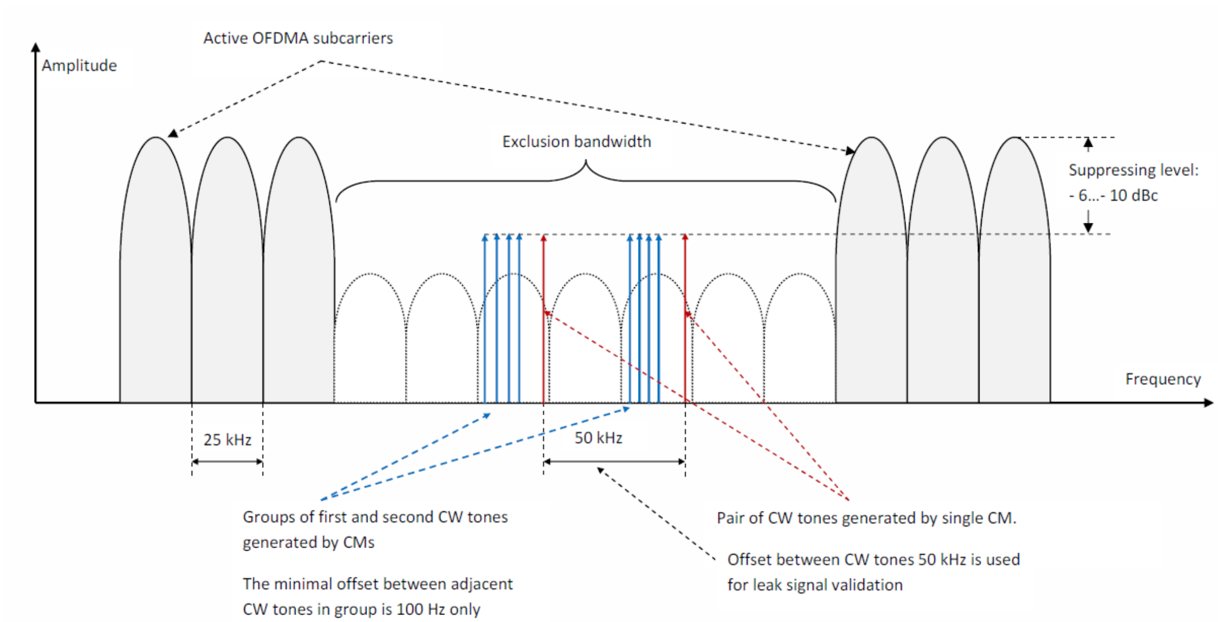



**Figure 11 - Illustration concept of continuous generation CW tones by all CMs**

### *7.2.2.1. Analysis of parameters of CW tone signal:*

The following parameters of the CW test signal are relevant for leakage detection and for compatibility with HFC data transmission:

- Frequency location of CW signal;
- Frequency offset between CW tones from different CMs within one node;
- Frequency offset between CW tones in each CM for leak validation;
- Level of CW tones relative OFDMA subcarriers and reasonable exclusion bandwidth.

- **The frequency location of CW tones** should be within or very close to the aeronautical band 108 - 137 MHz for accurate FCC reporting. Given that 108 MHz is the edge frequency for FDX, it makes sense to assume that for high split HFC, the upstream OFDMA spectrum also will be from 108 MHz to 204 MHz. This means that the CW tone signal could be placed within the OFDMA spectrum at some exclusion BW, or below the edge frequency of 108 MHz at the guard band of the lower adjacent OFDMA upstream signal.

- **The frequency offset between CW tones from different CMs within node** should be big enough to provide good frequency resolution of tones from different CMs in the leak detector FFT processor for correct measurement of leak levels. Absent this frequency offset, tones from different CMs will add with different phases, and the leak signal within the hardline will have random fluctuating levels, depending upon the number of accumulated CW tones. On the other hand, the frequency offset should be as minimal as possible, to reduce the required exclusion bandwidth in OFDMA spectrum. The frequency resolution of current FFT leak detectors is below 10 Hz, so a minimum frequency offset could be selected as 100 Hz. For a typical number of 250 CMs in a node, the CW tones will be grouped in two bandwidths (see Fig.10) of 25 kHz each within one OFDMA subcarrier.

- **The frequency offset between CW tones in each CM is used for leak signal validation**. This offset should be two times more than the bandwidth occupied by each group of CW tones (see Figure 11) to prevent overlapping groups of CW tones in the frequency domain. Therefore, the offset depends both upon the minimum offset and number of CMs in the node. For minimal frequency offset = 100 Hz and the number of CMs in node equal to 250 the minimal offset for leak validation will be 50 kHz as shown in Fig.10.

- **The level of each CW tone** should be as high as possible to provide good sensitivity of leak detection. On the other hand, the energy of CW tones from all CMs in node will be combined at the CMTS Rx side. This means that the level of CW tones should be limited (suppressed), relative to the level of the OFDMA subcarrier, to prevent interfering with and overloading the CMTS. It should be noted that increasing the excluded BW allows an increased level of the CW tones, from a point of view of saving the total energy of the signal in the same BW. Additionally, according to the DOCSIS 3.1 specs, OFDMA pilots can be boosted by at least 4.7 dB:[1]

> The CM MUST boost pilots and complementary pilots by a factor of 3 in power (about 4.7 dB).

With this, we can assume the energy of all CW tones must be no more than energy of all excluded subcarriers, plus 4.7 dB. Based on this assumption, the relative level of one CW tone is defined by formula:

$$L\ (\text{dBc}) = 10\ \text{Log}\ (M/2K) + 4.7\ \text{dB},$$

where:

M is number of excluded subcarriers;

K is maximum number of CMs in node.

Table 2 below shows the relative level of CW tones dependent on the exclusion zone and the number of CMs. Continuously dedicated spectral exclusion bands of multiple MHz are material in the challenges they present to achieve the goal of Gbps US services.

**Table 2 - Relative level of CW tones vs OFDMA subcarriers, dBc**

| **Exclusion BW** | **Number of CMs in node** | | | | |
|---|---|---|---|---|---|
| | 100 | 200 | 300 | 400 | 500 |
| **400 kHz** | -6.27 | -9.28 | -11.04 | -12.29 | -13.26 |
| **800 kHz** | -3.26 | -6.27 | -8.03 | -9.27 | -10.25 |
| **1,600 kHz** | -0.25 | -3.26 | -5.02 | -6.26 | -7.24 |
| **2,000 kHz** | +0.72 | -2.29 | -4.05 | -5.03 | -6.27 |

## 7.3. OUDP Burst Test Signal (BTS)

This leakage detection method uses an OFDMA Upstream Data Profile (OUDP) burst that is generated by each high split cable modem, which is used to detect and monitor leakage in the aeronautical band of a high-split (204/258 MHz) HFC network. Within the DOCSIS specification, there are several predefined OUDP pilot patterns. Existing pilot pattern 11 contains the densest concentration of pilots, and as such it makes sense to use exactly this pattern for the CM burst signal used for detection. Detection of the signal is realized by utilizing a matched filter[1] for the predefined pilot pattern. Scheduling and overall configuration of the cable modem OUDP burst signals will be done through the CMTS service gateway (SGW.) OUDP burst test signal (BTS) has several advantages compared to the previous solutions, the most noteworthy being not having to modify existing D3.1 specifications for cable modem upstream signal generation requirements, and not having to update firmware in existing CMs to add the capability of generating CW carriers. Because there will initially be a limited number of high split cable modems, this approach is also advantageous in that it accommodates the overall time needed to generate the OUDP test bursts. Even in a larger node, sufficient time will exist for data to be interleaved into that spectrum, as needed. In the future, when all modems are high split or FDX capable, the OUDP test bursts can be scheduled only when needed, freeing that spectrum for data bursts most of the time.

An illustration of this OUDP BTS approach, with one frame of 8 symbols and 4 minislots, is shown **Figure 12.**

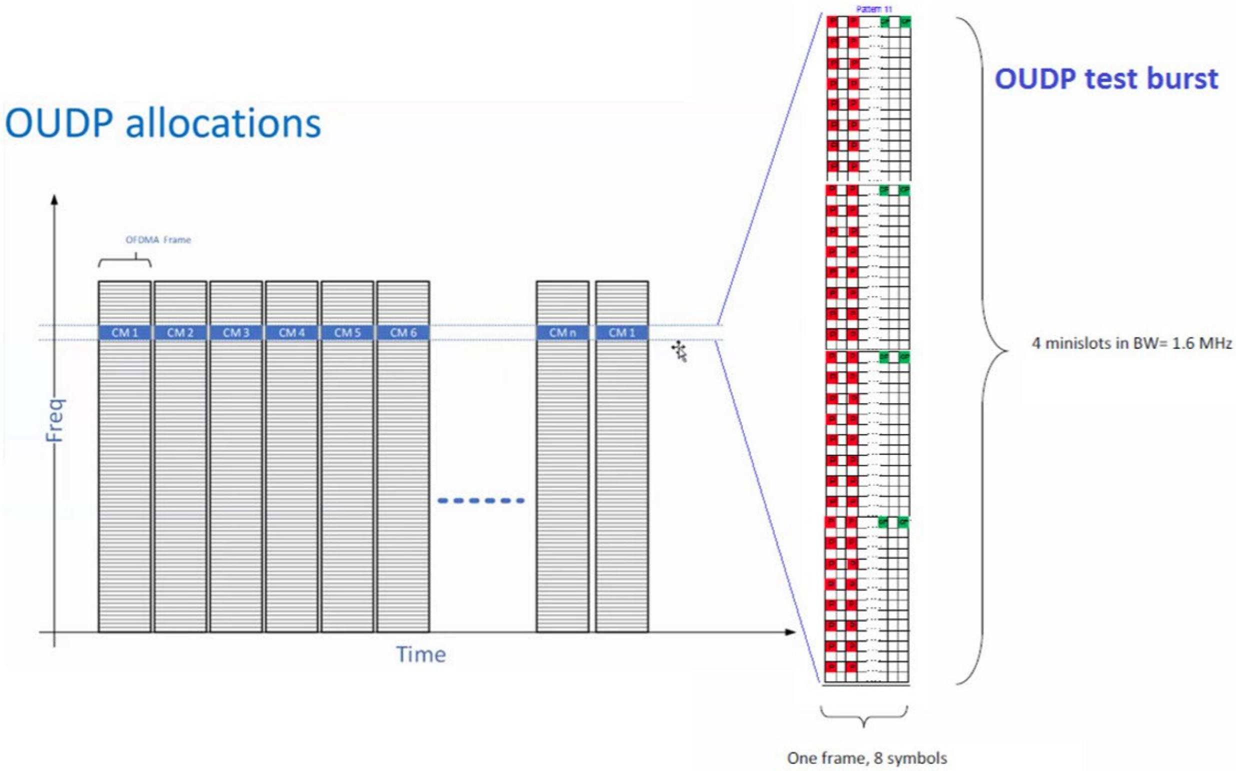



**Figure 12 - Generation of OUDP Test Bursts in a Service Group**

Using an OFDMA OUDP burst allows configurability in optimizing frequency placement in the upstream band; minimizes any impact to the overall upstream bandwidth/throughput; and optimizes duration to maximize the sensitivity of the receiver. The OFDMA OUDP burst is able to cycle through all the cable modems on the node and have a good probability of intercept (POI) for leakage measurements, as detailed in Section 10 Probability of Intercept: Moving Vehicle Analysis.

One example of an OUDP Burst Signal which can be configured in a high split cable modem is detailed below and shown in Figure 13. The parameters defining the OUDP signal are used to generate the matched filter within the leakage detector:

- Symbols Per Frame (K) = 6 (may be modified to improve network efficiency and robustness)
- Modulation Order = 64 QAM
- Pilot Pattern = 11
- Center Frequency of OUDP Signal = 136.0125 MHz
- 4 Minislots (1.6 MHz Upstream Bandwidth with the 4 adjacent minislots to the center frequency above)
- Number of Frames = 8 and 2.16 mS in transmit time duration. (For 256 House Holds Passed total roundtrip time = 552.96 mS)
- Transmit Power equal to the surrounding OFDMA P= 1.6 MHz channel transmit power
- 4K Fast Fourier Transform (FFT) = 40 uS per symbol + Cyclic Prefix
- Cyclic Prefix = 5.0 uS (may be modified to improve network efficiency and robustness)

- Window Roll off Period = 0.9375 uS (may be modified to improve network efficiency and robustness)

The pattern described above and illustrated in the far right of Figure 13 utilizes 8 frames of OUDP pilot pattern 11. This configuration provides the most pilot energy within the OUDP burst signal, which results in optimized sensitivity for detection, as compared to the other variants shown below. If there was the ability to define a new OUDP pilot pattern within the DOCSIS spec that contained an even more dense configuration of pilots, that would be a more spectrally efficient approach, yielding improved sensitivity.

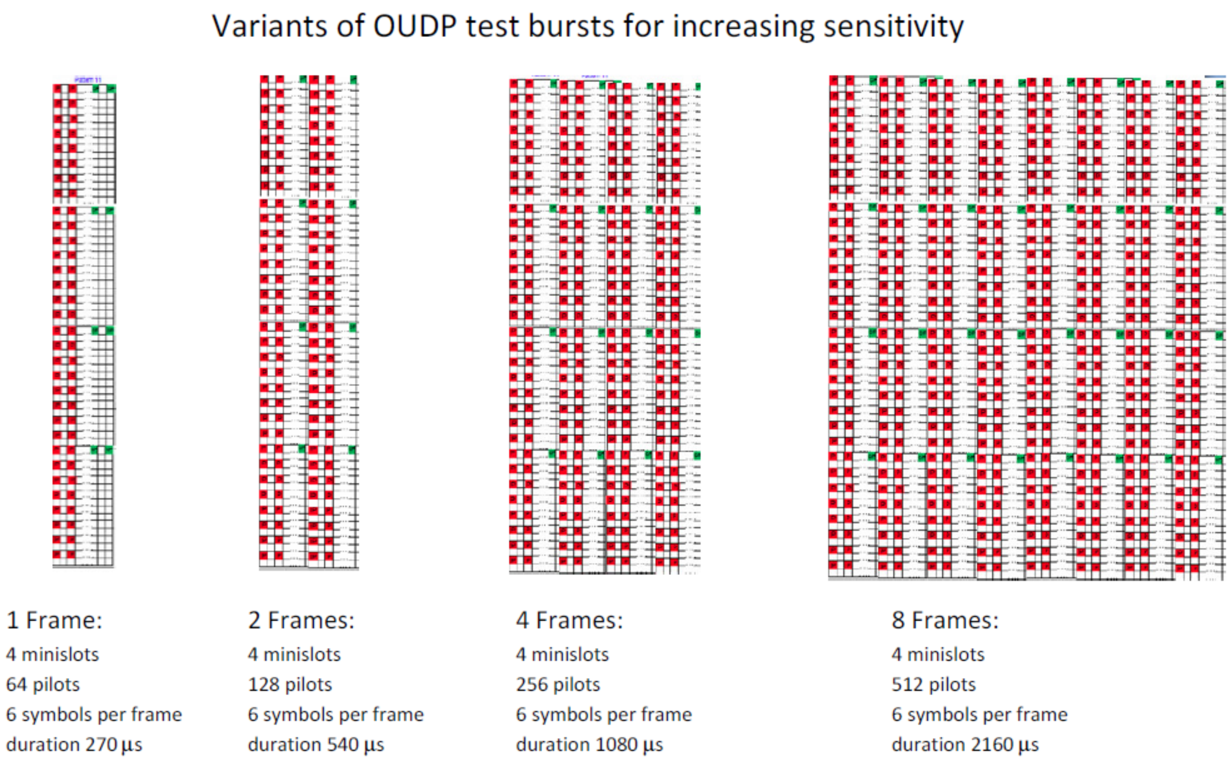



**Figure 13 - Patterns of OUDP Test Burst in Time-Frequency Domain**

# 8. Receiver Sensitivity analysis of the proposed detection approaches

## 8.1. Downstream Out of Band (OOB) CW pilots

The receiver sensitivity of this approach is identical to the status quo and well-known downstream leakage equipment widely used today. As such, no discussion on sensitivity is required.

## 8.2. CW Time-Division Multiple Access (TDMA)

**Estimated sensitivity of leak detection**

The sensitivity of the leak detector in the aeronautical band is a relevant parameter for FCC compliance. Technical standard § 76.605 specifies a signal leakage limit for digital signals at 17.4 µV/m @ 3 meters. This leakage level should be measured at a bandwidth of 6 MHz for QAM, which is why it is be reasonable to assume that the energy of OFDMA leakage should be calculated in the same 6 MHz bandwidth.

Based on the above assumption, the sensitivity of OFDMA leak detector is calculated as follows:

$S_{OFDMA}$ (dBmV/m) = $S_{test}$ (dBmV) + AF (dB/m) + N (dBc),

where:

$S_{test}$ (dBmV) is sensitivity of CW test signal receiver;

AF (dB/m) is antennas factor;

N (dBc) is coefficient of recalculation level of OFDMA signal in BW= 6 MHz to the measured level of CW test signal.

The sensitivity $S_{test}$ depends on the BW of the detected signal, receiver noise figure, and detection threshold over the noise floor. For a test signal with a duration of 1 ms (BW = 1 kHz), the maximum realized sensitivity for a detection threshold of 6 dB is around -85 dBmV.

The antennas factor (AF) for a monopole antenna at 135 MHz is around 8 dB/m.

The coefficient N is defined by the formula:

N (dBc) = 10 Log(M) - K (dBc),

where:

M is number of subcarriers in BW = 6 MHz. M=240 for 25 kHz subcarriers spacing and M= 120 for 50 kHz subcarriers spacing;

K (dBc) is boosting gain of CW test signal.

Therefore, for 25 KHz spacing OFDMA signal (M=240) coefficient N (dBc) equals:

N (dBc) = 10 Log(240) - K = 23.8 – K

Finally, the sensitivity of the OFDMA leak detector can be estimated as follows:

$S_{OFDMA}$ (dBmV/m) = - 85 dBmV + 8 dB/m + (23.8 - K) dBc = - 53.2 - K dBmV/m

Table 3 below shows the estimated sensitivity for different boosting gains K:

**Table 3 - Estimated Sensitivity for Different Boosting Gains, K**

| Boosting gain K, dBc | Sensitivity | |
|---|---|---|
| | dBmV/m | µV/m |
| 0 | -53.2 | 2.19 |
| 4.7 | -57.9 | 1.38 |
| 10 | -63.2 | 0.69 |
| 15 | -68.2 | 0.39 |
| 20 | -73.2 | 0.22 |

Note, the above sensitivity estimation is for ideal conditions. In real life, in the presence of ambient noise, actual sensitivity will be less. For example, if ambient noise spectral density is anticipated to be 20 dBc above the thermal noise at the receiver, then the actual sensitivity will be also 20 dB (ten times µV/m) worse. This is why a maximum boosting of a CW test signal is preferable for robust leak detection.

## 8.3. CW Frequency-Division Multiple Access (FDMA)

**Estimated sensitivity of leak detection**

Similar to the logic of the CW TDMA approach described above, for this approach (FDMA) the energy of OFDMA leakage also should be calculated in the same 6 MHz bandwidth.

Based on this assumption, the sensitivity of OFDMA leak detector is calculated as follows:

$$S_{OFDMA}(dBmV/m) = S_{test}(dBmV) + AF\ (dB/m) + N\ (dBc),$$

where:

$S_{cw\_tone}(dBmV)$ is sensitivity of CW tone receiver;

AF (dB/m) is antennas factor;

N (dBc) is coefficient of recalculation level of OFDMA signal in BW= 6 MHz to measured level of CW tone signal.

The sensitivity $S_{cw\_tone}$ depends upon receiver noise figure, bin spacing at FFT processor, and detection threshold over noise floor. In modern leakage detectors currently utilized, the sensitivity of detection for similar CW tone signal at OFDM and Pilot/QAM modes is around -100 dBmV.

The antennas factor (AF) for a monopole antenna at 135 MHz is around 8 dB/m.

The coefficient N is defined by formulas:

$$N\ (dBc) = 10\ Log(M) - L\ (dBc),$$

where:

M is number of subcarriers in BW = 6 MHz. M=240 for 25 kHz subcarriers spacing and M= 120 for 50 kHz subcarriers spacing;

L (dBc) is relative level of CW tone signal (see Table 2).

For 25 KHz spacing OFDMA signal (M=240) coefficient N (dBc) equals to:

$$N\ (dBc) = 10\ Log(240) - L = 23.8 - L$$

Finally, the sensitivity of the OFDMA leak detector can be estimated as follows:

$$SOFDMA(dBmV/m) = -100\ dBmV + 8\ dB/m + (23.8 - L)dBc = -68.2 - L$$

By using result for L (dBc) from Table 2, it can be seen that to provide sensitivity at around -60 dBmV/m (1 µV/m), a reasonable exclusion BW should be 800 kHz.

This sensitivity is sufficient for FCC compliance.

### 8.4. OUDP Burst Test Signal

The sensitivity of the OFDMA leak detector, in the case of the OUDP approach, is calculated as follows:

$$S_{OFDMA}(dBmV/m) = S_{OUDP}(dBmV) + AF\ (dB/m) + N\ (dBc),$$

where:

$S_{OUDP}(dBmV)$ is the sensitivity of the OUDP test signal receiver;

AF (dB/m) is the antennas factor;

N (dBc) is the coefficient of the recalculation level of the OFDMA signal in BW= 6 MHz to the level of the signal at the output of the OUDP-matched filter.

The sensitivity $S_{OUDP}$ depends on the number of pilots in the OUDP test burst, cyclic prefix duration, receiver noise figure, and detection threshold over noise floor. In a matched filter scenario, the energy of all pilots are coherently combined within time slot T of one OFDMA symbol, plus any cyclic prefix. So, the sensitivity $S_{OUDP}$ equals the sensitivity of the detection CW burst with duration T and level boosted K times, where K is the number of pilots in the OUDP test burst:

$$S_{OFDMA}(dBmV/m) = S_{CW\text{-}T}(dBmV) - 10\ Log(K)$$

The antennas factor (AF) for a monopole antenna at 135 MHz is around 8 dB/m.

The coefficient N is defined by formula:

$$N\ (dBc) = 10\ Log(M),$$

where:

M is number of subcarriers in BW = 6 MHz.

For 25 KHz spacing of an OFDMA signal, the number of subcarriers M is 240, and coefficient N equals to 23.8 dBc. Thus, the sensitivity of an OFDMA leak detector for 25 KHz spacing and T = 45 µs (symbol 40 µs plus cyclic prefix 5 µs) can be estimated as follows:

$$S_{OFDMA}(dBmV/m)= S_{CW\text{-}T} - 10\ Log(K) + 8 + 23.8 = S_{CW\text{-}45} - 10\ Log(K) + 31.8$$

The sensitivity $S_{CW\text{-}45}$ of detection CW burst with duration 45 µs is 13.47 dBc (in 22.2 times) worse than maximal sensitivity of detection CW burst with duration 1 ms and threshold 6 dB (see analysis sensitivity for CW burst approach). But lab tests showed that in case of OUDP the detection threshold should be increased at least to 12 dB or on + 6 dBc to prevent false alarms. Thus, the sensitivity $S_{CW\text{-}45}$ can be estimated as follows:

$$S_{CW\text{-}45} = -85\ dBmV + 13.47\ dBc + 6\ dBc = -65.5\ dBmV$$

Finally, the sensitivity of the OFDMA leak detector equals:

$$S_{OFDMA}(dBmV/m) = -65.5 - 10\ Log(K) + 31.8 = -33.7 - 10\ Log(K)$$

As follows from the above formula, increasing the sensitivity requires increasing the number of pilots. This means increasing the number of OUDP minislots and frames, and using a pilot pattern with the maximum number of pilots (pattern 11 within the existing specifications). Table 4 shows the estimated sensitivity for pilot pattern 11 and for different combinations of minislots and frames. This sensitivity is sufficient to meet the FCC's signal leakage requirements.

**Table 4 - Sensivity for Pilot Pattern 11**

| Number of minislots / frame | Number of pilots (K) | Sensitivity | |
|---|---|---|---|
| | | dBmV/m | µV/m |
| 2 /1 | 32 | - 48.8 | 3.6 |
| 2/2 or 4/1 | 64 | - 51.8 | 2.6 |
| 2/4 or 4/2 | 128 | -54.8 | 1.8 |
| 2/8 or 4/4 | 256 | -57.8 | 1.3 |
| 4/8 | 512 | -60.8 | 0.91 |

## 9. Using Full Band Capture to Evaluate Potential Aeronautical Band Leakage Issues

One of the features of D3.0 and consequent devices is the ability to view the downstream spectrum using full band capture (FBC). Comcast's network has 40M+ devices with FBC and this feature is widely used as part of our proactive network maintenance (PNM) program.

Prior to installing a high split device, FBC can be used to evaluate the quality of the home network by looking at ingress in the FM band from 88-108 MHz. This band is at the edge of the aeronautical band, so, high ingress will indicate the potential for leakage issues into that spectral region. The level out of the cable modem in the aeronautical band can be more than 2000 times higher than the downstream level into the cable modem. Below are two examples of FBC screen captures showing ingress. In Figure 14, the noise floor in the FM band is very low, indicating a home with high network quality, that is a good candidate for high split service with potentially little leakage.

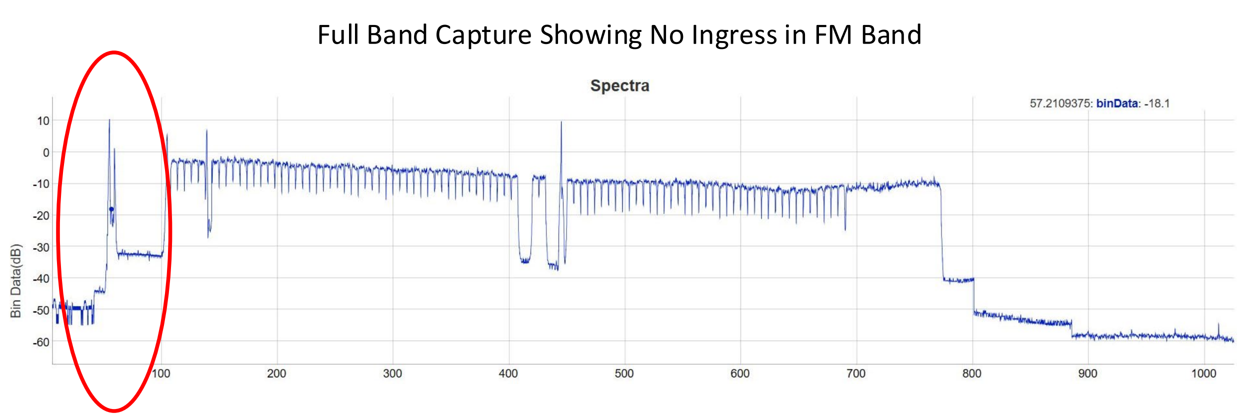



**Figure 14 - FBC Capture Showing No Ingress in FM Band**

Figure 15 shows high ingress and the potential for leakage if converted to a high split and transmitting in the aeronautical band. In this instance, remediation can be performed prior to providing high split service, to minimize leakage issues in the FM band.

Full Band Capture Showing High Ingress in FM Band

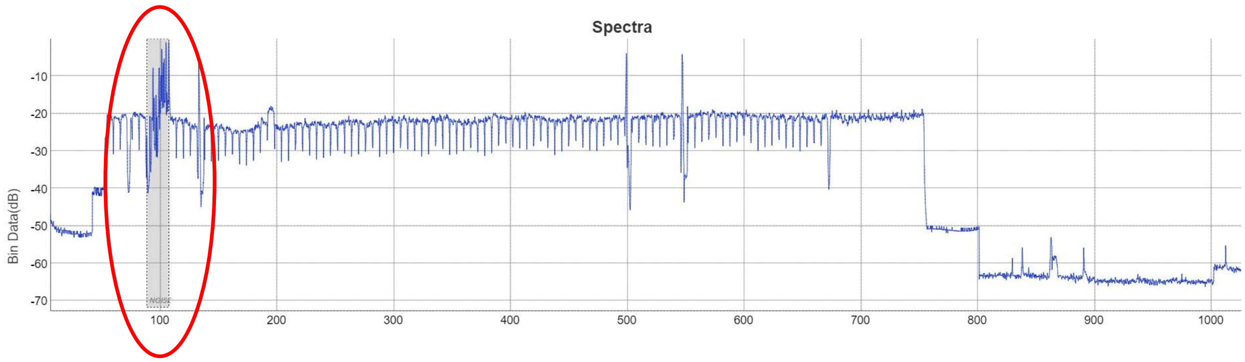



**Figure 15 - FBC Showing Ingress in the FM Band**

## 10. Probability of Intercept: Moving Vehicle Analysis

If upstream test signals used for leakage detection are bursty in nature, a careful examination needs to be conducted to assess how many bursts can be detected by a moving vehicle (in a one second time interval), equipped with a leakage detector. The probability of intercept (POI) is the probability of capturing a transmitted signal based on Tx/Rx timing and should be 100% of the time. With the burst signal approaches, including burst CW or OUDP, the transmit duration and cycle time can be configured such that each CM transmits approximately 2x per second. The real time FFT within the leakage detector is continuously on, so with certainty (timing-wise), signal detection will occur if the amplitude of the signal at the detector is greater than the sensitivity of the detector. See Figure 16.

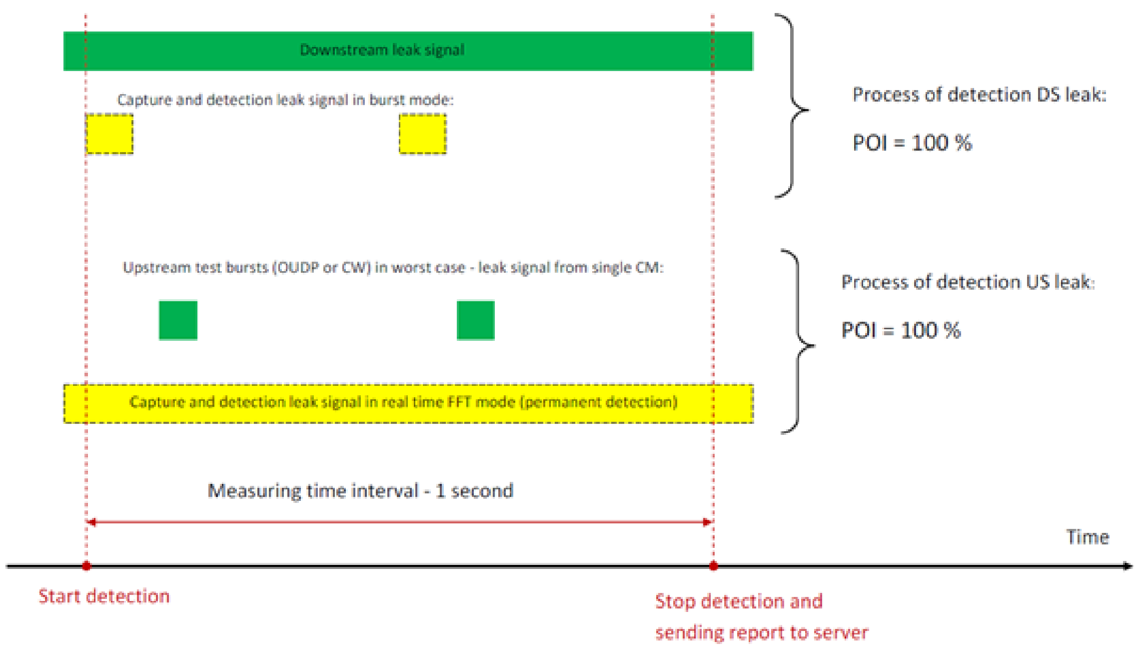
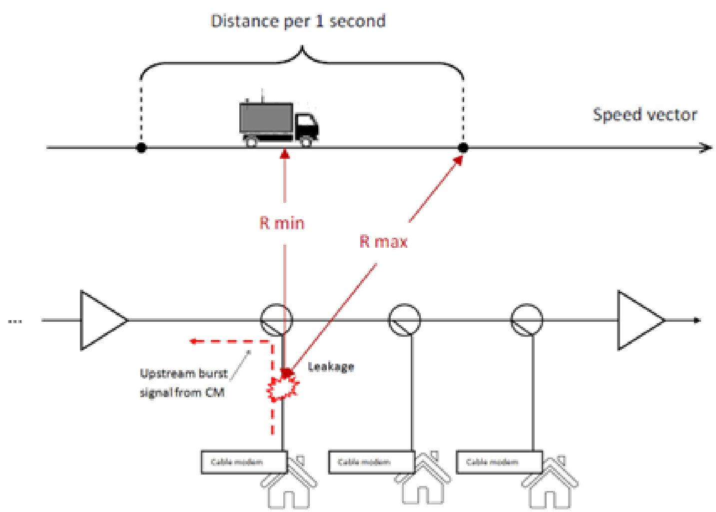



**Figure 16 - Probability of Intercept (POI), Detection of DS and US leaks from moving vehicle**

Figure 17 show the results of a model that was built to compare the ratio of the minimum to maximum distance a vehicle could have travelled before receiving a burst signal. The ratio allows an estimate of the change of a leaking signal's level, at a vehicular Rx point, during the 1 second measuring session. The maximum ratio of 1.78 applies to a max speed of 60 mph and a minimum distance (Rmin) of 30 feet. Definitely not a realistic scenario, but even in this case, the field strength variation will not be so big. For a typical scenario, of a vehicular speed of 30 mph and an Rmin of 60 ft, the ratio will be only 1.07. It means the same as changing 1.07 in µV/m or 0.58 dB in dBmV/m, a trivial difference.




| Speed, mph | Distance, ft | Ratio Rmax / Rmin , % | | | | |
|---|---|---|---|---|---|---|
| | | Rmin = 30 ft | Rmin = 40 ft | Rmin = 60 ft | Rmin = 80 ft | Rmin = 100 ft |
| 20 | 29.3 | 1.11. | 1.07 | 1.03 | 1.02 | 1.01 |
| 30 | 44.0 | 1.24 | 1.14 | 1.07 | 1.04 | 1.02 |
| 40 | 58.8 | 1.40 | 1.24 | 1.11 | 1.07 | 1.04 |
| 50 | 73.3 | 1.58 | 1.36 | 1.17 | 1.10 | 1.07 |
| 60 | 88.0 | 1.78 | 1.49 | 1.24 | 1.14 | 1.09 |

**Figure 17 - Distance covered in 1 second versus vehicle speed and ratio of the minimum distance to the maximum distance a vehicle could have travelled**

Using real time signal processing for upstream leakage detection allows the MSO to provide a 100% probability of burst leak capture (POI). The variation of leak level(s) at the moving vehicle will be within one dB and therefore can be ignored. With high-split cable modems following a gradual rollout, the total time needed to have all cable modems in a service group (SG) to burst leakage detection signals is lowered, allowing the 1.6 MHz BW used for the OUDP burst to transmit upstream data part of the time, as illustrated in Figure 18 - Leakage Detection OUDP Test Bursts and Data Transmission for a SG below. This technique of maximizing the use of the spectrum for data, while also ensuring the reliability of leakage compliance, helps meet the goals of moving to the 204 MHz split for both capacity and 1 Gbps upstream performance. This scheduling capability can be easily facilitated with the virtual CMTS (vCMTS) architecture; other CMTS architectures can provide similar capabilities.

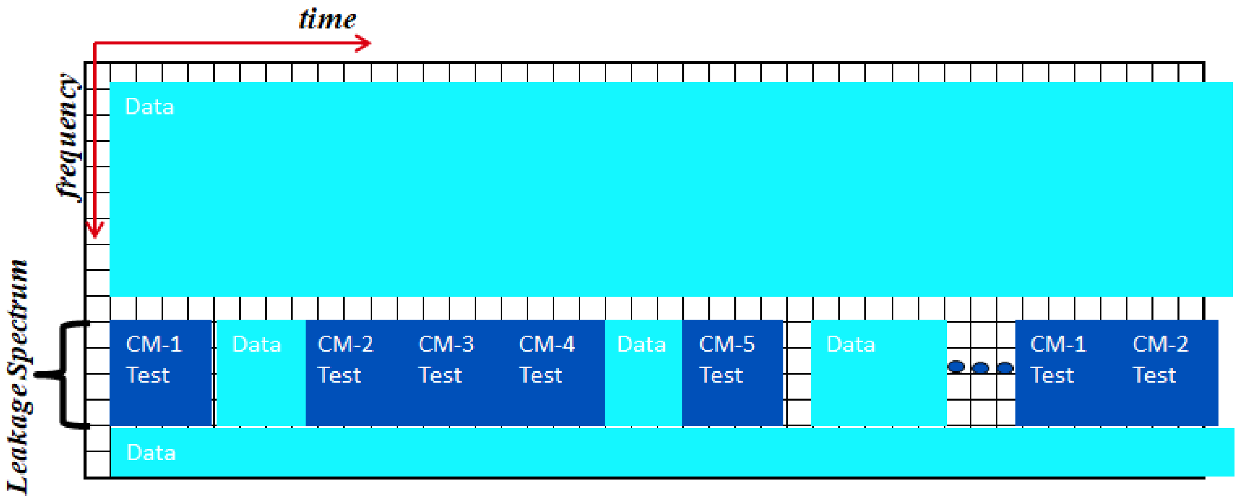



**Figure 18 - Leakage Detection OUDP Test Bursts and Data Transmission for a SG**

# 11. Digital Leakage Detection Test Results

Testing was performed on the various methods described within this paper to validate the concepts and determine minimum sensitivities for each.

## 11.1. CW Time-Division Multiple Access (TDMA)

To prove out the proof of concept for CW TDMA leakage detection, the test setup in Figure 19 was utilized. A DOCSIS generator supplied the OFDMA channel, and to create the exclusion zone within which the CW Burst carriers were placed. The test signal was directly connected to the leakage detector.

The CW test burst in the time and frequency domain are shown in Figure 20 below.

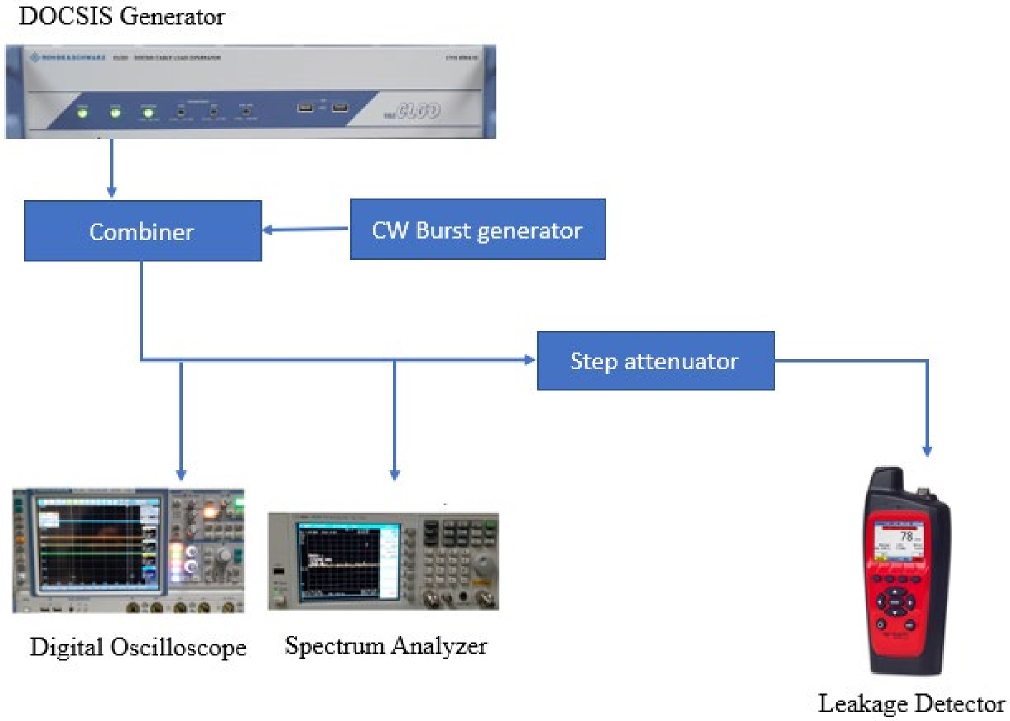



**Figure 19 - CW Leakage Detection Test Setup**

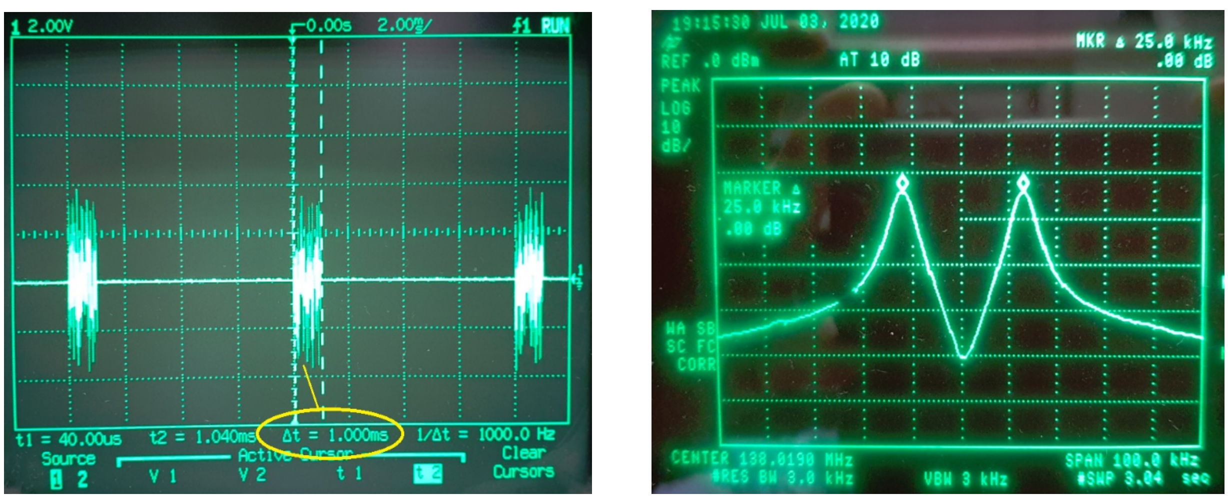



**Figure 20 - CW test burst in time domain and spectrum of CW bursts**

The test setup occupied a 4-subcarrier exclusion zone within the OFDMA, for an exclusion bandwidth of 100 kHz. The spectrum of the CW carriers within this exclusion bandwidth is shown in Figure 21.


**Figure 21 - Spectrum of CW test bursts within exclusion BW of OFDMA signal**

The FFT detection results and the corresponding leakage detection display results are shown in Figure 22. Boosting gain was K=+10dBc. In the top image, the detection result was 104µV/m. The CW carrier spacing is 25kHz. The signals were attenuated to a detected level of 10µV/m, and further attenuated to 1µV/m, which is just above the detection noise floor.

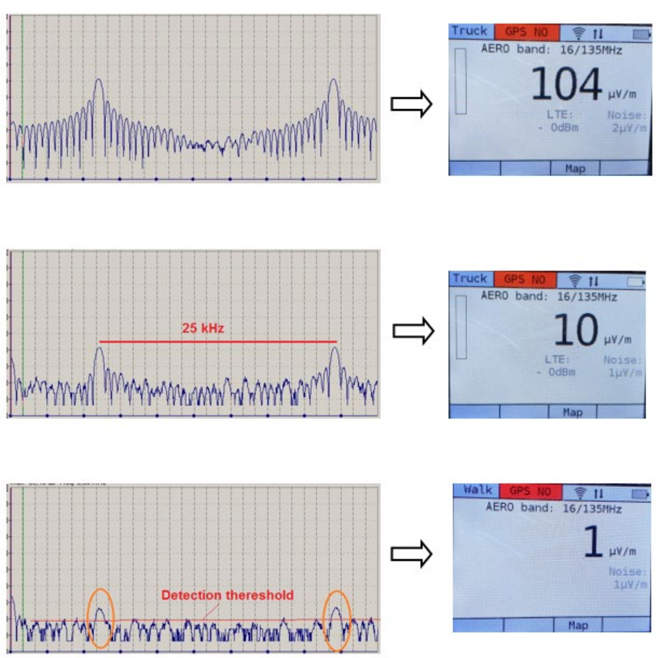



**Figure 22 - FFT spectrums and results of leak detection for boosting gain K=+10 dBc**

The measured sensitivity detection of OFDMA leakage in the aeronautical band is approximately 1 to 2 µV/m in ideal lab conditions, using a conductive test with a boosting gain +10 dBc. Increasing sensitivity during radiated tests in the presence of strong ambient noise could be provided, with extra boosting of the CW test signal if required.  The sensitivity of this approach is sufficient for FCC mandated leakage compliance.

## 11.2. CW Frequency-Division Multiple Access (FDMA)

To prove out the proof of concept for CW FDMA leakage detection, the test setup in Figure 23 was utilized.  A DOCSIS generator provided the OFDMA channel and to create the exclusion zone within which the CW tones were placed. The test signal was directly connected to the leakage detector.

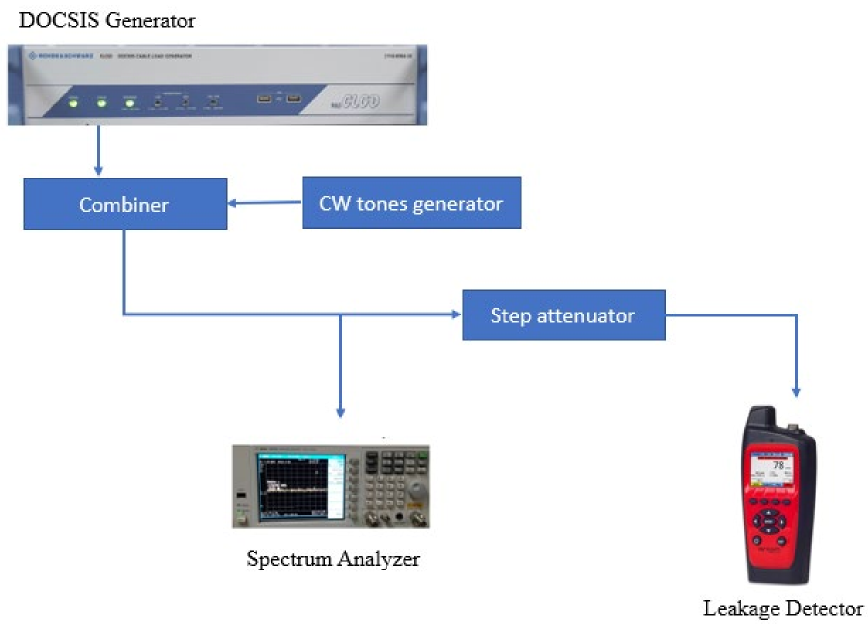



**Figure 23 - Continuous CW leakage Detection Test Setup**

The spectral response of the groups of tones within the OFDMA excluded bandwidth are shown in Figure 24.  The left image displays both groups of CW tones, and the right image focuses on just one group containing 100Hz offsets from each other.

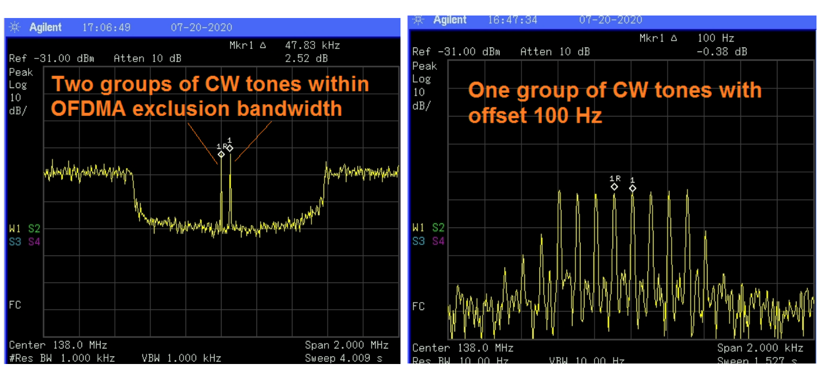



**Figure 24 - The Spectrum of Groups of CW tones within OFDMA exclusion BW**

An example of how the detector was configured is shown in Figure 25, importantly showing that with proper configuration, the detector is able to detect all the different tones simultaneously, with no change in detector setting required.  An example of the detection test result of the minimum detected signal level is shown below.

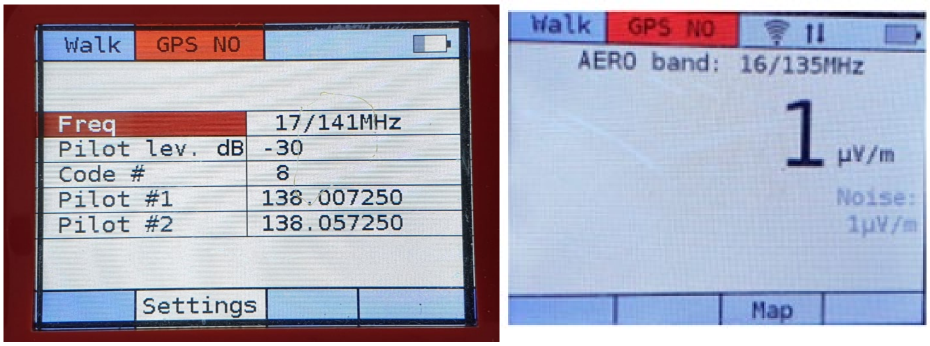



**Figure 25 - Leakage Detector settings for detection of CW tones and minimum detected signal**

Sensitivity of detection OFDMA leakage in the aeronautical band is approximately 1…2mV/m and can be provided by selection of an exclusion bandwidth of 800 kHz, which is a reasonable capacity loss while still meeting the goals of the high split. In this case, the CW tones level will be approximately 6 to 8 dB below the level of OFDMA subcarrier, or approximately - 30 dBc below energy of OFDMA signal in BW = 6 MHz. It's a very similar scenario of the status quo detection of pilots between QAMs in the downstream, with well-known results.

## 11.3. OUDP Burst Test Signal

To prove out the proof of concept of the OUDP Burst Test Signal detector, a method was needed to simulate the OUDP burst.  Again, a DOCSIS generator supplied the test signal, which, after an attenuator, was directly connected to the leakage detector.   The test setup is shown in Figure 26.

The test pattern supplied by the DOCSIS generator is shown in Figure 27.

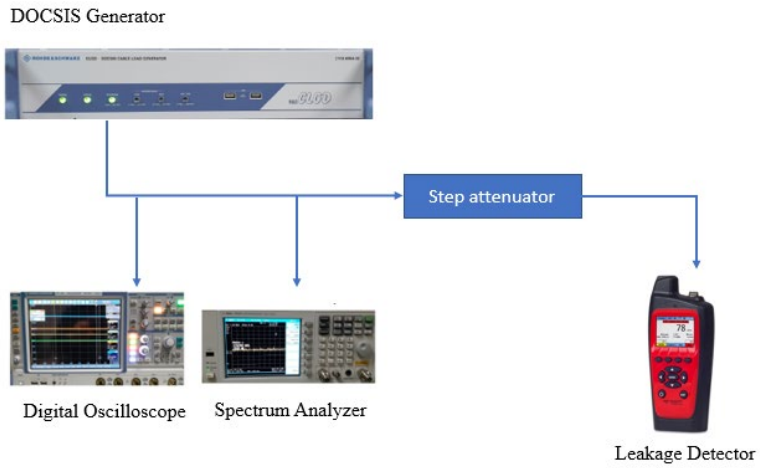



**Figure 26 - Test bench block diagram**

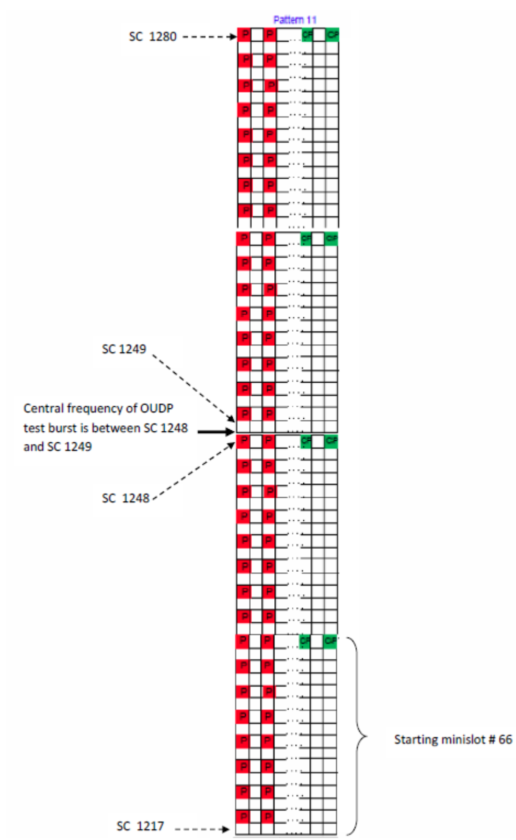
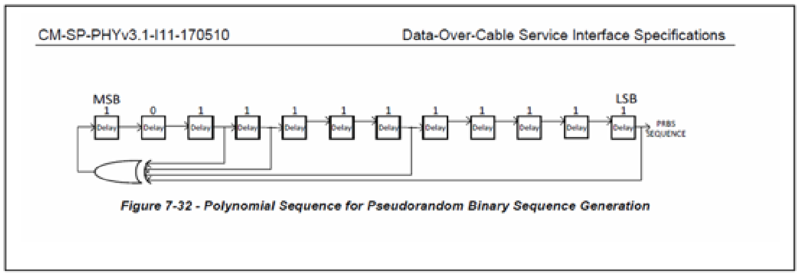



**Figure 27 - Pattern of the OUDP test burst in time – frequency domain**

The modulation of the OUDP test burst is shown in Figure 28.



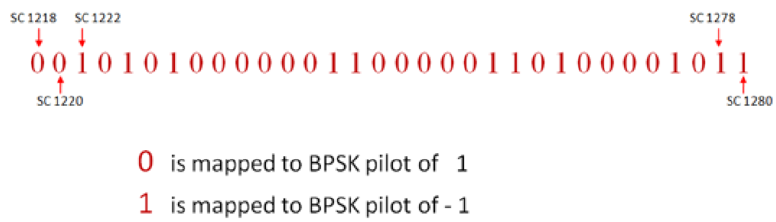




**Figure 28 - Pilot's BPSK modulation in OUDP test burst in Figure 27 [1]**

shows how the OUDP burst signal appears in the frequency domain, including central frequency, minislots, and subcarriers.

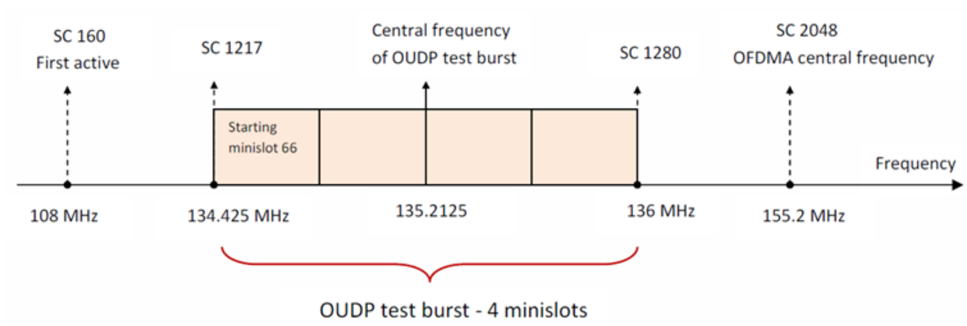



**Figure 29 - Allocation of OUDP test burst in frequency domain of aeronautical band**

Figure 30 - Arbitrary waveform generation settings at DLCG for simulation OUDP test burst shows the settings that were used in the configuration of the DOCSIS generator to simulate the OUDP burst signal.

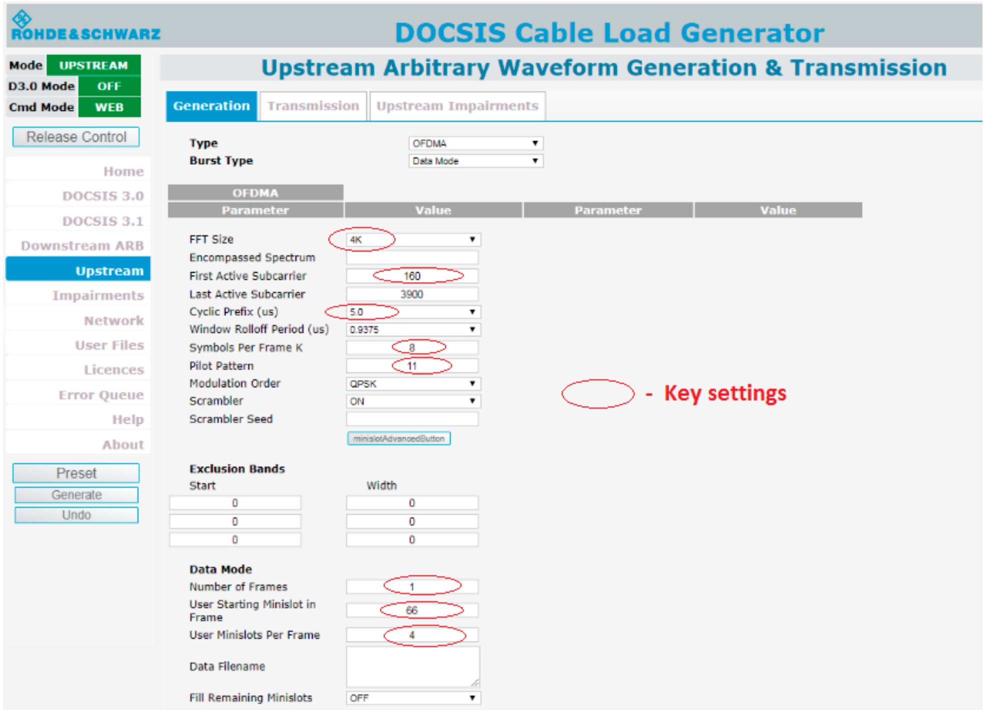



**Figure 30 - Arbitrary waveform generation settings at DLCG for simulation OUDP test burst**

The configuration of the RF transmission of the DOCSIS generator was performed as in Figure 31 - Arbitrary waveform transmission settings at DCLG for simulation OUDP test burst.

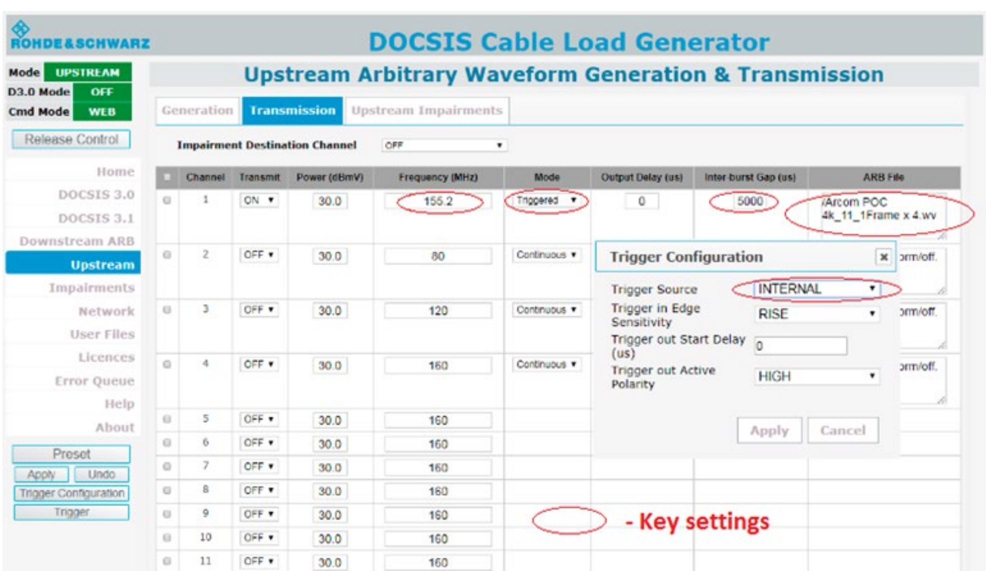



**Figure 31 - Arbitrary waveform transmission settings at DCLG for simulation OUDP test burst**

The simulated OUDP burst signal in the time and frequency domain is shown Figure 32 .

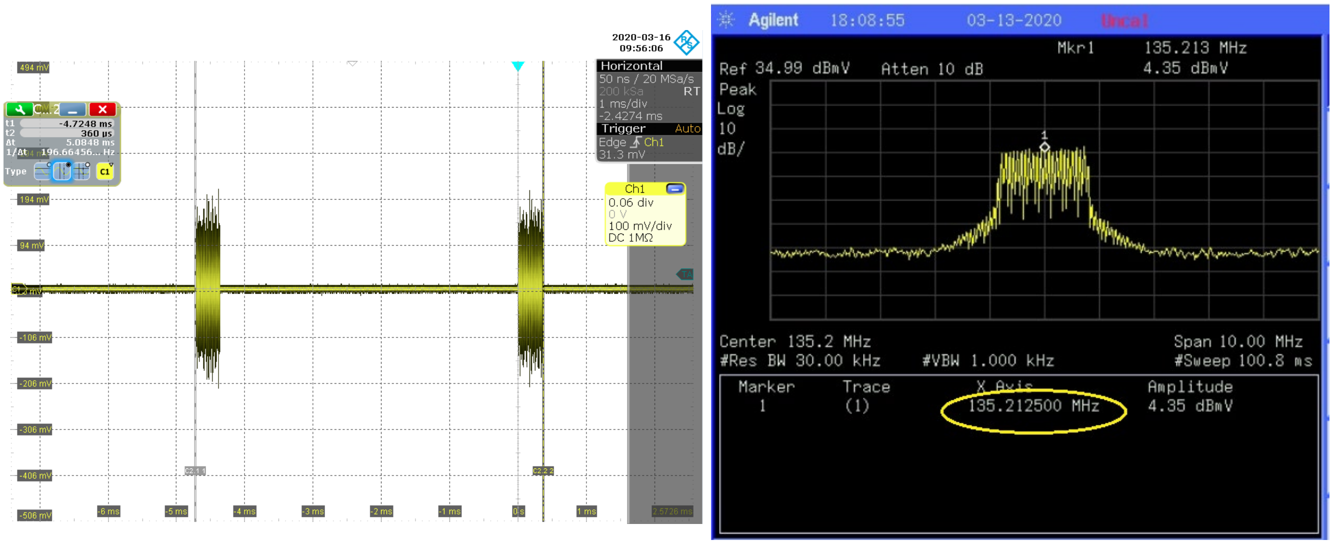



**Figure 32 - OUDP test burst in time and frequency**

The response of the matched filter in the time domain is shown below. The peak of the cross-correlation function represents the detected leak magnitude. The envelope of the OUDP burst signal is also visible.

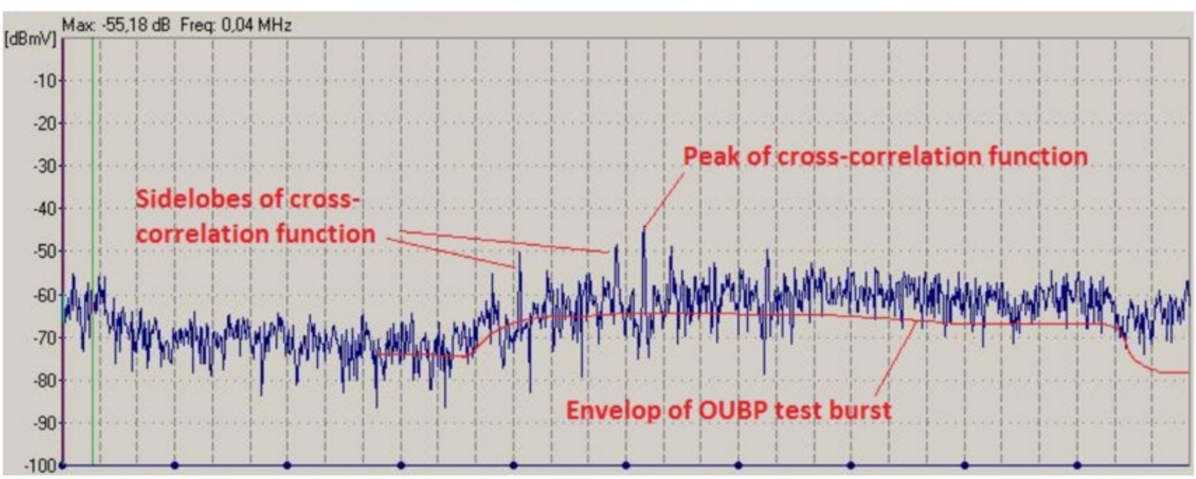



**Figure 33 - Response of matched filter for OUDP test burst with pilot pattern 11.**

In Figure 34 , the minimal detected leak level (sensitivity) for 4 minislots, with one frame in the conducted test, was 4µV/m as shown on the left. In order to investigate improved sensitivity, the test setup was re-run using 4 minislots and eight frames. Sensitivity was improved to 1µV/m, as shown on the right.

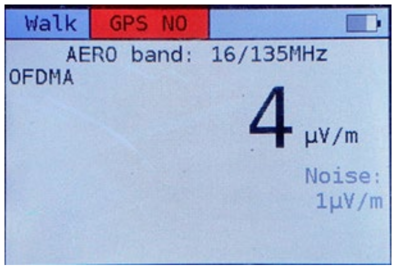




**Figure 34 - Results of implementation of UUDP burst detector into field meter**

This approach, of matched filtering detection of the OUDP pilot pattern 11, is sufficient to meet FCC requirements. The estimated sensitivity detection of the OUDP test bursts burst is approximately 4 µV/m for 4 minislots (BW = 1.6 MHz) with one frame, and approximately 1 µV/m for 4 minislots (BW = 1.6 MHz) with 8 frames. Therefore, operators will have an opportunity to select the optimal BW of OUDP test bursts for leak detection, depending upon desired sensitivity.

## 12. Conclusions

As cable systems evolve and the need for more bandwidth continues, high split systems are now needed; FDX systems that will be used in the near future and are presently being developed.

Current leakage methods are well established, and the need to build off these legacy techniques, while evolving to support new technologies and spectral designations is both necessary and required by federal regulations.

These new systems, and the inverted signal levels that high split systems create, pose unique challenges to leakage measurements and FCC compliance that have not been considered in the 60+ years of cable and broadband evolution. As discussed in this paper, there are several options to move forward with leakage measurements. In addition, operators need to evaluate FCC requirements based on signal type and transmission level in the aeronautical band.

The initial stance to detect leakage in a high split system is typically to continue to use and measure leakage tones in the downstream direction. A leak is a leak, right? However, the differences in signal levels from leakage tones in the downstream, vs actual upstream signals generated at the cable modem, are difficult to correlate. Complex GPS and system mapping algorithms are needed. Acceptance by the FCC for using calculated leakage values and not measuring in the aeronautical band will be difficult. All of the other proposed methods have shown, from a detection sensitivity perspective, to be sufficient for FCC compliance purposes.

Using CW tones -- either continuous or burst generated in the cable modems -- seems like the next logical solution. Cable modems are not designed to create CW tones, and they are designed specifically not to continuously transmit signals in the upstream band. If implementing one of the CW approaches is desired, certainly the logistics required for the CM software updates would be formidable, and the cost of doing so would need to be analyzed. If the CW-TDMA approach is implemented, additional complexity involving CMTS capabilities would be required, in the form of controlled CM burst timing.

If the CW-FDMA approach is of interest, there exists the additional complication of tracking frequency designations for each CM in a node – a challenging task, made more so by the common practice of node splitting. One additional benefit of the CW-FDMA approach is that even if only the Tx frequency of one CM in a node is known, it is possible to precisely measure the frequency of the two detected CW leakage tones, and therefore exactly resolve which CM supplied the detected leak. This could result in multiple operational benefits.

In a High Split system, it is advantageous to use OFDMA blocks for as much of the spectrum as possible, for maximum upstream throughput. Measuring the OFDMA signal from normal traffic would be the ideal solution, but this is not feasible. DOCSIS 3.1 provides for an OUDP test burst to be generated, and this is the ideal signal to use for leakage measurements. It is configurable in both frequency and duration and can be set to the same transmit level as the cable modem. It provides the tools necessary to manage both the capacity and the leakage compliance, with flexibility for the operator. The pilot pattern can be chosen and configured such that the sensitivity of this signal at the detector is equivalent to the CW approaches currently used in the downstream.

Table 6 shows a summary of the solutions evaluated in this paper. Take note that the OUDP approach is already supported by both the CM firmware and DOCSIS specifications. This approach is also supported in FDX, and the frequency of the OUDP test burst can be configured higher in frequency as the upstream band is extended in FDX and other topologies.

**Table 5 - Summary of Leakage Detection Methods**

| | Leak Detection Method | | | |
|---|---|---|---|---|
| | OUDP | CW-TDMA | CW-FDMA | DS Pilot |
| Detected signal level correlated with actual aeronautical band signal level | yes | yes | yes | no |
| Detection sensitivity sufficient for FCC compliance | yes | yes | yes | yes |
| Realizable within current DOCSIS specification | yes | no | no | no |
| Realizable with current firmware in all High Split cable modems | yes | no | no | yes |
| Requires permanent orchestration from the CMTS | yes | yes | no | no |
| Requires some dedicated US Bandwidth | yes | yes | yes | no |

With the High Split leakage options evaluated in this paper, operators can derive a roadmap for continued leakage monitoring that not only allows for continued regulatory compliance, but also consistent plant monitoring and maintenance for optimal system performance.

# Abbreviations

| | |
|---|---|
| AF | antenna factor |
| AP | access point |
| bps | bits per second |
| BW | bandwidth |
| CATV | community antenna television |
| CFR | code of federal regulations |
| CLI | cumulative leakage index |

| | |
|---|---|
| CM | cable modem |
| CMTS | cable modem termination system |
| COVID | corona virus disease |
| CPE | customer Premises equipment |
| CW | continuous wave |
| DAA | distributed access architecture |
| dBc | decibel from Carrier |
| dBmV | decibel Millivolt |
| DOCSIS | data over cable service interface specification |
| DSG | DOCSIS set-top gateway |
| DS | downstream |
| ESD | extended spectrum DOCSIS |
| FCC | Federal Communications Commission |
| FEC | forward error correction |
| FDC | forward data carrier |
| GPS | global positioning system |
| HFC | hybrid fiber-coax |
| f | frequency |
| FBC | full band capture |
| FDX | full duplex DOCSIS |
| FFT | fast fourier transform |
| FM | frequency modulation |
| Gbps | gigabit per second |
| HD | high definition |
| Hz | hertz |
| IOT | internet of things |
| ISBE | International Society of Broadband Experts |
| K | maximum number of cable modems on a node |
| K | symbols per frame |
| K (dBc) | boosting gain of CW test signal |
| KHz | kilohertz |
| L | relative level of CW tone signal |
| m | meter |
| M | number of excluded sub carriers |
| M | number of subcarriers in 6 MHz |
| MAC-PHY | media access control channel physical layer |
| Mbps | Megabit per second |
| MHz | megahertz |
| mS | millisecond |
| MSO | multiple system operator |
| MVPD | multichannel video programming distributor |
| N (dBc) | coefficient of recalculation level of OFDMA signal in BW= 6 MHz to the measured level of CW test signal. |
| NCTA | National Cable Television Association |
| OOB | out of Band |
| OFDM | orthogonal frequency division multiplexing |
| OFDMA | orthogonal frequency division multiple access |
| OTT | over-the-top |

| | |
|---|---|
| OUDP | OFDMA upstream data profile |
| POI | probability of intercept |
| QAM | quadrature amplitude modulation |
| RF | radio frequency |
| RPD | remote physical device |
| R-PHY | remote physical layer |
| RX | receive |
| SC-QAM | single carrier quadrature amplitude modulation |
| SCTE | Society of Cable Telecommunications Engineers |
| $S_{cw\_tone}$ | sensitivity of CW tone receiver |
| $S_{OFDMA}$ | sensitivity of OFDMA leak detector |
| $S_{test}$ | sensitivity of CW test receiver |
| STB | set-top box |
| $S_{CW}$ | sensitivity detection of CW burst |
| $S_{cw\_tone}$ | sensitivity detection of CW tone |
| SG | service group |
| STD | standard |
| TCP | total composite power |
| TDMA | time division multiple access |
| uV/m | microvolt per meter |
| uS | microsecond |
| US | upstream |
| Wi-Fi | wireless fidelity |

# Bibliography & References

1) [PHYv3_1] Physical Layer Specification, CM-SP-PHYv3.1-I17-190917, September 09, 2019, Cable Television Laboratories, Inc

2) In signal processing, a matched filter is obtained by correlating a known delayed signal, or *template*, with an unknown signal to detect the presence of the template in the unknown signal.

3) *Another Look at Signal Leakage, The Need to Monitor at Low and High Frequencies*; Ron Hranac, Greg Tresness, SCTE EXPO '12

4) Code of Federal Regulations, Title 47, Part 76 MULTICHANNEL VIDEO AND CABLE TELEVISION SERVICE

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