Leakage Detection In Full Duplex DOCSIS

Identification and Measurement of Leakage Levels in a Multigigabit Symmetrical Full Duplex DOCSIS Network

A Technical Paper prepared for SCTE/ISBE by

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1. Introduction

Operators of cable networks are very familiar with the mandated requirements for monitoring signal leakage. In standard and mid-split deployments, leaks are discovered using a variety of techniques such as direct Quadrature Amplitude Modulation (QAM) measurement, direct detection of Orthogonal Frequency-Division Multiplexing (OFDM) signal components, and detection of Continuous Wave (CW) signals generated at the headend or Node Remote PHY Device (RPD) in the downstream direction. In high split deployments, leaks in the aeronautical band are discovered by monitoring the upstream for a specific test burst generated by the cable modem under control of the Cable Modem Termination System (CMTS.)

With the introduction of Full Duplex DOCSIS (FDX), some of the status quo practices for leakage detection will need to be changed due to the inherent differences between the traditional network and FDX which pushes the upstream (US) frequency up to 684 MHz. This paper explores several subjects related to detection and measurement of leakage in the FDX network. We will discuss how this will now necessitate leakage detection methods in both the downstream (DS) and US direction simultaneously in the aeronautical band, and we will discuss the potential benefit to perform additional Long-Term Evolution (LTE) band frequency measurements for upstream leakage when using full bandwidth FDX implementations.

We will additionally share lab test results demonstrating concurrent upstream and downstream leakage detection and we will propose a new test methodology for use in a controlled environment which will allow meter sensitivity testing for the new simultaneous upstream and downstream leakage detection.

Capabilities of Full Duplex DOCSIS

Full Duplex DOCSIS is targeted at significantly increasing upstream capacity by using coaxial spectrum for synchronized upstream and downstream communications by means of full duplex techniques. As part of the industry "10G" initiative, the primary objective of DOCSIS 4.0 FDX is to enable multi-Gigabit symmetric data services over the Hybrid Fiber Coax (HFC) network, while also adding significant new upstream bandwidth for continued capacity growth. The DOCSIS 4.0 FDX specification in conjunction with FDX Node and Amplifier specifications are intended to provide the requirements that enable DOCSIS 4.0 Full Duplex performance over "Node+x" HFC architectures. The overlapping DS and US spectrum, which is the key new physical (PHY) component of FDX, necessitates the need for Echo Cancellation capability in the node and amplifier, as well as other digital processing blocks to manage two-way signal passage, while maintaining platform stability and signal fidelity.

Building on a long history of delivering significant capacity improvements – most recently powered by advances in the implementation of DOCSIS 3.1 -- operators continue to develop and build on customers' future 10G needs leveraging DOCSIS 4.0.

FDX allows blocks of channels, via "Resource Block Assignments," as shown in Figure 1 to be used in both the upstream and downstream direction dynamically, significantly increasing the upstream throughput capability of the HFC network. Figure 2 displays the spectrum grid definition called out in the DOCSIS 4.0 FDX specification along with the overlapping Aeronautical and LTE frequency bands. In addition to managing signal overlap at the physical layer, FDX operation also requires new scheduler techniques that groups users based on their relative isolation characteristics to prevent co-channel interference from one FDX US Transmit (Tx) onto another's FDX DS Receive (Rx). The vCMTS (virtual Cable Modem Termination System) creates "Interference Groups" and "Transmission Groups" to ensure compatible devices are given access to the spectrum when it is shared. Finally, Figure 3 shows that due to cable loss at higher frequencies, the cable modem will now be responsible for providing uptilt in the upstream direction out to 684 MHz to account for cable loss with a nominal tilt of 10 dB that can be adjusted to 8-12 dB (1 dB relaxation for 12 dB tilt).

Sub-Band 1	Sub-Band 2	Sub-Band 3
DS	DS	DS
DS	DS	US
DS	US	DS
US	DS	DS
DS	US	US
US	DS	US
US	US	DS
US	US	US

108 MHz 300 MHz 492 MHz 684 MHz

Figure 1 - FDX Resource Block Assignments ("RBAs")

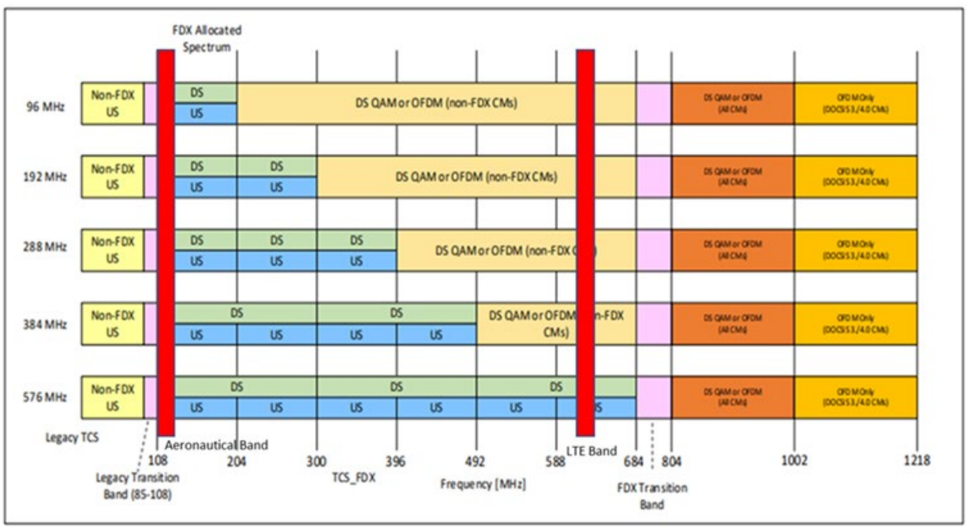

Figure 2 - Configurable FDX Allocated Spectrum Bandwidths with Aeronautical and LTE Bands Shown

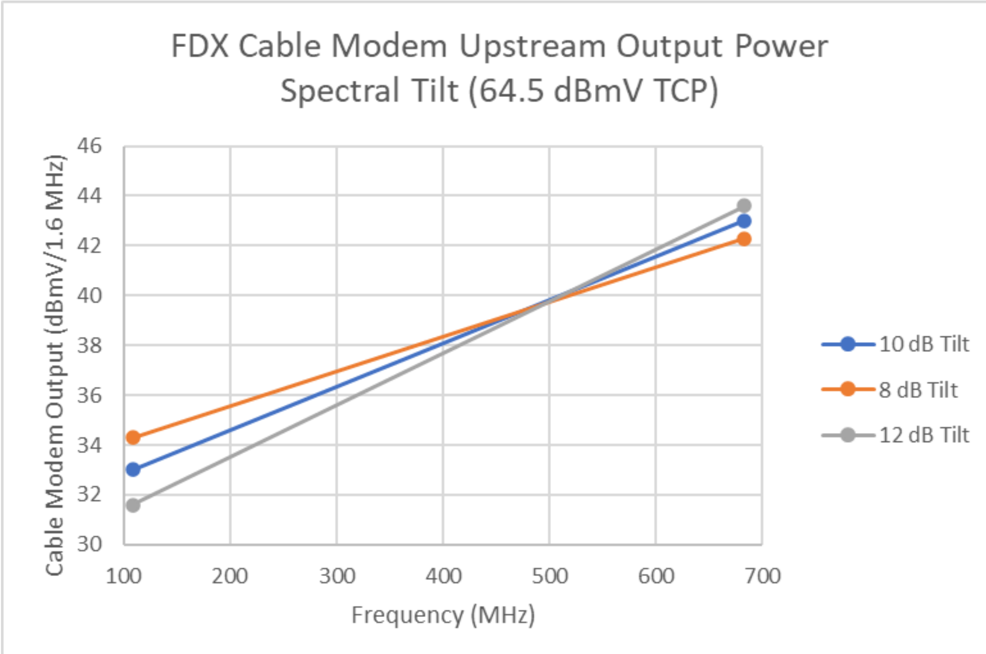

Figure 3 - FDX Cable Modem Upstream Output Power Spectral Tilt (64.5 dBmV TCP)

Differences in leakage detection for Full Duplex DOCSIS (FDX) versus tradition standard/mid/high split systems

In standard and mid split networks, aeronautical band signals are only transmitted in the DS. As such, DS leakage detection is required to comply with mandated leakage regulations. In high split networks, signals transmitted in the aeronautical band are exclusively in the US. As such, for high split US leakage detection where leakage test signals are generated from the cable modem (CM) becomes a necessity.

Figure 4 provides an illustration of the US and DS signal levels in an FDX network at 108 MHz and 684MHz. When looking at the levels the inverted nature of signal levels in the network becomes obvious, where US signal levels are at a maximum in the 'Drop', and DS signal levels are at a maximum in the 'Feed' section of the plant. This makes it such that legacy aeronautical DS leakage detection techniques are insufficient to maintain visibility to US leakage.

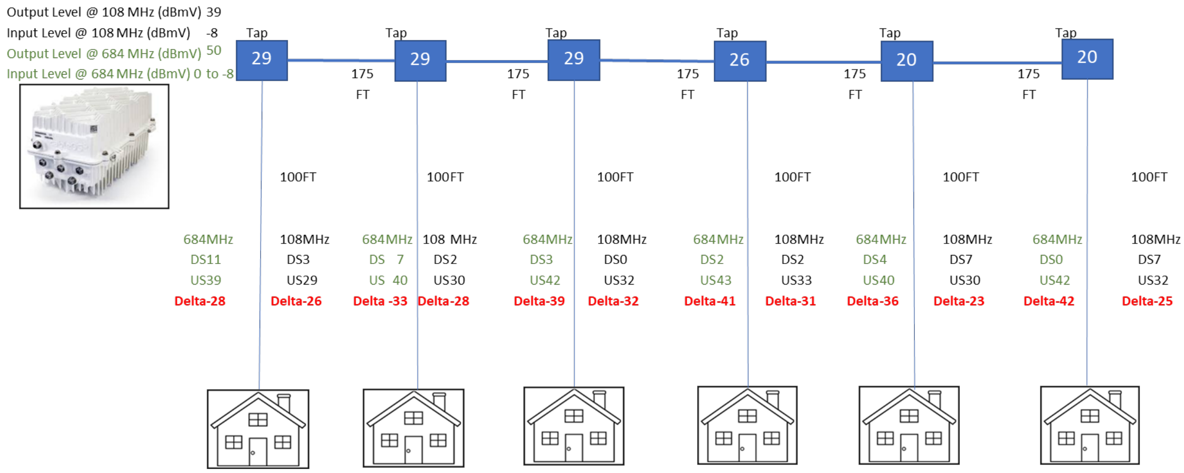

Figure 4 - FDX Network Downstream to Upstream Signal Level Deltas

With FDX, this drives a need for US leakage monitoring in the aeronautical band; in addition to the traditional DS aeronautical band leakage monitoring. This simultaneous monitoring provides full visibility to all aeronautical band network egress. If only DS detection was enabled, there would not be visibility to US leakage. And if only US detection was enabled, there would not be visibility to DS leakage.

2. Leakage detection techniques appropriate for FDX

There are many different techniques currently employed for leakage detection. Many of the techniques are optimized and directly tied to the signal format transmitted at the desired detection frequency. For example, DS detection at frequencies where OFDM signals are present is most easily performed by direct detection of existing signal componts of the OFDM channel. This technique has the benefit of no extra signals being inserted into the network and no corresponding additional headend equipment required. It has an additional benefit that the amplitude of detected signal is significantly higher than alternative inserted low level carrier approaches, so depending upon the vendor implementation, the realized meter sensitivity can be superior to alternative approaches. Figure 5 illustrates the OFDM signal harmonics utilized for DS signal detection in one implementation.

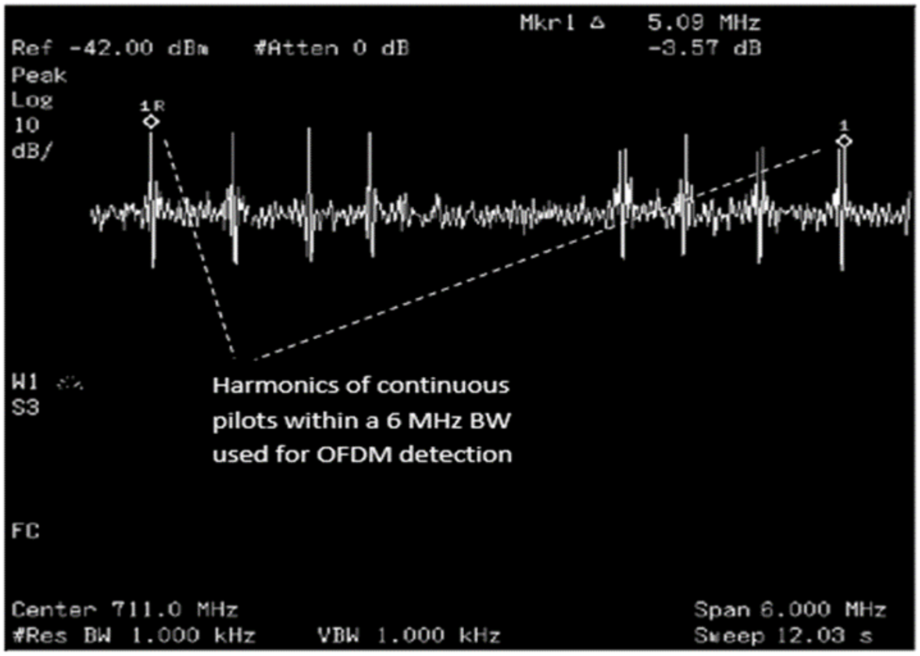

Figure 5 - OFDM harmonics used for DS leakage detection-

The US signal format for FDX is Orthogonal Frequency-Division Multiple Access (OFDMA). The 2020 SCTE paper, Leakage in a high split world describes a methodology where an OFDMA upstream data profile (OUDP) test burst is used for aeronautical band leakage detection. The paper details how this approach provides ample sensitivity for Federal Communications Commission (FCC) compliance. This OUDP approach has now been accepted as a standard as the methodology used for US signal detection. With the OUDP approach, each CM on a node, under control of the CMTS – will sequentially generate an OUDP test burst with known signal characteristics. The leakage detector is then able to lock onto this OUDP test burst and detect signals egressing the coaxial network.

The spectrum of an OUDP burst generated by a CM is shown in Figure 6.

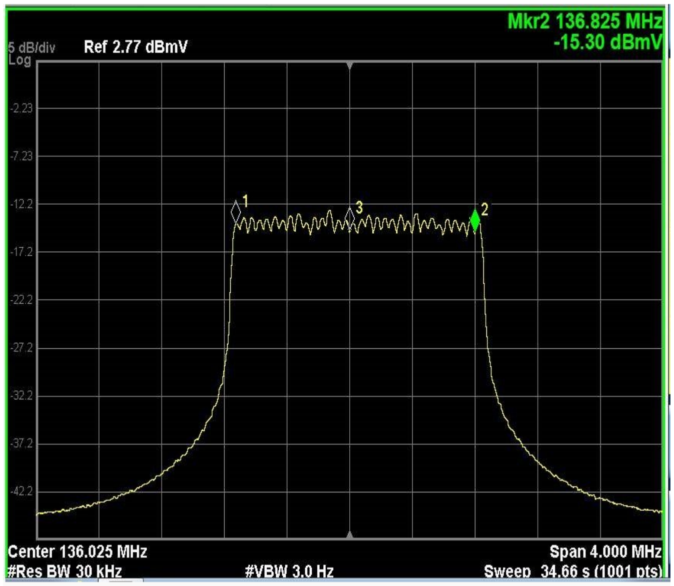

Figure 6 - Spectrum of OUDP burst generated by a CM

With FDX, regardless of the FDX bandwidth, the DS signal format will be exclusively OFDM. Similarly, the US signal format is exclusively OFDMA. As such, for DS leakage detection the direct detection of OFDM signal component techniques should be employed; and for US leakage detection the OUDP technique should be employed.

3. Monitoring of potential FDX LTE egress

As a best practice, in addition to FCC mandated aeronautical band leakage detection, cable operators today regularly monitor downstream LTE frequencies for leakage ingress. Benefits resultant from this effort include hardening of the plant which improves network quality, and it additionally helps to ensure that signals egressing from the plant do not adversely affect the licensed spectrum utilized by mobile operators. Figure 2 shows the spectrum bandwidths configurable for FDX and highlights the overlap with the aeronautical band and a lower LTE band. In the full 576 MHz FDX implementation, there is an FDX bandwidth (BW) overlap with the 600 MHz LTE band which is widely utilized by a mobile operator in the United States. As such, if a network is utilizing the full 576 MHz FDX bandwidth, attention should be paid as to not cause harmful interference to this licensed spectrum.

The 2012 Society of Telecommunications Engineers (SCTE) paper, Another Look at Signal Leakage, explored the lack of correlation between signal leakage in the aeronautical band and signal leakage at 700MHz LTE frequencies. A conclusion of the paper was that monitoring solely at the aeronautical band provides inadequate visibility to signal leakage at or near the LTE band. This was an impetus for the high frequency DS leakage detection performed today. This conclusion holds true with FDX – if utilizing full 576 MHz FDX, the OUDP US detection performed at the aeronautical band will not provide visibility to any US egress in the 600MHz band. Depending upon the detection frequency and upon antenna BW, the DS detection at or near the LTE band should provide adequate coverage of DS egress at the 600 MHz LTE band, but it will not provide visibility to US egress at this band.

What will be required in such a situation in order to effectively monitor US egress is a 2nd OUDP US detection session, performed at some frequency below 684 MHz.

An additional factor which supports the conclusion that aeronautical band US detection does not correlate with egress in the 600MHz band is related to the significant tilt between 108 MHz and 684 MHz. This tilt which is illustrated in Figure 3, will result in any signal leakage at the higher FDX frequencies having correspondingly higher levels as compared to leaks at lower frequencies such as the aeronautical band.

Simulated Full Duplex DOCSIS Leakage Detection Test Results

A signal leakage meter was designed and built for FDX operation, capable of simultaneous US and DS detection. Testing was performed within the CTA channel 16 bandwidth. To verify the concurrent US and DS aeronautical band detection, a test setup was built as shown in Figure 7.

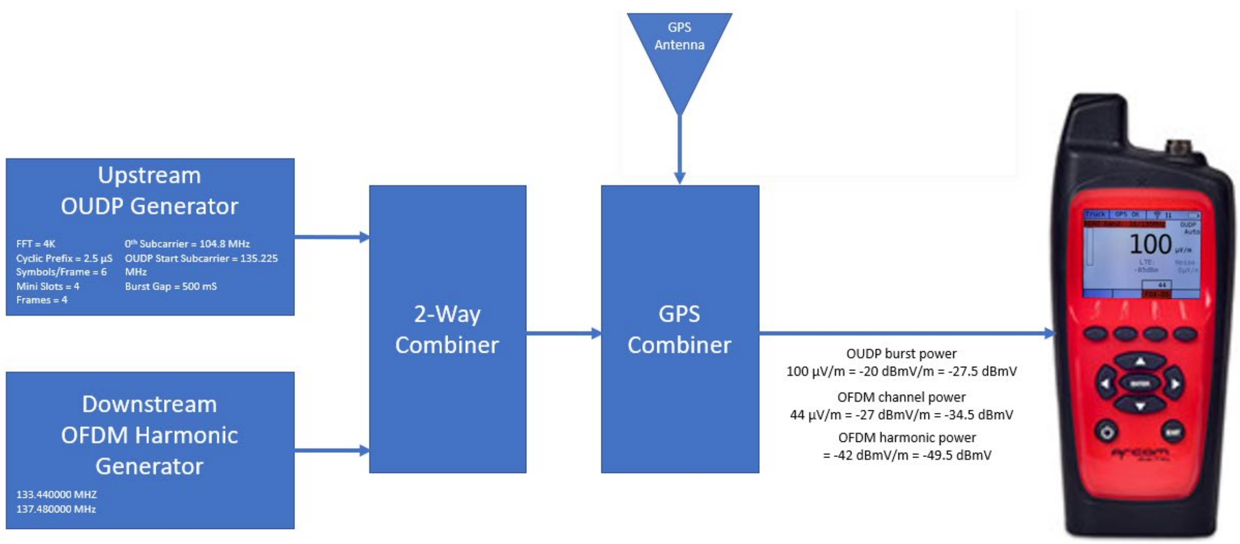

Figure 7 - FDX test setup block diagram

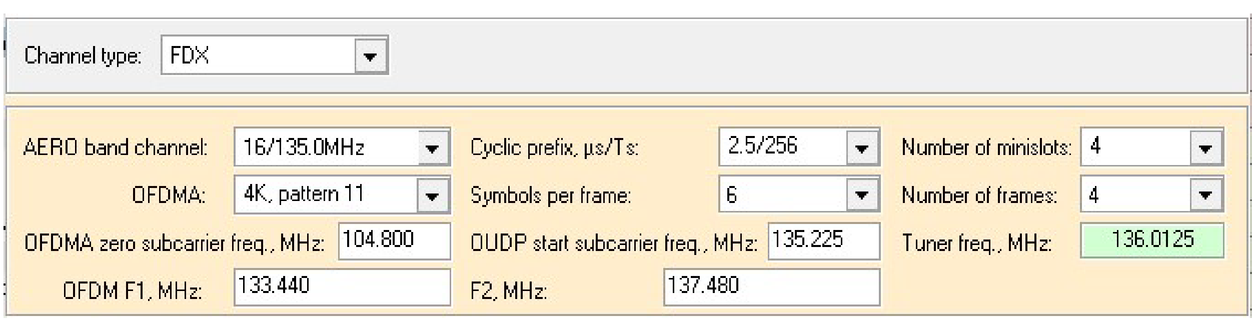

Figure 8 - FDX meter configuration

The detection results are shown on Figure 9, where the meter displays the measured signal level for both US and DS. Here, the US OUDP showed the expected 100 µV/m and the DS OFDM detection showed the expected 44 µV/m, which were the measured signal level input into the meter as illustrated in Figure 7. Two views of the display are provided, each with the prominent US/DS detection location alternated.

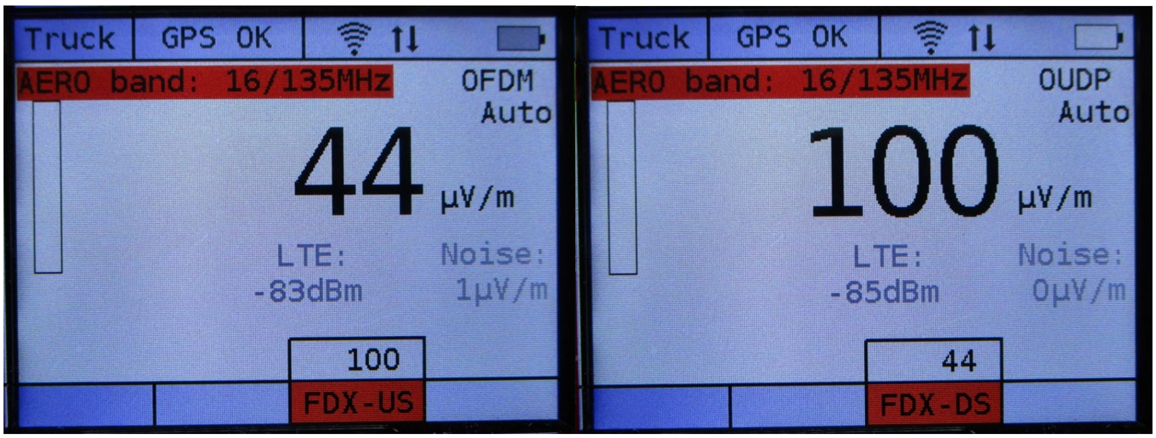

Figure 9 - FDX DS and US detection results

Radiated Three Meter Open Air Sensitivity Testing in an Anechoic Chamber

The test procedures described below can be used for all HFC Standard, Mid and High split leakage meter testing as well as Full Duplex DOCSIS testing. Legacy downstream OFDM and upstream OUDP bursts will be retained as the source signals as defined in previous technical papers and specifications. By simultaneously transmitting an upstream OUDP and downstream OFDM signal, FDX functionality of the leakage detection meter can be evaluated.

1 Source Signal Details

US OUDP Signal Details:

1. Symbols Per Frame (K) = 9
2. Modulation Order = 256 QAM
3. Pilot Pattern = 11
4. Center Frequency of OUDP Signal = 136.0125 MHz, 603 MHz
5. 4 Mini-slots (1.6 MHz Upstream Bandwidth with the 4 adjacent mini-slots to the center frequency above)
6. Number of Frames = 8 and 2.16 mS in transmit time duration. (For 256 House Holds Passed roundtrip time = 563.2 mS)
7. 4K Fast Fourier Transform (FFT) = 40 uS per symbol + Cyclic Prefix
8. Cyclic Prefix = 1.5625 uS
9. Window Roll off Period = 0.9375 uS

DS OFDM Signal Details:

1. Channel 16, 88
2. 135 MHz, 609 MHz
3. Cyclic Prefix = 2.5 uS
4. 4K Fast Fourier Transform (FFT)

2 Baseline Test Setup

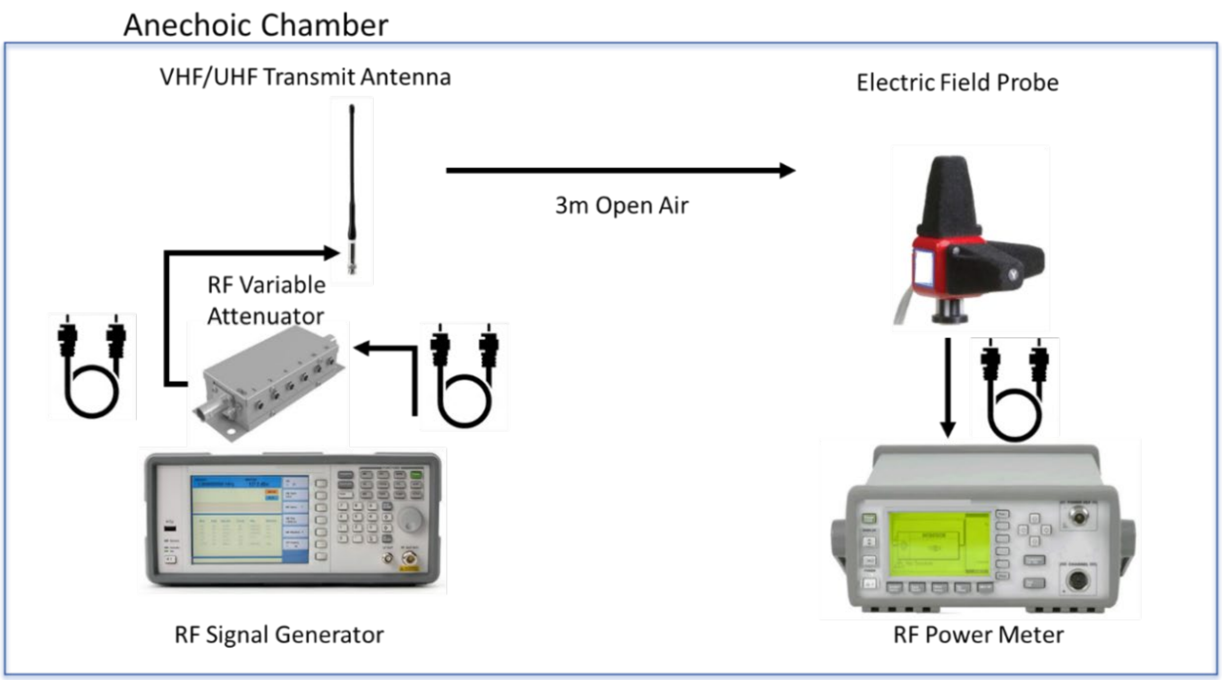

Figure 10 - Baseline Leakage Detection Setup

3 Baseline Test Procedure

1. Set the Radio Frequency (RF) Signal Generator to output a CW carrier at each of the center frequencies given in the “Source Signal Details” section.
2. Connect the RF signal generator, all cables used for the test, and the RF variable attenuator to the power meter. Confirm the RF power level with the RF power meter and account for any cable loss and 0 dB attenuator setting using the Amplitude offset on the power meter.
3. Verify that all of the switches in the RF variable attenuator are within 5% tolerance of their expected values.
4. Connect the RF Signal Generator to the Very High/Ultrahigh Frequency (VHF/UHF) transmit antenna.
5. Measure and verify the distance between the VHF/UHF transmit antenna and Electric Field Strength Probe is 3 meters.

6. Connect the RF Power Meter to the Electric Field Strength Probe and measure the RF level of the CW carrier.
7. Confirm the measured field strength is correct taking into account the gain/antenna factors of the antennas and Free Space Path Loss (FSPL) during calibration.
    a. 3m Free Space Path Loss is ~24.65 dB at 136 MHz
    b. 3m Free Space Path Loss is ~36.68 dB at 609 MHz

4 FDX Leakage Detector Test Setup

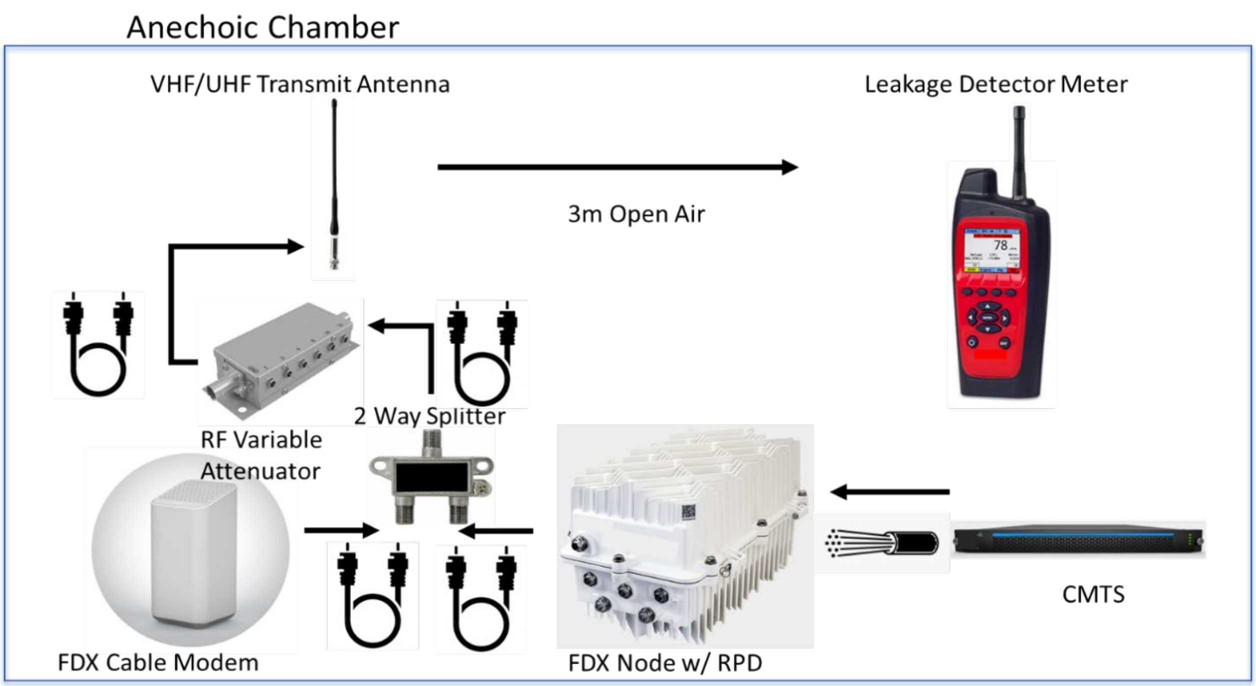

Figure 11 - Leakage Detection Meter Test Setup

5 FDX Leakage Detector Meter Test Procedure

1. Configure the FDX cable modem/gateway to output continuous OUDP signals defined in "US OUDP Signal Details" and the FDX node to output downstream signals defined in sections "DS OFDM Signal Details."
2. Confirm each RF power level with the RF power meter and account for any cable loss and RF variable attenuator insertion loss.
3. Verify that all of the switches in the RF variable attenuator are within 5% tolerance of their expected values.
4. Connect the FDX cable modem and Node to the VHF/UHF transmit antenna through the RF variable attenuator.
5. Measure and verify the distance between the VHF/UHF transmit antenna and leakage detection meter is 3 meters.

6. Make sure the meter is configured properly to the settings given in "Source Signal Details" and measure the RF level of the Aeronautical Band Signals in both the upstream and downstream direction.
7. Make sure the meter is configured properly to the settings given in "Source Signal Details" and measure the RF level of the LTE Band Signals in both the upstream and downstream direction.
8. Add 6 dB of attenuation to change the distance to ~6m. Repeat Steps 6-7.
9. Continue to add attenuation in 6 dB steps doubling the distance each time until you get to ~192m (36 dB total attenuation). Repeat Steps 6-7 each time. Record all Measurements.
10. Configure the FDX cable modem to output an OUDP burst 2 times per second with the parameters given in "US OUDP Signal Details" and repeat steps 6-9.

Note 1: The Device under Test (DUT) should rotate 360 degrees while the antenna raises and lowers in 1 or ½ meter steps up to 3 meters to account for antenna patterns.

Note 2: A more advanced test setup can be created to simulate mobile detection in the anechoic chamber by connecting a function generator to the RF variable attenuator and simulate signal strength increasing to a peak and then decreasing in a real-world scenario where the leakage detector meter's position is changed relative to the source of leakage.

Conclusions

With cable networks advancing, the demand for higher download and upload speeds continues to be met. FDX is a great way of utilizing existing bandwidth in the network transmitting data in both the downstream and upstream directions at the same time. These state-of-the-art FDX networks require leakage detection meters that can detect and record leakage levels simultaneously in the DS and US direction to stay in compliance with FCC regulations, as well as keeping the entire network integrity in good working order. In FDX implementations utilizing the full 576 MHz bandwidth, there is the potential for egress affecting licensed 600MHz LTE – so additional US leakage monitoring using a second high frequency OUDP test session should be considered. Test equipment capable of the concurrent US and DS monitoring was demonstrated. Lastly, with the test procedure given in this paper, operators can reliably assess the sensitivity of FDX and all HFC leakage detection meters in a precise setting allowing for continued leakage monitoring that not only allows for sustained regulatory compliance, but also reliable plant monitoring and maintenance for optimal system performance.

Abbreviations

BW	bandwidth
CATV	community antenna television
CM	cable modem
CMTS	cable modem termination system
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
DS	downstream
DUT	Device under test

FCC	Federal Communications Commission
FEC	forward error correction
GPS	global positioning system
HFC	hybrid fiber-coax
HSD	High Speed Data
f	frequency
FDX	full duplex DOCSIS
FSPL	Free space path loss
Gbps	gigabit per second
Hz	hertz
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
LTE	Long Term Evolution
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
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
OUDP	OFDMA upstream data profile
QAM	quadrature amplitude modulation
RF	radio frequency
RPD	remote physical device
R-PHY	remote physical layer
RX	receive
s	Second/s
SC-QAM	single carrier quadrature amplitude modulation
SCTE	Society of Cable Telecommunications Engineers
STB	set-top box
STD	standard
TCP	total composite power
TDMA	time division multiple access
TX	transmit
UHF	Ultrahigh Frequency
µV/m	microvolt per meter
µs	microsecond
US	upstream
vCMTS	Virtual Cable Modem Termination System
VHF	Very High Frequency

Wi-Fi	wireless fidelity

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