

UHF Signal Leakage and Ingress

Understanding the Challenges

A Technical Paper prepared for the Society of Cable Telecommunications Engineers
By

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Overview

For decades cable operators have managed signal leakage by monitoring in or near the 108-137 MHz very high frequency (VHF) aeronautical band. A relatively new problem has cropped up over the past two years or so: Leakage and ingress in the ultra high frequency (UHF) spectrum encompassing the upper end of the downstream frequency range, especially where it overlaps the 698-806 MHz long term evolution (LTE) band. The impact of UHF leakage and ingress may pose liability and risk to the cable industry. Recent field tests by the authors and others corroborate previous studies that show there is little or no correlation between leakage field strengths at VHF and UHF, and emphasize the need for visibility into what is happening at the higher frequencies.

This paper and its accompanying technical workshop review some of the common mechanisms that cause UHF leakage, help clarify cable operators' responsibility when interfering with other over-the-air service providers, and discuss the difficulties encountered when attempting to measure leaking quadrature amplitude modulation (QAM) signals. This paper and the workshop presentation recommend how to deal with affected LTE and other service providers when leakage-related interference occurs; highlight currently available commercial digital leakage solutions; and provide guidelines on interim "homebrew" UHF leakage detection solutions that can be used until commercial detection and measurement gear are obtained for use at the local system level. Leakage and ingress mitigation techniques along with proposed best practices are included.

Industry experience with UHF signal leakage

The U.S. cable industry has since the 1970s monitored and measured signal leakage in or near the 108-137 MHz aeronautical band. This particular aeronautical band is located in the VHF spectrum.¹ Until recently, there was little concern about leakage outside of the VHF aeronautical band. There are several reasons for this.

First, the existing leakage detection equipment that is used widely by cable operators was designed to operate only in or near the VHF aeronautical band. Second, while FCC Rules specify signal leakage limits over a wide range of frequencies, the emphasis has been on ensuring that leakage in the aeronautical band is controlled. Third, some in the cable industry may have assumed that keeping their plants tight by monitoring for leakage in or near the aeronautical band was sufficient to ensure little or no leakage on most or all downstream frequencies. We now know the latter is definitely not true.

In the last two years or so, cable operators have become aware of signal leakage in the UHF spectrum causing interference to LTE equipment. Going the other direction, signals from LTE equipment have been identified as the source of ingress and direct pickup interference to cable networks and customer premises equipment (CPE).

Verizon Wireless launched the first large-scale LTE service in North America in 2010, and has been aggressively rolling out LTE technology since that time. Other service providers also are rolling out new LTE networks. Several bands are used for LTE, including allocations within the 698-806 MHz spectrum. The latter overlaps part of the downstream frequency range used in many cable networks.

As LTE technology was rolled out, service providers naturally wanted to ensure that interference to their equipment was minimized so that network performance would not be affected. In addition to the usual interference sources (from their own LTE equipment, other LTE providers, defective fluorescent light fixtures, jammers, etc.), LTE field engineers found a new interference culprit: Signal leakage from cable networks.

When LTE field engineers contact local cable system personnel about leakage-related interference, system technicians may accompany the LTE field engineers to the location identified as the likely source. More often than not, existing leakage detection equipment indicates little or no leakage in the VHF aeronautical band, yet the LTE field engineers' test equipment clearly shows leaking cable signals in the 698-806 MHz spectrum.

Cable operators have been increasingly cooperative when contacted by LTE field engineers about UHF leakage that has been identified as a source of interference.² However, cable system technical personnel have in many instances faced challenges when it comes to confirming the presence of UHF leakage with their existing test equipment, however. Recall that existing leakage detectors were not designed to

¹ International Telecommunications Union nomenclature for frequency and wavelength (<http://life.itu.int/radioclub/rr/art02.htm>) subdivides the radio frequency spectrum into nine bands. Band 8 is the VHF band, covering 30-300 MHz, and Band 9 is the UHF band, covering 300-3000 MHz.

² There have been reports of FCC involvement in some cases of leakage-related interference to LTE equipment.

operate in the UHF spectrum, nor were they designed to measure noise-like QAM signals – the most likely signal type carried at higher frequencies in cable networks.

Test equipment manufacturers have introduced, or are introducing digital-compatible leakage detectors that operate in the UHF spectrum. Some of the currently- or soon-to-be-available commercial UHF leakage detection equipment is discussed later. Also discussed are “home-brew” solutions that may work in the short-term to allow cable operators to at least confirm the existence of UHF leakage and the effectiveness of a repair until commercially-manufactured products are obtained.

The bottom line is that most cable operators have limited experience detecting and measuring UHF leakage. This will remain the case until commercial leakage detection equipment is more widely available at the local system level. It is very important to understand the risks that exist when UHF leakage, ingress, and direct pickup interference occur. These risks also are discussed later.

FCC leakage rules

Part 76 of the FCC Rules defines maximum allowable field strengths caused by signal leakage. Specifically, §76.605(a)(12) spells out maximum leakage field strength limits versus frequency.

(12) As an exception to the general provision requiring measurements to be made at subscriber terminals, and without regard to the type of signals carried by the cable television system, signal leakage from a cable television system shall be measured in accordance with the procedures outlined in § 76.609(h) and shall be limited as follows:

Frequencies	Signal leakage limit (micro-volt/meter)	Distance in meters (m)
Less than and including 54 MHz, and over 216 MHz	15	30
Over 54 up to and including 216 MHz	20	3

The signal leakage limit applicable to the UHF spectrum is 15 $\mu\text{V}/\text{m}$ measured 30 meters from the plant. The 30 meters value can be correlated to a free-space field strength value at 3 meters using the following formula.

$$E_{\mu\text{V}/\text{m}} \text{ at 3 meters} = E_{\mu\text{V}/\text{m}} \text{ at 30 meters} * (30/3)$$

where $E_{\mu\text{V}/\text{m}}$ is field strength in microvolts per meter.

Converting the 30 meters field strength limit of 15 $\mu\text{V}/\text{m}$ to an equivalent field strength limit at 3 meters gives 150 $\mu\text{V}/\text{m}$. If a cable network just meets this limit (or has even lower levels of leakage) in, say, the LTE band, does that mean the cable network meets the requirements in the FCC Rules? Not necessarily.

Part 76 also includes a harmful interference clause (§76.613), which says, in effect, if leakage of any field strength causes harmful interference, the leakage must be fixed regardless of its actual field strength. The following is from §76.613.

§ 76.613 Interference from a multichannel video programming distributor (MVPD).

(a) Harmful interference is any emission, radiation or induction which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs or repeatedly interrupts a radiocommunication service operating in accordance with this chapter.

(b) An MVPD that causes harmful interference shall promptly take appropriate measures to eliminate the harmful interference.

(c) If harmful interference to radio communications involving the safety of life and protection of property cannot be promptly eliminated by the application of suitable techniques, operation of the offending MVPD or appropriate elements thereof shall immediately be suspended upon notification by the District Director and/or Resident Agent of the Commission's local field office, and shall not be resumed until the interference has been eliminated to the satisfaction of the District Director and/or Resident Agent. When authorized by the District Director and/or Resident Agent, short test operations may be made during the period of suspended operation to check the efficacy of remedial measures.

(d) The MVPD may be required by the District Director and/or Resident Agent to prepare and submit a report regarding the cause(s) of the interference, corrective measures planned or taken, and the efficacy of the remedial measures.

What is in the affected RF spectrum?

The concept of frequency reuse allows cable operators to carry signals on frequencies inside of their networks that may be used for something entirely different in the over-the-air environment. In some cases over-the-air VHF TV signals are or have been carried on-channel in cable networks (VHF TV channels use the same frequencies for over-the-air and cable applications), but more often than not, the signals on most frequencies inside of a cable network have no relationship to signals in the same part of the spectrum in the over-the-air environment.

In the U.S., the over-the-air UHF TV broadcast band covers the frequency range 470-698 MHz, comprising channels 14-51. Over-the-air UHF TV channels do not line up with cable channels as is the case in the VHF band – there is a 2 MHz overlap. This is shown in the following figure.

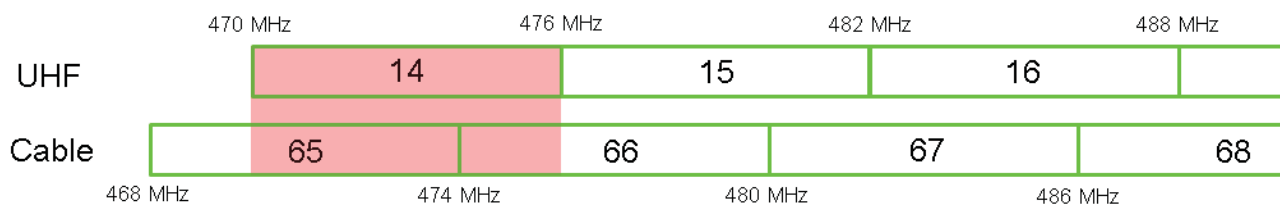


Figure 1. Non-alignment of over-the-air UHF TV and cable channels

LTE and public safety communications can be found in the 698-806 MHz range, and 800 MHz trunked two-way radio systems and some cellular services operate in the 806-902 MHz range. The following figure shows an example of over-the-air signals in the 500-806 MHz spectrum as measured with a Rohde & Schwarz PR100. Several UHF 8-VSB (eight-level vestigial sideband) signals and one analog TV signal can be seen in the first roughly two-thirds of the spectrum, along with LTE and public safety signals in the right one-third of the spectrum. Some leaking QAM signals are visible in the upper end of the UHF TV band and lower end of the LTE spectrum.

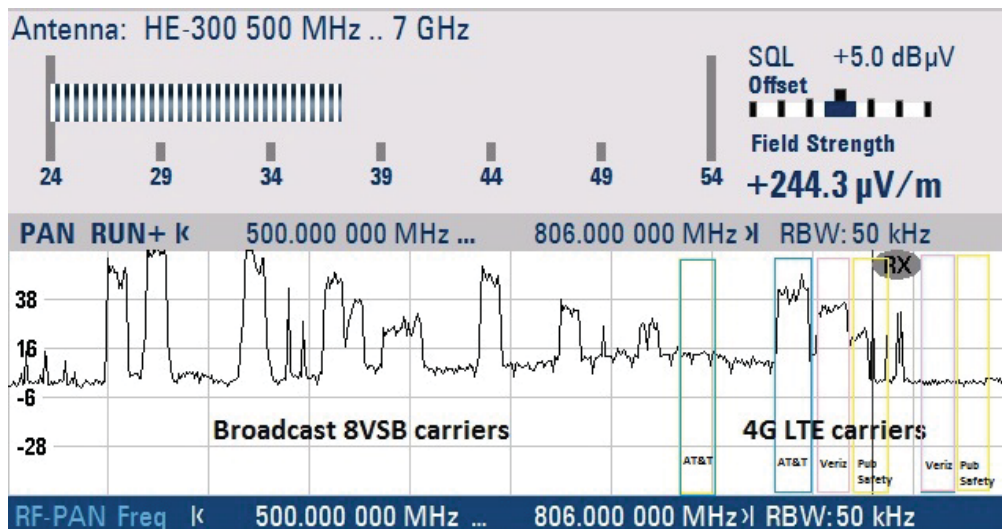


Figure 2. Over-the-air signals in the 500-806 MHz spectrum

UHF leakage

The mechanisms that cause UHF leakage are the same as those that cause VHF leakage. Anywhere the shielding effectiveness of the hardline plant and subscriber drop portions of the network is compromised, leakage is a possibility. The **Outside plant and subscriber drop** section of this paper includes a discussion about some of the mechanisms that cause UHF ingress. Those same mechanisms also cause UHF leakage.

Impact of leakage on over-the-air users of higher frequencies

Signal leakage in general can affect any over-the-air services operating on the same frequencies used by cable networks. Looking at just the higher frequencies, UHF leakage in the 470-698 MHz range may affect antenna-based TV reception and some non-TV services that exist within that part of the spectrum; leakage in the 698-806 MHz range may affect LTE tower sites (uplink) and LTE user equipment or UE (downlink), as well as public safety communications. And so on. The impact of signal leakage on over-the-air users may, depending on the ratio of the desired signal to the leakage and other

factors, vary from no noticeable impact at all to mild or moderate degradation, to complete disruption.

Licensed over-the-air users expect to be able to operate without interference degrading or disrupting their respective services. If leakage-related harmful interference occurs, the cable operator **MUST** fix the problem regardless of the leakage field strength, as stated in §76.613: “An MVPD that causes harmful interference shall promptly take appropriate measures to eliminate the harmful interference.” In harmful interference cases involving “safety of life and protection of property,” the FCC has the authority to require a cable operator to shut down the offending signals until the problem has been resolved! This is clearly a risk to cable operators.

UHF ingress

Ingress is the opposite of signal leakage. Ingress occurs when over-the-air signals “leak” into the cable network through a shielding defect. Ingress may happen anywhere the cable network’s shielding effectiveness has degraded, such as loose, improperly installed, or damaged connectors; cracked shielding; rodent chews; and so forth. It is important to understand that there is also little or no correlation between leakage field strengths and ingress levels. To understand why, consider the following example.

Assume a loose connector causes signal leakage, and the field strength produced by the leak is 20 $\mu\text{V}/\text{m}$ when measured 3 meters from the connector. As discussed later in the paper, a free-space 20 $\mu\text{V}/\text{m}$ field strength 3 meters from a leak requires a “transmit” source power (assume the loose connector is behaving like an isotropic antenna) of just $1.20 * 10^{-10}$ watt.

Now imagine that a Citizen’s Band (CB) antenna is located 50 feet from the leak on the other side of the pole, and that the CBER is transmitting with the legal limit of 4 watts into a half-wave dipole antenna, losing only 1 dB of power in the coax feedline. On a free-space basis, the field strength produced at the cable network’s loose connector by the CB signal will be 829,054 $\mu\text{V}/\text{m}$.³ The amount of RF power coupled into the coax from the nearby CB transmitter will depend on several variables, but will be substantial, certainly far more than the $1.20 * 10^{-10}$ watt radiated by the loose connector. (Note: If the cable network’s loose connector were replaced by a 27 MHz resonant half-wave dipole, the signal level at the dipole terminals produced by a field strength of 829,054 $\mu\text{V}/\text{m}$ would be +63.3 dBmV. The latter equals 28.55 mW, or $2.855 * 10^{-2}$ W.)

Cable operators have dealt with ingress for decades. Ingress in the upstream spectrum (5-42 MHz in North America) arguably is the most common, but downstream ingress from VHF TV signals, FM broadcast radio in the 88-108 MHz band, 2-meter (144-148 MHz) ham radio signals, 150 MHz pagers and two-way radios, and so on, also have been problematic. Some of the more common sources of UHF ingress have

³ The math for this example is included in a column by coauthor Hranac. See “Just How Strong Is That Ingress,” June 2011 *Communications Technology*;
<http://www.cable360.net/ct/sections/columns/broadband/46498.html>

included 450 MHz two-way radio and pager signals, UHF broadcast TV signals – both analog and digital – and more recently, 698-806 MHz LTE signals.

Ingress generally occurs when an external signal is coupled onto the outer surface of the coaxial cable's shielding,⁴ creating a common mode current. That common mode current propagates along the outer surface of the cable's shield and its support strand. If the common mode current reaches a shielding defect, some of the common mode current may be coupled into the inside of the coax, creating a differential mode current that now propagates along with the desired signals and potentially interferes with those signals.

“Digital” ingress versus “analog” ingress

It is not unusual to differentiate analog ingress from digital ingress – for example, interference from an over-the-air analog TV signal versus interference from an over-the-air digital TV signal. Technically speaking, both are analog signals, but their effects on cable signals are quite different.

An over-the-air digital TV signal is noise-like, and ingress interference from a digital TV signal to a cable network's analog TV or QAM signals is similar to degrading the carrier-to-noise ratio. The pictures of an affected analog TV signal will appear snowy as the amplitude of the ingressing digital TV signal increases. A QAM signal will suffer degraded modulation error ratio (MER), and if the digital ingress is severe enough may cause, in increasing order of severity, bit errors that are correctable, uncorrectable codeword errors, and eventually packet loss. For data signals, the impact may be retransmissions, while for digital video some errors can be successfully hidden by video decoder error masking. The most severe packet errors will ultimately degrade perceived video quality to the user. The point is that while ingress of over-the-air TV or LTE signals into the plant may not be strong enough to produce subscriber complaints, it may indeed be causing network performance degradation as seen by metrics such as the number of uncorrectable code word errors. The latter may be able to be used to detect potential ingress before subscribers notice the impact.

Ingress interference from an over-the-air analog signal, depending on the type of signal, may produce lines (think co-channel beats and similar interference) in the picture of an analog TV signal, ghosting, or other picture impairments. A QAM signal can suffer the same potential degradations as mentioned in the previous paragraph.

If the affected QAM signal is carrying video content, the picture and sound quality will remain unaffected by ingress interference from analog or digital signals until the so-called “digital cliff” is reached, at which point tiling and blocking often start to become visible to the subscriber. Another half dB or so increase in the amplitude of the interference, and the picture may freeze, or disappear altogether.

One factor to keep in mind: In the VHF TV spectrum, cable channels and over-the-air channels occupy the same frequencies. In the UHF spectrum, cable channels

⁴ The outer surface of the coax shield may behave like a long-wire antenna, and pick up the interfering over-the-air signal in that manner. The interfering signal also may be coupled to the coax shield's outer surface via a conduction mechanism, such as code-required neutral bonds at the subscriber premises and/or utility poles.

and over-the-air channel slots overlap by 2 MHz, such that one interfering UHF TV signals can affect two adjacent cable signals.

Two-way radio, pager and similar narrowband ingressors can fall anywhere within an affected cable channel slot.

Ingress interference from LTE is a bit trickier. The interfering LTE signal, which is digital and thus noise-like, can be up to 10 MHz wide. For instance, Verizon's downlink signal from tower-to-user equipment occupies 746-756 MHz. This overlaps cable channels 116 and 117.

Outside plant and subscriber drop

The hardline plant and subscriber drop portions of the network are both susceptible to UHF ingress interference. Anywhere shielding effectiveness is compromised, ingress interference is a possibility.

Damage to the hardline plant from rodent chews, tree limb abrasion, corrosion, fallen power lines, bullet holes, radial cracks, and so on degrades shielding performance, as does poor craftsmanship. Some cable operators have found loose hardline connectors beneath heat shrink tubing, suggesting the connectors were not adequately tightened when the system was originally built or rebuilt, perhaps years before. Warped amplifier housing lids (often caused by improper tightening), loose passive device faceplates, and similar gremlins create potential UHF ingress points.

RF levels are lower in the subscriber drop than in the hardline distribution plant, so a nearby transmitter may cause more ingress interference in the drop than in the hardline plant, largely because the carrier-to-interference ratio may be worse in the drop (the opposite also is true, of course). Loose, improperly installed, or damaged/corroded F connectors remain common subscriber drop ingress points, as well as sources of leakage.

The drop, especially the in-home portion, is typically out of control of the cable company. For instance, subscribers disconnect and connect cabling when furniture is rearranged, or when new TVs and other CPE are installed. A common problem is the use of poorly shielded retail-store cables and components. And even if the subscriber doesn't touch the drop, cable company and contractor craftsmanship issues may contribute to shielding problems.

Some homes and buildings may be wired with old copper-braid drop, which generally has poor shielding compared to modern bonded foil-braid designs.

Multiple dwelling units (MDUs) are often susceptible to ingress, because of poor craftsmanship, older cabling and components, loop-through versus home-run cabling, and tampering or theft of service by residents.

Some cable operators have abandoned frequencies affected by strong ingress. At best this can be considered a short-term solution, because it simply is not practical to continue abandoning valuable RF spectrum whenever ingress is problematic. Eventually the plant will have to be fixed, so that ingress and leakage are brought under control.

Impact on technician troubleshooting efforts

Troubleshooting UHF ingress can be challenging, to say the least. When UHF ingress is suspected, a common response is to search for VHF aeronautical band leakage using existing leakage detection equipment. The assumption is that where signals are leaking out, ingress is getting in. Unfortunately, the presence of VHF leakage does not necessarily mean that UHF ingress (or leakage) is occurring at that same point. In many instances UHF leakage may exist when there is little or no VHF leakage. Likewise, VHF ingress may enter the plant through some shielding defects, UHF ingress may enter through others, and both may enter via yet others.

If system personnel have access to UHF leakage detection equipment, locations with UHF leakage *might* be where some of the ingress is entering the plant, but even that isn't assured. In pedestals and cabinets with numerous connectors, adapters, actives and passives, it may be difficult to isolate the shielding defect. A near-field probe – which is available from some leakage detector manufacturers (see Figure 3 for



Figure 3. Home-made near-field probe

an example of a home-made near-field probe) – in conjunction with suitable test equipment such as a spectrum analyzer, interference receiver, etc., can often be used to identify to within a couple inches or less the specific location where UHF leakage is occurring, which might also be a UHF ingress point.

Further complicating the troubleshooting efforts, UHF ingress may be hidden beneath QAM signals occupying the same spectrum. It is generally not acceptable to temporarily turn off downstream signals to see if the suspect ingress is present, with the possible exception of doing that kind of service-disruptive work in a maintenance window.

One option when troubleshooting ingress is to use test equipment that displays the noise floor beneath an affected QAM signal. Some manufacturers have equipment with this feature available, variously called QAM Ingress (JDSU), i-QAM (Sunrise Telecom/VeEx), and QAM Error Vector Spectrum (Trilithic).

A tried-and-true troubleshooting approach is the divide-and-conquer technique to locate the ingress point, using one of the previous methods. Alternatively, it may be possible to use a QAM analyzer to find out where in the plant a given QAM signal's bit

error ratio (BER) or similarly the uncorrected code word error ratio, MER, and possibly also the constellation have been degraded by the ingress, and where the QAM signal is unimpaired.

Technicians must pay particular attention to ensure that over-the-air signals do not inadvertently enter their test equipment setups when troubleshooting problems or performing routine maintenance. Ingress can occur via a poorly shielded test jumper or a loose F connector on an amplifier test probe. This sort of scenario will lead troubleshooting efforts astray, and these false alarm situations may cause valuable time to be wasted.

Depending on the proximity of an active device to an LTE, broadcast, or other transmitter, over-the-air signals can cause ingress interference when an active device's lid is open. Degraded carrier-to-noise ratio (CNR), MER, and BER could occur on a handful of downstream signals with frequencies that overlap over-the-air signals. Many subscribers downstream may be affected, especially if the fiber node or first amplifier is the one with the open lid. One best practice is to keep the housings closed and secured, and use an external test point even if it must be created using a permanent tap installation.

Direct pickup interference

Direct pickup interference is similar to ingress, except that the interference enters a susceptible set-top, cable modem, TV set, or other device *directly*, often without any cables or other external devices physically connected. If the susceptible device's outer case or cover is inadequately shielded, then the internal wiring, printed circuit board traces, and/or components may directly receive interfering over-the-air signals. In some CPE, for instance, ventilation holes and case or cover seams may have physical dimensions and/or shapes that allow them to behave like UHF slot antennas. Sometimes affected devices have poor common mode rejection, and may be susceptible to common mode currents traveling on the outer surface of cabling (coax, power, video and audio, etc.) connected to the device. Any one of these, or a combination, may contribute to a device being affected by direct pickup interference.

Symptoms and impact on CPE performance

Many cable operators have in the past several years experienced direct pickup interference to digital set-tops from non-LTE cell phones sitting near or on top of the CPE. The interference manifested itself as tiling, blocking, or complete loss of picture and sound on digital video signals – sometimes on-channel, and sometimes on all channels, the latter in the case of fundamental overload of the CPE by the interference.

Direct pickup interference by LTE UE causes the same symptoms.

Cable modems experiencing direct pickup interference may suffer mild to severe correctable and uncorrectable codeword errors, packet loss and degraded data throughput. Embedded multimedia terminal adapters (eMTAs) may have voice quality problems and dropped calls.

Older CPE often are more susceptible to direct pickup interference, largely because when those early products were designed and manufactured there was no

concern about UHF direct pickup interference from mobile devices. Newer CPE are designed to meet more stringent shielding requirements, and typically are less susceptible to direct pickup interference.

Calculated field strength created by LTE UE

The maximum LTE UE transmit power is +23 dBm (199.53 mW), with a ± 2 dB tolerance, and the minimum is -40 dBm (0.0001 mW). Typical values for UE antenna gain range from about -1 dBi to -3.5 dBi. The following example shows what the calculated field strength might be 1 meter away from an LTE UE if that device were transmitting at the maximum +23 dBm power output (the ± 2 dB tolerance could mean that some UEs transmit as high as +25 dBm at maximum output, but the +23 dBm value is used in this example). The transmit frequency range for a Verizon LTE handset is 777-787 MHz, so the middle of that range (782 MHz) is used for the calculation.

Free space path loss is calculated with the formula

$$Loss_{dB} = 20\log(f_{MHz}) + 20\log(d_{km}) + 32.45$$

where

f_{MHz} is the frequency in megahertz, and d_{km} is the path length in kilometers (1 meter = 0.001 km).

The free space path loss over a 1 meter distance at 782 MHz is 30.31 dB.

Assume a resonant half-wave dipole antenna at the point where field strength 1 meter away from the LTE UE is being measured. The received signal power at the receive dipole's terminals is:

Transmit power (dBm) – transmit feedline loss (dB) + transmit antenna gain (dBi) – free space path loss (dB) + receive antenna gain (dBi)

Further assume a worst-case scenario in which a transmit antenna with -1 dBi gain is connected *directly* to the transmitter's power amplifier stage – no feedline loss, no filter insertion loss. Also assume that there is no additional attenuation to the LTE UE's transmitted signal caused by someone holding the device. Plugging in some numbers gives

23 dBm – 0 dB + (-1 dBi) – 30.31 dB + 2.15 dBi = -6.16 dBm at the dipole's terminals.

Converting the received power in dBm to dBmV is done by adding 48.75 to the dBm value: -6.16 dBm + 48.75 = +42.59 dBmV. This assumes the receive dipole's impedance is 75 ohms, which is close to a half-wave dipole's free-space impedance value of approximately 73 ohms. Next, convert dBmV to field strength in $\mu\text{V}/\text{m}$ using the formula:

$$E_{\mu V/m} = 21 * f * 10^{(dBmV/20)}$$

where $E_{\mu V/m}$ is field strength in microvolts per meter, f is frequency in MHz, and $dBmV$ is the signal level in decibel millivolts at a dipole antenna's terminals produced by a given field strength.

$$21 * (782 \text{ MHz}) * 10^{(42.59 \text{ dBmV}/20)} = 2,212,718 \text{ } \mu\text{V/m}$$

From this, the maximum field strength 1 meter away that could be produced by an LTE UE operating at maximum transmit power is approximately 2.2 million microvolts per meter, or ~2.2 volts per meter (V/m). Doubling the distance to 2 meters will still result in a calculated field strength of around 1.1 V/m.

CPE shielding effectiveness

What kind of shielding effectiveness is necessary in CPE to reduce the likelihood of direct pickup interference? If the CPE is located 1 meter away from an LTE UE transmitting at +23 dBm, the field strength is likely going to be fairly close to the previously calculated 2.2 V/m. The latter suggests minimum CPE shielding effectiveness should at least be somewhat greater than 2.2 V/m. To provide headroom for the ± 2 dB tolerance in the LTE UE's transmit power, which could create a field strength as high as about 2.8 V/m 1 meter away,⁵ the shielding effectiveness should be sufficient to withstand at least 3 V/m.

Of course, using CPE with suitable shielding effectiveness is for naught if the interconnecting cables, connectors, and other components connected to the CPE have worse shielding effectiveness than the CPE.

Other direct pickup problems

Some cable operators have experienced direct pickup interference to certain headend or hub site equipment. The source of the interference was from collocated LTE towers. The tower-to-UE downlink signal produced sufficient field strength inside the adjacent headend or hub site building, resulting in direct pickup interference.

The usual ingress troubleshooting techniques failed to resolve the direct pickup interference problems: replacing questionable connectors and cabling, tightening loose connectors, installing terminators on unused ports, ensuring proper grounding/bonding, and so forth. Even with no input/output cables connected to the affected equipment, the interference persisted. The resolution involved modification or replacement of the affected equipment by the manufacturer.

⁵ An LTE UE transmitting at +25 dBm will produce a calculated free-space field strength of 2,782,441.54 $\mu\text{V/m}$ (2.78 V/m) 1 meter away using the assumptions in the previous example.

UHF leakage mechanisms

The mechanisms that cause UHF leakage are the same as the ones that cause VHF leakage. UHF leakage tends to be more common in the hardline plant, in large part because signal levels there are greater than they are in the subscriber drop. Tilted active device outputs elevate the upper end of the downstream spectrum relative to lower frequencies. But both the hardline plant and drop can be the source of UHF leakage. As mentioned previously, some of the typical causes of UHF leakage are loose connectors and adapters, radial shield cracks, loose passive device faceplates, damaged or missing gaskets in actives and passives, rodent chews, and so on.

The following photos illustrate a few examples of typical sources of UHF leakage in the outside plant.



Rodent damage



Loose tap faceplate



Tree limb rubbing on coax



Power line fell on coax, melted shield



Illegal MDU connection



Tree limb grown around coax



Corroded and loose terminators



Radial crack in feeder cable



Bad F connector in MDU box



More rodent damage

Leakage field strength vs. frequency

As discussed earlier, the coaxial cables and components which carry RF signals to and from subscribers comprise a shielded network that allows something called frequency reuse. That is, frequencies inside of the cable network are generally used to carry signals that are completely different than signals on the same frequencies in the over-the-air environment. Hypothetically, a cable network can coexist with the over-the-air environment, and the two will not interfere with one another because the cable network is a shielded environment.

Signal leakage occurs when the cable network's shielding effectiveness is degraded for some reason, allowing signals inside of the network to leak out into the over-the-air environment. If the leakage field strength is sufficiently strong, interference to over-the-air users may occur. Conversely, ingress interference may occur when over-the-air signals leak into the network.

The combination of a shielding defect and the outer surface of the coaxial cables, strand, and equipment may behave much like an antenna – in some cases a long-wire antenna – “transmitting” or radiating the cable network's RF signals into the space around the leak. A leak mechanism such as a loose connector is far from a perfect antenna. The radiation pattern is seldom uniform, and some frequencies may be radiated much more efficiently than others. Indeed, it is not unusual to see situations in which a given leak mechanism produces little or no VHF leakage, while there is significant UHF leakage. Sometimes the opposite is true: There is VHF leakage but no UHF leakage. Occasionally both VHF and UHF leakage may be produced by the same mechanism. However, in field studies to date, no obvious correlation has been seen between the *levels* of leakage field strength at VHF and UHF.

One question that comes up is why do some leakage mechanisms produce different field strengths across frequency? Signal levels inside of the plant at the point where the leakage is occurring certainly play a role. But of greater importance is the physical nature of the leak mechanism itself: Its dimensions, shape, and the way in which it behaves as an antenna.

For instance, a missing or damaged gasket on a tap faceplate may allow the faceplate-to-tap housing gap to behave like a slot antenna. A free-space quarter-wavelength at 750 MHz is 3.93 inches. The length of one edge of a tap faceplate, depending on make/model, may be quite close to that dimension. Two adjacent sides' combined gap lengths may be close to a half-wavelength at 750 MHz. There is at least one known example of a defective tap faceplate gasket reducing shielding effectiveness by as much as 40 dB in the vicinity of 750 MHz compared to 133 MHz.⁶

Here is another example: The circumference of the threaded portion of the main- and back-nuts on a three-piece 0.500 hardline connector is about 3 inches. When the main and/or back nut is loose (and it doesn't have to be much more than about a turn or turn-and-a-half from tight), UHF-only leakage may occur. The loose connector resembles a radial crack in the coax shield. Numerous instances of UHF-only leakage caused by slightly loose hardline connectors have been observed by the authors and others during the past two years.

⁶ Hranac, R., “Some Thoughts On LTE Interference,” October 2011 *Communications Technology*;
<http://www.cable360.net/ct/sections/columns/broadband/48482.html>

An informative discussion about how cable networks radiate RF energy when leakage exists can be found in a paper presented at Cable-Tec Expo '12 by Shaw Communications' Dean White.⁷

Given the lack of correlation between VHF and UHF leakage field strengths from the same leak mechanism, the following important point cannot be overemphasized: VHF aeronautical band leakage monitoring alone is not enough. At the very least, leakage must be monitored in both the VHF and UHF ranges.

Leakage Measurements at VHF and UHF

What is field strength?

The measurement of signal leakage *field strength* – a term used extensively in this paper – often is taken for granted. The procedure is fairly straightforward: Using a dedicated leakage detector with a resonant half-wave dipole antenna (or equivalent), orient the antenna to get a maximum reading and see what value the leakage detector reports. The measured field strength is stated in microvolts per meter,⁸ and hopefully is below the maximum limit defined by the FCC.

The field strength in $\mu\text{V}/\text{m}$ can be converted to a dBmV value at the dipole antenna's terminals using the formula

$$dBmV = 20 \log \left[\frac{\left(\frac{E_{\mu\text{V}/\text{m}}}{0.021 * f} \right)}{1000} \right]$$

where $E_{\mu\text{V}/\text{m}}$ is the field strength in microvolts per meter, and f is frequency in MHz.

But that still doesn't explain what field strength is. Things get even more confusing when measuring leakage at more than one frequency. Assuming the same field strength – say, 20 $\mu\text{V}/\text{m}$ – at two frequencies and the use of separate resonant half-wave dipoles for the measurements, the dBmV values at the two dipoles' terminals will be different. For example, a field strength of 20 $\mu\text{V}/\text{m}$ at 121.2625 MHz will produce -42.1 dBmV at the terminals of a resonant half-wave dipole for that frequency. A field strength of 20 $\mu\text{V}/\text{m}$ at 782 MHz will produce -58.29 dBmV at the terminals of a resonant half-wave dipole for that frequency.

To understand what is happening, consider the following example, based upon the assumptions in Table 1.

⁷ White, D., "Multi-Band Leakage Monitoring for the Future." In *Presentations and Collected Technical Papers*, SCTE Cable-Tec Expo '12, October 17-19, 2012, Orlando, FL

⁸ Outside of the North American cable industry, field strength measurements are more commonly stated in decibel microvolts per meter, or dB $\mu\text{V}/\text{m}$.

- Measurement frequencies are 121.2625 MHz and 782 MHz
- Antennas for the two frequencies are lossless resonant half-wave dipoles
- Field strength at the point of measurement is 20 $\mu\text{V}/\text{m}$ for both frequencies
- Measurement distance from the leak is 3 meters, which is in the far field for this exercise
- Each antenna is terminated by a load equal to its radiation resistance (approximately 73 ohms for a half-wave dipole)
- Each dipole is oriented for maximum received signal level
- Each antenna does not re-radiate any of the intercepted signal
- The polarization of the RF coming from the leak is linear and is the same as the orientation of the dipoles when the field strength measurements are made

Table 1. Assumptions for example

Visualize a loose connector radiating RF into the space around it. Now imagine a 6-meter diameter balloon surrounding the loose connector, with the connector at the center of the balloon. Assume the RF leaking from the loose connector is uniformly “illuminating” the entire surface of the balloon from the inside. Next, imagine a 1 meter x 1 meter square drawn somewhere on the surface of the balloon. The task at hand is to measure the RF power density within the 1 meter x 1 meter square. The power density in that square also can be expressed as a voltage, which is how field strength is expressed: volts per meter. In other words, field strength is the RF power density in a 1 meter x 1 meter square (in free space, in the air, or, as in this example, on the surface of an imaginary 6-meter diameter balloon), expressed as a voltage – hence, the “volts per meter” or “microvolts per meter” designation.

The RF power transmitted by the loose connector in the center of the balloon is designated P_t , and is called the source power. In order to produce a field strength of 20 $\mu\text{V}/\text{m}$ 3 meters away P_t must equal 0.00000000012 watt or $1.2 * 10^{-10}$ watt. Because the RF source power P_t is uniformly illuminating the entire balloon (an analogy is a light bulb at the center of the balloon), the power density P_d on the surface of the balloon in watts per square meter is simply the source power P_t divided by the surface area of the balloon, or

$$P_t / 4\pi r^2$$

where r is the radius of the balloon. Since the balloon’s diameter is 6 meters, $r = 3$ meters. Plugging the just-discussed values for P_t and r into the formula, the calculated power density on the surface of the balloon is equal to about $1.06 * 10^{-12}$ watt per square meter (the actual value is 0.0000000000106103295 watt per square meter).

The impedance Z of free space is 120π , or about 377 ohms. Using the formula

$$E = \sqrt{PZ}$$

the voltage E on the surface of the balloon in volts per meter is

$$E = \sqrt{([1.06103295 * 10^{-12} \text{ watt}] * 120\pi)}$$

= 0.000020 volt per meter, or 20 $\mu\text{V}/\text{m}$.

So far, so good: A source power P_t of $1.20 * 10^{-10}$ watt “transmitted” by the loose connector illuminates the surface of the balloon 3 meters away to produce a power density P_d of about $1.06 * 10^{-12}$ watt per square meter, which is equal to a field strength of 20 $\mu\text{V}/\text{m}$. This relationship is true for both frequencies.

Next, the resonant half-wave dipoles are placed one at a time in the square on the balloon, and the field strength within that square measured. The question is how much of the power in the square will be intercepted by each dipole and delivered to the load connected to each antenna’s terminals? All of it? Only an amount occupying an area equal to the physical dimensions of each antenna? Or some other amount?

Visualize what happens when a dipole is placed at the surface of the balloon, where RF from the loose connector 3 meters away is passing by at the speed of light. The RF field induces a voltage V in the dipole, resulting in a current I through the ~ 73 ohms impedance at the antenna terminals. What’s of interest is the power P delivered by the antenna to that impedance, where $P = I^2 R_T$. Here R_T is the sum of the antenna’s radiation resistance (~ 73 ohms) and loss resistance, the latter assumed to be zero for this example. The book *Antennas, Second Edition*⁹ illustrates a scenario using a horn antenna.

Let the...power density of the plane wave be S watts per square meter and the area of the mouth of the horn be A square meters. If the horn extracts all the power from the wave over its entire area A , then the total power P absorbed from the wave is $P = SA$ (W). Thus, the electromagnetic horn may be regarded as an aperture...

The same is true of a dipole antenna – that is, it can be regarded as an aperture with a specific area that extracts power from a passing wave and delivers it to the load connected to the antenna terminals. Defining aperture isn’t quite as simple as one might assume, though. According to *Antennas, Second Edition*, three types of aperture describe

...ways in which power collected by the antenna may be divided: into power in the terminal resistance (effective aperture); into heat in the antenna (loss aperture); or into reradiated power (scattering aperture).

A fourth aperture, called collecting aperture, is the sum of the three previous apertures. Finally, physical aperture is basically “a measure of the physical size of the antenna,” but surprisingly doesn’t have all that much to do with how much power is intercepted by an antenna.

Since the dipoles in this example are assumed to be lossless, effective aperture – more specifically, maximum effective aperture A_{em} – is the criteria that will be used to describe how much of the RF power in the 1 meter x 1 meter square is intercepted and delivered to the load at the antenna terminals. Mathematically

⁹ *Antennas, Second Edition*, by John D. Kraus (© 1988, McGraw-Hill, Inc., ISBN 0-07-035422-7)

$$A_{em} = (\lambda^2 / 4\pi)G$$

where λ is wavelength in meters ($299.792458/f_{\text{MHz}}$) and G is the antenna's numerical gain (1.64 for a half-wave dipole). A linear half-wave dipole's maximum effective aperture is an elliptically shaped aperture with an area equal to $0.13\lambda^2$, as shown in Figure 4.

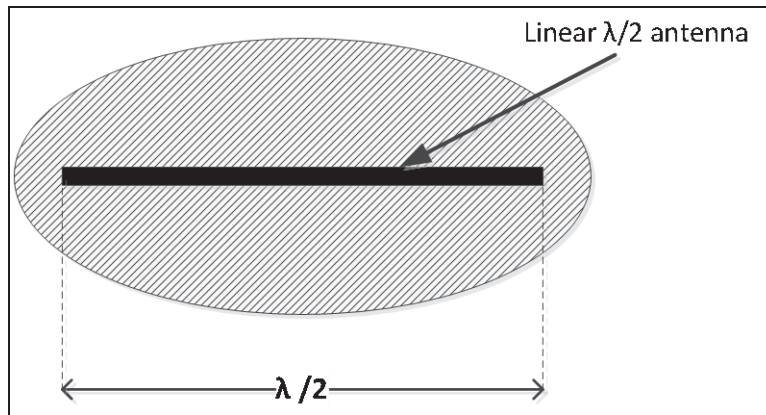


Figure 4. A linear half-wave dipole's maximum effective aperture A_{em} is represented by an ellipse with an area of $0.13\lambda^2$. (After Kraus, J., *Antennas*, 2nd Ed.)

The free-space wavelength for 121.2625 MHz is approximately 2.47 meters (2.47226024534) and for 782 MHz is approximately 0.38 meter (0.383366314578). Plugging these numbers into the previous formula gives a maximum effective aperture of 0.797668339532 m² for the 121.2625 MHz dipole, and 0.0191805865422 m² for the 782 MHz dipole. The A_{em} values denote what percentage of the power within the 1 meter x 1 meter square is intercepted by each dipole and delivered to the load at the antenna terminals. The difference between the two A_{em} values in decibels is

$$10\log(A_{em}^{dipole\ 1} / A_{em}^{dipole\ 2})$$

or 16.19 dB, which is equal to the antenna factor¹⁰ difference between the two dipoles.

In other words, when measuring a 20 $\mu\text{V/m}$ field strength at 121.2625 MHz and 782 MHz with resonant half-wave dipoles, the lower frequency antenna intercepts and delivers more power to its load ($\sim 8.46 \times 10^{-13}$ watt) than the higher frequency antenna does ($\sim 2.04 \times 10^{-14}$ watt). Here, too, the decibel difference is the same as the antenna factor difference. All of this jibes with the two different signal levels at the dipoles' terminals: -42.1 dBmV at 121.2625 MHz and -58.29 dBmV at 782 MHz, for the same 20 $\mu\text{V/m}$ field strength at the two frequencies.

¹⁰ The antenna factors for the VHF and UHF dipoles in this example are 8.12 dB/m and 24.31 dB/m respectively. For more information about antenna factor, see "The Antenna Factor," published in the 3Q12 issue of *Communications Technology*, available on-line at http://www.cable360.net/ct/sections/columns/broadband/The-Antenna-Factor_53420.html

Loss of effective sensitivity at higher frequencies

The different antenna factors for the VHF and UHF dipoles equate to an effective loss of RF sensitivity in the UHF range compared to the VHF range, by an amount equal to the antenna factor difference (16.19 dB in the previous example). This is why a half-wave dipole and spectrum analyzer setup for UHF leakage detection is usually inadequate, especially when attempting to measure low-level leakage. More often than not, one will need a higher gain antenna than a dipole and possibly also a preamplifier to improve overall equipment sensitivity. Otherwise the low- to moderate-field strength signal leakage may be hidden beneath the test equipment's noise floor.

Difficulty of measuring leaking QAM signal field strength

Accurate measurement of leaking QAM signals with existing leakage detection equipment is for the most part impossible. First, downstream QAM signals are noise-like signals, each of which occupies a full 6 MHz or 8 MHz channel bandwidth. Second, the digital channel power¹¹ of a QAM signal is typically set to be 6 dB to 10 dB lower than the peak envelope power (PEP) of what an analog TV signal's visual carrier would be on the same frequency. Third, the bandwidth of an existing leakage detector is very narrow, typically less than about 10 or 15 kHz. The latter means that the leakage detector will measure power in only a tiny slice of the leaking QAM signal's actual bandwidth, further reducing the apparent amplitude of that signal. Fourth, existing leakage detectors were not designed to measure noise or noise-like signals.

One of this paper's authors wrote an article about leakage from all-digital cable networks in the February 2009 issue of *Communications Technology* magazine.¹² The following is an excerpt from that article.

"One major challenge is measuring leakage when the signal leaking out of the plant is a noise-like 64- or 256-QAM (quadrature amplitude modulation) "haystack." Consider a 20 microvolt per meter ($\mu\text{V}/\text{m}$) leak on Ch. 16. A field strength of 20 $\mu\text{V}/\text{m}$ on that channel works out to about -43 dBmV at the terminals of a half-wave dipole antenna. If the signal being measured is a continuous wave (CW, or unmodulated) carrier or an analog TV channel's visual carrier, no problem. The power being measured is largely confined to the carrier. But a QAM signal's amplitude, or digital channel power, is the average power across the entire channel! We have to account for the bandwidth difference between the QAM signal being measured and the intermediate frequency (I.F.) bandwidth of the leakage detector, because the detector will measure only a tiny portion of the 6 MHz-wide noise-like signal.

"Assuming the leakage detector's I.F. bandwidth is 15 kHz, the indicated leak amplitude will be approximately $10\log(6,000,000/15,000) = 26$ dB lower than it really is, or about 1 $\mu\text{V}/\text{m}$ (-69 dBmV) for what is really a 20 $\mu\text{V}/\text{m}$ leak. Making matters worse is trying to figure out whether an indicated 1 $\mu\text{V}/\text{m}$ noise-like signal is Ch. 16's QAM signal leaking from the cable plant, or just over-the-air background noise. A moderately high level leak of, say, 100 $\mu\text{V}/\text{m}$ (-29 dBmV dipole level on Ch. 16) would register about 5 $\mu\text{V}/\text{m}$ on the leakage detector, or approximately -55 dBmV equivalent dipole level."

If leaking QAM signals are so difficult to measure, one might be inclined to think that over-the-air services are less likely to be affected by signal leakage-related interference when the leaking signals are QAM signals. After all, a narrow bandwidth

¹¹ Also called digital signal power

¹² Hranac, R., "Signal Leakage in an All-Digital Network," February 2009 *Communications Technology*;
<http://www.cable360.net/ct/operations/bestpractices/33882.html>

two-way radio might behave much the same as a narrow bandwidth leakage detector, effectively reducing the noise power bandwidth of the noise-like interference to negligible levels. While this scenario is certainly possible, unfortunately, the opposite has been shown to be true in many cases.

One of this paper's authors co-presented a paper at Cable-Tec Expo '09, summarizing the results of field testing that clearly showed leaking QAM signals can cause harmful interference to over-the-air services – including interference to narrow-bandwidth receivers – under the right conditions.¹³ The field test results also confirmed the difficulty of accurate measurement of leaking QAM signals using existing leakage detection equipment. Since that paper was published and presented, the cable industry has had to deal with numerous instances of documented interference to LTE service, most often to the tower uplinks, by leaking QAM signals.

As mentioned earlier, when leakage-related interference occurs in the 698-806 MHz spectrum, LTE service provider field engineers may contact local cable system personnel about the problem. That interference has generally been located and confirmed using specialized interference detecting equipment.¹⁴ Cable company technicians then attempt to corroborate the existence of signal leakage in the affected area by measuring in the VHF aeronautical band with existing leakage detection equipment. The majority of the time the VHF leakage is very low or nonexistent because of the lack of field strength correlation with leakage at higher frequencies,¹⁵ yet the LTE field engineer's test equipment clearly shows the QAM haystacks every 6 MHz across the LTE band. An example of this is illustrated in Figure 5.



Figure 5. Leaking QAM signals in the 698-806 MHz LTE band

¹³ Hranac, R., Thomas, R., "Characterizing Signal Leakage From an All-Digital Cable Network." In *Presentations and Collected Technical Papers*, SCTE Cable-Tec Expo '09, October 28-30, 2009, Denver, CO

¹⁴ AT&T, Verizon and other LTE service providers commonly use a Rohde & Schwarz PR100 for location and identification of interference.

¹⁵ Hranac, R., Tresness, G., "Another Look at Signal Leakage: The Need to Monitor at Low and High Frequencies." In *Presentations and Collected Technical Papers*, SCTE Cable-Tec Expo '12, October 17-19, 2012, Orlando, FL

Measurement bandwidth

One question that needs additional research pertains to the measurement bandwidth that should be used for detecting and measuring leaking QAM signals, especially those outside of the VHF aeronautical band. §76.611(a)(2) states, “The half-power bandwidth of the detector shall be 25 kHz.” The latter is from a section of the FCC Rules pertaining to flyover measurements of leakage, with those measurements made “within the VHF aeronautical band 108-137 MHz or any other frequency in which the results can be correlated to the VHF aeronautical band.” Other sections of Part 76 also reference power within a 25 kHz bandwidth¹⁶ (one section specifies 30 kHz bandwidth,¹⁷ but that is for a power limitation in that bandwidth near certain frequencies).

Leakage measurements made in a narrow bandwidth such as 25 kHz certainly make sense in the aeronautical band, because of the narrow signal bandwidth and channel spacing used in that part of the over-the-air spectrum.

However, in some parts of the spectrum, leaking QAM signals – which are 6 MHz wide in North America – may interfere with wide bandwidth receivers such as those in TVs used to receive over-the-air digital VHF and UHF broadcast TV signals. LTE equipment supports downlink and uplink bandwidths up to 10 MHz. As such, these and potentially other wide bandwidth equipment may be susceptible to interference from the full channel bandwidth of leaking QAM signals.

It is the opinion of the authors that when measuring leaking QAM signals, regardless of the actual measurement bandwidth, the results should be correlated to 6 MHz bandwidth in addition to a narrow bandwidth such as 25 kHz.

What can be done?

LTE service provider communications and relationships

Establishing and maintaining effective communications and positive relationships with local LTE service provider field engineers are critical. When contacted by LTE field engineering staff about possible UHF leakage-related interference, the important words are *cooperation* and *responsiveness*. As stated previously, cable operators have been increasingly cooperative when contacted by LTE field engineers about UHF leakage that has been identified as a source of interference.

The following guidelines will help to ensure a positive working relationship with LTE field engineers when local system personnel are contacted regarding UHF leakage interference.

- Respond to the contact or service request immediately. Do not delay the response.
- Schedule technicians to accompany the LTE field engineers to the problem location as soon as possible. Do not put this off, because if harmful interference

¹⁶ See §76.610 and §76.612(a)

¹⁷ See §76.616(b)

is occurring, the problem must be fixed promptly. FCC fines or even the forced shutdown of the offending cable signals are not out of the question.

- Go ahead and check for leakage in the VHF aeronautical band, but don't be surprised if little no leakage is found.
- There could well be significant UHF leakage present even when VHF leakage is nonexistent.
- If commercial UHF leakage detection equipment is available, use it to measure leakage in the area identified by the LTE field engineers before and after repairs are made.
- If commercial UHF leakage detection equipment is not readily available, use a spectrum analyzer, preamplifier, and high-gain UHF antenna to confirm the presence of leaking QAM signals before attempting repair, and check again after repair. See the "**Home-brew**" **short term solutions** section of this paper for more information. If a downstream analog carrier exists above 500 MHz, try to measure it before and after repair, since that carrier may be easier to identify on a spectrum analyzer than leaking QAM signals. (Note: If your system incorporates a CW test carrier in the 700 MHz band, make sure it is not located atop an active over-the-air LTE signal.)
- Fix the problem to the satisfaction of the LTE field engineers. In most cases they are not concerned about absolute field strengths, but are concerned when they see leaking QAM haystacks in the LTE band on their test equipment.
- Provide appropriate local contact information to the LTE field engineers in case future problems occur.
- Advise customer service representatives to immediately direct inquiries from LTE service providers to the appropriate local system personnel.
- Document everything.

Commercial solutions

The authors are aware of the following commercially-manufactured digital-compatible UHF leakage detection products, which were available or under development at the time this paper was written. The reader is urged to contact the manufacturers for additional information. This listing is not intended to be an endorsement of the manufacturers or their products, nor is it intended to be an exhaustive list.

Company: Arcom Digital
Products: QAM Snare, Navigator, Isolator, and SP-10 headend signal processor
Web site: <http://www.arcomlabs.com/>

Company: Cable Leakage Technologies
Products: C LITE detector and antenna
Web site: <http://www.wavetracker.com/>

Company: ComSonics
Products: QAM Sniffer and QAM Marker
Web site: <http://www.comsonics.com/>

Company: Effigis
Products: CPAT Flex with DRV3 meter and DSG1 signal generator
Web site: <http://effigis.com/>

Company: Rohde & Schwarz
Products: PR100 portable receiver and HE300 antenna; EFL 110/220 cable TV analyzer and leakage detector
Web site: <http://www.rohde-schwarz.com/>

Company: Trilithic
Products: Seeker D detector and CT-4 digital leakage tagger
Web site: <http://www.trilithic.com/>

Products from three of the manufacturers – ComSonics, Effigis, and Trilithic – work by injecting a low-level, non-interfering test signal in between two adjacent QAM signals. A very narrow-bandwidth, high-sensitivity receiver detects and measures the test signal leaking out of the network. The products from Arcom Digital use a correlation method to directly detect and measure QAM signal leakage, by comparing with a cross correlation detector the leaking QAM signal to a reference captured at the headend or from the outside plant. The products from Cable leakage Technologies provide spectrum analyzer-like functionality for detection and measurement of leakage. The PR100/HE300 from Rohde & Schwarz are the same instruments used by LTE field engineers to identify and locate interference to their facilities, including leakage-related interference. The EFL 110/210 provide spectrum analyzer-like functionality for detection and measurement of leakage.

“Home-brew” short-term solutions

As discussed in the previous section, several manufacturers now have available or are planning to introduce UHF- and digital-compatible signal leakage test equipment. Cable operators should understand that commercial products are recommended as the first choice for detecting and measuring UHF leakage, and ensuring compliance with FCC Rules.

Given the reality of budget cycles and the purchasing process in most companies, it will take time for the new products to be as ubiquitous at the system level as existing leakage equipment. What can be done in the short-term if, for example, an LTE service provider contacts system personnel about leakage-related interference, and commercial leakage equipment is not yet available locally?

One option that may work to confirm the presence of UHF leakage is to use “home-brew” solutions comprising an existing spectrum analyzer, high-gain antenna, and external preamplifier. Additional research is required in this area.

At the time this paper was being written, SCTE's Network Operations Subcommittee Working Group 1 (NOS WG1) had just conducted in-depth field tests to determine the effectiveness of a variety of home-brew solutions. Prior to the work by NOS WG1, the authors performed some very preliminary tests comprising limited combinations of antennas, a spectrum analyzer, and preamplifier. Antenna types included a resonant half-wave dipole, a 400-1000 MHz printed circuit board-type log-periodic antenna,¹⁸ and an older consumer-grade UHF television antenna.¹⁹ The spectrum analyzer was Sunrise Telecom's (now VeEx) AT2500RQv,²⁰ and the preamplifier an Antronix 1 GHz drop amplifier.²¹

The following is a summary of the preliminary test results, which were mixed.

- A resonant half-wave dipole and spectrum analyzer combination does not have sufficient sensitivity to detect the presence of low- to-moderate field strength UHF leakage. This is in large part because of the antenna factor difference between VHF and UHF dipoles, and the effective loss of sensitivity discussed earlier. This combination was able to detect a CW carrier at 703.25 MHz that produced a field strength of approximately 150 $\mu\text{V}/\text{m}$, but the CW carrier was too close to the spectrum analyzer's noise floor for reliable measurements at field strengths much below about 75 $\mu\text{V}/\text{m}$.
- At a field strength of approximately 75 $\mu\text{V}/\text{m}$ using the dipole/spectrum analyzer combination, leaking QAM haystacks were just visible above the noise floor on the analyzer display, but their amplitude was too low to allow measurement of full-channel field strength.²² When the field strength was decreased by 6 dB to approximately 37 $\mu\text{V}/\text{m}$, the QAM haystacks were buried in the spectrum analyzer's displayed noise floor.
- The small log-periodic antenna provided about 3 dB of additional sensitivity compared to the dipole. When combined with just the spectrum analyzer, sensitivity was still insufficient for low- and moderate-field strength leak detection.
- The UHF TV antenna provided approximately 5 dB of additional sensitivity compared to the dipole. When combined with just the spectrum analyzer, sensitivity was still insufficient for low- and moderate-field strength leak detection.
- The UHF TV antenna, preamplifier, and spectrum analyzer combination provided sufficient sensitivity to detect the presence of moderate- and some low-field strength leakage. Because the actual gain of the antenna was unknown, this combination could not be used for accurate field strength measurements. It could, however, be used to confirm the *presence* of UHF leakage before repairs, and the presence or absence of leakage after repairs. Note that this equipment combination is too unwieldy to be used in a vehicle, and is recommended only for fixed testing after a possible leakage location has been identified by other means

¹⁸ Kent Electronics 400-1000 MHz printed circuit board antenna. <http://www.wa5vjb.com/products1.html>

¹⁹ Make/model and specifications unknown. Boom length 5'9".

²⁰ <http://sunrisetelecom.veexinc.com/products/at2500rqv.php>

²¹ Antronix FRA1-1510, 15 dB gain, 3 dB noise figure. http://www.antronix.net/uploads/specs/DS-1030-AR-A04_FRA%20Serie_51_0.pdf

²² The amplitude of the QAM signals had been measured at a much higher field strength from a calibrated leak, then a precision lab-grade variable attenuator was adjusted to achieve the desired lower leakage field strengths.

(e.g., an LTE service provider). Note that portable AC power may be necessary for some of the equipment, depending on make/model. A bandpass filter may be necessary to prevent preamplifier overload by strong out-of-band signals.

- If a CW carrier is available for UHF leakage detection using home-brew equipment configurations, ensure that the carrier's placement in the cable network's downstream spectrum does not overlap existing over-the-air LTE signals, UHF TV signals, etc. When leakage does occur, the CW carrier will be less likely to cause interference to over-the-air services if it is in an unused part of the over-the-air spectrum. Likewise, the CW carrier will be easier to see on the test equipment display if an over-the-air signal is not covering it. A challenge here is that most cable operators are reluctant to give up the channel slot necessary to support a CW carrier dedicated to UHF leakage monitoring.

The NOS WG1 field tests corroborate the authors' preliminary test results. While the NOS WG1 results were still being analyzed as this paper was being finalized, the data confirm that a combination of high-gain antenna, preamplifier, bandpass filter, and spectrum analyzer is necessary to reliably detect the presence of UHF leakage.

Do today's solutions work?

The following comments are not intended to be an endorsement of any test equipment manufacturer or its products by the authors or by the companies for whom we work, but rather to emphasize that commercial solutions for detection and measurement of signal leakage well outside of the traditional VHF aeronautical band are available from several sources. Both of the authors have personal experience observing and/or using commercially-manufactured digital-compatible leakage detection equipment from Arcom Digital, ComSonics, and Trilithic, as well as interference locating equipment from Rohde & Schwarz. The respective manufacturers' products, when configured and used according to equipment-specific instructions, appear to work as specified.

Results with the limited combination of home-brew solutions were mixed. Additional field tests by SCTE's NOS WG1 were, as previously mentioned, completed while this paper was in its final editing stages, and support the results of the preliminary tests regarding the viability of other equipment combinations. At the very least, a combination of spectrum analyzer, preamplifier, high-gain antenna, and a bandpass filter (if needed) can be used to at least confirm the presence of UHF leakage.

Leakage mitigation

Finding and repairing leakage

The cable industry has decades of experience detecting, locating, and repairing leakage in the VHF aeronautical band. The procedures are well-understood, and many system personnel have developed their own tips and tricks for tracking down leakage sources. When combined with technologies such as global positioning system (GPS)-based detection equipment, determining the locations of leaks has become easier.

As the system technical workforce grows more efficient through predictive DOCSIS®-based tools, full-band capture in new CPE,²³ and service repair order routing, plant issues are prioritized more effectively and repairs are categorized and tracked better as well, which can be associated with a reduction in trouble calls over time. System managers are more likely to purchase new equipment, and supervisors are more likely to use this equipment, especially as it becomes clear just how much RF leakage detection and repair pay back. The manager's return on investment viewpoint is "show me the cost savings, because my techs already have enough work to do."

Many cable operators have moved to the previously-mentioned GPS-based leakage detection technology over the years, and the benefits are positive. Prioritizing problematic leaks in each field service area leads to fuel savings, and provides peace of mind with respect to ensuring compliance with FCC Rules and a lower chance of interfering with over-the-air users. Some operators who perform both ground based leak detection and flyovers may realize cost savings when mobile units provide accurate coverage percentages, allowing easier and more accurate cumulative leakage index (CLI) calculations for filing FCC Form 320.

By incorporating new digital-compatible UHF GPS-based leakage equipment, outside plant personnel can expect to identify numerous previously undiscovered leaks. A primary effort will need to focus on managing the perception of the workforce and formulating a plan to begin blocking and tackling the leaks, which will put the operator at lower risk after repairs have been made. It is important to emphasize to the workforce the benefits of leakage management, which results in reduced trouble calls as well as a likely link to downstream ingress reduction. Preliminary data indicates that there may be some correlation between UHF leak repairs and downstream ingress in the upper frequency ranges.

Quality assurance inspectors can attest that the number of leaks found, along with the strength of those leaks, is a clear indication of how well the system operates and how good end-of-line performance tests will be in that particular system. Also, few will argue that coaxial plant repairs related to signal leakage pay back in the improvement of overall coaxial plant integrity, which supports the higher reliability needed to provide valuable content to the subscribers. In fact, deploying new technology such as DOCSIS 3.1 with its higher orders of modulation will make this a definite requirement.

Preventing future leakage

The bottom line here is effective management of signal leakage, regardless of frequency. Performing new installations, reconnects, service calls, and routine hardline plant maintenance with the "do it right the first time" attitude is critical. Many leaks are caused by craftsmanship issues, which are completely preventable with training, use of quality materials and components, and follow-up quality control inspections. Leaks caused by environmental factors, third-party damage, and even our own subscribers are more challenging.

²³ Full-band capture is a feature available in the latest Broadcom and Intel chip sets, which provides downstream spectrum analyzer-like functionality in the CPE. Some operators are now using full-band capture to remotely troubleshoot downstream RF problems.

Abandoning affected channels to avoid leakage-related interference is not a viable long-term option; rather, a consistent level of effort toward identifying and repairing leaks is the only option the industry can afford. Leakage monitoring outside of the 108-137 MHz aeronautical band must become more than a good idea, since LTE service providers are offering lifeline services in the 698-806 MHz spectrum. Leakage-related interference to LTE equipment represents a potential liability for the cable industry.

Cable operators must develop and implement an effective signal leakage program to include both VHF and UHF band leakage monitoring. “Rolling out” versus “handing out” such a program will be the difference in its success. To get everyone on board the program must be credible, achievable, and results tracked.

Best practice strategies used by technicians today

To ensure optimum UHF leakage and ingress performance, operators should follow the same practices widely implemented for reducing VHF leakage and ingress, including use of a) tri-shield drop cable throughout the customer premises network, b) a dry-type flooding compound in overhead drops to help minimize corrosion damage to the cable (and traditional flooded cable in underground applications); c) high-quality compression-type F connectors; and d) premises splitters and other drop components which meet or exceed relevant SCTE and other industry standards. All F connectors should be wrench-tightened²⁴ and properly weatherproofed at the tap, ground/bonding block, splitters, etc., and carefully tightened on the equipment supplied to the customer by the cable operator.²⁵

Also, consider a change in process for how installations are performed to mitigate leakage and ingress while connectors are being prepared and attached. One example is the “reverse installation,” where the drop connection to the tap port is the last step. When all cable preparation and drop connector attachments are completed, prior to signal being applied to the customer premises network verify that there are no frequency conflicts to deal with. Installation test equipment is available which can display the RF spectrum coming from the drop toward the tap, allowing the installer or technician to look for drop-related ingress. Any observed ingress should be resolved prior to completion of the job at each subscriber premises.

The workforce should be educated about UHF band frequencies and over-the-air signals on those frequencies. Technicians should be shown how the LTE data device on their belt or in their pocket could influence troubleshooting through interference they are inadvertently introducing while performing service work.

Recommended best practice strategies going forward

Cable operators should update their preventive maintenance, signal leakage, and ingress management programs to emphasize proactive efforts in this space.

²⁴ Nominal tightening torque in the 20 to 30 pound-inch (lb-in) range, but other values may be recommended by the connector and/or equipment manufacturer.

²⁵ F connectors on consumer equipment generally cannot be tightened as much as on splitters and other cable devices, since damage to the mating connector can occur.

- Implement both a VHF and UHF leakage detection ground-based patrol approach. Commercially-manufactured digital-compatible UHF leakage detection equipment is now available, so operators should be planning near-term implementation of a UHF leakage monitoring program.
- Understand which LTE providers and UHF broadcast stations are in the system's operating area. Sometimes it helps to know where their towers are located. Be aware that wireless carriers are deploying more and more micro-cell transceivers, meaning potentially more locations where signal leakage could pose problems.
- Enable the work force to identify leaks throughout the work day, and to repair larger leaks in a timely manner. This reduces mean time to repair and fuel consumption, it lowers exposure and risk, and helps prevent a backlog of work.
- Incorporate GPS-based leakage equipment to minimize ambiguity in leak location.
- Full system coverage during ground-based patrols will ensure that technical personnel include areas of the plant, especially those closer to LTE towers where a higher potential for interference may exist.
- Take advantage of new CPE-based technologies such as full-band capture for remote troubleshooting of possible ingress problems.
- Use both compliance requirements and plant betterment communications to drive efforts.

Summary

UHF leakage, ingress, and direct pickup are solvable challenges. UHF leakage was identified as a problem in the last two to three years, and is far more common than many assumed. The latter is largely because of the lack of sufficient correlation between VHF and UHF leakage field strengths from the same leak mechanism. The cable industry has done a commendable job managing VHF leakage for many years. Only recently have cases of leakage-related interference to LTE equipment in the UHF spectrum pointed toward the need to monitor outside of the traditional 108-137 MHz VHF aeronautical band.

The cable industry has experience with UHF ingress, mostly from UHF TV signals. Direct pickup interference to older set-tops and other CPE from cell phones has been a known problem for a few years, and LTE UE is now on the list of devices that can cause direct pickup interference. More recently, some cable operators have experienced direct pickup interference to certain types of headend and hub site equipment, typically requiring the manufacturer to modify or replace the affected equipment.

The new kid on the block is UHF leakage. Since existing leakage detection equipment was designed to operate in or near the VHF aeronautical band, cable operators have had little or no visibility into their networks' leakage performance at higher frequencies. Fortunately, test equipment manufacturers have introduced or are introducing digital-compatible leakage detection products that operate in the UHF

spectrum. There are some homebrew combinations of test equipment that may be usable as short-term solutions for at least determining the presence of UHF leakage, until commercially-manufactured UHF detectors are obtained locally. However, preliminary field tests discussed in this paper had mixed results. To the extent possible, the commercial solutions should be the first choice.

The authors cannot overemphasize the need for the cable industry to take UHF leakage and ingress seriously. There are significant risks for the potential of harmful interference to over-the-air users such as LTE service providers. Unchecked, harmful interference may result in FCC enforcement action, including fines and in severe cases involving safety of life and property, and orders to turn off the offending cable signals until the problems are resolved.

Going the other direction, ingress and direct pickup can interfere with cable services, causing subscriber dissatisfaction and increased churn. UHF ingress may affect the ability to reliably deploy next-generation DOCSIS technology, or to obtain the highest spectral efficiency (bits per Hz) from it.

The industry needs to approach the challenges from several directions: One is to implement UHF leakage management programs in conjunction with existing VHF leakage management programs. Another is to make sure future leakage problems are avoided, which can be done with training, good craftsmanship, quality control, and effective maintenance programs. Adopting best practices strategies for today and the future are key.

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Abbreviations and Acronyms

A_{em}	maximum effective aperture
BER	bit error ratio
CATV	cable television (originally community antenna television)
CLI	cumulative leakage index
CNR	carrier-to-noise ratio
CPE	customer premises equipment
CW	continuous wave
dB	decibel
dB _i	decibel isotropic
dB _m	decibel milliwatt
dB/m	decibel/meter
dB _{mV}	decibel millivolt
dB _{μV/m}	decibel microvolt per meter
E	volt or voltage
eMTA	embedded multimedia terminal adapter
$E_{μV/m}$	field strength in microvolts per meter
f	frequency
FCC	Federal Communications Commission
G	gain
HFC	hybrid fiber/coax
I	current
IF (I.F.)	intermediate frequency
kHz	kilohertz
km	kilometer
log	logarithm
LTE	long term evolution
MER	modulation error ratio
MHz	megahertz
MVPD	multichannel video programming distributor
mW	milliwatt
NOS WG1	Network Operations Subcommittee Working Group 1
P	power
P_d	power density
PEP	peak envelope power
P_t	source (or transmitted) power
QAM	quadrature amplitude modulation
r	radius
RF	radio frequency
R_t	radiation plus loss resistance
SC-QAM	single carrier quadrature amplitude modulation
SCTE	Society of Cable Telecommunications Engineers
TV	television
UE	user equipment

UHF	ultra high frequency
URL	uniform resource locator
VHF	very high frequency
V/m	volt per meter
W	watt
Z	impedance
8-VSB	eight-level vestigial sideband
λ	wavelength
$\mu\text{V/m}$	microvolt per meter