Leakage Detection Using Test Signal Phase with GPS

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Abstract

This paper describes a leakage detection system that measures received phase and magnitude of a stable continuous wave (CW) test signal versus distance. The received complex signal samples are used to mathematically construct a synthetic phased array (SPA), which points to (vectors) the leakage signal source. The latitude and longitude of a leak source are located where the vectors intersect. The use of a CW test signal with synthetic phased array provides superior receiver sensitivity. Having both signal strength and a detection distance determines if the leak is over Federal Communications Commission (FCC) limits. Practical test considerations and samples of field tests are provided.

BACKGROUND

The FCC has mandated for many years that cable operators routinely test their plant to verify that signal leakage field strengths are below prescribed thresholds. Historically, testing has been done in or near the 108 MHz to 137 MHz very high frequency (VHF) aviation band. In 2012 Hranac and Tresness presented a paper (1) that showed that leakage in the ultra-high frequency (UHF) band is not tightly correlated to leakage in the VHF band. Testing in only the VHF band does not guarantee that UHF leakage is not taking place. The conclusion that can be drawn is that to avoid interference with services like long term evolution (LTE) tower sites and mobile devices, testing should be done in both bands.

THE INVENTION

CableLabs engineers came up with an idea to assist technicians with their routine testing for leakage by pinpointing the source's location. Most test gear in the past used signal strength, or magnitude, and the signal's phase angle was ignored. As a test antenna was moved closer to the leak, the field strength was expected to get stronger.

Our initial experiment was to simulate a leak by radiating a stable CW signal and receiving it with a complex In-phase and Quadrature (I-Q) demodulator using a matching stable CW signal for demodulation. This is illustrated in Figure 1. Inserting a single CW signal is relatively easy for an operator, because only a small narrow vacant bandwidth is required. If a CW signal is being used for AGC (automatic gain control), that signal can also be used for leakage detection. To provide the necessary local oscillator stability, 10 MHz rubidium frequency sources were used on both transmit and receive sides. A global positioning system (GPS) disciplined clock could have alternately been used, but the rubidium sources were chosen to allow indoor testing and to simplify headend installs. As a test antenna was moved closer to a leakage source, a dot (single constellation point) on the test equipment's

I-Q polar plot could be observed to move in a counter-clockwise circle, and in a clockwise circle as the antenna got further from the leak. If the received signal got stronger, a radius associated with the dot increased. The rotation of the dot on the I-Q plot is essentially a manifestation of Doppler shift caused by a decrease of phase angle between antennas.

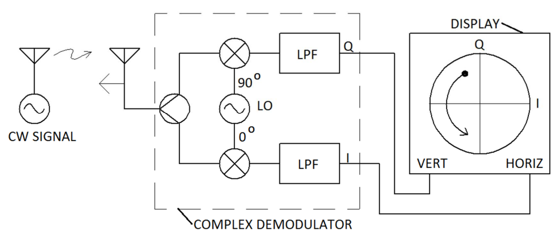

Figure 1. Constellation point rotates counter-clockwise when the test antenna approaches the leakage source, and clockwise when the test antenna is moved away from the leak.

It is mathematically possible to determine a bearing angle between the leak and the test antenna's drive path by measuring the velocity of the test antenna, and comparing it with an expected Doppler shift. For example, if the test signal was 900 MHz, its wavelength would be 0.3 meters (λ=f/c). If the test antenna was traveling directly towards the leak at 10 meters per second (m/sec), a Doppler shift of +33.33 Hz would be expected. If a lower frequency was measured, such as 20 Hz, one could compute that the test antenna was not traveling directly towards the antenna, but at an angle of ACOS(20/33.33) = 53.13 degrees. The leak source lies somewhere on a 3-dimensional cone, with the test antenna at the cone's apex, and the angle is half of the cone's apex angle. See Figure 2. Since a cable operator generally knows what side of the street the plant is on, where the cone intersects the cable plant is the leak's source (2).

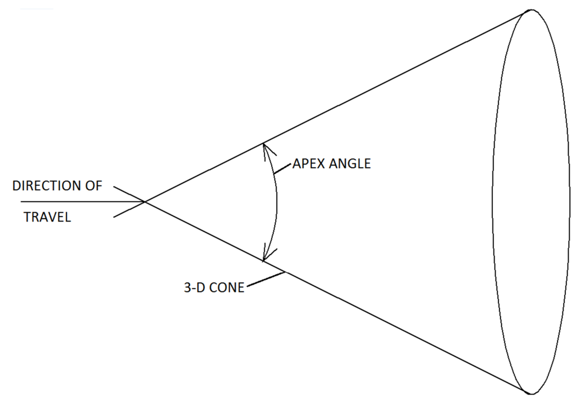

Figure 2. The source of a leakage signal lies somewhere along a three dimensional cone, where the test antenna is at the cone's apex.

This test worked well with a single leakage source, but the dot was observed to move erratically when there were multiple leaks that added in and out of phase as the test antenna moved. A solution was to capture the complex I-Q samples as the test antenna was moved and insert the values into an inverse fast Fourier transform (IFFT) after windowing. The net result was the creation of a synthetic phased array, where each I-Q voltage sample formed another virtual element. Typical element separation was 10-15 cm. Because the Fourier transform is a linear transform, it became possible to observe multiple leaks simultaneously. A magnitude plot of the transformed coefficients makes a Doppler plot. An example Doppler plot is shown on Figure 3. Each leak's bearing angle can be read, as well as the strength of each leakage signal. As one drives by a leak, it appears on the right (positive frequency), increases in strength as the test antenna approaches, passes through zero hertz (Hz) (center) as the test antenna passes, and then moves to the left side (negative frequency) and then disappears.

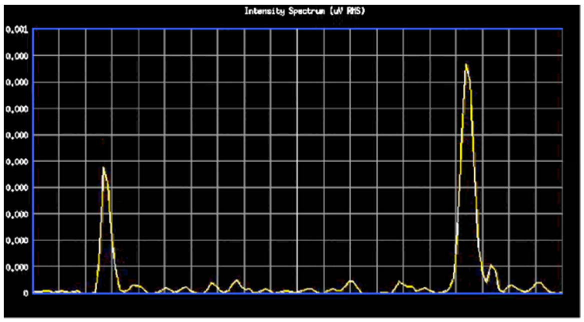

Figure 3. A Doppler plot formed by inserting I-Q values into an inverse discrete Fourier transform. 0 Hz is in the middle. Note that there is a leak (on right) ahead and a leak (on left) further behind.

By plotting bearing angles (vectors) from different test antenna positions, the intersections of the vectors locate the leak's source location. In practice, objects can obstruct the radiated leakage test signal. For example, a leak may originate behind a house and cannot be observed while the test antenna is in front of the house, but can be measured when approaching and again when driving away from the house.

Figure 4 shows a Doppler frequency vs. distance plot illustrating a rapid frequency shift for a leak near the drive path, and a more gradual frequency shift for a leak that is distant from the drive path. Figure 5 is an integral of Figure 4 and shows phase angle vs. distance for a travel path 'A' that comes close to the leak and phase angle vs. distance for a travel path 'B' that does not come as close to the leak.

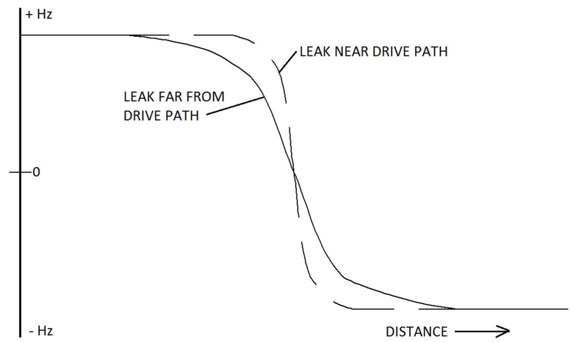

Figure 4. A plot of Doppler shift for two drive-by cases, leak source far from road and leak source near road.

The cone of Figure 2 intersects level ground on two lines, and the vector intersections create a false leak source location and a true leak source location. If one wishes to get rid of the second (false) intersection point, it can be accomplished with a second antenna that rides alongside of the first antenna. As the test vehicle passes the leakage source, the phases of the two antennas' received signals will diverge, as illustrated in Figure 5, and then re-converge.(3) Simple phase subtraction reveals what side of the antennas' drive path the leak is on.

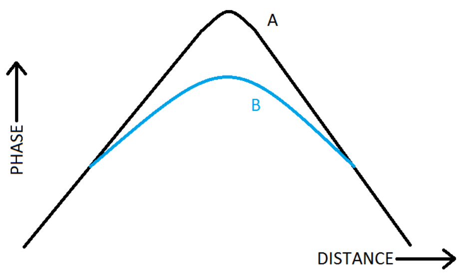

Figure 5. A plot of phase vs. distance for an antenna 'A' that comes closer to a leakage signal vs. an antenna 'B' that does not come as close to the leakage signal. The antenna that achieved the highest phase value came closest to the leakage source.

Figure 6 is a plot of phase difference for a drive-by of a leak. The upper line is when the leak is on the right side of the vehicle and the lower line is for when the leak is on the left side of the vehicle.

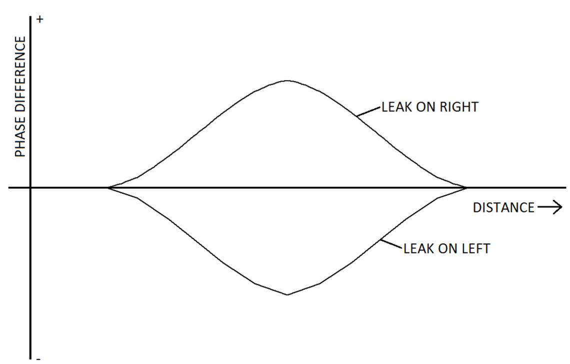

Figure 6. Phase difference between 2 antennas vs. distance. Upper plot is for leak on right and lower plot is for leak on left. Peak phase angle is a function of CW test signal wavelength and separation between the two antennas.

Figure 7 is a visual aid showing a static wave pattern for a source in the center. Note that antenna 'A' comes near the source while antenna 'B' does not get as close. For illustration, the waves are all shown equal in amplitude, but in practice the amplitude of the waves drops 6 dB every time distance from the center doubles. Only the In-phase (I) component is illustrated. The quadrature (Q) component will be shifted by 90 degrees.

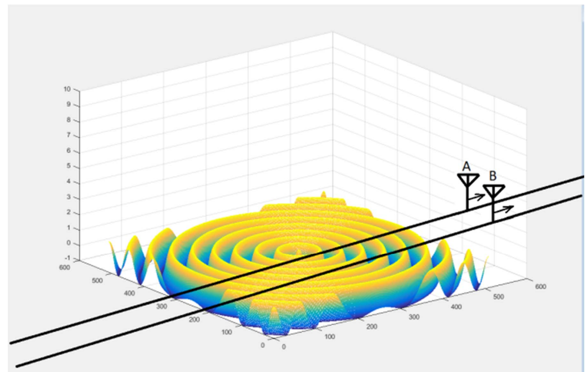

Figure 7. A leakage source static wave visual model. Leak source is in the middle and phase radially increases from the center. Antenna A, which passes close to the source, experiences more phase shift (wave cycles) than antenna B, which passes further from the source. Each full wave cycle corresponds to 360 degrees rotation on the DISPLAY of Figure 1.

The testing was done using an Ettus B210 software defined radio (SDR) connected to a MAC laptop computer. Monopole omnidirectional antennas were used. Incorporating a GPS with the SDR allows the latitude and longitude of the leaks to be recorded. Knowing the velocity of the test antenna along with the exact time when measurements are taken also allows spacing between synthetic phased array elements to be calculated, as well as providing a compass function.

FIELD TESTS ON THE SYNTHETIC PHASED ARRAY

A CW test signal was inserted on the downstream spectrum of live plant at 800 MHz and a hunt for leakage signals began. Testing was not done at VHF frequencies, but this technique should work in this band as well. A GPS module provided latitude and longitude coordinates to locate the test antenna’s position. Driving experience revealed what was expected: leakage signals can be dispersed by passing through an object, like a tree, a structure, or by reflections. One helpful way to visualize diffusion from inside a house at UHF frequencies is like a transparent structure illuminated from inside with visible light. The house is made of frosted glass with multiple curved mirrors inside. Walls and roofing diffuse RF signals while metal, such as appliances and cars in a garage, reflect them.

Fortunately, dispersed signals are generally weaker, and they can frequently be ignored when computing intersecting vectors. Generally outdoor environments are more benign for dispersion relative to indoor environments. Figure 8 is a ‘fan’ display showing how a leak from outdoor overhead plant appeared as it was passed. There is yet another leak ahead. Our evaluation software assumed far-field conditions, which were not necessarily always valid. Our synthetic phased array typically used 128 virtual elements, but for near-field detection the length of the synthetic phased array may be reduced. The fan plot also illustrates the antenna’s speed (upper center), a compass function (upper right), and a Doppler plot in the upper left graph.

With calibration, the system method knows the field strength of a leakage signal. The proximity of the leakage source to the drive path is revealed by the grid on the circular fan diagram of Figure 8. Factoring test antenna distance to the leak source with the field strength can reveal whether FCC limits were exceeded.

Figures 9, 10, and 11 are examples of causes of UHF leaks detected with this test method. Figure 9 illustrates a hole worn through the hard line and Figure 10 illustrates a radial crack found underneath heat shrink tubing. Figure 11 shows a radial crack created on an expansion loop. The smaller geometries of defects on UHF leaks explain one reason why the strength of a VHF leakage signal was reduced: the antenna aperture is smaller.

The defects illustrated in Figures 9, 10, and 11 have an effect on cable signals, particularly downstream signals. When a transmission line has an impedance discontinuity, some of the energy will be reflected backwards towards the source. If the RF source (frequently an amplifier) has a good output return loss, the reflected energy will be absorbed. Transmitted energy will then have much lower amplitude and be reduced at end points, such as cable modem (CM) terminals, tap ports, or other downstream test points. As mentioned previously, Figure 11 shows a radial crack. After repair, the operator's operations support system (OSS) revealed 43 homes in the node’s service area fed by this cable went from “yellow” status to "green."

One application for this measurement technique is automatic data logging as a test vehicle, perhaps even a pizza delivery truck, is driven around town. Leakage data and GPS coordinates can be uploaded and analyzed overnight when the vehicle is parked. Another application is hand-held test devices and yet another application is airborne testing, both using fly-overs and drones. With a typical UHF amplifier launch signal level being 48 dBmV per 6 MHz channel, and a tap level of 15 dBmV, a leak on a hard line has a potential for 2000 times more power (33 dB). Because of the sensitivity of this technique, individual houses with leakage problems are detectable, even when their leakage signals are well below FCC limits. These houses will be vulnerable to ingress from LTE and other signals.

This test method has exceptional sensitivity for a number of reasons. One is the use of a CW signal and a resulting narrow receiver bandwidth, typically only a few hundred Hz. The CW test signal's narrow bandwidth also makes it easier to find and use a smaller part of the spectrum on a cable system. Another reason is averaging of multiple points to make a single I-Q sample. And finally, use of a synthetic phased array further enhances sensitivity due to directionality.

One weakness of this test system is standard GPS accuracy. The system knows accurately where the leaks are relative to the test antenna, but a low cost GPS receiver system only determines the absolute location of the test antenna to within 4-5 meters. A premium GPS system could provide better absolute accuracy. A photograph of a leak source, with a source in the center of the picture, could also provide improved reporting.

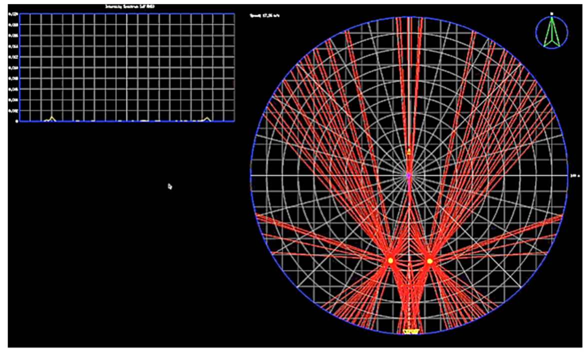

Figure 8. A GPS driving plot featuring drive direction (compass arrow in upper right), drive velocity (upper center), Doppler shift plot (upper left) and fan plot (right side). The polar grid is 10 meters and test antenna's current position is in the center of the polar plot. A purple line in the center of the polar grid displays the length of the synthetic phased array. Using a second antenna reveals which side of the road the leakage source is on. Leak is at the intersection of vectors.

Figure 9. A hole was rubbed through a hardline coax shield causing UHF leakage.

Figure 10. A radial crack causing UHF leakage.

Figure 11. This is a radial crack that was not producing a VHF leakage alarm. After repair, signal quality improved for homes fed by this cable.

BENEFITS

This technique has operational benefits above the required FCC testing and responding to LTE interference reports. The traditional techniques require human support to direct the antenna toward the leaks in order to discriminate which side of the road the leak is on, and to discrimination of multiple leaks. This system allows you to unequivocally pinpoint location of leaks. The unmanned nature of this technique enables these leak finding systems to be placed in any and all vehicles from an operator's fleet to collect leak location data and feed that information into a common database. All technicians may have that information available, and the operator will be able to plan ahead of time how many leaks need to be fixed by which technician. Leakage information can also be used to collaborate other problems, such as UHF or LTE ingress, weak receive levels, high transmit levels, intermittent service, etc.

CONCLUSION

Using GPS data with a leakage signal's phase data as well as magnitude can improve leakage detection by providing latitude and longitude coordinates for the leakage source. A leakage signal's source is identified at the intersection of bearing angles. Signal leakage elimination is more than just a FCC testing requirement; it is an opportunity to improve operations. A repaired leak means less possibility for leakage-related interference to over-the-air services and ingress interference from those same over-the-air services, and less degradation to the cable network's signals.

REFERENCES

(1) Another Look at Signal Leakage – The Need to Monitor at Low and High Frequencies by Ron Hranac and Greg Tresness, 2012 SCTE Cable-Tec Expo

(2) If the leakage testing is being done by an aircraft, piloted or a drone, an intersection of the ground with the cone will form a parabolic shape, assuming flight is straight and level.

(3) Also, if the test antenna's drive path varies, by changing lanes or turning, the false image diverges and the true image converges.

Many thanks to reviewers of this article who provided valuable feedback, and to cable operators who hosted our testing.