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Independent Study 192

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Perimeter Security using a RF coupled Leaky Coax System

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Abstract

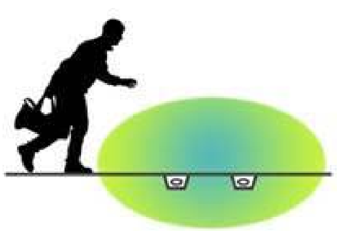
For over 30 years the leaky coaxial cable (LCX) has been used as a viable mean of perimeter detection, in particular in military, nuclear and airport installations. Current market designs involve the lining of the perimeter with two parallel LCXs buried 2 inches below ground for detection. I have designed a system to illustrate the possibility of using a series of leaky coaxial cables to detect both intrusions and extrusions of a specified area. Three cables of 11 feet each were place parallel to each other. An invisible EM field is created by sending a 150 MHz sine wave signal in the central transmitting LCX (tLCX) while the two receiving LCXs (rLCX), placed 2 meters on either side, couple the field simultaneously. This signal is then measured by a computer for processing and analysis. Detection occurs when the intruder (extruder) disturbs the field and the coupled signal deviates from the stable reference signal.

The data acquisition and analysis of the coupled signal is processed by LabView, which is well suited for real time analysis. National Instrument equipment BNC 2110 DAQ board with 12bit A/D conversion has the ability to capture the signal with the necessary rate and precision. I present here various situations of detection, including the time responses of the system, intrusion and extrusion responses, speed of object and limitations. The LabView VI program as well as the user interface design will also be shown.

Introduction

Concept

For the past 30 years the use of buried cable structures as a perimeter detection tool has been used extensively in military, industrial facilities and nuclear installations. The covert deployment and terrain following property made this class of sensors the preferred choice for many scenarios. There have been many different designs of buried cables, ranging from strain-gauged cables that respond to intruder-induced ground motion, to ported coaxial cables that generate an invisible volumetric EM field which would be monitored for any intruder-induced disturbance[1]. This study focuses on the working and improving of the ported LCX design.



LCX systems are classified as active detection systems because energy is constantly inputted into the 'volume' wished to be protected. Disturbances in this energy are monitored and would trigger an alarm accordingly.

The system designed in this study is the next logical step in improvement of the current design by using three cables instead of the current two, the direction of the movement can be known. While the detection of extrusions may at first seem illogical, the system can be used to detect any unauthorized departure of a certain area, ideal when items of interest wish to be restricted to a certain designated area. This directional improvement can be used, for example, to secure aircraft parking sites, where individual aircrafts can be monitored. Any intrusion into the immediate vicinity of an aircraft and the departure of an aircraft out of its designated parking spot can be known. Installation, however, requires physical removal of soil throughout the perimeter to form two trenches up to two inches deep and three inches wide and hence initial cost can be very high.

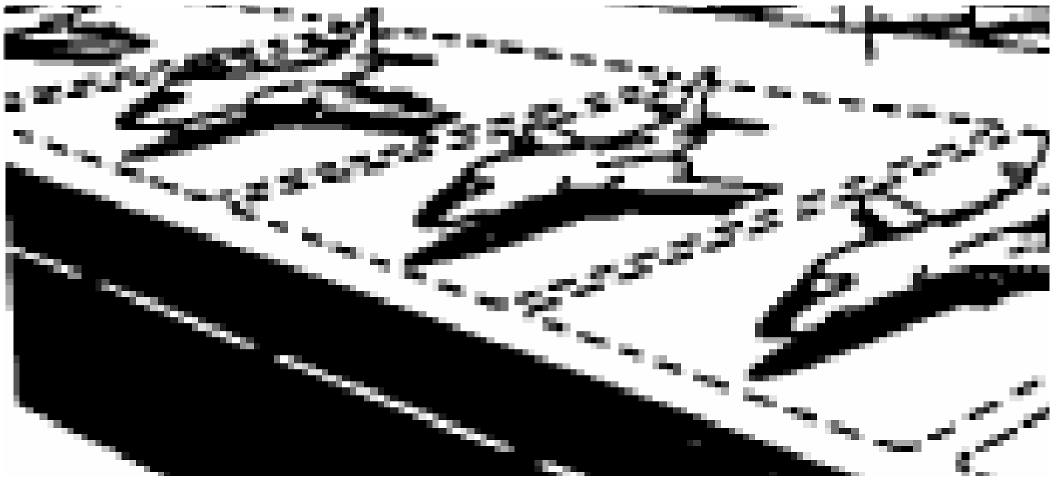
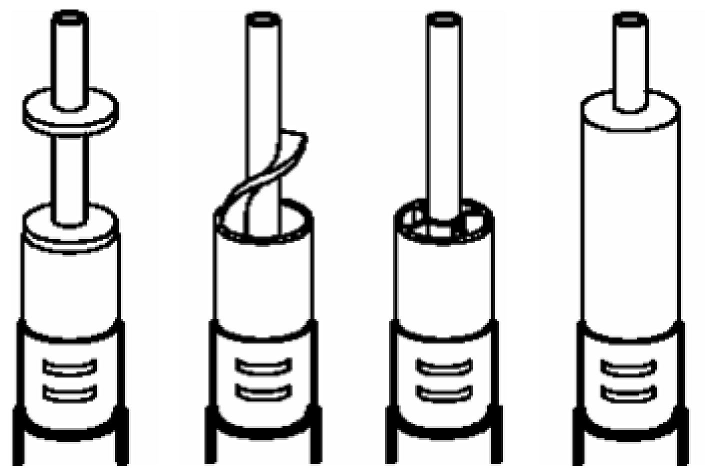


Figure I1: Using the improved system the direction of movement can be known and can be used in securing the location of objects such as aircrafts in their designated location. Authorization for individuals to approach the object and to remove it from the location can be monitored.

Theory of LCX design

In all types of LCXs, they are open EM waveguides in which, while similar in structure to normal coaxial cables, have specific space slots punched into the outer conductor sheath to purposely leak and radiate the transmitted signal. The signal energy is guided by the length of the LCX, its generated field confined both inside and outside the cable in its immediate vicinity, thus enabling the signal to be coupled into mobile communication units. Based on the coupling and radiating mechanisms are two different categories of LCX, each with their own performance characteristics. The first, radiating mode LCX is designed with non-regular non-periodic slots. The apertures are typically periodically configured with spacing comparable to the operational frequency and hence less bandwidth, but greater radiating distance. These cables are more costly to manufacture due to the special patterns of the slots. The arrangement also results in less longitude attenuation and higher-ordered spatial harmonics, increasing the effective radial distance. The second type called coupling mode, is less costly and consists of smaller spaced and regular structured slots that are smaller that the operating wavelength. The increase in slot frequency means that higher-ordered spatial harmonics comes into play, guiding the signal further down the longitudinal direction. However, the result of further distance means less energy to dissipate in the radial direction, and therefore less effective distributing distance and coverage volume away from the cable. Its lack of signal frequency means that it can afford a much larger and wider frequency bandwidth.



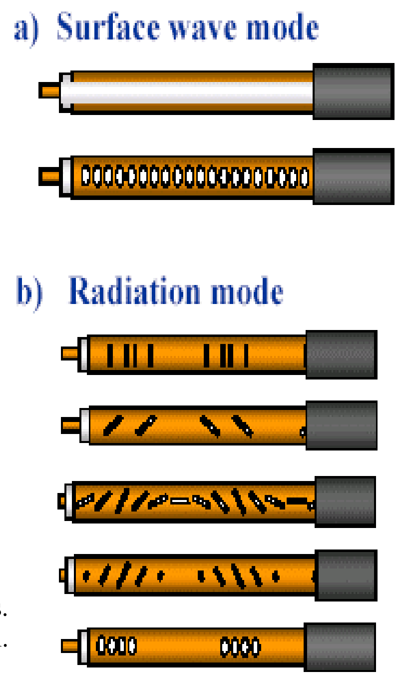


Figure I2: *Above*: The four different types of LCX axial structures. The inner and outer conductors are separated to conduct the signal. *Right*: The two types of LCX modes with different applications.

The axial structure differs little from regular coaxial cables: inner core surrounded by outer sheath. The signal is carried by a alternating voltage difference between the inner and outer. There are four main designs, bamboo joint, lotus, spiral and foam filled, the first three using conventional insulation while the forth polyethylene. The first three structures are being phased in and replaced by the forth as they can not resist water penetration in the axial direction. If part of the cable becomes damaged and water enters, the *whole* cable needs to be checked and replaced as water can migrate. The extra foaming, however, makes the forth type more expensive.

Like regular coaxial cable, the propagation of signal relies on a difference in voltage between the inner core and outer sheath. If we deliberately cut a slot such as to interrupt the current flow lines, the currents have to go round the slot and this gives rise to a distortion of the electric field and magnetic field patterns inside the guide. The slot acts as a dipole antenna and will radiate, and the energy leaks out from the waveguide. This principle is used to construct slot antennas in waveguide. Hence measurements and characterization of one slot or one slot pair is often the approach to mapping the EM field of LCX: the LCX is considered to be an array of dipole antennas.

An important application of slotted waveguide is to construct a "slotted line" for measurements. This is usually done for the TE10 mode pattern, which is the only mode which will propagate for sufficiently low frequencies. The slot is cut parallel to the guide axis, in the middle of the wide face. It is a non-radiating slot, and the field pattern inside the guide is but little disturbed by it. A probe may be put into the slot to sample the local electric field strength, and moved up and down the slot along the waveguide to see the standing wave patterns and to measure the VSWR directly[2].

Mathematics behind the study

When an electromagnetic signal travels in medium other than air or vacuum, its propagation velocity is determined by the dielectric constant of the material, in particular, reduced by the square root of the dielectric constant ε. The velocity of propagation (v) with foam polyethylene insulator with dielectric constant ε = 1.25,

$$v = \frac{c}{\sqrt{\varepsilon}} \qquad (1)$$
$$v = 2.68 \times 10^{8}\, m/\sec$$

This is important when techniques of detection rely on the propagation speed of the signal down the tLCX. It is assumed that the coupling time is essentially zero as the signal is traveling in air.

Surprising, only until very recently did mathematical formulation appear to characterize the leaked EM field. The equation to describe the field of a periodic structure, relating the geometry of the slots, is given by[3]:

$$\mathbf{E}(r,\phi,z) = E_p(r,\phi,z)e^{-jk_z z} \qquad (2)$$

where $k_z= \beta - j\alpha$, β and α being the propagation and attenuation constants of the basic mode of the perturbed cable respectively in the z direction. These can be related mathematically with β_0 and α_0 of the unperturbed cable linearly, such as $\alpha= \alpha_0\kappa'$ and $\beta= \beta_0\kappa$. $\beta_0= k_0\sqrt{\varepsilon_r}$, where k_0 is the wave number of free space, κ′ and κ the function of many factors of the cable, such as slot size, placement, arrangement and operating frequency, and ε_r the relative permittivity of the dielectric material of the cable. For basic TE10 slot configurations of the LCX that is being studied here, κ and κ′ can be approximated to equal 1[4]. Since $E_p(r,\phi,z)$ in (1) are the periodic field functions of the slots in the z direction, it can be expanded into Fourier Series[9]:

$$\mathbf{E}(r,\phi,z) = \sum_{m=-\infty}^{\infty} E_{pm}(r,\phi)e^{-j\frac{2m\pi}{P}z} \qquad (3)$$

Therefore,

$$\mathbf{E}(r,\phi,z) = e^{-\alpha z}\sum_{m=-\infty}^{\infty} E_{pm}(r,\phi)e^{-j\beta_m z} \qquad (4)$$

where

$$\beta_m = \beta + \frac{2m\pi}{P} \qquad (5)$$

P is the period of slots. In particular, the propagation of the mth harmonic in the radial direction is[5]:

$$\eta_m^2 = k_0^2 - (k_0\sqrt{\varepsilon_r} + \frac{2m\pi}{P})^2 \tag{6}$$

in order to suppress higher ordered harmonics of the LCX field, the operating frequency should be:

$$-mf_1 < f < -mf_2, \quad m < 0 \tag{7}$$

Suppression of higher ordered harmonics are important for systems which employ the zoning technique since multiple frequency signals are passed into the tLCX and distributed in different zones. The location of the movement depends on the coupled signal's frequency.

The attenuation of coaxial cable is the sum of its resistive, dielectrics and radiating loss. In normal coaxial cables the resistive loss plays the dominating role. However, LCX are designed to radiate the RF signal over distance. LCX with large diameter and large slots will enable a longer sensor cable[6]. Intuitively, the coupling mechanism has a large effect on the total attenuation of the cable:

$$\alpha = \alpha_1 \cdot \sqrt{f} + \alpha_2 \cdot f + \alpha_3 + \alpha_4 \tag{8}$$

where α is the attenuation at a given frequency (db/100m), α_1 the loss coefficient of conductors, α_2 the loss coefficient of dielectric, α_3 the loss coefficient of coupling. α_4 the losses in the near magnetic field due to environment and f the frequency of the signal. The attenuation of the LCX is measured in accordance to the standard IEC 61196-4. In the free form method, attenuation is calculated by the following formula:

$$\alpha = \frac{N_e - N_s}{L} \cdot 100 \cdot [1 - 0.002(T - 20)] \tag{9}$$

where N_e and N_s are the signal strengths at the end of the antenna and at the source respectively, L the length of the antenna and T the temperature of the surrounding in ^{o}C.

Besides dealing with the mathematics to characterize the LCX, some measurement calculations need to be defined. The *Nyquist* Theorem is used to determine the maximum frequency that can be detected using a given sampling rate. In particular, it states that the highest frequency which can be accurately represented is less than one-half of the sampling rate:

$$f_{sampling} \geq 2 \cdot f_{signal\ of\ interest} \tag{10}$$

In order to capture and accurately reconstruct the transmitted signal, ample sampling points must be made dependent on the signal frequency.

Field Regions

The volume surrounding an antenna can be classified into three types of regions, each with its own EM field characterization. The furthest of the three, far field, only the radiated fields exist. This is mostly concerned with in communication systems where distanced distribution of signals occurs. However, in this LCX system, both transmitting and receiving are within a few meters of each other. In this case, depending on the frequency of the signal, they can either be in the reactive near field, or radiating near field, the later being further than the formal.

The IEEE definition of the reactive near field is 'that portion of the near-field region immediately surrounding the antenna, wherein the reactive field dominates'. The boundary of this field can be calculated by:

$$R < 0.62\sqrt{\frac{D^3}{\lambda}} \tag{11}$$

where D is the largest dimension for the antenna[7]. Calculations for the cables in the study puts D just over 3m, λ=1.78m from (1) and therefore the reactive near field boundary is approx. 2.41m The rLCXs are thus placed in the reactive near field and therefore any far field characterizations and generalizations are of limited use in this study.

Current use of LCX in wireless communications

The use of leaky coaxial cable is very new in the field of wireless communications. Proposed in 1956 by *Monk*, leaky feeders were originally conceived to provide subterranean radio propagation, for example in railway tunnels[8] and coal mines. Recently they have been considered as an alternative to conventional antennae for indoors micro-cells[9]. Studies of RF signal delivery in confined areas point out two major problems of conventional dipole antennas: large wave fluctuations[10] and high attenuation[11].

a) Discrete antenna b) LCX

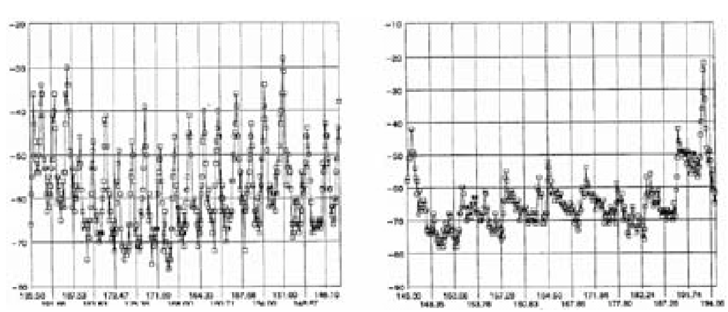
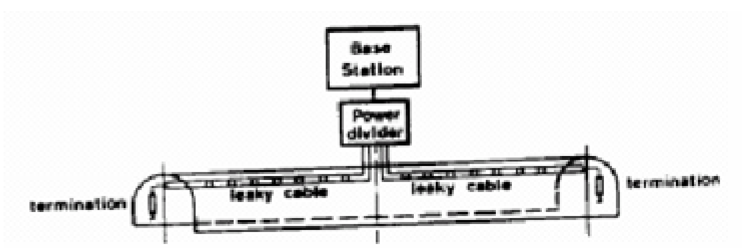
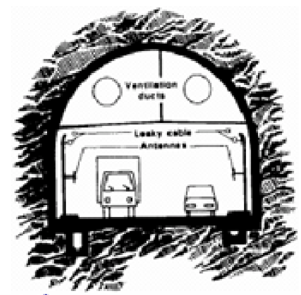


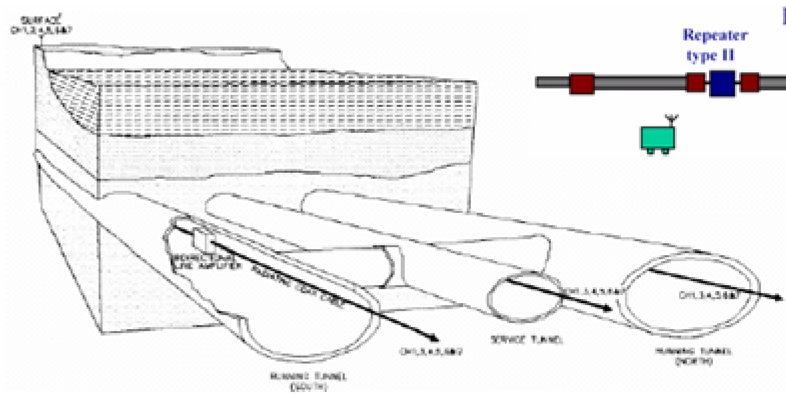
Figure I3: Results from a study comparing the field distribution of discrete antenna and LCX at 800 MHz in the Washington DC Metro system tunnels[9]. Note the large variations of signal magnitude in a) Discrete antenna compared with b) LCX

Because of these problems with conventional antenna signal delivery, LCX has been widely employed to provide continuous access guided communication (CAGC). These include but not limited to:

Mine Shafts, underground explorations and other ground confined areas (eg. subway systems and tunnels): Due to the complicated and unpredictable geometry of mine shafts and underground explorations, signals from conventional dipole antennas attenuate greater at subnormal distances. The turning and twisting, as well as the compositions of the tunnel walls, makes the transmission and reception much more difficult. Constant and reliable communication between miners and with the surface is vital for safety. LCX have been used in the English Channel, linking England to France, and in the 1.67 miles Ted Williams Tunnel connecting the Greater Boston Area and Logan International Airport.. A distributed antenna system--small interior antennas strategically placed throughout a structure to distribute RF signals along the curvature of the tunnel--was ruled out because of the sheer number of antennas that would be required. The state of the art train to track transmission system CROMATIC uses LCX lined tracks to bring about automatic train control and operations.







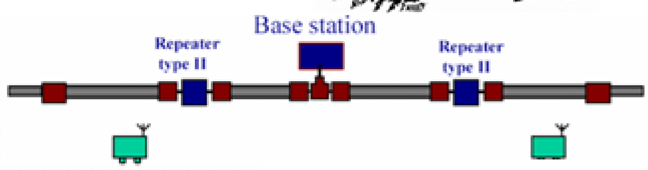


Figure I4: Illustrating the employment of LCX in underground transport systems. The length of each LCX section is limited to approx 150m before a signal booster or repeater is needed. This idea is often used in highway and subways too.

High rise buildings and skyscrapers: Even in ideal situations, analog radios can not penetrate more that five floors of steel and concrete[12]. Even digital radios can not fare better than six floors without repeaters placed strategically according to Motorola. This problem was also noted by the New York Fire Department when dealing with high rise structures[13]. The employment of LCX for communications between ground floor and higher levels can be seen in the World Trade Center, New York. LCXs were lined in elevator shafts that stretched tens of floors in the central part of the building to provide maximal distribution of RF signal. However firefighters did not receive the order to evacuate the building which was issued after a second plane hit the south tower because the LCXs were cut by the burning aircraft in the elevator shaft.

Objective

The objective of this study is to design a system to detect both the intrusion and extrusion of human sized objects using RF coupling coaxial cables. The user should alerted by the system visually if the perimeter is breached. In particular, the system should deliver clear messages the direction of the movement, whether into or out of the defined perimeter has occurred. The relationship between speed of movement and detection efficiency will be analyzed. Also the coupled signal magnitude will also be addressed for different situations. Since the strength of the coupling signal depends heavily on onsite factors, the user should have the ability to configure the threshold level of detection.

Approach

There are two parts to this study: the designing of the physical system capable of detecting and discriminating the direction of the movement of the breach, whether it being an intrusion or extrusion. Initial testing of the LCX cables will be done in parallel pairs to determine the range of coupled signal amplitudes in the rLCX. A separation distance between the tLCX and rLCXs is set to 1.5m, similar to the recommended for current existing systems[1]. Later testing of the system's response to speed of movement will involve changing this parameter. Signal with frequencies determined by the S11 ratio would be generated into the tLCX. In all cases, LabView will be used for signal measurement, capture and viewing[1].

The second part of the study will involve programming and designing an user interface with LabView to analysis and process the measured signals of the two receiving cables. The user will interact with the LabView using user-friendly and intuitive controls on the LabView front panel. Interactions will include user specified input of the threshold voltage for the alarm response as well as options for the user to preset threshold levels[14]. Initially, it is imperative that the understanding of LabView code, the structure and application of various tools be attained. This will require a substantial portion of time spent leaning about the fundamentals such as wiring techniques, various toolbox used for measurements and signal conditioning etc... In particular, since there are significant interactions between various hardware, compatibility and limitations must be addressed.

The aim of the study is to successfully design a system to fulfill the objective of directional detection. The applications of mathematical equations state in previous sections for calculations are, therefore, few. Results will consist of signals captured in various situations, analysis and explanations will be given. The LabView user interface, as well as the accompanying code will be explained in detail.

[1] Measurements were made using waveform capture.vi. Sampling rate of 2 KHz, for 10 seconds period used.

Experimental Setup and Preparation

Components used

Leaky Coaxial Cable: Andrew Institution Radiax RXL4.5-1 Coupled mode 5/8"

This cable is made from corrugated, welded copper outer conductor over low density foam[15] was used as the LCX. It is a coupling mode cable, capable of handing frequencies up to 2.4GHz. It was selected for its low attenuation at distances similar to current perimeter detection systems of 100m (2.3dB/100m), its low coupling loss and its low cost ($6/ft). Being a coupling mode cable means that signals can travel further and less higher-ordered spatial harmonics generated. Also the signal is less radiating, confining more to immediate vicinity which is advantageous to couple signals in distances 1-2m away.

Power generator: MGL Model 15122 RF Power Generator

The signal supplied into the tLCX must have enough power so that the leaked signal can be coupled into the adjacent rLCX. This is done by using MGL Inc. Model 15122 RF Power Generator[1] capable of delivering power up to 60W and frequencies of 200 MHz. A built in N type connect connected the tLCX with the generator. Refer to fig. E1.

Data Acquisition: NI E-Series PCI card, BNC 2110 data acquisition box

The 12bit A/D with max sampling rates of 200KHz provides necessary resolution for measurements needed in this study. It provides an easy interface and is compatible with LabView. Multichannel analog input is needed for the three LCX system. Refer to fig. E1.

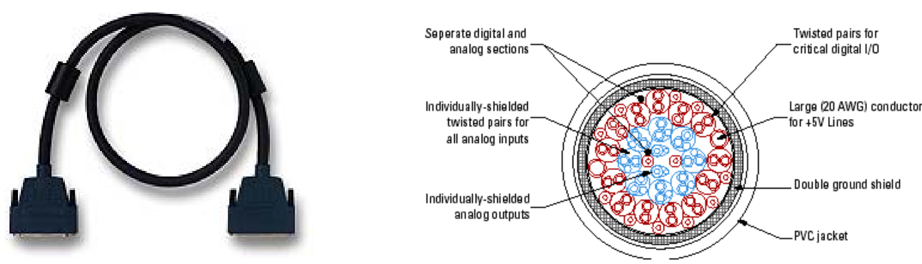


Figure E1: The NI SH68-68EP 100PIN cable connecting the 2110 to the E Series PCI card.

Connectors RG 58A/U cable to 2110, NI SH68-68EP to computer

By fitting an N-type-BNC adaptor on the end on the rLCX, we can probe the signal using conventional BNC probe. The RG 58A/U with 50Ω impedance was used so that the signal can be transferred with minimal reflection. National Instrument SH68-68EP cable connected the 2110 to the computer. This 100PIN cable is designed with channels independently shielded to provide minimum noise and signal interference.

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[1] Note: More detailed specifications of the power generator could not be found online. Apparently this machine has been sitting in the lab unused for many years. The power supply cable is dated back to 1970.

Figure E1: Left: MGL Model 15122 RF power generator capable of outputting 60W power from 50MHz to 200MHz. Standard N type connecter shown bottom left connects to the LCX via N type-LCX adaptor. Output options include continuous sine wave or pulsated. A BNC sampling channel is also available. The generator can take over 5 minutes to warm up. Right: National Instruments BNC 2110 12 bit A/D DAQ board with 8 analog channel input, 2 analog channel output. Two analog inputs are utilized to simultaneously monitor the signal coupled into the two rLCX. Two measurement references settings are available: signal wrt ground or wrt a floating point. A 100PIN shielded cable connects the 2110 with an E-Series PCI card. Each channel is independently shielded from each other in the cable to prevent cross interference.

Figure E2: *Left:* Typical setup of the three LCX system. Cables are placed 1m apart with the tLCX in the center. The cables are each 11feet in length, terminated by two 100Ω resistors soldered between the inner and outer conductor. *Right:* N type-BNC adaptors were attached to the rLCXs. A standard 50 Ω probe connected the cables to the 2110. *Note*: The 2110 is free from the computer for demonstration purposes.

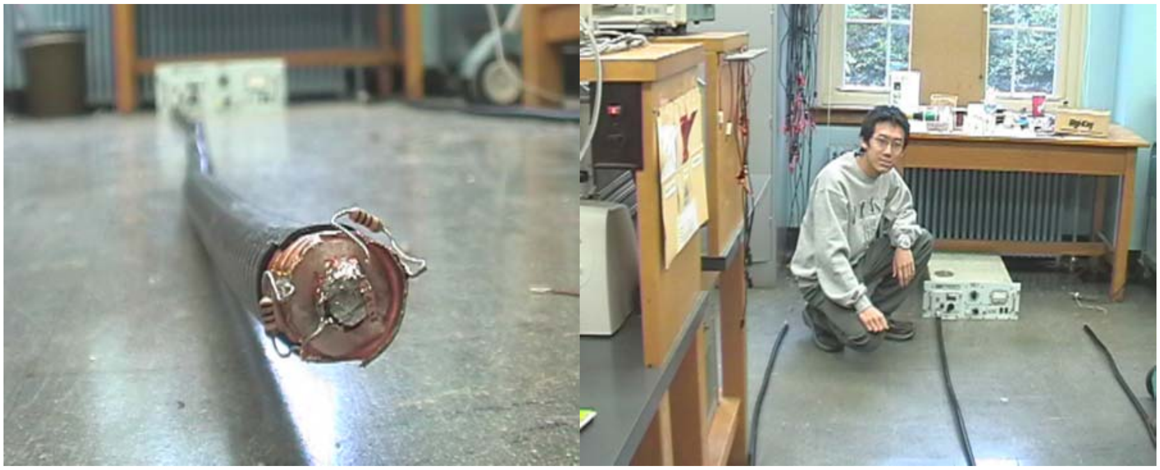

Figure E3: *Left:* Two 100Ω resistors were soldered on the end of the tLCX to act as a 50Ω terminating load. The load impedance matched the impedance of the cable to eliminate any reflections. Reflections are minimized as any power reflected back into the RF power generator can cause damage. The two resistors were soldered on opposite ends so that the current distribution can be kept as symmetrical as possible so not to affect the leaked EM field geometry. *Right*: Subject used to conduct coupling measurements. *Note*: Initially four 200Ω were used to further distribute the current evenly and to minimize each resistor's current throughput. However, the exposed resistors were easily moved and the solder did not stick to the inner and outer conductors. Two 100Ω resistors were hence used instead.

Construction

A two LCX system was first constructed to measure the basic parameters such as the power output of the generator and the separation distance. The cables were prepared by fixing type N connectors[16] onto one end and two 100Ω resistors in parallel on the other to simulate a 50Ω load for termination. Two 100Ω in parallel were used instead of a single 50Ω so that the current and signal distribution can be kept as symmetrical as possible. The load was matched to the cable impedance so that reflections are minimized. This is important as any reflections from the cable will damage the function generator. To find the optimum frequency at which signals leak out the most, the S11 ratio was measured using an HP 4395A Network/Spectrum/Impedance Analyzer. The S11 ratio remained at 0.88 throughout the frequency sweep with a S11 at 150 MHz the lowest. This meant 150MHz signals had the lowest returning magnitude and therefore implied that it was attenuated the most. Since radiating loss dominates in LCX, it meant that the cable leaked 150 MHz signals most effectively.

The tLCX was connected the 15122 outputting 5W power at 150 MHz[1]. The amplitude of the coupled signal when movement occurred was recorded[2]. Due to automatic scaling of LabView[3], amplifications of the coupled signal were done automatically and a true

[1] As displayed on the RF Power Generator and independently verified by HP 5400C oscilloscope and the RMS value.
[2] Subject: Male, 140lbs, 1.7m waling speed of 1.5m/s. Measurements were made using waveform capture.vi. Sampling rate of 2 KHz, for 10 seconds period.
[3] Note: It was extremely frustrating to calibrate the measurement of LabView. Initial measurements suffered influences from nearby RF sources, a problem Dr. R. George suggested me to go 'sniffing' - 0.7VDC were observed in a open circuit. Furthermore, LabView automatically adjusts a scaled gain so that

voltage signal was only measured by an HP 54600A oscilloscope to be approx. 540mV. LabView was able to amplify the signal to give a peak of approx. 5V in amplitude, a 100 in gain. It is necessary to address the issue of sampling rate. The sampling rate used to capture the waveforms is 3 KHz. According to (10) this is way below the required sampling rate in order to monitor the 150 MHz signal. While this is true, our detection method does not need accurate monitoring and reconstruction of the signal, and, instead, designed so that it relies on aliasing to detect the change in amplitude. We do not need to sample at 300 MHz (10) in order to detect the change in magnitude. Our signal of interests is the modulated carrier frequency created by the movement of the intruder/extruder and therefore 3 KHz is enough to catch the set of samples at which the amplitude has changed. The use of 150 MHz was simply because the tLCX leaked signals of the frequency the most.

Experimental Results[1]

Different situations of movement across the two LCX system are presented.

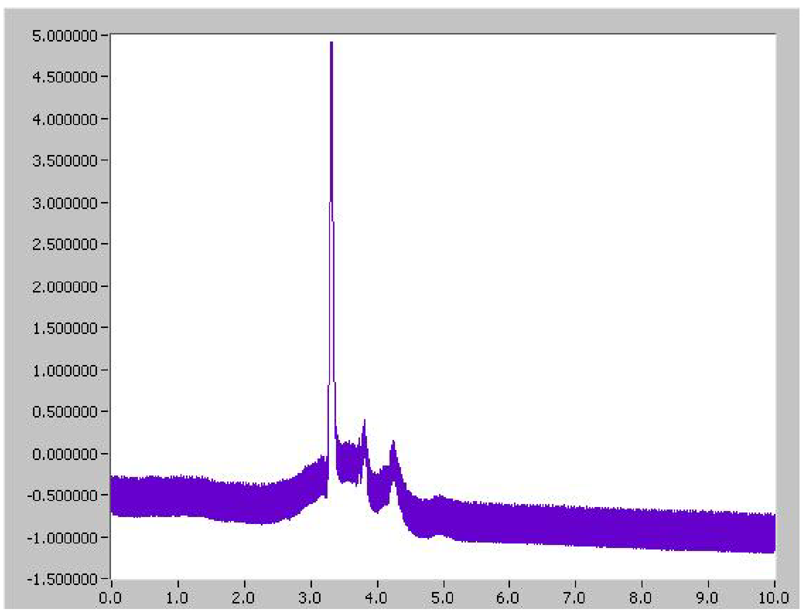

Figure R1: Signal coupled into rLCX placed 1m away from tLCX during movement. Subject was traveling at a speed of 1.5m/s (typical walking speed) from the tLCX to the rLCX direction perpendicularly. He stepped over rLCX at approx 3.0 seconds after start of measurement and did not touch either the tLCX or the rLCX during travel. Date: 3/22/03

small signal amplitudes can still be viewed, an annoying problem that, while it does not influence the design of the system (actually improving the results), it altered the measurements in an unknown way.

[1] Note: The presence of the second rLCX did not influence and interfere with the coupling signal of the first rLCX and therefore it can be assumed that some studies and measurements can be translated to the second rLCX. All measurements taken using *waveform capture.vi* @2 KHz sampling rate. x-axis voltage y axis time. In all measurements subject is a 140lbs, 1.7m male in t-shirt, shorts and sneakers unless otherwise stated.

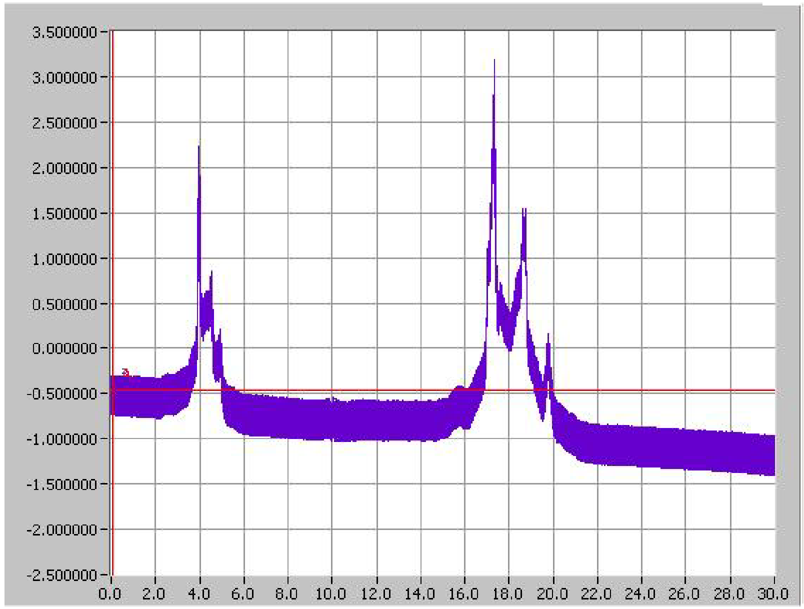

Figure R2: Subject walks from tLCX-rLCX direction twice in 30 second period. The first time he traveled at normal walking speeds of 1.5m/s and second time, twice as slow at 0.7m/s Note the increase in signal amplitude, the longer time of the disturbance and also the increased in time between initial and successive peaks.

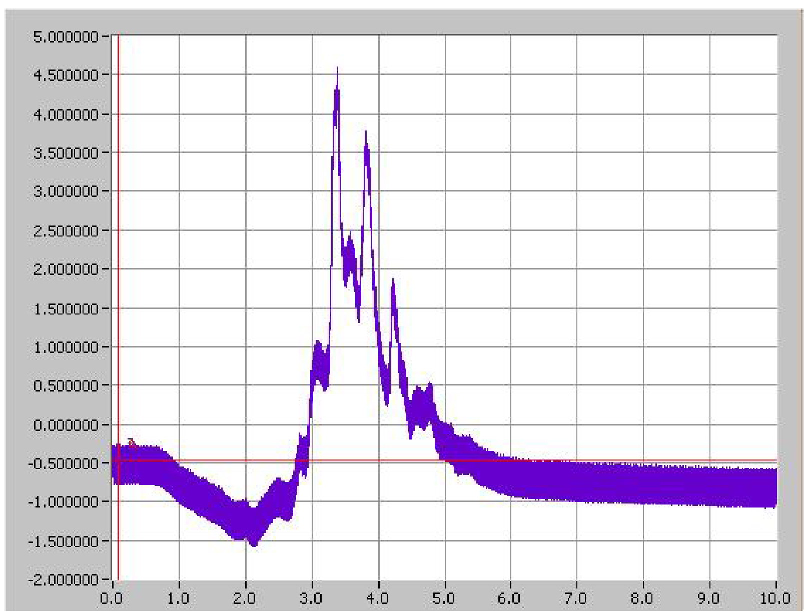

Figure R3: This signal was captured with the movement of two subjects, male, 1.6m, 170lbs and female, 1.5m, 110lbs at normal walking speed of 1.5m/s. Note the initial negative dip before a series of disturbances, with noticeable increase in fluctuations and peaks. The length of disturbance, however, remains at approx 2 seconds.

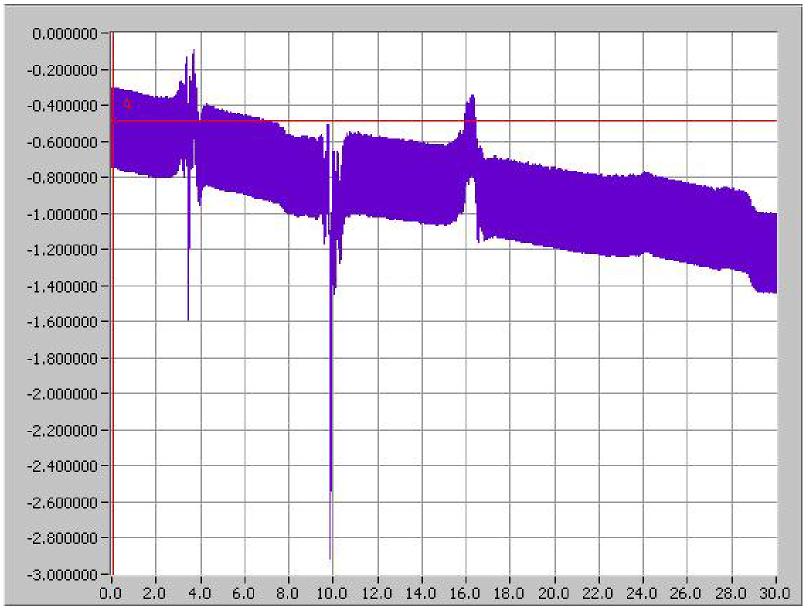

Figure R4: Subject leaped across the rLCX twice and brisk walked (>2m/s). A phase shift and negative amplitude can be seen.

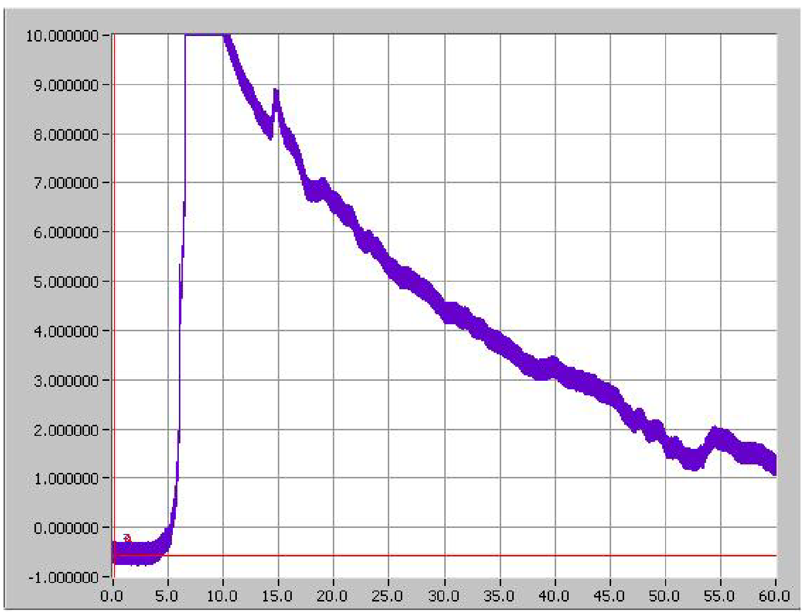

Figure R5: Subject stood on the rLCX for a 1 min period. The transient response was evident with a signal voltage of approx 12V. Capacitive coupling seems to have occurred with the body. The time constant is calculated to be 28 sec.

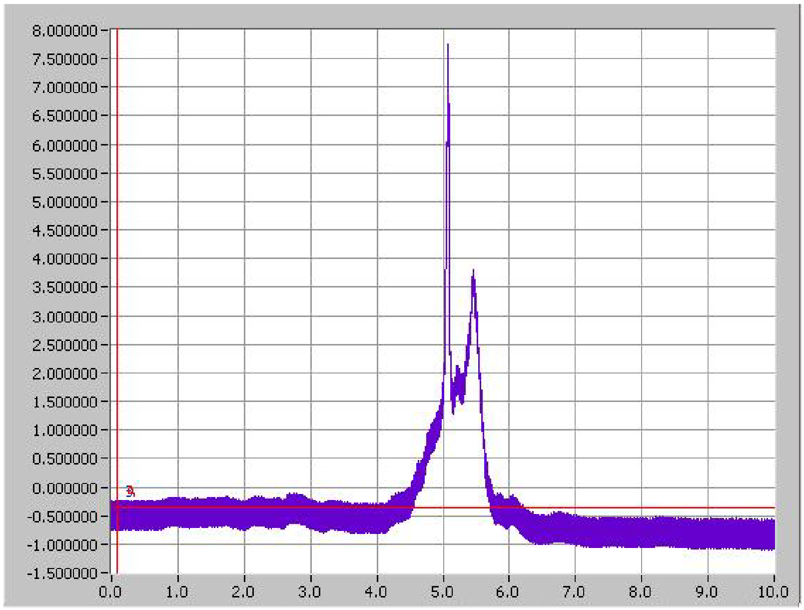

Figure R6: A typical signal for response rate study. The subject crosses the boundary of the rLCX at 5 seconds after measurement begins. Note the third peak has a greater amplitude than the second, compared to other waveforms.

Time of direct crossover (sec)	LabView index (#)	LabView index time (sec)	Time difference (sec)
5.0	10244	5.12	0.12
5.0	10160	5.08	0.08
5.0	10083	5.04	0.04
5.0	10204	5.10	0.10
5.0	10172	5.08	0.08

Table R1: The difference in time of disturbance of the rLCX between actual time of direct crossover and LabView measured time. Subject traveled at 1.5m/s (typical walking speed) from perpendicularly from tLCX to rLCX. Starting point was approx. 3m away from rLCX and travels were timed so that crossing of rLCX occurred 5 seconds after measurements started. *Waveform capture.vi* sampling rate was set to 2 KHz for 10 second time period.

Analysis and Discussion

Part I: Disturbance measurements

With the automatic gain that LabView uses to magnify signals, all movements across the boundary of the rLCX of the two LCX system produced sufficient changes in amplitude such that peaks cane be identified and located using LabView code. In general:

a) all disturbances produce a initial peak followed by two smaller amplitude peaks.
b) There is constant signal coupling of approx 0.5Vpk-pk in all the signals captured.

c) A negative DC offset is seen. This is more attributed to LabView automatic scaling as DC offsets were not observed in oscilloscope confirmations.
d) Negative drifting in signal voltage after the disturbance. This was especially evident in fig R4.

Theory of disturbance
It is theorized that the increase in signal amplitude can be attributed in either, or both an increase in reflection and RF coverage, or the creation of Eddie currents during movement.

Reflection and coupling of otherwise dispersed energy.
Radiation and energy distribution from small dipole antennas can be model as energy from a point source in a isotopic manner. In the tLCX, the relatively long length of the LCX suggests a cylindrical radiating pattern along the cable. The many slots, while each can be modeled as a dipole source, can be model as an array of dipoles. Studies have shown that the presence of a body in a RF field can create a shadowing effect, blocking, absorbing and attenuating the signal in that direction[17]. It can be speculated that while most of the absorbed energy will be converted to heat, some of the signal's energy will be reflected by the body and onto the rLCX. In this theory the magnitude of the coupled signal should depend on the cross sectional area, the geometry and the angle of the object wrt the cable. Also, the slower the object, the longer it will remain in the optimum reflective region and therefore leading to longer disturbance times.

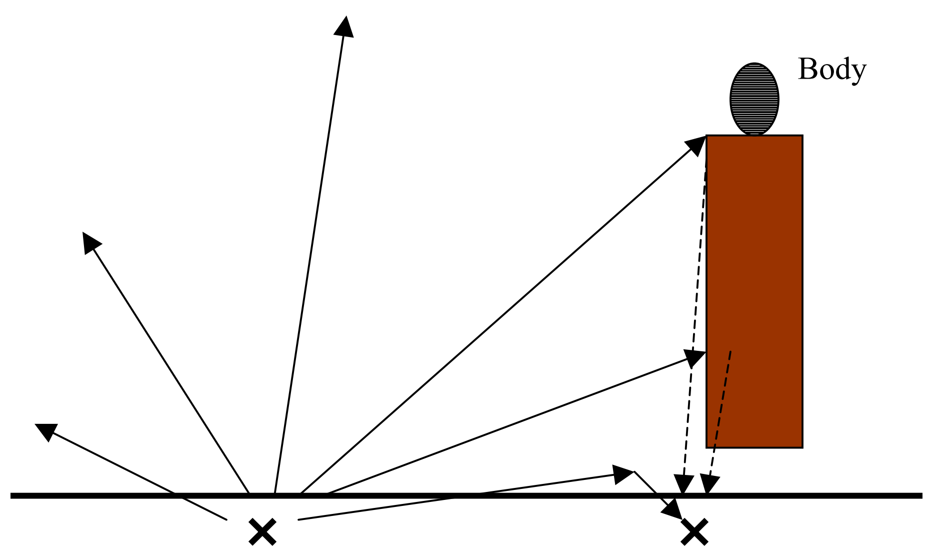

Figure D1: Energy that is otherwise lost to surrounding is blocked by the body. As the body reaches directly above the rLCX (Dashed) signals are reflected and coupled into the rLCX.

Eddie currents

Similar to the magneto effect observed in EM, the movement of an otherwise steady field will generate Eddie currents in the field. The movement of the body in the region increases the fluctuation of the field in the region, leading to a higher coupling of energy into the rLCX. In this theory, the object's conductivity and permittivity will play a role in the disturbance of the field. The magnitude of the coupled signal will depend on the speed of movement, the mass, the cross sectional area and the acceleration of the object, in accordance with the magneto effect. The complex permittivity of the body muscle is given by:

$$\varepsilon = \varepsilon_0 \varepsilon_r + j\frac{\sigma}{\omega} \tag{12}$$

where σ is the conductivity of the object. σ = 0.95S/m for muscle at 150 MHz. Essentially the body is a salty bag of water. The movement of this in a B,E field will create massive disturbances in the field[16].

Relating results to theory

Results seem to support both theories of energy coupling. The signals in fig R2 show the difference in speed at which the object is moving as it crosses the rLCX boundary. The slower the movement, the longer it will remain above the rLCX resulting in higher signal amplitude and longer disturbance times. The high resolution also shows the difference in time period between the first and successive peaks, the slower the body travels, the longer that time. This result seems to support the reflection theory. Fig. R3 further supports the reflection theory. By having two subjects move across, the effective cross sectional area for any reflection increases. More of the escaping radiating energy is blocked and shadowed by the increase in coverage of the two people.

The results from fig R3 can also support the Eddie theory. By increasing the mass movement, larger fluctuations will be induced into the region, leading to a higher coupling amplitude. Fig R5 shows the signal coupling when the subject remains motionless above the rLCX. Initial transient response can be observed. However, the signal amplitude slowly decays, similar to a capacitive discharge. The coupling energy decreases slowly and returns to normal, despite the continuous reflection of signal claimed by the reflection theory. Further, if the movement of the body creates Eddie currents in the region, we should see disturbance patterns far earlier in time, before the object reaches the region above the rLCX.

It seems that both theories of coupling and disturbance mechanism play a part in the increase in amplitude of the measured signal in the rLCX. Results seem to contradict, in terms of relying on a single mechanism of energy transfer.

In the near field, only the magnitude and the phase of the signal can be altered by external disturbances. Fig R4. shows a negative amplitude increase as the subject leaped across the rLCX. The signal was equally large in magnitude but only negative. This change can be attributed to either the movement towards the rLCX from the tLCX, movement away from both the rLCX and the tLCX, or the movement from rLCX to the tLCX. Such shifts were, however, not seen in other signals captured during movement from rLCX to tLCX direction.

Part II: Distance of separation and response rate

Referring to fig R1 the response rate of the system is very fast. The transient response was quickly picked up by the *waveform capture.vi* as the subject passed directly over the rLCX. The time delay between the moment of crossing the rLCX and the peak generation is approx.0.08 seconds, which is not a problem in this study.

With this fast response rate it is expected that the instant the subject passes across the rLCXs a peak will be generated and hence, the time of disturbance can be determined by the LabView program. Indeed, referring to table R1 measurements were made to relate the actual time of crossing the rLCX and that the index number registered by the LabView code. LabView builds an array to store measurements-the data is arranged in a matrix relating index number with values measured. Therefore, by relating to the sampling rate of the vi and the index at which the measurement reached the threshold level, the alarm triggering time can be determined. In the above case the sampling rate was set to 2 KHz and therefore 2000 samples were taken in one second. The index at which the threshold level is reached is divided by 2K to determine the actual time.

What it observed here, similar to that of Part I discussion, is that peak generation, the bases of detection in this system, occurs no where except when the subject crosses directly over the rLCX. The field is minimally disturbed by movements occurring on the sides of the rLCX. Maximum coupling is achieved with the body directly over the rLCX. This suggests that the system designed does not generate a volumetric region of detection, but instead two walls of detection, the base of the walls lined by the rLCX.

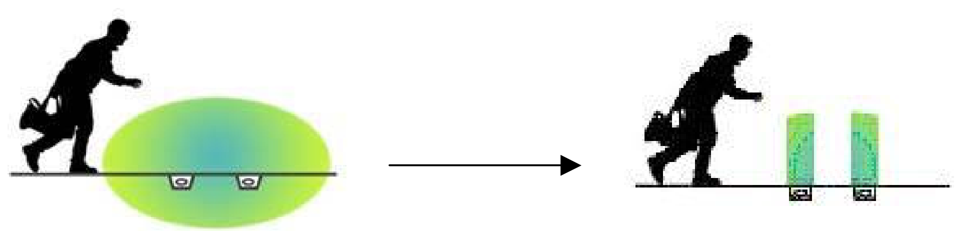

Figure D2: Results from the time of maximal coupling (peak generation) suggests that the system designed did not detect movement in the regions around the cables but instead, only in the region directly above the rLCX. Rather that a volumetric detection system, the system is a ‘wall’ region detection system directly above the rLCX.

This effect is, in all ways, advantageous. Fig R2. illustrates the difference between the system in this study and that of the claimed detection coverage of other systems. The fact that each rLCX’s detection region is limited to the area directly above it means that disturbance of one rLCX will not affect and disturb the other rLCX in the three LCX design. The order of disturbance, and hence the direction of movement can be determined much more accurately. Furthermore, this supports the initial assumption that tests and measurements on a two LCX system can be transferred to the second rLCX in the three LCX system.

Using this data, the separation distance of the LCXs can be determined so that the order of disturbance can be known. Referring to table R1, the average delay in response of 0.08 can be approximated to instant response. In fact, with such a response rate the separation of the LCXs will not depend on the speed nor the size of the object, but instead, on the coupling quality. If the coupling signal has low amplitude, then the LCX should be placed closer. It should, however, never be placed out of the near field region distance (2.41m from (11). As mentioned before, the speed of the object will affect the signal amplitude: placed as close to the tLCX as possible for high speed objects.

Part III: LabView

LabView was chosen as the platform for data acquisition and analysis for it real time signal capturing ability. The many measurement toolboxes available meant that complex procedures can be simplified to a simple point and click procedure. The coding interface is particularly easy to pick up and learn. Coming from National Instruments meant that it is fully compatible with the other equipment which was also from NI, the BNC 2110. Its ability to simultaneously monitor and measure two analog input channels is also necessary for the three LCX design.

Discussion on LabView detection code

User interface: The objective was to create a simple and easy to use computer interface which would monitor the LCX detection system using LabView. The user should be informed with a clear and concise message ‘Warning, intrusion detected’ or ‘Warning, extrusion detected’ depending on the movement direction, either visually or otherwise. As mentioned before, the signal coupled into the rLCX at steady state depends greatly on onsite factors such as moisture levels of both the air and the soil, the type of soil etc, initial calibrations and threshold levels must be set to differentiate between normal levels of signal coupling and that from movement.

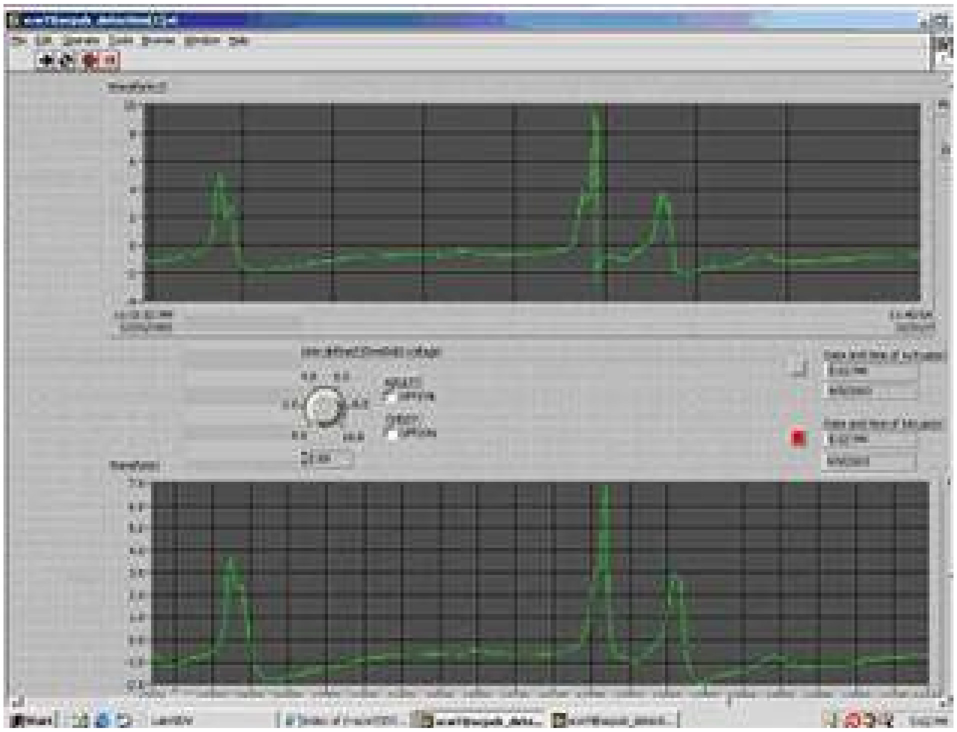

Figure D3: Showing the signal captured by the two channels monitoring the two rLCX. By determining which channel passed the threshold first, the order of disturbance of the cables can be determined and hence the direction of movement. Note that the peak signal captured by cable A (waveform above) is slightly ahead of the signal captured by cable B (waveform below) and therefore, in the above case configuration, an intrusion LED alarm is triggered along with the time of occurrence.

Referring to fig D1 showing the user interface and its response to movement, the user can observe the signal measured by the two channels of the 2110. Movement above the cables will trigger similar peaks observed in the *Results* section and by comparing the magnitude of the captured signal with the user defined threshold levels, the system reacts accordingly by triggering a visual LED alarm as well as giving the date and time of intrusion. LabView can also be programmed to execute other .exe commands and can, via 2110, output a voltage to drive a relay device and, in turn, trigger electronic measures such as a gate, alarm, CCTV etc.

Virtual Instrument (vi) coding: LabVIEW is a program development application that uses a graphical programming language, G, to create programs in block diagram form[18]. User wires various tools together to manipulate, analyze and perform measurements on incoming data. The foundation of data processing and storage is by using *arrays*- tables and matrixes of numbers.

The basis of the detection system code is to be able to find the location of peaks that are above the threshold level, either predefined during onsite installation, or user defined value. Once the locations of valid peaks are found for both of the cables, they are compared to see which one appeared first- the order of disturbance is determined. From there, the appropriate warnings and alarms are given. The following explains the stages of LabView data process. Please refer to fig D2.

User input: Using Boolean logic, LabView check to see if the options for predefined threshold levels are checked by the user on the *user interface* panel. If not, the user defined threshold level is used for peak detection. This value is wired into the *threshold peak detector.vi* for later usage.

Array manipulation and data input form channel: The while loop defines the continuity of the detection by running the encapsulated code over and over again. An array sized 10000 is first initialized with all elements equal to zero and wired into a *replace array element.vi*. This vi has three input ports: index number, element data and array. This vi essentially replaces the specified index number in the inputted array with the new data it receives, in this case from the *Analog input sampling channel.vi*[1]. Being in a for loop, this process is repeated 10000 times. Essentially we are replacing the initial 10000 array with new data measured by the 2110. We have created an array with 10000 new points of voltage measurements. The above operation is done twice, once for each channel. The overall output from the for loop is two 10000 updated arrays.

Array process and analysis: The arrays are wired into a *threshold peak detector.vi* where each point is compared with the inputted threshold level from the user input stage. If there are points that are above the threshold level, the index location is outputted. By comparing the index values for the two arrays from the two rLCX, the order of the peaks can be determined. Using Boolean logic the values are compared and a T/F output will by trigger to show the appropriate warnings displayed in the user interface. The time and date will also be displayed.

Detection window: While the process so far can identify the location of the peak where the signal measurement is above the threshold voltage, a problem arises when the coding will not correctly identify the direction of movement. Since the *threshold peak detector.vi* works by an input of array, data is channeled in packets of 10000 measurements at a time. If the program is at the end of competing an array of data during which movement is in progress between one rLCX to the other, the peaks will be registered in different arrays and the order which the cable were disturbed will not be correctly identified. To solve this problem, the whole detection code is placed inside a case loop. Only if the coupled signal is above 0.7 that of the threshold.(due to onsite calibration), the recording of the data set for peak detection will be conducted. Taking 10000 samples will take approx[1] 10 seconds and therefore a 10 second window of data recording occurs only if there is a chance that movement arises. The above processes are repeated for constant detection of peaks.

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[1] Note: The sampling rate is not controlled by the user. This vi is not the employed in the *waveform capture.vi* used in earlier measurements where the waveform is to be accurately captured. The sampling rate of *AI sampling channel.vi* is set to 1000Hz. However, this value is computer memory dependent and will slow down depending on memory usage. This is one of the disadvantageous of LabView and should be improved upon.

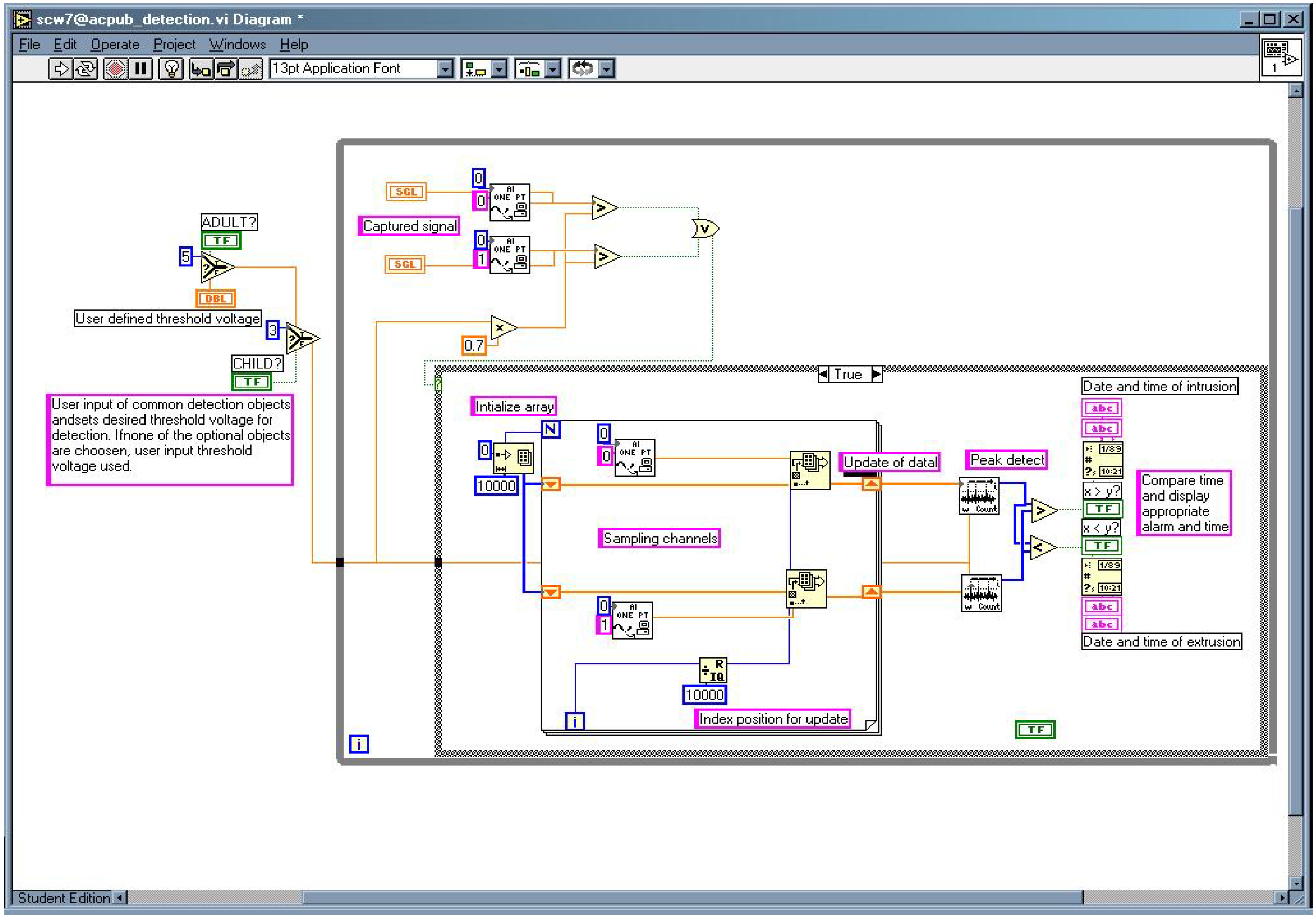

Figure D2: LabView uses G language, a graphical interface for coding. Here we see Boolean logic control for user input, for loop within a while loop, various array operations, two input channels 0 and 1 from device 1 (2110), peak detection and Boolean logic for peak location comparison.

Real world applications and considerations

Combining with other LCX detection techniques.

While the passage and movement of objects above the rLCX will cause an alarm, the user will not know where on the length of the cable the movement occurred. There are two types of LCX system design to address this issue: zoning and timed reflection analysis.

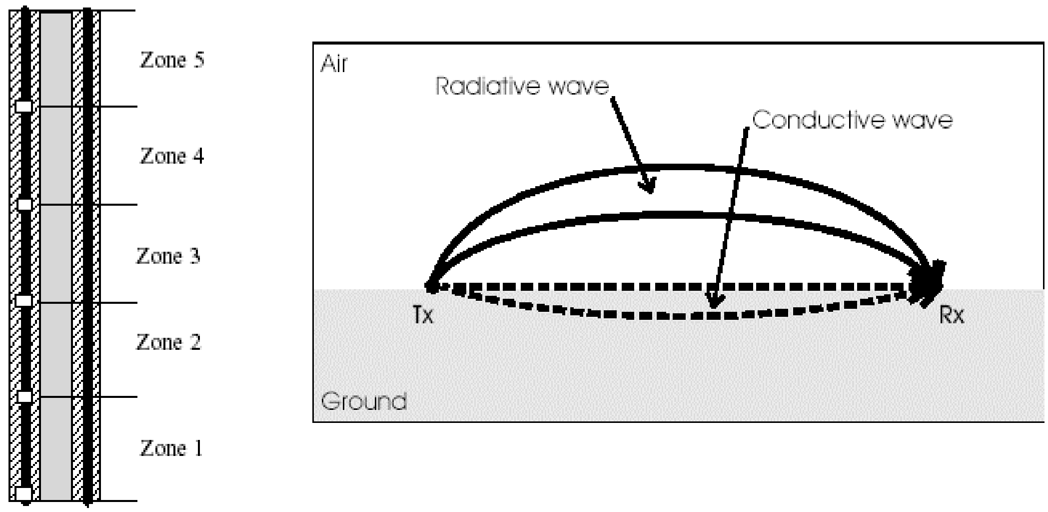

Figure I 1: ***Left:*** In the zoning method, different frequency signals leak out at different areas depending on the slot configuration and therefore by analyzing the coupled signal in the rLCX the location of movement can be known. *Right:* Onsite calibrations are extremely important because the effectiveness of coupling of the rLCX depends on many environmental factors such as soil type, humidity, moisture content, buried depth etc. Two paths of coupling exist: radiative and conductive.

Zoning: The aim of this LCX design is to specify which zone in the perimeter the movement occurred. The perimeter can be sectioned into different zone of approximately 50m each. Since the leakage of the signal is determined by the slotting arrangement and geometry, each zone can have different slotting configurations. By sending multiple frequency signals down the tLCX, different zones will leak signals at different strengths. By analyzing the type of signal coupled into the receiving cable when an intrusion occurs, the user can determine which zone the movement is in. In this sort of system it is important to employ coupling mode type LCX for it has the structure to support multiple frequencies and higher bandwidth. Furthermore a lower frequency efficient LCX should be used. When the analysis of the coupled signal depends on the frequency, (10) demands measuring equipment with higher sampling rates. The limits of NI BNC 2110 is at 200KS/s, and will not accurately differentiate different signals.

Time Domain Reflectometry: The second method used to locate the movement is to use pulsated signals. Similar to TDR used in locating damaged pipelines, pulsated signals can be transmitted into the tLCX. By knowing the velocity of propagation down the tLCX (1) and when exactly the signal is coupled into the rLCX, the distance from the power source to the movement can be calculated and, from that, the location of the movement will be known.

There are two competing paths of coupling from the tLCX to the rLCX: radiative and conducting. Since the conducting wave travels through the soil and below ground, it is not disturbed by the movement of the intruder/extruder. It is for these reasons that when the conductive wave is strong in relative to the radiative wave, then such configuration is more sensitive to; surface water accumulation, change in burial medium and burial depth. Similarly, it is less sensitive to detect a jump over intrusion[5]. Therefore, the installation of the LCX should ensure that the radiative wave path dominate over the conductive wave path. This can be done by lowering the water content of the soil, burying the LCX closer to the surface etc.

Results have shown that the number of bodies moving across the cable can not be determined with the detection coding in this study. The difference between 2 and 3 people is the increase in fluctuation of the disturbance, which is not monitored by the LabView code. Such a problem can be overcome by employing multiple security systems in tangent to the LCX system. The LabView code has the ability to call upon external switches and computer .exe command and therefore if the alarm is coupled with a Video Motion Detector system, the operator can immediately be alerted of the movement and have visual confirmation.

The movement of water and metallic objects in the surrounding area can change the nominal coupling signature. Underground drains and pipes, collection of surface water etc can affect the performance of the system greatly. This places restrictions on the installation of the LCX system to high, dry terrains and at least 6ft away from fencing and pipes. Also the changing types of soil in a given stretch of LCX can induce fluctuations in signal quality by having different conductivity and dielectric constant. ‘Drastic decrease in detection sensitivity caused by the heavy clay with conductivities of nearly 200S/m’[1], in due to the dominating conductive path over the radiative path. Unacceptable detection performance, the article concludes, will likely occur with soil mediums with conductivity above 200mS/m. The number of transitions from material, should be kept to a minimum.

Future work and direction of study

There is *much* to investigate in the usage of LCX in perimeter security. While the system has been in use for over 30 years, simple studies such as medium characterization and its affect on detection performance has been done only lately. In particular, in this study, the method of detection can be further improved by the use of correlation of known object signatures with the incoming signal to further refine the detection process. LabView’s automatic gain adjustment, while helpful in this study, needs to be further investigated and understood[1]. The use of an extra LCX will not only increase the probability of detection, but also the cost. Better characterizations of the field generated by LCX will also mean a more supported theory on the coupling and disturbance mechanism. The mechanism of reflection, for example, can be investigated by using reflective metal sheets placed in systematic and quantifiable ways to confirm the influence of reflection

[1] Contact with NI representative was made but the results were unhelpful.

on the detection mechanism. Different masses of water simulating the body can be moved at different speeds with different rates of acceleration to analyze the Eddie current theory.

Summary

The employment of leaky coaxial cables (LCX) as a means of perimeter security has been proven successful for over 30 years. This study aims to improve the current design by allowing user to determine the direction of movement, necessary in certain applications. Many factors, such as signal coupling and threshold levels are site dependent and therefore initial onsite calibrations must be made. Additionally, the high cost of installation may be a deterrent for some. However, with the invisible and covert detection method, along with its terrain following ability, the LCX systems remain a viable option in perimeter security. This study has shown the successful implementation of a three LCX design. The distance of separation of the cables is determined by the speed of the object which we wish to detect. Results have shown the fast time response, in the order of milliseconds and therefore separation of the cables depend on the limiting coupling signal amplitude the most.

Acknowledgements

This is the first independent study for me and without the help of many professors the generation of results and analysis would not be possible. First of all I would like to acknowledge Mr. Ray Knowles from RKGuards. It was him who suggest the idea of investigating the use of LCX in perimeter security systems. Secondly, Dr. Joines and Dr. George, Duke University for their help with lab equipment. Dr. Cummer, Duke University for providing valuable insights. Roger, Duke University for those extremely interesting ideas and concepts, and also help with results generation and measurement. Lastly, special thanks to my advisor Dr. Gary Ybarra, DUS Duke University ECE for his *consistent and powerful motivation in this independent study.*

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[12] Harry Goldstein, "Radio Contact In High-Rises Can Quit On Firefighters," *IEEE Spectrum*, April 2002.
[13] As noted by Frank Gribbon, Deputy Fire Commissioner for the New York Fire Department in a debriefing report.
[14] Often the preset values are determined by initial onsite calibrations during installation of the system.
[15] Detail specifications can be found at Andrew Institute
http://www.andrew.com/search/docviewer.aspx?docid=3892
[16]Supply of the N connectors and specifications:
http://www.andrew.com/search/docviewer.aspx?docid=3840
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[18] Taken from LabView 5.0 Student Edition help file. For more help please visit www.ni.com.