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Abstract

The objective of this project is to demonstrate a method and develop hardware to use a metal pipeline as the backbone of a communication system for sensors that monitor the right-of-way. Transmission pipelines are sometimes damaged by construction equipment in spite of being buried in a well-maintained and marked right-of-way. There is a need for a continuous monitoring system to detect encroachment by construction equipment and other events along the pipeline. Although several concepts have been proposed and are in various states of development, there is no commercially viable method for detecting or preventing third-party damage that is acceptable to the industry.

The fundamental issues preventing continuous monitoring of pipelines are the high dollar cost of deploying, powering, and communicating with such a geographically dispersed system. The various means of sensing pipeline parameters have, in general, been effective. What has been lacking is a cost-effective means of powering sensors and collecting the data. Recent developments in low-power embedded microcontrollers and wireless communication suggest continuous monitoring is now possible.

Gas Technology Institute (GTI) proposed new technology to reduce the risk of excavation damage to pipelines by providing the following features:

- A network of continuously active sensors, buried along the right-of-way
- A central interrogator connected to the pipeline that collects data from the sensors
- A communication method to collect the sensor data
- A continuously present locating signal on the pipeline or tracer wire
- Continuous monitoring of the pipeline or tracer wire impedance to detect damage
- Means to correlate sensor data such as impedance, impact, and pipe potential

The pipeline itself will be the communication medium that links the network of sensors together. The emergence of Radio Frequency Identification (RFID) has brought with it a body of low-frequency radio technique (frequencies below 160 kHz) that can be adapted to underground signaling. The approach in this project is to combine/modify/optimize existing technologies to develop the networked RFID system. A key enabling technology is detection of backscattered signals from an RFID tag.

The system components are RFID enabled sensors and a device to interrogate them. The system required balancing optimization points, for example energy transfer from a carrier current to a RFID tag increases with frequency while the range of signal transmission on the pipeline decreases. Breadboard circuits were designed, built, and optimized. Proof-of-concept was established. The system was demonstrated in the laboratory. It was also demonstrated on a buried 4-inch diameter steel pipe, where a battery assisted RFID tag was buried next to the pipeline. The battery powers the microprocessor, but does not provide energy for communication; this is accomplished by a backscatter modulation. For the purposes of demonstration, temperature data was transmitted on the steel pipeline for a distance of 100 feet; any sensor that provides an electronic output signal could be used in practice. The continuously present carrier frequency is at an operating frequency which permits an acceptable the range. A proprietary version of the report was also written to protect patentable information.

Activities/Deliverables Completed during this Project by Task Number

Task 1. Develop a Practical Current System

- Analyzed cathodic protection, pipe location, and RFID tag technologies in terms of trade-offs and optimizations that need to be made.

- Selected the frequency range and designed the first experiments.

- Designed and built initial breadboard hardware for the always on "tracer" signal generator.

- Designed and constructed RFID coils and other circuitry to test the potential for communication between the coil and base station.

- Demonstrated proof-of-concept of backscatter detection.

- Selected battery powered acoustic amplifier sold for automotive applications to drive the carrier current onto the pipeline.

Task 2. Develop a Battery Assisted RFID Tag

- As work progressed on Tasks 1, 2, and 3, improvements in one aspect generated improvements in the others. This process was repeated several times resulting in significant improvements to all parts of the system.

- Developed an improved method to rapidly modulate transmitter coil signal. The design permits sharp transitions between high and low states and provides high power isolation of the RFID tag's microprocessor from the transmitter coil.

- Selected the frequency shift keying (FSK) modulation scheme with IEEE P1902.1 as the communication protocol.

- Investigated a number of microprocessors to modulate the data at the RFID tag. The microprocessor selected has excellent signal processing capabilities, and has an analog-to-digital convertor to read sensor voltages. It is also an extremely low power microprocessor.

- Programmed the microprocessor to gather data from the sensor in the RFID tag, format it, and send the data to a software defined modulation routine.

- Completed design and construction of a breadboard, battery assisted RFID tag. The battery does not power the communication signal on the pipeline.

Task 3. Develop Electronics to Receive Information from the Prototype RFID Network

- Developed circuitry that detects the backscattered modulation signal from the RFID tag.

- In a series of steps, made significant improvements to the design of the interrogator, especially better circuitry to detect and condition the backscattered modulation signals.

- Increased the frequency shift keying (FSK) frequencies to 400 and 500 Hz.

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- Constructed final breadboard interrogator with a combination of analog circuitry and a microprocessor. The microprocessor performs digital filtering and processes demodulated signals from the RFID tag.

- Implemented digital Infinite Impulse Response (IIR) filtering after analog amplification and filtering to improve demodulation and decoding.

- Selected temperature as the tag sensor because of ease in changing and documenting data transmission.

Task 4. Testing the networked RFID System

- Demonstrated robust one-way communication from the RFID tag to the interrogator breadboard in several laboratory tests.

- Demonstrated data transmission over 100 foot distance on a buried 4-inch diameter steel pipe on GTI's main campus.

- Demonstrated changes in temperature as measured by the RFID tag sensor are correctly transmitted from the RFID tag to the interrogator.

- Documented data transmission rates of 5 Baud on a buried 4-inch pipe; which is sufficient for pipeline monitoring needs. During one 16.3 hour test, 266,112 bits were transmitted error free.

Task 5. Management and Reporting

- Completed all of the reporting requirements on schedule.

- Started the process of obtaining a U.S. Patent on the technology.

Technical Status and Schedule (description of tasks completed, data from test results, research findings and/or discoveries)

The approach to this project was to combine/modify/optimize existing technologies to develop the networked RFID system. A key enabling technology is detection of backscattered signals from an RFID tag.

Some of the technologies have conflicting optimization points. The components were analyzed to optimize the system. Initial breadboards were made and used to demonstrate proof-of-concept that backscattered signals created in a tag can be detected. The next steps made the improvements to all parts of the system to make the approach practical. As work progressed, improvements in one part of the system generated improvements in the other. This process was repeated several times resulting in significant improvements to all parts of the system.

One key discovery was an improved method to rapidly modulate transmitter coil signal. The final design permits sharp transitions between high and low states and provides high power isolation of the RFID tag's microprocessor from the transmitter coil. The second key to the technology was development of robust circuitry to isolate and process the backscatter modulation signal from the carrier current. This circuitry/signal processing resides in the interrogator. The research discovered that several steps are required to amplify, analog filter, digitally filter, and then decode the data.

All of the key features of the system were developed. Compact breadboards were made for the interrogator and battery assisted RFID tag. These were successfully demonstrated on a buried 4-inch diameter steel pipe, where a battery assisted RFID tag was buried next to the pipeline.

- A battery assisted RFID tag can be used. The battery powers the microprocessor and sensors in the tag; however, it does not provide energy for backscatter communication.

- Communication rates of 5 Baud were demonstrated on buried steel pipe. This Baud rate is more than sufficient for the communication requirements of the monitoring system. In one 16.3 hour period, 266,112 bits were transmitted error free.

- Frequency shift keying (FSK) modulation scheme with IEEE P1902.1 as the communication protocol can be used.

- The RFID tag can encode data from any electronic sensor. For the proof of concept, temperature data was transmitted on a buried 4-inch diameter steel pipe over a distance of 100 feet.

Although not incorporated into the proof-of-concept version, the IEEE 1902 protocol supports, two-way communication between the interrogator and multiple RFID tags.

Business Status Section (resource changes, comparison of planned to actual, computation of cost per unit output, and reasons for variance

Resource Changes

There were no resource changes.

Items Originally Planned but not Completed by Task

Task 1. Develop a Practical Current System

- Completed as planned.

Task 2. Develop a Battery Assisted RFID Tag

- Planned to construct 3 RFID tags. One was built.

Task 3. Develop Electronics to Receive Information from the Prototype RFID Network

- Although the interrogator breadboard has the required capabilities, software to address three RFID tags was not completed.

- Although the interrogator and RFID tag breadboards have the required capabilities, software to implement two-way communications was not completed.

Task 4. Testing the networked RFID System

- The system was not tested at a utility over a long distance.

Task 5. Management and Reporting

- Completed as planned.

Calculation of Cost per Unit of Output

The units of output completed during this project were:

- Analysis of the best starting frequency range and design of the initial experiments
- Proof-of-concept of the ability to detect backscatter modulation by internally shorting a low frequency RFID tag
- Development of practical backscatter modulation signal
- Selection of the communication protocol
- A preliminary design for the RFID tag
- A preliminary design for the interrogator
- Improvements in generation of a practical backscatter modulation signal
- Construction of a RFID tag breadboard
- Construction of an interrogator breadboard
- Demonstration on a buried pipe at GTI
- Reporting and project management

The project was funded at $215,133. Thus cost per unit of output for these eleven items was approximately $ 19,560.

Reasons for Variance from Established Objectives

The level of effort to develop robust circuitry to isolate and process the backscatter modulation signal from the carrier current was much larger than expected. More effort was expended to identify the effective signal processing steps than originally estimated; more steps in the signal processing were required. Because the detection of backscattered signals from an RFID tag is the key technology that enables the entire system, GTI believes completion of that work was critical.

As a consequence, construction of two of the three RFID tags, and completion of the software for two-way communication and addressing of individual RFID tags was not completed. However, these features are commonly implemented in systems using the same IEEE P1902.1 communication protocol used for this project; therefore future implementation is not an issue.

GTI has facilitates that provide a reasonable simulation of a functioning gas pipe. These were used to test the system.

Issues, Problems or Challenges (including anything that may cause a schedule delay)

There are no issues, problems, or challenges that caused a schedule delay.

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Introduction

General Concept

The technology developed in this project is the use of the pipeline to act as a communication conduit between an interrogator and RFID (radio frequency identification) tags distributed along the pipeline. As illustrated in Figure 1, an impressed current rectifier station provides a convenient location for the interrogator. The interrogator superimposes an alternating current signal (carrier current) on the cathodic protection direct current. Each RFID tag is formed from a coil of wire (inductor), a capacitor, and other identification (ID) circuitry. The tag's resonant frequency is determined by the values of the tag's inductance and capacitance. The tag absorbs energy from the magnetic field created by the alternating carrier current. Modulating the impedance of the RFID coil changes the amount of power absorbed; thereby changing the load impedance seen by the interrogator. The process of monitoring the reflected impedance of the RFID tag seen at the interrogator is called backscatter modulation. Communication between the interrogator and RFID tag is created by appropriately varying the backscatter modulation.

The RFID tag could be battery powered or could draw power from the carrier signal. Ideally, none of the RFID tag's battery power would be used for the communication signal. A backup communication approach is for the RFID tag to short the pipe to ground. That is less desirable because it requires connections to the pipe. In certain cathodic protection applications however there is an existing metallic connection to the pipe.
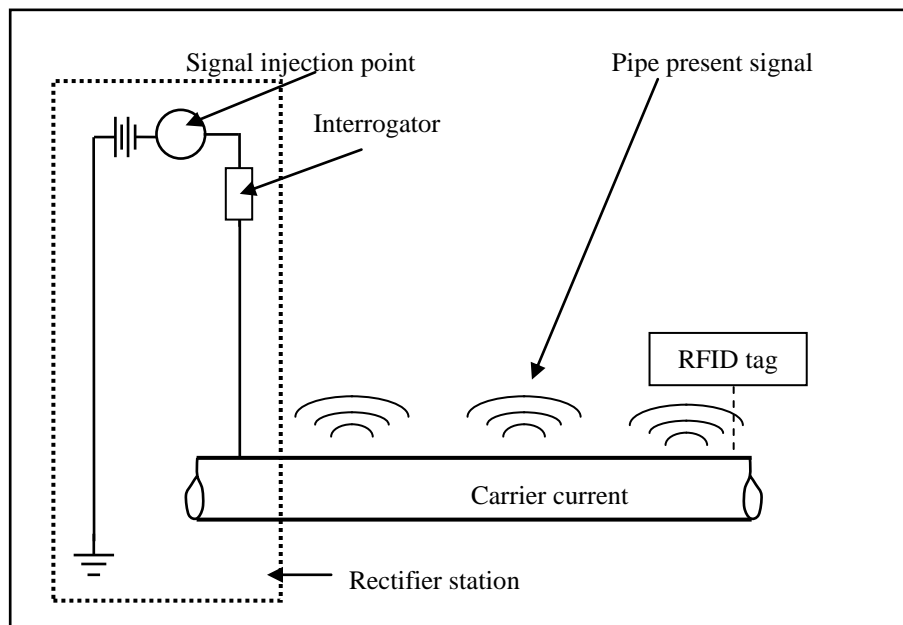

Figure 1. Injected current is used to communicate with RFID tags

Another function of the alternating current injected onto the pipe is to provide a continuous pipe present signal which can be detected by electromagnetic (E&M) pipe location equipment. Commercially available E&M pipe locators consist of a signal generator and a separate sensor to detect the signal. A signal generator is temporarily attached to the pipe, during which time it

applies an alternating current to the pipe. The current creates a magnetic field which can be detected by sensors at the surface of the ground. The new system will provide a continuous electromagnetic signal that can be used to detect the pipe. Because it is always present, passive sensors could be mounted on construction equipment, thereby, minimizing 3rd party damage to pipelines.

Pipeline companies use impressed current cathodic protection equipment to apply a continuous current to prevent corrosion. A successful RFID pipe monitoring system requires combining and optimizing these items without compromising the integrity of the pipeline.

The approach to the project was to utilize and/or adapt existing technologies. These technologies included RFID tags, electromagnetic pipe locators, and impressed current cathodic protection equipment. There is an existing body of applications and products for RFID tags, most of which operate at high frequencies. There are also a number of RFID products specifically designed for buried service that operate in the frequency range below 160 kHz.

General Analysis of the system

The first step was to analyze the proposed system to evaluate the items we can control, practical limitations, and trade-offs. The goal was to understand the key issues and to make a selection of a logical starting point for hardware design. The analysis included how magnetic fields are generated around the pipe, how they can be detected, cathodic protection issues, and factors related to the shape of the impressed signal.

Generation of magnetic fields around a pipeline

An electric current propagating (ref 1) along a straight wire (pipeline) generates a magnetic field. As illustrated in Figure 2, the magnetic field forms cylinders concentric with the pipe.
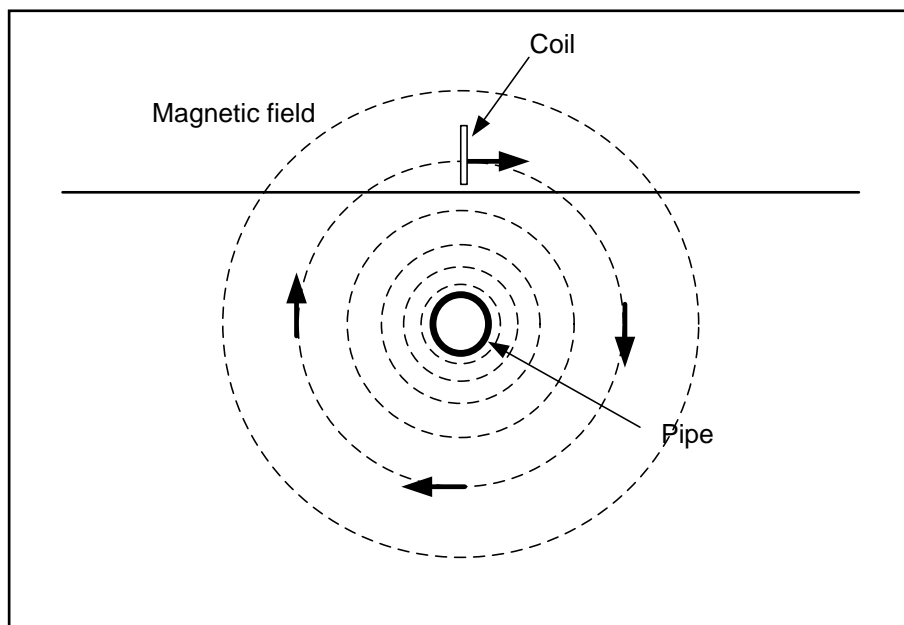

Figure 2. Magnetic field generated around current conducting pipe.

The magnetic field at a distance r from the wire can be calculated from the Biot-Savart Law given in equation 1.

$$B = 2 k' I/r \hspace{8cm} \text{eq. 1}$$

where $k' = 1.00 \times 10^{-7}$ n/amp^2 (mks units), I = the current flowing in the wire (amps), and r is the distance from the wire in meters. Increasing the current increases the magnetic field. If the current is alternating, the magnetic field changes direction and magnitude at the same frequency.

The amount of current flowing through the pipe, not the voltage, determines the magnitude of the magnetic field. In order to conduct current there must be a complete loop. The metal pipe provides one path. The ground (soil) provides the return path. The dielectric permittivity, the magnetic permeability, and the conductivity of the soil affect the return path. The soil surrounding the pipe behaves as if there are a series of small capacitors attached all along the pipe (ref 2). Capacitance increases with surface area of the pipe, thus the pipe diameter affects the distance a signal will carry. A higher soil dielectric constant will also increase the capacitance. Higher soil conductivity improves the functioning of the soil as a return path. Even though higher dielectric constant and conductivity increase the amount of current coupled into the pipe, they also make it easier for the current to drain away as the current flows along the pipe. Because of the larger amount of soil in contact with the pipe, the current will leak away over a shorter distance from a large pipe than from a small one. During the application of pipe locators, it has been observed for all soils that the higher the frequency of the current injected into the pipe, the greater the attenuation. That is, the maximum distance the current can travel decreases as the frequency is increased. Conversely, lower frequencies will propagate greater distances. Obviously, there is little control over the soil properties the pipeline is buried in. However, lower frequency currents have the advantage in terms of range of propagation.

An electromagnetic pipe locator works by connecting a wire to the pipe and injecting a current into the pipe. The operator walks along the suspected path of the pipe carrying an instrument that can detect magnetic fields. When the sensor is positioned over the pipe, the magnetic field is detected. In theory, dc currents could be used. In practice they are not used because alternating currents are easier to detect. Frequencies used in pipe locators range from 50 Hz to 480,000 Hz. The changing magnetic field will also couple with the RFIDs tuned to the same frequency.

Detection of magnetic fields around a pipeline

A voltage is induced in a coil of wire if it is placed at the correct orientation in a changing magnetic field. The magnitude of the induced voltage is proportional to the number of turns in the coil, the cross sectional area of the coil, the strength of the magnetic field, and the frequency of the field. The magnitude of the induced voltage is inversely proportional to the distance from the center of the pipe to the center of the coil. The orientation of the coil to the magnetic field is also important: the coil needs to be oriented so the magnetic field lines pass through the coil. A coil of wire is commonly used as magnetic sensor because of its low cost. The voltage induced in a coil is given by Faraday's Law:

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V = -N $d\Phi_B/dt$ eq 2.

where N = the number of turns (loops) in the coil, Φ_B = the magnetic flux through the coil, and $d\Phi_B/dt$ is the time rate of range of magnetic flux through the coil. The magnetic flux Φ_B across a surface area is defined as

$\Phi_B = \int \mathbf{B}d\mathbf{A}$ eq 3.

where **B** and d**A** are vectors with BdA being their dot product. The direction of d**A** is perpendicular to the surface area of the coil. In the special case where the magnetic field is uniform across the area and the direction of the magnetic field is parallel to the area vector, Φ_B = BA. Figure 2 illustrates a coil at the optimum orientation—the direction of the coil surface vector is parallel to the magnetic field. Conversely, if the magnetic field is perpendicular to the area vector, d**A**, the dot product is zero and no voltage is induced. This has the practical consequence that the orientation of the coil can be used to maximize or to minimize the voltage generated in the coil.

For a sinusoidally varying magnetic field, B = $B_o \sin(2\pi f\, t)$, the only portion of Φ_B that varies with time is the $\sin(2\pi f\, t)$. The time rate of change of B = $2\pi f\, B_o \cos(2\pi f\, t)$. Substituting into equation 2 gives:

V = -N $d\Phi_B/dt$ = $-2\pi f\ N\ A\ B_o \cos(2\pi ft)$ eq 4.

Equation 4 assumes that the magnetic field is uniform across the surface of the loop. Although this is not strictly true for our application, it is close enough to estimate the induced voltage.

The key ideas expressed in equation 4 are that the voltage created in the coil increases when the number of loops in the coil, the magnitude of magnetic field, the size of the coil, or the frequency of the magnetic field is increased. From equation 1, the magnetic field increases as the current in the pipe increases and as the coil is placed closer to the pipe. Some RFIDs operate at frequencies as high as 900 MHz and at very close distances (a few feet) which permit very small (less than 0.25 by 1 inch) and inexpensive coils. Such coils have only a few turns. Our application requires data transmission over much longer distances. Based on the discussion in the previous section, lower frequencies should be used. Our sensors do not need to cost a few pennies; therefore it is possible to use a large number of turns in the coil. We will need to use higher currents and more turns in the coil to compensate for lower frequencies. Equation 4 was used to design the RFID test coils.

Cathodic protection

A pipeline company installs cathodic protection rectifiers at locations along the pipeline to prevent corrosion. If the pipeline is maintained at a voltage negative with respect to the soil, -0.85 volts being typical, it does not corrode. This can be accomplished in one of two ways: anodes and impressed current rectifiers. Sacrificial anodes, typically made of magnesium, are attached to the pipeline and buried. They corrode instead of the pipe. Impressed current rectifiers inject a DC current onto the pipeline to prevent corrosion. Attachment to the pipeline

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is made at locations close to an electrical power supply. This is convenient for our application because an extra excavation is not required to connect to the pipeline and because electricity is available to power the equipment. The approach is to superimpose a carrier signal on the pipe on top of the cathodic protection potential. It is critical that the networked RFID signals not interfere with the cathodic protection functions.

The potential for successful deployment of the carrier current is promising when one compares pipe location and cathodic protection currents. Because they must be portable, pipe locators are battery powered. Pipe location currents can be as high as a few amperes. A single impressed current rectifier can protect pipes up to a few miles in length. In order to maintain the pipe-to-soil potential at -0.85 volts or greater at the farthest point on the pipeline, the voltages at the injection point are much higher than -0.85 volts. Commercial impressed current equipment uses a full wave rectifier to convert alternating 60 Hz power into DC voltage. The output ratings of commercial cathodic protection rectifiers range from 9 to 150 volts and from 3 to 150 amperes. Thus the current injected at impressed current stations can be a factor of 30 times larger than those used by portable pipe locators.

Shape of the impressed signal

Because we are generating the signal impressed on the pipe, in principle any waveform can be used. In practice there are some limits. The sensing antennae of RFID's are inexpensive coils of wire. They are normally tuned to resonate at a single frequency for two reasons: a single frequency optimizes the energy transfer in a resonant coil and the frequency band can be made very narrow so the RFID responds to only a matching interrogator. For similar reasons, pipe locators also use coil sensors and one sinusoidal frequency at a time. Thus, a sinusoidal frequency is a logical candidate for the networked RFID system.

The sinusoidal signal will be superimposed on top of the DC cathodic protection voltage. However, cathodic protection of the pipeline requires that the average DC voltage on the pipe be negative with respect to earth; typically -0.85 volts. In theory, an alternating current does not cause corrosion because there is no net transport of charge. In practice it has been shown that a sufficient level of AC current can overwhelm the DC cathodic protection and cause metal loss. The probable mechanism is that the metal loss occurs at the positive peaks of alternating current, when the pipe potential is most positive with respect to the earth. This effect has been clearly documented at 50-60 Hz but may be less pronounced at higher frequencies. An additional consideration is that the voltage on the pipe may not be so high as to pose a shock or spark hazard. There are a variety of waveform choices that can avoid these issues. Using a sinusoidal waveform with amplitude less than 1 volt severely limits the amount of current that can be injected into the pipe, limiting the communication range. To maximize the range, a sine waveform with a DC offset voltage large enough to ensure the waveform does not go positive can be used.

Another approach is to rectify either a square wave or a sinusoidal wave and reverse the polarity such that the voltage does not go above zero. Rectified square and sine waves are composed of many frequencies. Thus, some of the energy does not couple into a resonant coil and is lost for our purposes. Fourier analysis (ref 3) can be used to calculate the frequency distribution of square and rectified waves. Each type of wave is composed of a fundamental

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frequency, f_o, and its multiples. Only odd harmonics are present in a square wave function. These frequencies: $1f_o$, $3f_o$, $5f_o$, $7f_o$, $9f_o$, etc., have amplitude ratios with respect to the fundamental frequency of 1, 1/3, 1/5, 1/7, 1/9, respectively. It can be shown that approximately 80 % of the energy of a square wave is in the fundamental f_o. A full wave rectified sinewave has only the fundamental and even harmonics. These frequencies: $1f_o$, $2f_o$, $4f_o$, $6f_o$, $8f_o$, etc., have amplitude ratios of ½, 1/3, 1/15, 1/35, and 1/63, etc. It can be shown that approximately 68 % of energy in the rectified sinewave is in the fundamental.

Initial Experimental Measurements

There are two modulation approaches for backscatter communication. One is modulating/shorting of the coil inside the RFID. That is the preferred approach because no metallic attachment to the pipe is required; the antenna coil need only be in close proximity with the pipe. The second approach is to attach a wire to the pipe and then use the RFID to periodically short the pipe to ground for the brief time required for communications. Although not the preferred approach, it may provide the best backscatter communication.

After analyzing the various conflicting optimization trade-offs, a starting frequency range was selected. The first measurements tested the feasibility of using internally shorted RFID tags made with custom coils. As described above, the amount of energy absorbed by the coil can be calculated as a function of its inductance, capacitance, diameter, and distance from the pipe/wire. Measurements agreed with calculations for each coil constructed.

Figure 3 is a schematic of the test set-up. A wire was used to simulate the pipe. This is viable because a current carrying pipe creates a magnetic field identical to a thin wire at the center of the pipe with the same current. The components of a RFID tag that absorb energy from the wire are the coil and capacitor, not the other ID circuitry. For the initial experiments we did not include the ID circuitry, thus the coil/capacitor was not strictly an RFID. A tuned coil was placed next to the wire. Circuitry was built that would periodically short the coil by opening and closing a mechanical relay. The relay made an audible clicking sound with each closure, making it easy for an observer to correlate closures with changes in the oscilloscope display. The current was monitored using an oscilloscope across the 5 ohm resistance in series with the wire. The current was adjusted to the low end of the current range—0.1 ampere. The resulting voltage across the wire wound resistor was 0.52 volts. As the relay opened and closed, the voltage changed by approximately 1% in sync with the relay. This change is sufficient to prove proof-of-concept.
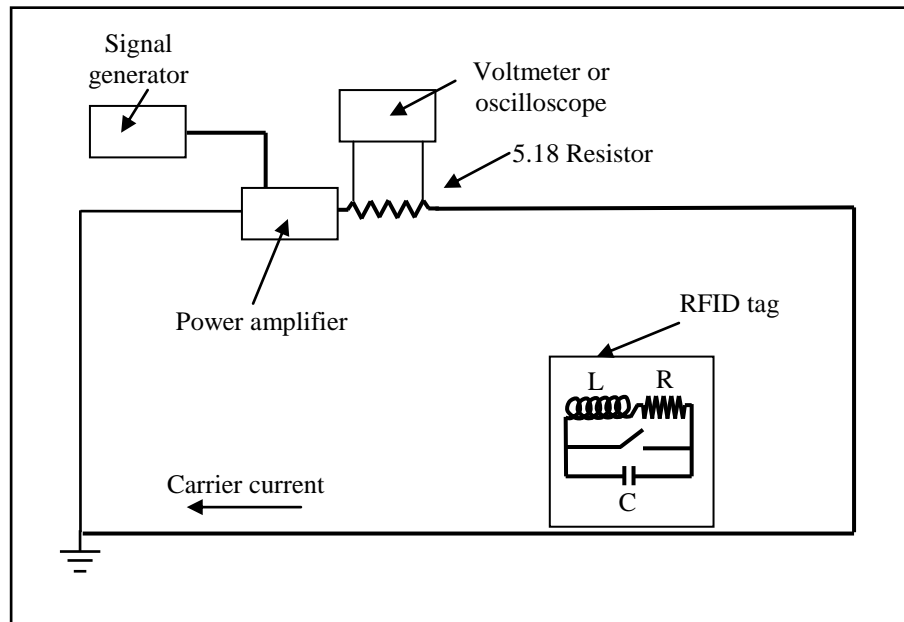
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Figure 3. Closing the RFID switch changes the impedance seen by the interrogator

Interrelationships between Components

The last section described the proof-of-concept. However, for a practical system the ability to detect this change had to be greatly improved. A substantial amount of effort was expended to make a practical system. As work progressed on the project, improvements in one aspect of the design identified needed improvements in other parts of the system. Making these improvements, in turn, generated additional improvements in the original areas. There were several accepted methods of implementing each part of the system; however, the interactions between components were not easy to predict. This process was repeated several times resulting in significant improvements to the system.

A description of all the steps and twists and turns would be unproductive. Instead, the key interrelationships are listed below. The following sections describe the final breadboard versions developed in this project. It should be noted that the final design of a manufacturable system would make additional improvements.

RFID Coil Tag

The RFID coil tag needs to efficiently absorb power from the carrier current and, at the same time, generate a strong backscatter communication signal that can be detected and processed by the interrogator. The distance between the RFID coil and the interrogator should be as great as possible. Several factors affect the operation of the RFID coil/tag:

Operating carrier frequency:
- Higher frequency gives better energy absorption

- Lower frequency gives better range

Coil design:
- Number of turns
- Cross-section area
- Distance of coil from the pipe
- Choice of inductance and capacitance values

Modulation of RFID antenna:
- Mechanical relay
- Optical relay
- Detuning coil

The communication protocol needs:
- Facilitate detection of low-strength signals in high noise environments
- Open architecture/ no licensing

RFID tag transmitter:
- Control of modulating signal
- Reading of sensor data
- Encoding of data into a format that can be communicated
- Choice of microprocessor
    - Built-in hardware for the communication
    - Software to send the information
    - Low-power microprocessor
- Choice of the two frequencies used for the FSK modulation
- Baud rate

Interrogator

The interrogator needs to impress the carrier current onto the pipe, create a continuous pipe-present signal, modulate the carrier current to communicate to the RFID tags, detect the backscatter modulation signals by suppressing the carrier current, and interpret data from each RFID tag. Several factors affect the operation of the RFID coil/tag including:

The methods used in carrier suppression:
- Tuned, low-Q resonant circuit (proof-of-concept)
- Diode rectifier with no amplification to strip off carrier current
- Heterodyning with AM demodulation
- Heterodyning with multiplier circuit as peak detector
- Replace heterodyne with instrumentation amplifier with direct DC off-set adjustment
    - Add comparator to define changes in amplitude more rigorously
    - Add a full-wave rectifier followed by a series of analog band-pass filtering and high gain amplifiers
    - Add digital filtering

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Noise suppression:
- 60 Hz
- Background

Software processing:
- Digital filtering
- Methods to detect zero and one logic states
- Maximize Baud rate
- Minimize signal error in data transmission

RFID Tag Design

The method of modulating the RFID coil is critical. The inductance and capacitive values of the coil affect the amplitude of the backscatter modulation. A method is needed that makes abrupt transitions between the high and low states with little energy from the tag itself. Such a method was developed and it proved very effective.

Figure 4 is a close-up of the final breadboard RFID circuitry. The MSP430F2012 microprocessor from Texas Instruments was selected to modulate the data at the RFID tag. In addition to its signal processing capabilities, it is an extremely low power microprocessor. The MSP430F2012 gathers data from sensors in the RFID tag, formats it, and sends the data to a software defined modulation routine. The resulting signal will modulate the coil, thereby transmitting the data. The microprocessor in the RFID tag has an analog-to-digital convertor that can be used to encode data from any sensor with a voltage output. Having a compact design for the tag and proper incorporation of decoupling and by-pass capacitors help reduce noise. The tag operates from a 9 volt battery in this demonstration. It can operate from a source as low as 2.5 volts.
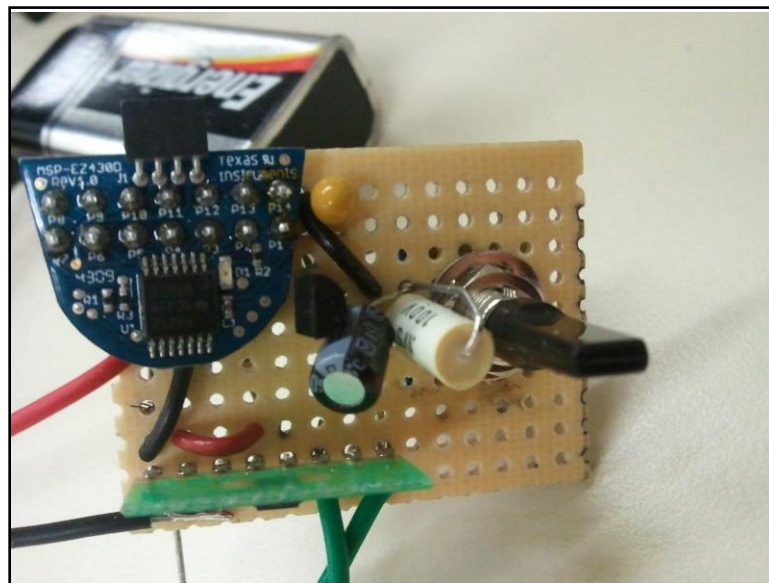

Figure 4. Close-up photograph of the RFID tag final breadboard

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Interrogator Design

The interrogator has several functions to perform:

- Generate the carrier signal that is placed upon the pipe

- Monitor the power output of the cathodic protection rectifier

- Balance the carrier power requirements with the cathodic protection current

- Decoding the backscatter modulation signal from the carrier current signal

- Store and time stamp the data received from the remote RFID sensor(s)

Key among these is deciphering the information superimposed on the carrier frequency. A method is required to remove the carrier frequency at the interrogator. A design was developed which suppresses the carrier, reduces 60 Hz and environmental noise, preserves the data sequence, and stabilizes the signal at a microcontroller compatible level. The process combines analog passive and active filters and amplifiers with digital signal processing. At one point the signal passes through one of two low-order Infinite Impulse Response (IIR) Filters. One narrow band-pass filter passes the frequency (500 Hz) for the logic level "one" and the other passes the frequency (400 Hz) for the logic level "zero." The last step is decision making in the digital domain. A Stellaris LM3S3748 microprocessor made by LuminaryMicro was used for the digital signal processing. Figure 5 is a photograph of the Stellaris microcontroller and signal conditioning breadboard that forms the heart of the interrogator. Figure 6 shows the frequency responses of the two IIR filters.

Another component of the field test exhibition included a wireless transmitter/receiver pair to record the data and status of the communication system. This was implemented so that a laptop could remain securely in a lab and not in the field where its security could be compromised during an extended testing period. This wireless system provided a seamless serial link between the microcontroller of the receiver circuitry and data-logging PC.
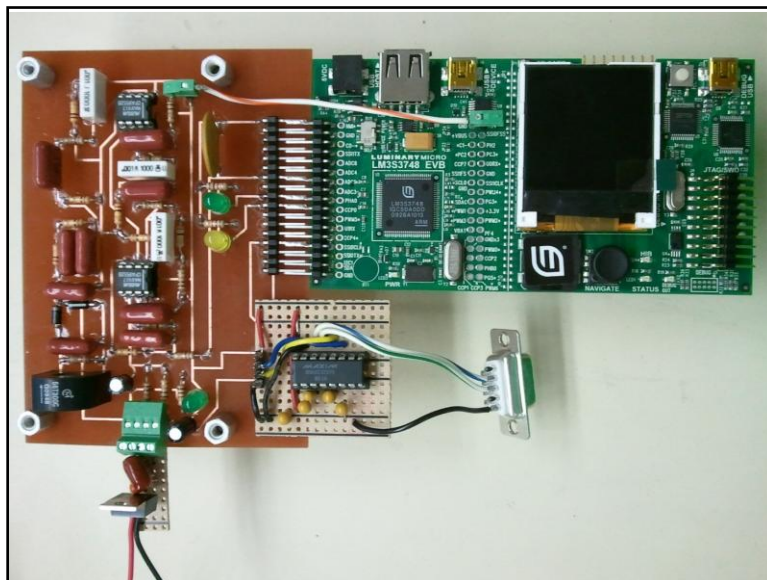

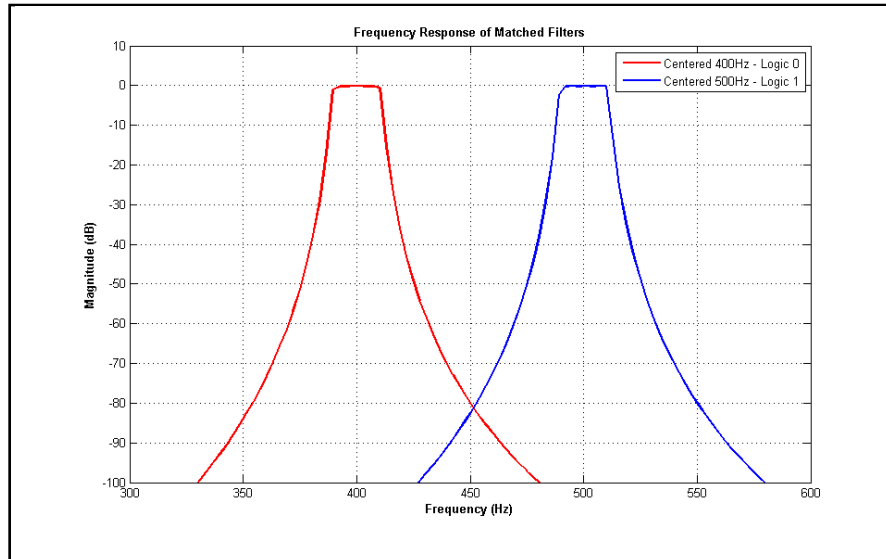Figure 5. Photograph of the receiver portion of the interrogator.

Figure 6. Frequency response plot of the digital infinite impulse response filters

Communication protocol

A communication protocol for transmitting the signal is required. There are a large number of standards available. After several improvements in signal-to-noise ratio had been made, it was possible to rationally assess the many potential choices for a communication protocol. Frequency Shift Keying (FSK) following IEEE P1902.1 protocol (ref 4) was selected as the best candidate for a number of reasons. FSK has been in use for decades for applications that use low data transmission rates in the presence of high noise. It is an open-standard protocol, with no licensing fees. IEEE P1902.1 protocol was specifically designed for RFID applications. Data is transferred using two frequencies sequentially superimposed on a carrier frequency. One frequency is used for a low value (digital zero) and second frequency for a high value (digital one). An idle line is signaled by the absence of any modulating frequency. Figure 7 is a schematic of the square wave shifting back and forth between two frequencies. FSK modulation frequencies are 400Hz and 500Hz. Current baud rate is 5 bits per second.
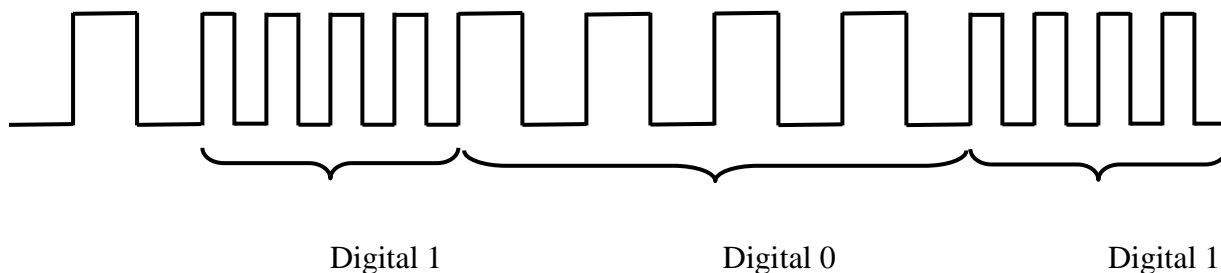

Figure 7. Schematic of frequency shift keying

The tag microprocessor was programmed to provide a repeating digital data signal to the modulator. This data stream was detected by the interrogator microprocessor. The interrogator was also programmed to recognize and record errors in the data stream. A continuous data stream was run over-night and statistics kept on the number of errors. One test on the buried 4-inch pipe lasted 16.3 hours. The Baud rate was 5 Hz and 266,112 bits were transmitted and received without error.

References

1   Halliday, David and Resnick, Robert, Physics, part II, John Wiley & Sons, Inc. New York 1960, chapter 34.

2   Radiodetection: "Fundamental principles and techniques in buried utility location"

3   Agnew, R., P., Calculus Analytic Geometry and Calculus with Vectors McGraw-Hill 1962 page 616-617.

4   IEEE P1902.1™/D1 Draft Standard for Long Wavelength Wireless Network Protocol

List of Acronyms

Acronym	Description
GTI	Gas Technology Institute
FSK	Frequency Shift Keying
ID	Identification
RFID	Radio Frequency Identification Detector

END OF REPORT