# CAAP Quarterly Report

Date of Report: *October 9, 2016*

Contract Number: *DTPH5614HCAP04*

Prepared for: *Arthur Buff, Project Manager, PHMSA/DOT*

Project Title: *Embedded Passive RF Tags towards Intrinsically Locatable Buried Plastic Material*

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Contact Information: *Dr. Yiming Deng (MSU) and Dr. Prem Chahal (MSU).*
**Dr. Deng's research team has moved to Michigan State University. The new PI at CU-Denver is Dr. Dan Connors. All the following work at CU was led by Dr. Deng.*

For quarterly period ending: *October 10, 2016*

## Business and Activity Section

### (a) Generated Commitments

**Project abstract:** Accurate and reliable locating, identifying and characterizing the buried plastic pipes from the ground surface in reducing the likelihood of hit them is critical and imperative to reduce the pipeline incidents. In this collaborative research, a new harmonic radar (frequency doubling) mechanism for smart RF tags design that can detect plastic pipes deeply buried in various soils conditions will be investigated, achieved through efficient tags and highly sensitive readers design, and coupled with intelligent signal processing. The proposed low-cost, small thin-film form passive RF tags can directly be embedded in plastic pipes. It will be able to withstand high temperature processing of plastics and stress involved with horizontal tunneling/drilling of buried pipes. The embedded RF tags have the capability to not only precisely locate the buried plastic pipes, but also have integrated sensing functionality, which can measure the strain-stress changes in the plastic materials. Finally, the vast amount of acquired sensing data from individual tags will be integrated to the advanced signal processing for better data categorization and mining. An innovative prognostics framework for better asset life-cycle management will be developed.

A complete solution is needed that helps in identifying individual buried pipes, their precise location, determining their integrity and sensing for leaks. Buried pipes are expected to have a lifetime of greater than 30 years that are designed to carry a range of liquid and gaseous materials. Among the many pipe technologies, demand for plastic pipes is growing largely because of their low-cost and potential for long life time. Any tags or sensors that are incorporated within these pipes should be able to withstand harsh conditions with a lifetime meeting or exceeding that of the pipes, and should be battery free (passive tag). Furthermore, the overall system should be compact, low-cost, and easy to operate. With advanced techniques to bury the pipes using tunneling approaches it is necessary that tags withstand the associated stress and handling during construction work. Typically, the pipes are buried 3 feet or deeper in the ground and thus the reader should be able to interrogate the tags at these and at higher depths (greater than 5ft is desired).

As summarized in Introduction section, significant advances have been made in the area of electronic tagging of buried objects. However, most of these tags are an afterthought as they are not integral part of the infrastructure. These tags are typically large and are buried along with the objects. This is simple if open trenching is carried out. However, for plastic pipes that are buried using tunneling this approach will not suffice without making the tags an integral part of the plastic pipe. Furthermore, no RF tags are commercially available that will allow in sensing of the environment and the integrity of the buried object during its life time. Smart RF tag designs are necessary as power harvesting and storage techniques will also have limited life time as the rechargeable batteries (or capacitors) and the associated circuit (e.g., piezo power harvester) will have a limited lifetime. Meanwhile, no advanced data processing algorithms are available for optimally manage and use the vast amount of information embedded into the received RF signals from the proposed new tags. Under this three-year project, the specific technical objectives/goals of the proposed research are:

1) Design and development of new passive harmonic radar based smart RF tags with long range detection guided by industry partners;
2) Design robust and miniature tags such that they can directly be embedded in plastic pipes during manufacturing;
3) Investigate on-tag strain-stress sensing capabilities and efficient data transmission;
4) Investigate new massive RFID data mining, processing and classification algorithms with experimental testing;
5) Develop a Bayesian Learning based pipeline hazardous prognostics methodology using discrete sensing data;
6) Intrinsically locatable pipe materials demonstration and field testing using representative pipe specimens with GPGPU acceleration.

Another equally important objective of this proposed research is to engage MS and PhD students who may later seek careers in this field by exposing them to subject matter common to pipeline safety challenges. Since the project being kicked off, three PhD students from both universities and several MS students have been recruited and trained through this CAAP program and apply their engineering disciplines to pipeline safety and integrity research. The PIs think the educational component is a very important part of the CAAP project and will integrate with research activities with various educational activities to prepare the next generation engineers for gas and pipeline industry. The educational and research impacts sponsored by CAAP has been recognized within the university (see *support letter 3 from Associate Vice Chancellor of university*) and nationally (Two current CAAP-funded students at CU haven been recognized at ASNT annual research symposiums in 2014 and 2015). Specific educational objectives and goals are:

1) Guide and train graduate students at University of Colorado-Denver and Michigan State University for the pipe integrity assessment and risk mitigation;
2) Integrate with existing mechanisms for undergraduate research at University of Colorado-Denver and Michigan State University for early exposure of pipe industry research to potential engineers;
3) Improve the current curriculum teaching at University of Colorado-Denver (ELEC5644 Nondestructive Evaluation and ELEC3817 Engineering Probability and Statistics) and Michigan State University (ECE802-1 Microwave and Millimeter Wave Circuits and ECE802-2 Electronic Systems Packaging) using the achievement from the proposed research;
4) Invite pipe industry expert (see support letters later in this proposal) to deliver seminar/workshops to undergraduate/graduate students about the challenges and opportunities in gas and pipeline industry;

5) Encourage the involved students to apply internships at DOT and industry to gain practical experiences for the potential technology transfer of the developed methodologies.

The above-mentioned goals and objectives of the proposed Competitive Academic Agreement Program (CAAP) project will be well addressed and supported by the proposed research tasks. Development, demonstrations and potential standardization to ensure the integrity of pipeline facilities will be carried out with the collaborative effort among different universities and our industry partners. The quality of the research results will be overseen by the PIs and program manager and submitted to high-profile and peer-reviewed journals and leading conferences. The proposed collaborative work provides an excellent environment for integration of research and education as well as tremendous opportunities for two universities supported by this DOT CAAP funding mechanism. The graduate students supported by this CAAP research will be heavily exposed to reliability and engineering design topics for emerging pipeline R&D technologies. The PIs have been actively encouraging students to participate in past and ongoing DOT projects and presented papers at national and international conferences. Students who are not directly participating in the CAAP project will also benefit from the research findings through the undergraduate and graduate courses taught by the PIs and attending university-wide research symposium and workshop, e.g. RaCAS at CU-Denver. The proposed research involves pipeline industry to validate and demonstrate scientific results and quantify engineering principles by working closely with industry partners. They will also collaborate with the CAAP team on this research which may include but is not limited to information exchange, mutual meetings, providing CU and MSU with appropriate technical support for the target application.

**(b) Status Update of Past Quarter Activities**

Task 1 – Experimental setup at University of Colorado, Denver

As discussed is the last quarter report CU build a respectively large soil container (5-ft x1.5-ft x 1.5-ft) for being able to measure more realistic signal. The near-field (reactive) effects reduced as the separation of the antenna from side walls gets bigger than 0.17-ft (reactive region for 915-MHz). The longer distance of the container (> 2-ft as per last setup) allows signal propagation and attenuation analysis possible to represent larger buried depths.

**Fig.1** Soil Container

The wave propagation in air within the container has been studied, shown in fig. 2 in the previous quarter and we have seen some waveguide effects due to the mismatching of boundaries.

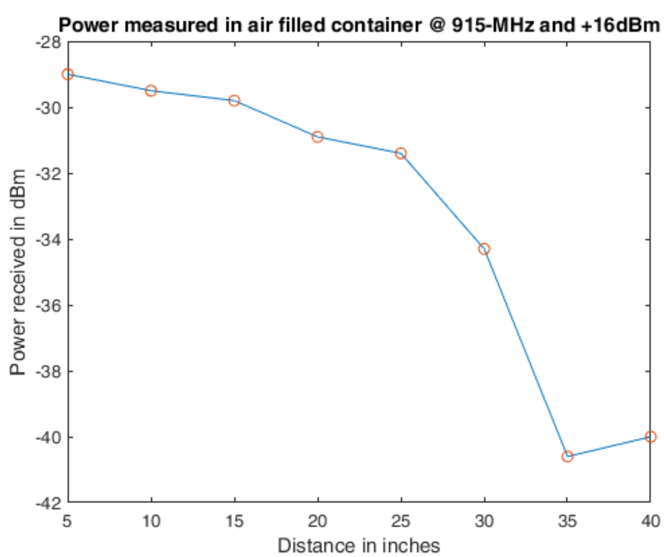


**Fig.2** Power received vs. Distance in empty container

The soil type has been changed from dry sandy to dry silica, the electrical properties of both soil types are similar ($\epsilon_r = 2.17\ and\ tan\delta = 0.0016$), so we can assume that all the changes in soil propagation results are mainly due to changes in container.

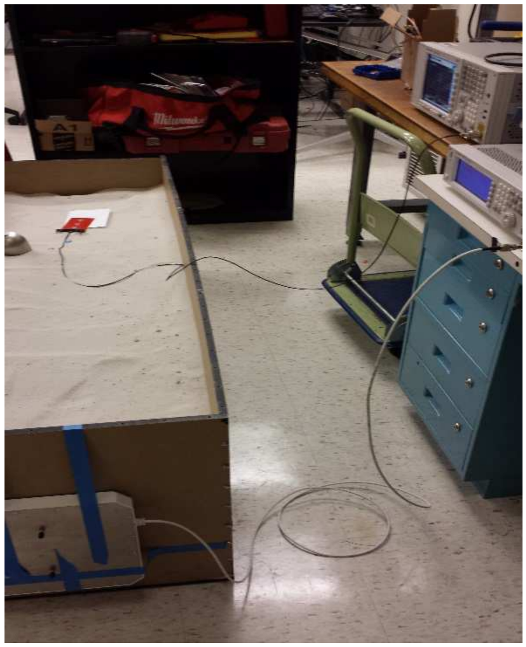

**Fig.3** Experimental Setup

Similar experiments have been performed as of previous quarter to make a comparison between different setups. In previous experiments most of the power from transmitting antenna was getting confined into smaller volume that results increase in power density within the box. The latest setup is respectively bigger and expected to disperse the energy into larger volume, which may give better approximation of real scenario. The power received in silica sand is shown in fig.4.


**Fig.4** Power received vs. Distance in soil filled container

The electromagnetic power should have been dispersed and attenuated with distance in soil medium. The experimental results shows that for smaller distances that the power received in soil is same as air, but as we move away from the source, standing wave pattern start building up and due to the reflection from walls power gets increased. If we compare the power received at different distances with last quarter soil measurement, the received power level gets down and it helps concluding that the dispersion and attenuation factor are more effective now than previous setups.

Multiple buried tags were also tested using Impinj RFID system, shown in fig.5. Three tags have been buried at a depth of 5-ft with 1-inch separation. The system has detected all three tags and characterize them.

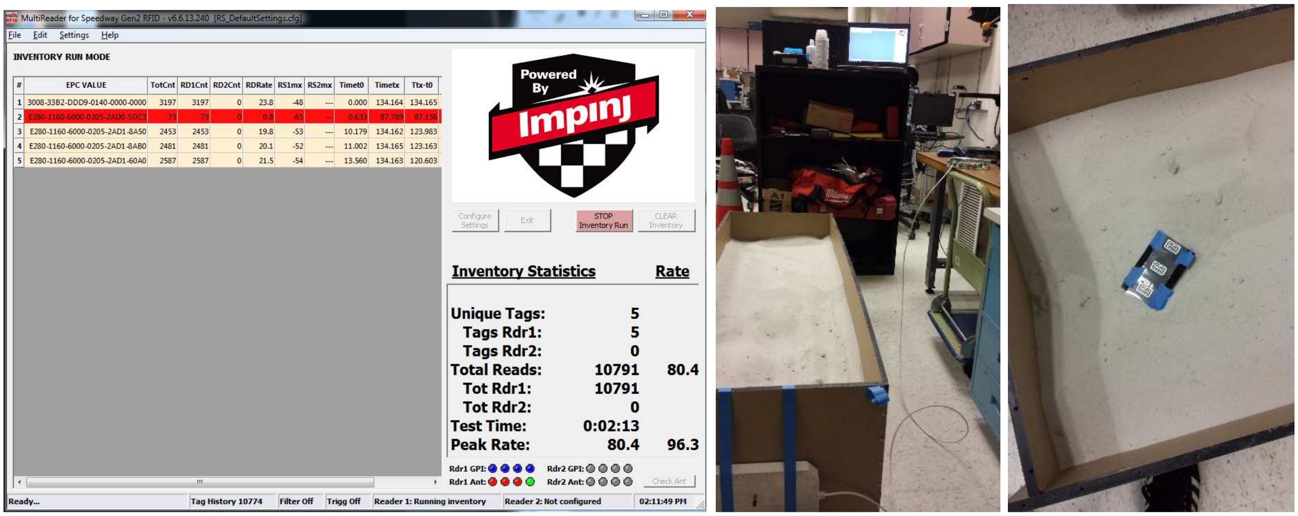


**Fig.5** Multiple tag reading with 5-ft burial depth

**Distance estimation:**

A close estimation of pipe burial depth using tag sensor is also a key feature to this project. The distance between electromagnetic source and observer can be estimated independently using two parameters i.e; time of flight or the phase of received signal. The time-of-flight estimation technique records both the time at which signal leaves the transmitter and reaches the receiver and estimates the distance according to the speed of propagation of signal into that medium. It requires a very high frequency and super accurate clock that may not be possible with current scenario due to passive tag and different receiving frequency. On the other hand, the phase of the signal can be detected at receiver's end where we have more degree of freedom in terms of power and machinery.

The distance estimation from phase requires a multiple frequency transmission and it is possible to accurately calculate the separation out of it. Initially, a homogeneous and noise free medium is chosen for start. Fig. 6 show the propagation of signals at five different frequencies in noise and attenuation free environment. The phase of signal after travelling 2-m in free space is observed shown in table 1.

| FREQUENCY | OBSERVED PHASE |
|---|---|
| **928-MHZ** | $67.2^{o}$ |
| **923-MHZ** | $54.84^{o}$ |
| **919-MHZ** | $46.0^{o}$ |
| **913-MHZ** | $30.83^{o}$ |
| **902-MHZ** | $4.8^{o}$ |

Table.1 Observed Phase

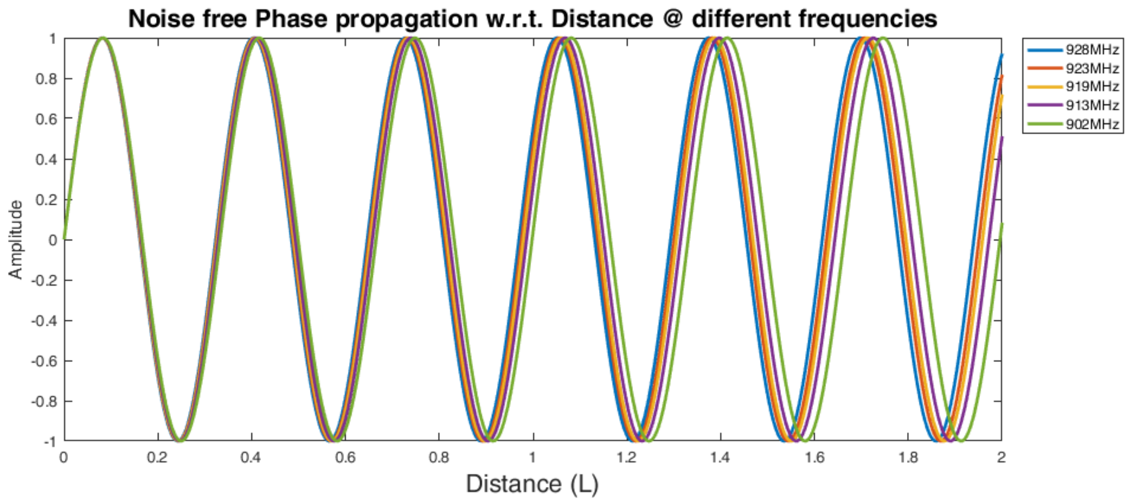


**Fig.6** Noise free signal

Distance estimation is as follows:

**Algorithm: Distance estimation using phase**

Step1: Input: Phase ($\boldsymbol{\phi}$), Highest and Lowest frequencies ($\boldsymbol{f_1}$ ***and*** $\boldsymbol{f_N}$), No. of transmission (N).

Step2: Beat Phase ($\boldsymbol{\Phi_i}$) $= [\boldsymbol{\phi_1 - \phi_i}]_{2\pi}$ for $\boldsymbol{1 \leq i \leq N}$

Step3: Beat Wavelength ($\wedge_i$) $= \boldsymbol{c/[f_1 - f_N]}$

Step4: **Initialize:** $\boldsymbol{M_1 = 0}$

Step5: $\boldsymbol{M_{i+1} = round\left[\left(M_i + \frac{\Phi_i}{2\pi}\right)\frac{\wedge_i}{\wedge_{i+1}} - \frac{\Phi_{i+1}}{2\pi}\right]}$

Step6: $\boldsymbol{L_c = M_N \wedge_N + \frac{\Phi_N}{2\pi} \wedge_N}$

The distance from given phase using above algorithm is estimated to be 2-m that is correct and proves the fidelity of algorithm for noise free and homogeneous medium. Moreover, the algorithm is also tested for noisy measurement. Fig. 7 shows the noisy signal of length 2-m and observed phase is shown in table 2.

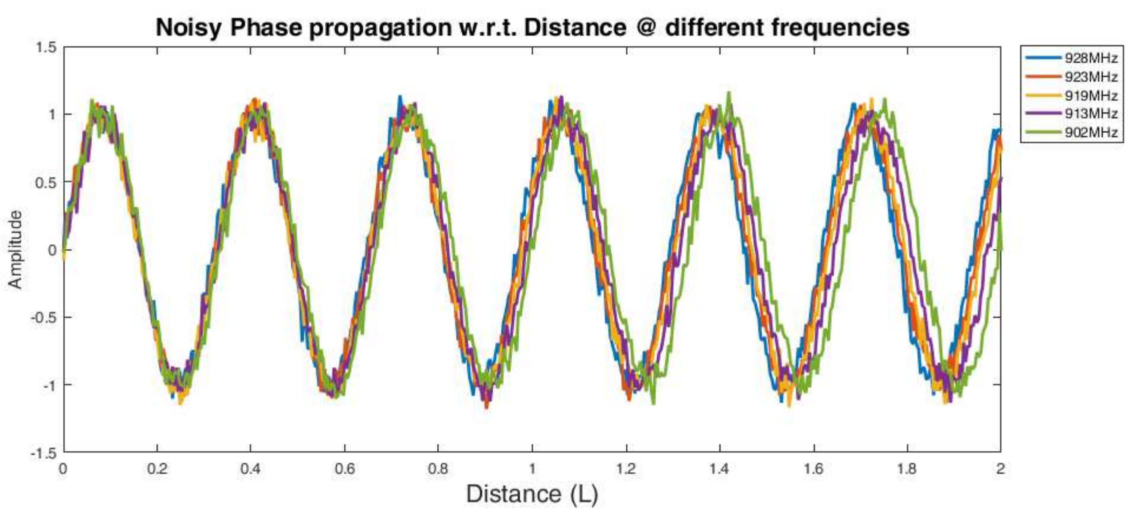


**Fig.7** Noisy signal

| FREQUENCY | OBSERVED PHASE |
|---|---|
| **928-MHZ** | $63.94^{o}$ |
| **923-MHZ** | $52.27^{o}$ |
| **919-MHZ** | $47.32^{o}$ |
| **913-MHZ** | $33.23^{o}$ |
| **902-MHZ** | $1.28^{o}$ |

Table.2 Observed noisy phase

With added white noise the phases at 2-m distance are shifted, the output of algorithm is 1.88-m which is a close approximation of original signal. In practical cases, the noise and the original signal comes hand in hand. The use of better phase detectors and filter may eliminate some of the noise but can't provide a very clean signal. So we can conclude that by using above algorithm, a distance can be estimated in close approximation with some low tolerance.

The signal propagation in lossy medium has also been tested, the measured phases in noise free environment are same as before because the attenuation factor is known and gives a correct distance estimation, shown in fig.8. The noise changes the phase by a bit due to randomness but ultimately the algorithm reaches 2.3544-m, a close approximation solution.

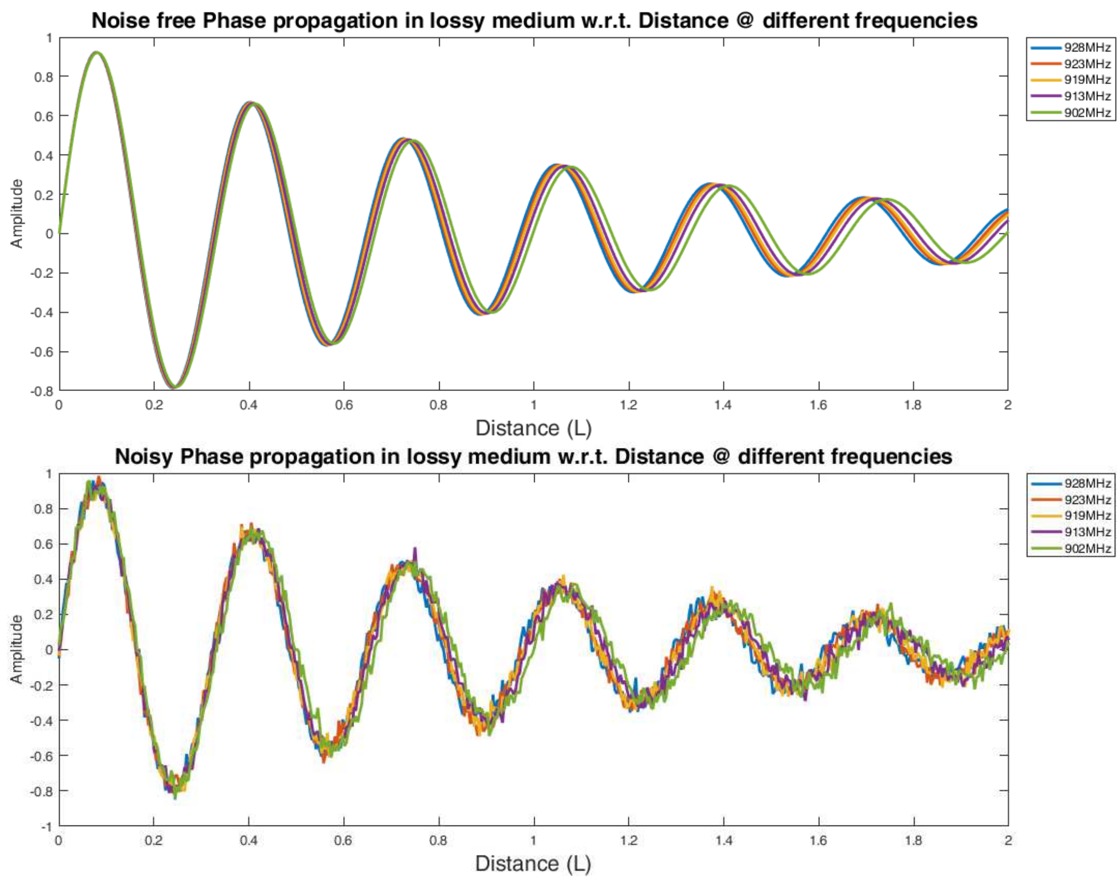


**Fig.8** Phase attenuation with Distance

Task 2 – Design and development of passive harmonic radar based smart RF tags

The task 2 demonstrates the improved version of passive harmonic tags (transponder) as markers for buried plastic pipes, power budget analysis for the minimum detection level and RF sensor tags for leakage or spill in Q3. In the previous report, we presented improved version of harmonic tag design based on double slot antenna for operation at fundamental frequency of 2.5GHz as shown in fig 9.

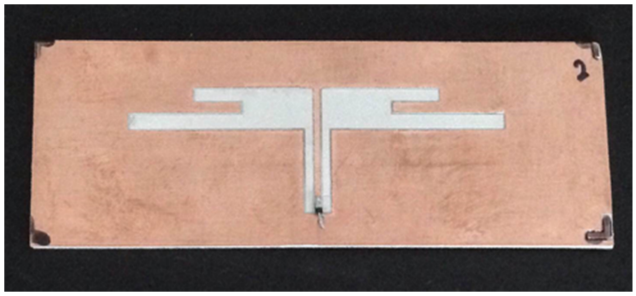

**Fig. 9** Harmonic tag operating at 2.5GHz

The report is divided into three sections: 1) Power budget analysis using the tag presented in Q3 to demonstrate the power estimation for minimum detection; 2) sensing capability of the developed tag in soil with different moisture content, and 3) an application of the developed tag for detecting pipe leaks and oil spills are presented.

**Section 1: Power Budget Analysis**

The detection of the buried harmonic tag is subject to a minimum power transmitted by the transmitting antenna, diode doubler efficiency and the minimum detectable SNR level at the receiver antenna. The signal goes through multiple environments such as air, soil and each environment includes multiple losses from different sources. The power budget estimation is a useful tool to pre-estimate the received power level provided a certain power level is transmitted. Fig 10, shows the radio link between the developed tag and transmitter receiver antennas passing through different environments.

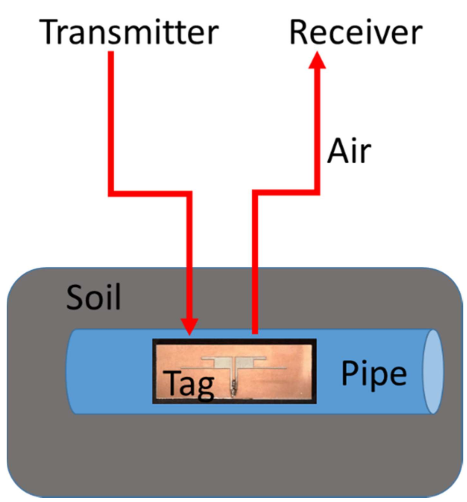


**Fig 10**. Radio link between the developed harmonic tag and the transmitter/receiver antennas.

The different losses in the entire system can be categorized as 1) Power Loss in Transmitter and Receiver, 2) Propagation loss in air, 3) Propagation loss in soil, 4) Losses at the air-soil interface and 5) Conversion losses in the harmonic tag. The Friis equation can be used to estimate the Received power at the tag ($P_r$) using the transmitted power ($P_t$) transmitter antenna gain ($G_t$) and the receiver antenna gain (Gr) as in equation [1]. The received power at the tag can be expressed as:

$$P_r = P_t \frac{G_t G_r \lambda^2}{(4\pi R)^2} \quad (1)$$

where $R$ is the distance between the transmitter and the receiver antenna and $\lambda$ is the wavelength in the medium. The equation is valid if the medium between the tag and the transceiver is free space. However, due to diffraction, reflection and scattering in the air and soil medium, the far field received power is not always inversely proportional to square of the distance ($R^2$). The received power $P_r(d)$ at a distance d with path loss exponent $\gamma$ can be expressed as [2]:

$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^{\gamma} \quad (2)$$

where $Pr(d_0)$ is the power received at reference point $d_0$. The value of $\gamma$ is 2 in free space. It varies from 1.6 to 5 depending on indoor (line of sight) or outdoor environment and also the medium of wave propagation. In this report, $\gamma_s$ represents the path loss exponent in soil and $\gamma_a$ represents the path loss exponent in air. The total path loss (PL) for air medium height of $d_a$ and soil medium depth of ds for a reference medium height $d_{0a}$ in air and medium depth $d_{0s}$ in soil can be represented as followed

$$PL = \gamma_a * 10log_{10}\left(\frac{d_a}{d_{0a}}\right) + \gamma_s * 10log_{10}\left(\frac{d_s}{d_{0s}}\right) \quad (3)$$

Other than the individual losses in air and soil medium, there is also a reflection at the air-soil interface. And conversion efficiency losses of the harmonic tag. For reflection co-efficient Γ, tag efficiency ε and cable loss (*CL)* the total loss (*TL*) can be calculated as:

$$TL = PL - 20log_{10}(|\Gamma|) - 10log_{10}(1-|\varepsilon|) + CL \quad (4)$$

$$|\Gamma| = \left|\frac{\sqrt{\varepsilon_r}-1}{\sqrt{\varepsilon_r}+1}\right| \quad (5)$$

Experiments were performed to determine the $\gamma_a$ and $\gamma_s$ using the harmonic tag presented in Q3 report. Received power at different heights were measured to determine $y_a$ for fixed $d_{0a}$ =1 feet as shown in Fig 11. Since the incoming signal to the harmonic tag and the outgoing signal from the harmonic tag are at two different frequencies, the loss co-efficient was measured individually at 2.5 GHz and 5 GHz. The average value of the measured loss co-efficient in air at 2.5 GHz and 5 GHz are 1.25 and 1.61, respectively.

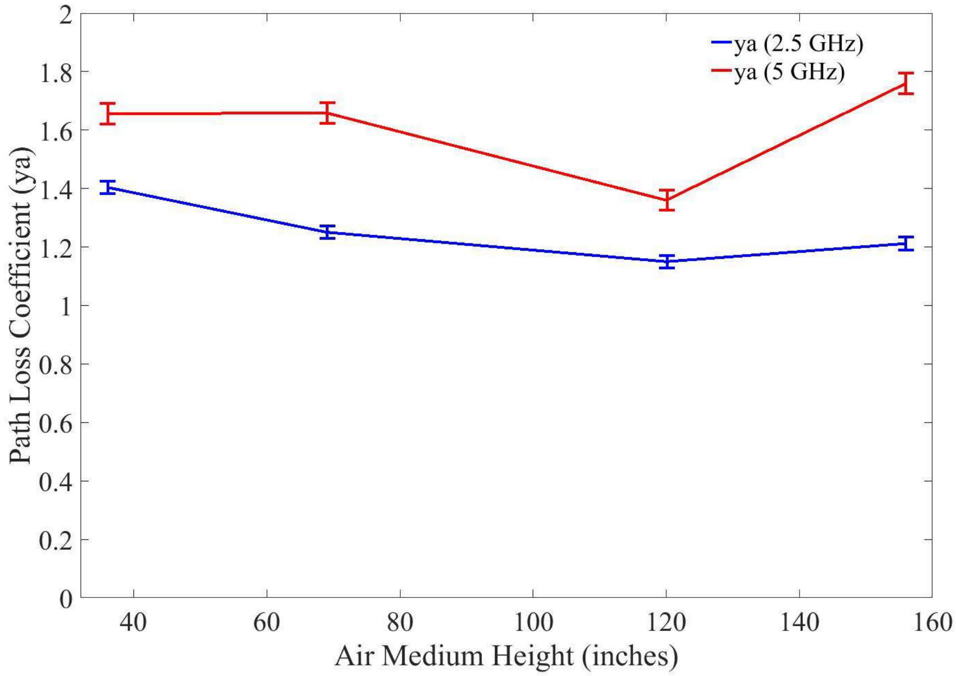


**Fig 11**. Measured path loss co-efficient in air for fundamental and second harmonic frequency.

The loss coefficient in soil ($\gamma_s$) was measured with one antenna kept under a tray full of soil and the other antenna in air interface at a constant distance of 1 foot from the tray. The thickness of the soil in the tray was varied by considering soil thickness of 3 inch as the reference point for the measurement. Measurements were done by increasing the height from 3 to 4 in steps of 0.5 inches and the average $\gamma_s$ for dry soil was found to be 4.9 at 5 GHz.

**Section II: Moisture Sensor – Water leakage**

The proposed tag is evaluated for its performance under different moisture content in soil. Two different experiments were performed to evaluate the sensitivity of the tag. In the first experiment, the tag (Tag-1) was enclosed in a plastic casing with air gap and was buried under 2 kg of soil at a depth of 3”. Measurements were done at an input frequency (fo = 2.5GHz with fixed power = 10dBm) and the output power at 2fo was recorded for different moisture contents in soil. The water- soil mixture was prepared by percent to weight at room temperature. (0%, 2.5%, 5% and 7.5% water content). In the second experiment, the tag (Tag-2) was in direct contact to the soil and the measurements were repeated. Fig 12. Shows the change in Received power as a function of increase in water content for tags with and without plastic enclosure (Tag-1 & Tag-2). The measurements were repeated twice and results were averaged out.

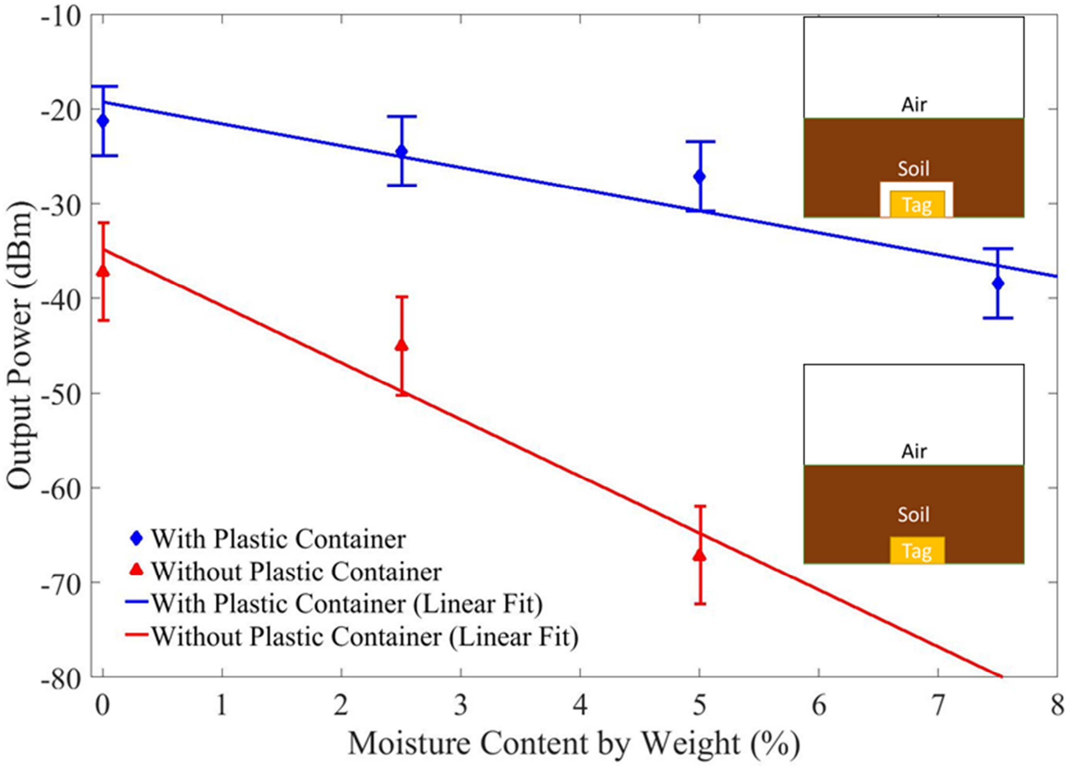


**Fig 12**. Measured power at second harmonic as a function of different moisture content in soil for fixed fundamental frequency of 2.5 GHz.

It can be inferred from the figure that at very low moisture content, the received power difference between Tag-1 and Tag-2 is about 15dB and as the moisture content increases to 5%, the difference is about 40dB. The Tag-1 is not in direct contact with the soil and can be used as a built in reference for Tag-2 to sense leaks in water pipes. This experiment shows that two tags can be used to detect water leaks. One tag is a reference tag whose antenna is isolated from moisture and the second tag whose antenna is close proximity to the wet soil. Moisture content near the tag can readily be determined by measuring the difference in signal received from these two tags. The advantage of this approach as compared to many reported in literature is that it is not a single use detector and also has a long life time, and requires no special moisture sensitive coatings.

**Section III: Leakage Sensor**

The harmonic tag as a leakage sensor (for oil or other hazardous chemicals) is targeted for potential applications in finding leaks/spills in oil and gas pipelines. The slot coupled harmonic doubler antenna have highly sensitive slots which can be used as sensor patches for different sensing applications. Unlike moisture in soil or in close proximity to antenna the oil/soil mixture is not lossy. However, the oil can dielectrically load the antenna and we take advantage of dielectric loading on antenna to detect oil leak. In order to demonstrate the concept, in place of oil, Iso propyl alcohol is used here for the first experiment. This allows faster characterization of the sensor. In this experiment, two drops of Iso propyl alcohol was spilled directly on the harmonic tag and the change in signal at the second harmonic was noted as it evaporates over time. Fig 13. Shows the change in measured power for evaporation of Iso propyl alcohol over time.

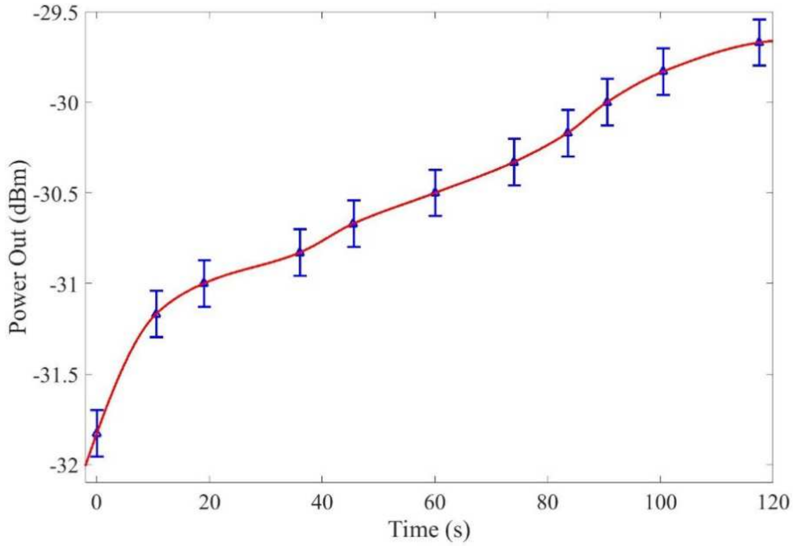


**Fig 13**. Measured power at second harmonic as a function of different evaporation time for Iso-propyl alcohol spill at a fixed fundamental frequency of 2.5 GHz.

In the next experiment, the change in output power is recorded for oil spillage on the sensitive regions of the harmonic doubler. The oil used was a car oil and the experiment was performed in air. This shows the capability of the sensor and can be adapted to sense any kind of oil. This makes the sensor more suitable for applications such as leak/spill sensor in oil and gas pipelines. The results are tabulated in Table 1. Similar to the moisture sensor, here also two tags for sensing are envisioned. One tag will act as the reference and the other will be loaded by the oil spill.

Table 3: Measured results for Oil leak/spill

| | Power Out (dBm) |
|---|---|
| Before Spill | -35.17 |
| After Spill | -55 |

### (c) Planned Activities for the Next Quarters

Besides the planned activities mentioned in section (b), here is the future work for the next quarter:

CU: ON-TAG SENSING, DATA MINING AND PROCESSING SETUP:

- In the next quarter, systematic and parametric study and testing of the RF tags in customized container environment.
- Study of RFID signals processing and features extraction that includes phase information extraction
- Design of on-tag sensing mechanism and implementation using additive manufacturing technologies.
- Integrate MSU developed tags with CU testing facilities.

MSU: NEW PASSIVE RFID TAG DESIGN:

- In the next phase, design of RF tag for operation at 915 MHz (UHF) to make it compatible with existing RFID frequencies.
- Development of a comprehensive power budget model. This will build upon the model presented in this report.

- Improvement in the existing design to achieve longer range of detection by incorporating time gating.
- Integrate commercial RFID chips to passive tags