The effect of different solutions on RFID Antenna Gain(AG)

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ABSTRACT

RFID Sensing is a versatile technology widely employed in various fields such as inventory management, access control, and livestock tracking. A key aspect of RFID applications is the identification of objects or individuals through the use of unique RFID tags or identifiers. However, we believe that RFID Sensing has the potential to be applied in other domains as well.

Pichorim et al. have demonstrated a novel use of RFID Sensing in measuring soil moisture for landslide monitoring. This innovative approach offers real-time prediction capabilities for landslides using RFID devices. By utilizing RFID technology beyond its conventional role in object identification, Pichorim's work highlights the extensive potential of RFID Sensing in diverse applications.

In particular, the purpose of our experiments were to expand upon results Aditya obtained last quarter while investigating unexplored applications of RFID Sensing. Last quarter, we initially obtained results showcasing the effect of saltwater on the RSS of a RFID signal.

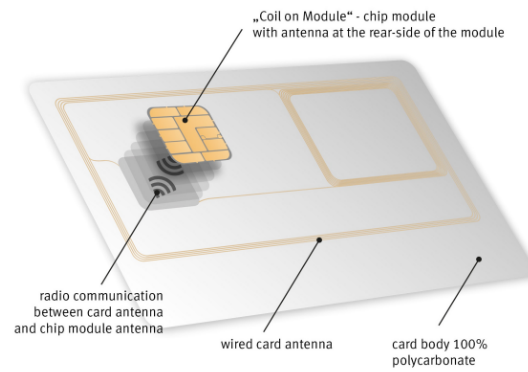
Our original motivation for this project was to create a setup that measure's chlorine concentration in water using RFID RSS. This would permit homeowners to measure chlorine levels in pools without the use of disposable test strips. Unfortunately, due to time constraints, we pivoted our motivation to accurately detect water salinity level using a low-cost setup through RFID RSS.

This paper ultimately showcases the effect of various solutes in water on the affect of RFID RSS. We also performed a regression analysis showcasing a strong causation between salinity and RFID RSS. Finally, we sought to explain the underlying cause for the effect that salinity/solutes have on RFID RSS. Our results can be found in a GitHub Repo found here. [1]

1 Background

The RFID wireless technology comes handy in use cases where we don't require a very high range or a large data rate, and require no/low power. RFID Sensing works with two components: tags and readers. RFID Tags have a microchip and antenna as shown in **Figure 1**. Communication is done between the reader and the tag; the RFID Reader will send out a signal and a RFID Tag will respond with its own custom signal that includes identifying information about an object.

Figure 1: Labeled Diagram of a Passive RFID Tag with its components [3]



The signal generated by the RFID Tag is a result of the radio signal (an electromagnetic wave) that is transmitted from the RFID Reader. The RFID Tag "harvests" energy from the radio signal (the received electromagnetic wave induces a current in the tag's antenna, which then powers the microchip; preparing the RFID Tag for signal transmission) and then sends back a signal to the RFID Reader. The RFID Reader will finally decode the signal.

As mentioned earlier, there are two types of RFID Tags; Active and Passive. Active RFID Tags contain their own power source, Passive RFID Tags rely solely on the energy provided by the signal transmitted from the reader. In this paper we will be focusing on applications observed with passive RFID.

Unfortunately, because the signals in Passive RFID rely on harvested energy from the RFID Reader, the signal is not very strong and can attenuate quickly. The measure of the strength of the radio signal that is received by the RFID Reader from the RFID Tag is called "RSS", which stands for "Received Signal Strength.

RSS can be used to estimate distance between the tag and the reader, however, this estimation can be highly inaccurate due to noise and interference. However, in Pichorim's work, RSS was used to accurately estimate soil moisture content.

In our experiments, we also use the RSS Values to explore further applications of RFID Sensing.

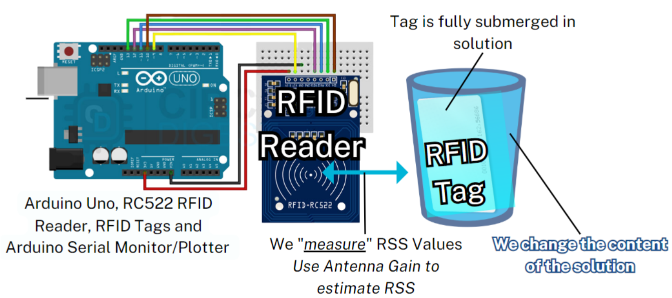
2 Experiments

We performed our experiments with very simple components as stated below:

2.1 Experimental Apparatus

1. Electronics + RFID Apparatus:
   (a) 1 Arduino Uno
      i. 7 Arduino Jumper Cables
      ii. 1 USB 2.0 Printer Cable
      iii. Laptop (to Interface with Arduino)
   (b) 1 RC522 RFID Reader
   (c) 1 S50 White Card (RFID Tag)
2. Equipment for Extra Equipment for Estimating Concentration of Some Soluble Materials
   (a) 1 Glass for holding liquid
   (b) Salt
   (c) Vinegar
   (d) Tape (pinning down equipment to keep measurements consistent)

Figure 2: Experiment Setup to estimate RSS using RC522 RFID Reader



Figures 2, 3 and 4 show how the experiment was setup to collect RSS measurements.

Note: The RC522 RFID Reader **does not directly measure RSS**, instead, Antenna Gain is adjusted to estimate RSS. When the tag is situated at greater distance, more Antenna Gain has to be set in order to detect a signal reflected back from the RFID tag. Therefore, A higher Antenna Gain implies a lower RSS and vice versa.

We used the work done by Chang Liu as a starting point for estimating RSS using the RC522 RFID Reader. [2] We had to further "upsample" the Antenna Gain to get a higher resolution reading of the RSS.

2.2 Description of Experiment

The following procedure is necessary to estimate concentration of soluble materials in water:

Figure 3: Top View of actual Experiment Setup to estimate RSS using RC522 RFID Reader

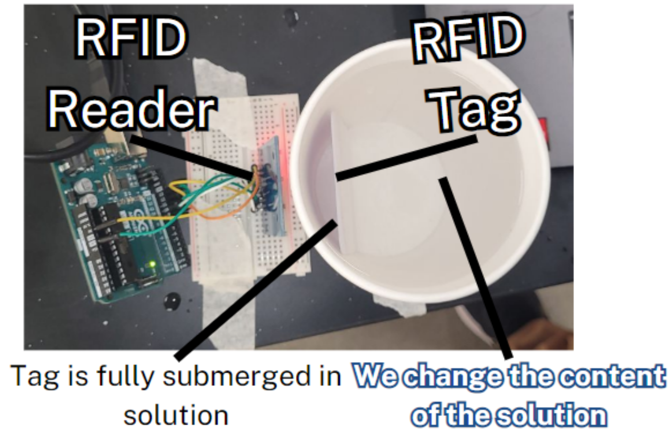
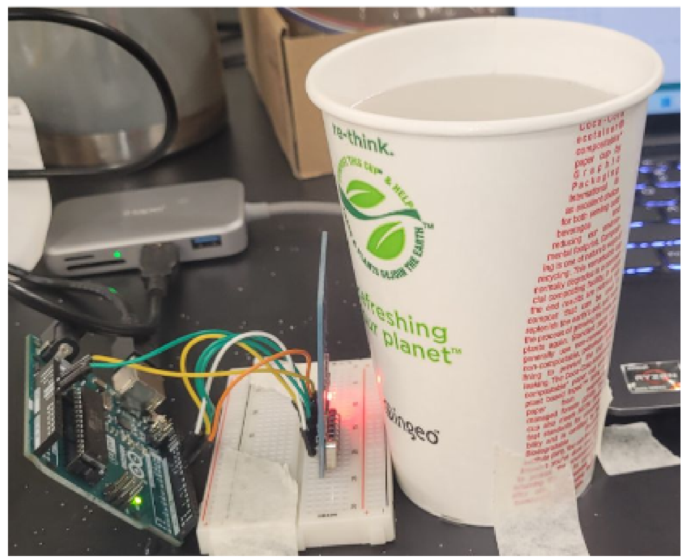


Figure 4: Top View of actual Experiment Setup to estimate RSS using RC522 RFID Reader



1. This procedure is more complicated and requires modifying the base code of Chang Liu's word [2] to scan through all Antenna gain values to measure the exact Antenna Gain Value at which the RFID Tag is detected. Our code is available in our GitHub Repository linked in the abstract.
2. Ensure RFID Tag Antenna and Sensor are facing RFID Reader
3. Ensure RSS Reading in Serial Plotter is displayed
4. Place Empty Glass in fixed location.
5. Fill Glass with liquid (any liquid)
6. **Submerge RFID Tag in Liquid**
7. Observe Effect of changing the liquid on the RSS Reader.

To change the content of the solution, add additional solute to the liquid in the cup.

3 Results and Discussion

It is important to note that all of the following results were obtained with the RFID Tag placed at the front of the cup.

3.1 Control: The effect of water on Antenna Gain

For our control we measure the AG without any water (only air in the cup) and the AG with pure water (no solutes in the liquid).We note there is a statistically significant effect of the presence of water on the measured AG.

This result differs from what was previous obtained by Aditya last quarter. We are not fully sure why but believe this is likely attributed to the different cup shape.

The cup-shape last quarter resulted in the RFID Tag being flush with the front of the cup - ultimately resulting in very little water coming in front of the tag. This quarter we used a more "bowl-shaped" cup that resulted in more water in front of the tag - affecting our measurements.

1. AG without water (only Air): 176 ± 0
2. AG with water (no solutes): 180 ± 0.81

3.2 The effect of the amount of water on Antenna Gain

There was no effect of the amount of water as long as the Tag was fully submerged. It is important to note that for all future experiments the card is fully submerged in the solution.

1. Tag not fully covered: 175 ± 0.6
2. Tag barely fully covered: 180 ± 0.81
3. Tag fully covered: 180 ± 0.81

3.3 The effect of the addition of vinegar on Antenna Gain

As mentioned earlier, our original goal for this project was to see if RFID RSS could be used to estimate the concentration of chlorine in a solution.

We tested to see if the addition of an acid would have a statistically significant affect on RFID RSS. Unfortunately, we did not see a statistically significant effect on AG.

However, we believe this is likely due to the low concentration of acid in store-bought vinegar (about 4 %). Vinegar is a conductor (affects the dielectric constant - an indicator for affecting RSS; further discussed in the explanation section) and we believe a more concentrated vinegar solution would have an affect RSS.

1. Tag covered with water: 180 ± 0.81
2. Tag covered with water and vinegar: 181 ± 0.81

3.4 The effect of salinity on antenna gain on Antenna Gain

From our experiments last quarter, we already knew that salt would have an effect on AG. We had already observed that increasing salinity also increases AG however, we wanted to perform a regression analysis.

The results of our experiments are shown in Figure 5.

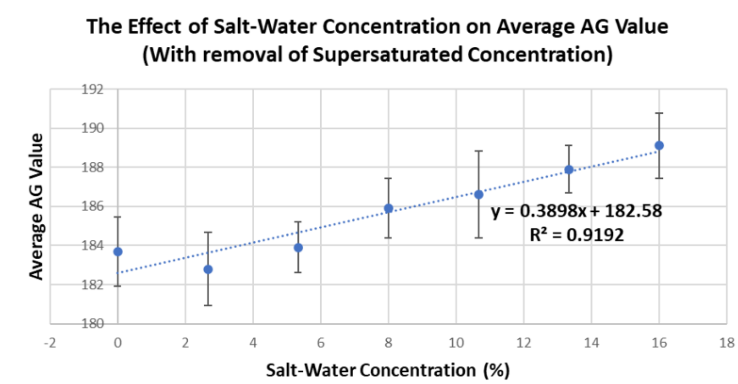
The results of our regression analysis are shown in Figure 6, where we get an R^2 of 0.92, indicating a strong, positive causation between Salt-Water Concentration and the Average measured AG Value. Note, we remove our tested concentration of 18% from our regression analysis as water is super-saturated at that point - meaning that the AG reading was inaccurate (we could see solid salt in the solution).

Our slope of 0.39 indicates a 0.39 increase in AG for every percent salinity increased. This minimal marginal AG obtained as Salt-Water Concentration increases is a limitation of our hardware and it would be interesting to experiment with other RFID Readers to see if we could get different (i.e a higher slope) results.

Figure 5: Raw Data from Salinity Experiments

Grams Salt (g)	0	0	10	20	30	40	50	60	70
Grams Water (g)	0	375	375	375	375	375	375	375	375
Concentration (%)	Control	0	2.67	5.33	8.00	10.67	13.33	16.00	18.67
AG Values Table									
	166	185	182	182	185	187	188	190	190
	167	183	183	185	185	186	187	191	190
	162	180	187	184	188	183	186	189	187
	168	186	181	184	186	188	188	188	189
	167	184	184	183	184	187	190	186	190
	165	182	183	184	185	184	187	187	189
	164	185	183	185	188	188	189	190	189
	166	183	182	184	187	186	187	189	188
	167	184	180	186	187	186	189	190	188
	170	185	183	182	184	191	188	191	187
Average AG Value	166.2	183.7	182.8	183.9	185.9	186.6	187.9	189.1	188.7
Median AG Value	166.5	184	183	184	185.5	186.5	188	189.5	189
STDEV AG Value	2.20	1.77	1.87	1.29	1.52	2.22	1.20	1.66	1.16

Figure 6: Regression from Salinity Experiments

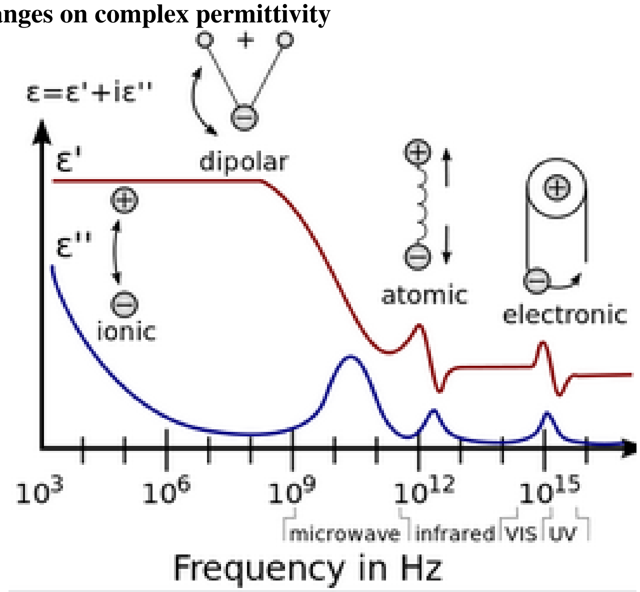


4 Explanation of saltwater results

Salt water effectively blocks RF signals because salt breaks down into ions, causing the liquid to be conductive. When the solution is conductive, the imaginary part of the permittivity in the complex system is higher. As a result of polarization from the radio-frequency signal, the imaginary part of its refractive index also increases, causing some of the waves to be reflected back upon reaching the surface. Therefore, RF signal will have lower penetration depth when the liquid is more conductive.

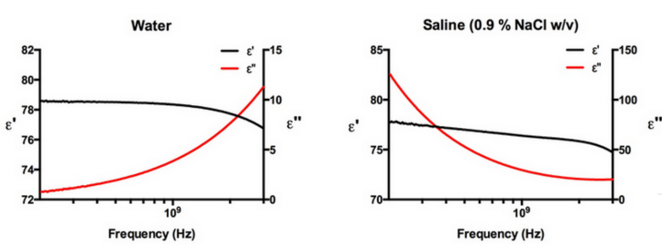
Salt water increases the conductivity, or equivalently, imaginary part of the permittivity because salt breaks down into Na^+ and Cl^- ions when dissolved into a solution. Those non-neutral ions cause the liquid to be electrically conductive. The conductivity of the substance varies with variety of additional factors such as temperature, pressure and incoming wave frequencies. In this experimental setup, we use radio frequency to read the RFID tag, and run in the room temperature environment with only atmospheric pressure applied to the liquid.

Figure 7: Effects of polarization of different frequency ranges on complex permittivity



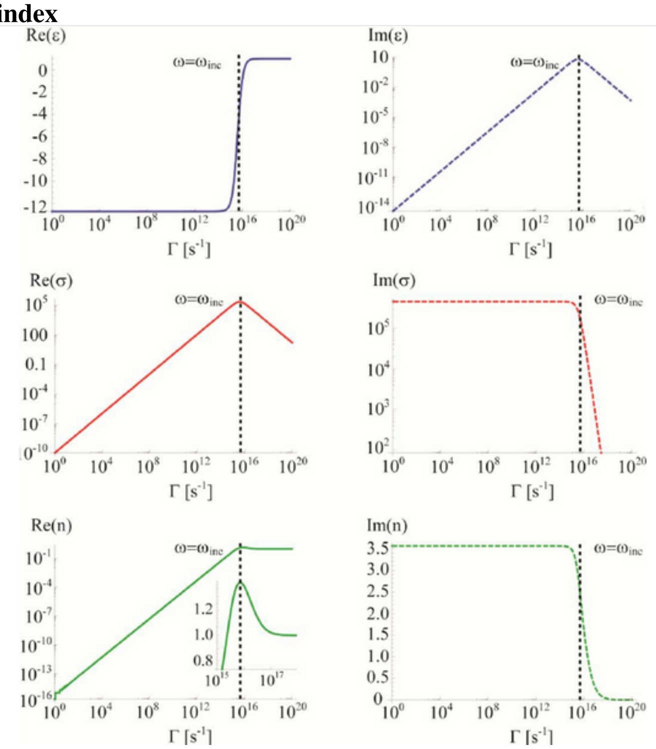
In ionic compound depicted in figure 7, the imaginary part of the permittivity, or conductiveness, is highest at incoming frequency equal to near zero. At a very low frequency range like RF, the imaginary part of the permittivity is very high due to the polarization of the ionic compound.

Figure 8: Effects of salinity over frequency ranges, comparing between real and imaginary part of the permittivity



According to figure 8, in pure water, the imaginary part of the permittivity is close to zero at RF range, while 0.9% NaCl w/v saline solution has significantly higher imaginative part, becoming a larger part of the permittivity itself. Meanwhile, the real component drops by a little when adding salt. Since RF provides a very low frequency range, we leverage the disparity of real and imaginary parts of the permittivity in the ionic compounds to achieve more dynamic in the result.

Figure 9: Effects of conductivity on complex refractive index



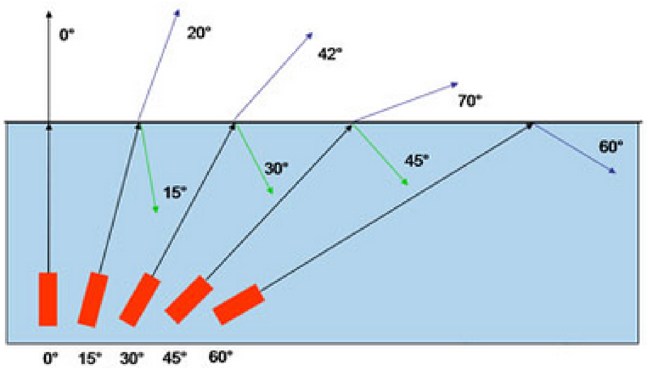
When the solution is conductive and has high imaginary component of permittivity, the imaginary part of refractive index also increases with this formula below, assuming the substance is non-magnetic ($\mu_r \approx 1$):

$$n_r \approx \sqrt{\frac{|\varepsilon_r| + \varepsilon_r}{2}}$$
$$n_i \approx \sqrt{\frac{|\varepsilon_r| - \varepsilon_r}{2}}$$
$$|n| = \sqrt{\varepsilon_r \mu_r}$$
$$|n| \approx \sqrt{\varepsilon_r}$$

Where n_r, k_i, $|n|$ are the real component, imaginary component, and the absolute value of the refractive index accordingly.

When the electromagnetic waves goes through a surface between two different substances, it undergoes refraction. Additionally, fraction of the signal will be reflected back to the original substance when the angle between the wave and the surface is getting lower. If the angle reaches the critical angle, all of the signal will be reflected back. This phenomenon is called "total internal reflection". Not only does the refractive index plays a role in bending the angle, the imaginative component of the complex refractive index de-

Figure 10: Refraction and total internal reflection



termines how deep the electromagnetic wave gets through the surface. As a result, salt water, which has high imaginary component of the refractive index, effectively attenuates the signal and requires more antenna gain to reach the RFID rag.

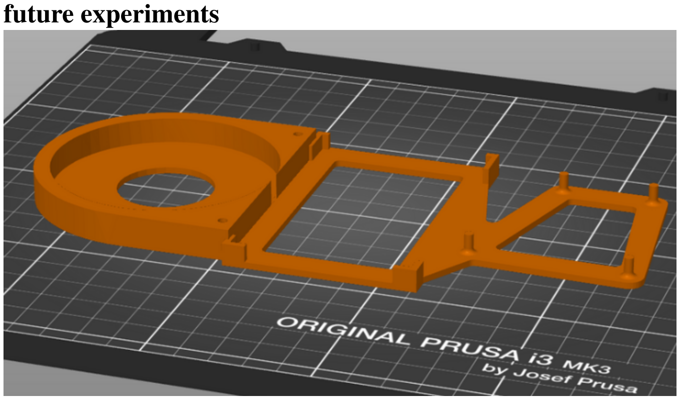
5 Future Work

We would like to continue our Saltwater Analysis.

1. Create a 3D-Printed "mount" that houses each component in a known location. This would enable us to have consistent "spacing" of all the apparatus. Currently, we rely on taping down all our equipment to maintain fixed distances between the RFID Tag and the RC522 module. Maintaining consistent spacing using a 3D-Printed mount as shown in Figure 11 would permit us to run future experiments.

2. We would like to setup experiments to measure the effect of chlorine on RFID RSS.

Figure 11: 3D Printed mount that ought to be used for future experiments



6 Conclusion

In this project, we showcased the effect of different solutions on RFID RSS. We have an easily replicable experiment setup, with minimal apparatus for each of the use cases, and analyzed the results. Last quarter, we encountered some unexpected results (e.g. sudden decrease in RSS for saltwater) which motivated us to do more research this quarter to determine the underlying reason for the phenomena.

Although our setup has some limitations we are still able to get measurements that are coherent with the existing explanations.

7 Acknowledgments

Thank You to Professor Omid Abari for teaching us the fundamental concepts that served as the foundation of this project. The last two quarter of instruction by you have been some of the most informative and enjoyable quarters we have had at UCLA.

Additionally, thanks for the superb guidance on not just this project, but on this course as a whole. We thoroughly enjoyed this course.

We learned valuable content that made us more interested in new connectivity technologies, our interest would not have been possible without your engaging instruction.

8 References

[1] Rathin Singha Aditya Mishra, Mark Theeranantachai. Solutions affecting rfid antenna-gain: https://github.com/morelap2015/solutions-affecting-rfid-antenna-gain/tree/main. In *UCLA CS 219 - IoT And Connectivity*, 2023.

[2] Chang Liu. Rfid (rc522) simple signal strength setection via changing antenna gain. In *Mendeley Data*, February 2018.

[3] Michael Hölzl Michael Roland. Evaluation of contactless smartcard antennas. In *Technical Report, University of Applied Science Upper Austria*, 2015.