RFID For In Vivo Sensing

EECS 189AB

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PROJECT

RFID for *In vivo* sensing. In other words, RFID sensing technology that takes place inside a living organism for potential tracking and data collecting purposes.

OBJECTIVE

To simulate an environment that emulates that of a living organism while test and observe the limitations of RFID sensing technology in that simulation.

EXPERIMENTAL BACKGROUND

We were assigned to use low-frequency RFID technology (125 KHz) for this experiment based on the future applications our experiment would relate to (diabetes patients, animal tracking). One main reason to why low-frequency tags would be used is that they can be passively powered (no external or on-board power supply), which allows the RFID tags to last for many years since it would need to accommodate the living organism's lifespan. Two other reasons would be that a low-frequency tag is less susceptible to interference (external noise) and its reading range (3 feet) as well as data transfer rates are sufficient for the future applications we had in mind. Unfortunately, for our experiment we operated at 13.56 MHz (high frequency) because we were unable to retrieve a respectable number of consistent readings using low-frequency. We attributed that problem to the variety of attenuations (air, glass, water) involved that disallowed us to conduct any data gathering at a low frequency. The higher frequency allowed us to obtain a much higher reading distance.

In simulating a living environment, we used water to be that substitute. We experimenting using water and salt because theoretically, that would give the closest emulation of a living organism since salt contains many ions and it can be argued that many microorganisms only interact with seawater the same as how human cells interact with blood. However, after conducting an experiment comparing our data results between just water and water + salt, we concluded that the data difference was insignificant and proceeded to use just water as our simulated living environment.

Since our simulation consisted of purely water, one of our main concerns was the microwave loss of water. Microwave loss is generally based on the medium the signal propagates from and to. This determines how much is transmitted and how much is reflected. In our case we are mainly dealing with ‘glass’ and ‘water’. A material’s ability to transmit an electric field is based on its permittivity. Basically, the higher the permittivity, the higher the difficulty of the electric field can be permitted in that material. Since the microwave signal is based on the magnetic and electric field, if the electric field cannot be transmitted, the signal cannot be transmitted as well. Water’s permittivity (72-80) is much higher than glass (4.5-10) so microwave loss in water (simulation) is expected to be high.

The capabilities of RFID technology is solely based on the frequency it operates at because that affects the overall integration of RFID technology in certain applications. Simply put, the higher the frequency, the higher the power consumption so the need to supply sufficient power becomes an issue because this can lead to size and convenience problems. The benefits of a higher frequency are greater reading distances and faster data transmission. In our case, our application is using RFID technology in a living organism.

PROJECT GOALS & ASSESSING EXPERIMENTAL ISSUES

The main goal of the project was to determine how well one would be able to apply RFID sensing technology in a living organism through experimentation and how that would translate in the real-world.

The methods we used to approach our main goal were designing a transmitter and receiver that acted how RFID readers and tags would cooperate. From there, we simulated an environment that of a living organism (water) and incorporated the transmitter and receiver to determine whether its application in a living organism would be efficient or inefficient. Before we conducted our experiment, we predicted that some solutions to better our methods would be isolating noise, using other materials to improve transmitting and receiving, possibly incorporating a signal amplifier or simply applying more power to transmitter and receiver.

Before we went into the experiment, we reviewed possible issues we would run into and attempted to assess the problem:

Problem: RFID reader and tag were not operational

Approach/Reason: We purchased a barebones RFID reader. We lacked RFID software to correspond reader to tags and a proper antenna for the reader. Contacted manufacturer of RFID reader for appropriate software but model was considered obsolete. We used a coaxial-connecting antenna but no signal was transmitted since the tags did not respond (most likely due to lack of software).

Outcome: Basically, we were unable to get any kind of reading with the reader regardless of our attempts.

Problem: Determining proper ratio of water to salt and a water temperature to correctly emulate a living organism (in our case, human beings).

Approach/Reason: Thorough research in the web and textbooks for any type of information relating to a specific amount of salt with a specific amount of water in the human body. Even though we could not get any information, we experimented with the 'water + salt' scenario with an arbitrary amount of salt but the changes in the signals were negligible. As for the temperature of the water, we lacked the equipment/tools to accurately heat (human body temperature) a large amount of water in the fish tank.

Outcome: Although we were unable to determine a very accurate representation of a living system, we decided to do without the salt since our experiment with salt and water did not yield any significance. We also did not heat the water since we lacked the proper tools yet we do believe temperature may have altered the signal because it can attribute to noise.

Problem: The transmitter and receiver did not transmit and receive as well as we wanted

Approach/Reason: We had a limited amount of materials to properly create a device that could transmit and receive a signal. We tested the wires inside the RFID tag, a metal coil, and an insulated wire. The insulated wire was ironically the best transmitter as well as receiver.

Outcome: Although the transmitter and receiver were not as efficient, it still worked adequately.

Problem: Finding equations to determine all theoretical results (attenuation, propagation, microwave loss, available power, signal to noise) accurately

Approach/Reason: Extensive research through online material and textbooks

Outcome: We obtained a few theoretical equations and explanations but also failed to find others.

Theoretical Analysis

To find the attenuation rate of the system, we used equations for power densities to model the behavior of the transmitted signals. The average power density is given in the equation below.

$$S_{av} = \frac{1}{2} Re\left[\underset{\sim}{E} \times \underset{\sim}{H}^*\right] \left(\frac{W}{m^2}\right)$$

Hence, we need to know the power density of the transmitted signal and compare it to the power density of the received signal to see how much loss there is due to noise and propagation mediums. Since the magnetic field phasor is proportional to the electric field according to the equation,

$$\underset{\sim}{H} = \frac{1}{\eta} \hat{k} \times \underset{\sim}{E}$$

Where η is the intrinsic impedance of the medium. From this, we can rewrite the first equation into

$$S_{av}(z) = \underline{z}\frac{|E_0|^2}{2|\eta_c|}e^{-2\alpha z}\cos(\theta_\eta) \qquad \left(\frac{W}{m^2}\right)$$

Where α is the attenuation constant and given by the equation

$$\alpha = \omega\left[\mu\varepsilon_r\frac{\varepsilon_0}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon_r\varepsilon_0}\right)^2}-1\right]\right]^{\frac{1}{2}} \quad \left(\frac{Np}{m}\right)$$

The symbols μ, σ, and ε are the permeability, conductivity, and permittivity respectively. This equation shows the behavior of the power density of the transmitted wave as it propagates through a lossy medium. According to the equation, there is an exponential decay of the signal strength the further away from the transmitter source we are.

To find the attenuation rate of the signal, we can use the gain in decibels to determine how much of the signal is lost.

$$G\,[dB] = 10\log\left(\frac{P_1}{P_2}\right) \quad (dB)$$

We can rewrite the equation to include the power densities of the transmitter signal and the receiver signal to find the attenuation rate.

$$A = 10\log\left[\frac{S_{av}(z)}{S_{av}(0)}\right] \; (dB)$$

Using this equation we found that the free space lost should be very small, almost zero, because the free space propagation attenuation constant is zero, which nullifies the exponential term of the power density equation.

Once we calculated the free space loss, we needed to determine the behavior of the power densities as it traveled from one medium to the next. We can find the power transferred through the use of the reflection coefficient Γ and the transmission coefficient τ, given by the equation

$$\Gamma = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1}$$

$$\tau = 1 + \Gamma$$

Through some algebraic manipulations we can rewrite the power density equation as it travels from medium1 to medium 2

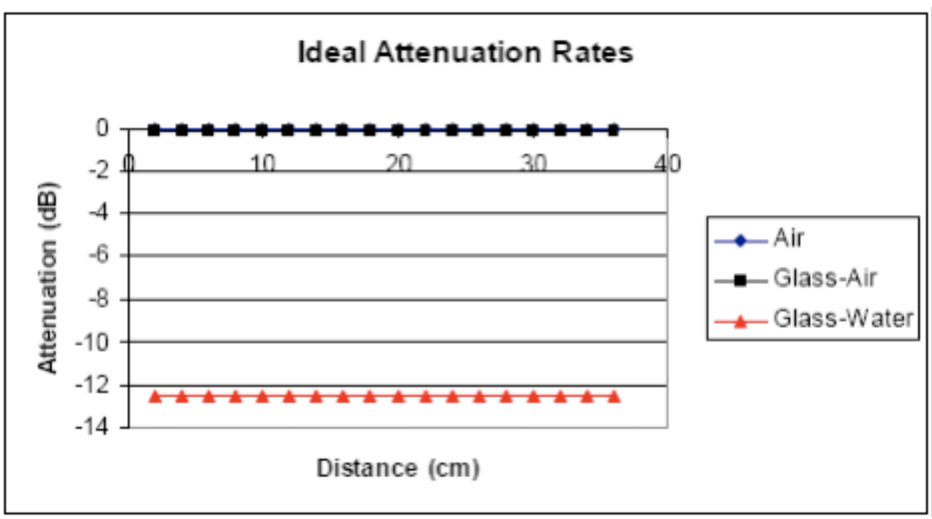
$$S_{av_1}(z) = \underline{z}\,\frac{|E^i|}{2\eta_{c_1}}\left(e^{-2\alpha_1 z} - \left(|\Gamma|^2 e^{2\alpha_1 z}\right)\right)\ \left(\frac{W}{m^2}\right)$$

$$S_{av_2}(z) = \underline{z}\,|\tau|^2 \frac{|E^i|}{2}\left(e^{-2\alpha_2 z}\right) Re\left(\frac{1}{\eta_{c_2}{}^*}\right)\ \left(\frac{W}{m^2}\right)$$

The attenuation rate equation can also be modified to include the two different mediums

$$A = 10\log\left[\frac{S_{av_2}(z)}{S_{av_1}(0)}\right]\ (dB)$$

The results of our calculations are shown in the graphs below.



Experimental Procedure

The original plan for our procedures was to use the RFID reader and tags. However, we were unable to find supporting software for the reader and hence could not get the tags to work with the reader. We had to modify our plans by modeling the RFID reader and tag instead of using them to conduct the experiment.

The model we created involved just using two antennas, one for transmitting and one for receiving. We used loop antennas because the tags we had were using loop antennas, so we made the antennas similar to the tags. The antenna lengths were made to be a quarter of the wavelength of the propagation frequency. Since our testing frequency was 13.56 MHz, the wavelength was about 22.1 m and hence the coil length was about 5.5 m. The wire used to make the coil loops were 105C-300V AWG 20 Wire.

Our experiment is to find how well an RFID tag would work within living systems. In order to do this, we decided to test how well the signals would be received underwater, since the tags will be within humans and humans are mainly made of water.

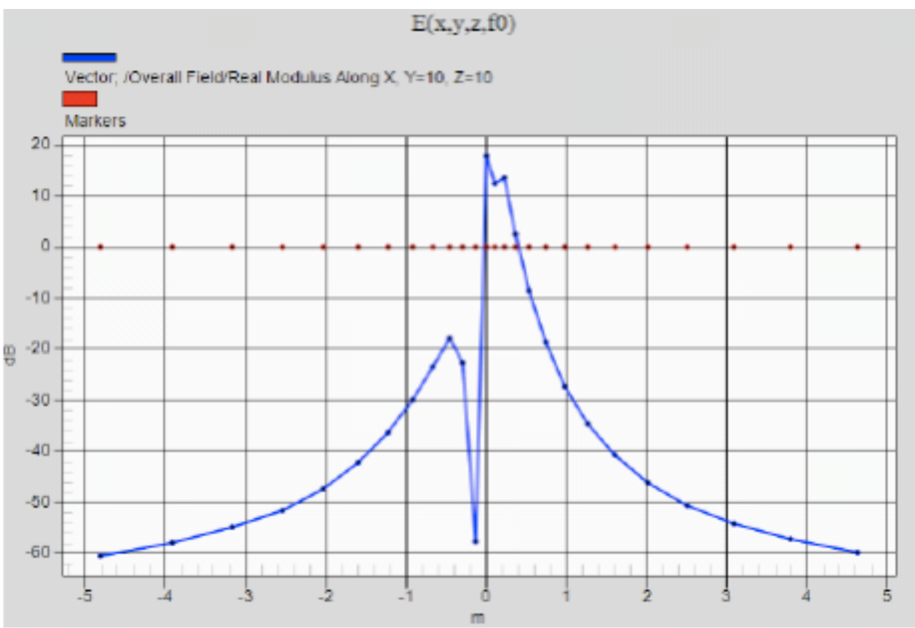
The first part of the experiment was to find the free space propagation loss. For the transmitting antenna, we used a breadboard and put our antenna in series with a 50 Ohm resistor. We measured the resistance of the wire and the resistance of the resistor using a multimeter. Then we sent a 5 V amplitude sine wave at a frequency of 13.56 MHz through the wires using a function generator and also measured the signal with an oscilloscope. For the receiving antenna, we hooked an oscilloscope into the ends of the antenna to measure the voltage of the incoming signal. We oriented the antennas so that the transmitting signal would have a normal incident onto the receiving antenna. We took voltage measurements of the receiving antenna at different distances from the transmitter until we could no longer find any readings. To find the power transmitted and the power received, we divided the square of the voltage readings and divided by the resistance of the wires.

Once we knew how much attenuation was in the air and in the antennas, we had to figure out how much attenuation the glass container for our water would cause. We repeated the same procedures for the free space propagation, except we enclosed the receiving antenna within the glass container.

After finding the attenuation of the glass, we filled it with water and repeated the distance measurements with the receiving antenna underwater and having the ends stick out of the water so the oscilloscope could measure it. The final analysis would be to find the attenuation of the water by subtracting the attenuation from free space and the glass container.

Simulations

To simulate the experiment, we used a program called SEMCAD X. We made a rectangular prism that had the same dimensions as the tank we were going to use. Then we selected the material for the rectangular prism to be water. For the transmitting antenna, we used an edge source with a 5 V amplitude at a frequency of 13.56 MHz. Then we ran the simulation to see how an electric field would react to the water and how well it would penetrate through. We looked at the sliced-view picture through the middle of the tank and saw that there is a large drop in the decibel readings for the electric field as it tries to penetrate through the tank of water. The resultant graph is shown below



The tank is located at the 0 axis and extends 36 cm into the negative direction, and the edge source is located at the 0 axis, that is where the field is strongest. The graph indicates a large drop in decibels of the electric field within the water tank, hence the signal that penetrates through the water would be very weak.

Results:

We first took some preliminary measurements of noise in the lab, the Vpp of the signal, the resistance in our antennas to use for later calculations. We will also list the specs of our antennas:

Transmitter: L = 8.69m, Rt = 0.6 Ohms,

Vpp of signal in Transmitter antenna = 20.24,

Value of resistor for impedance matching = 51.2 Ohms

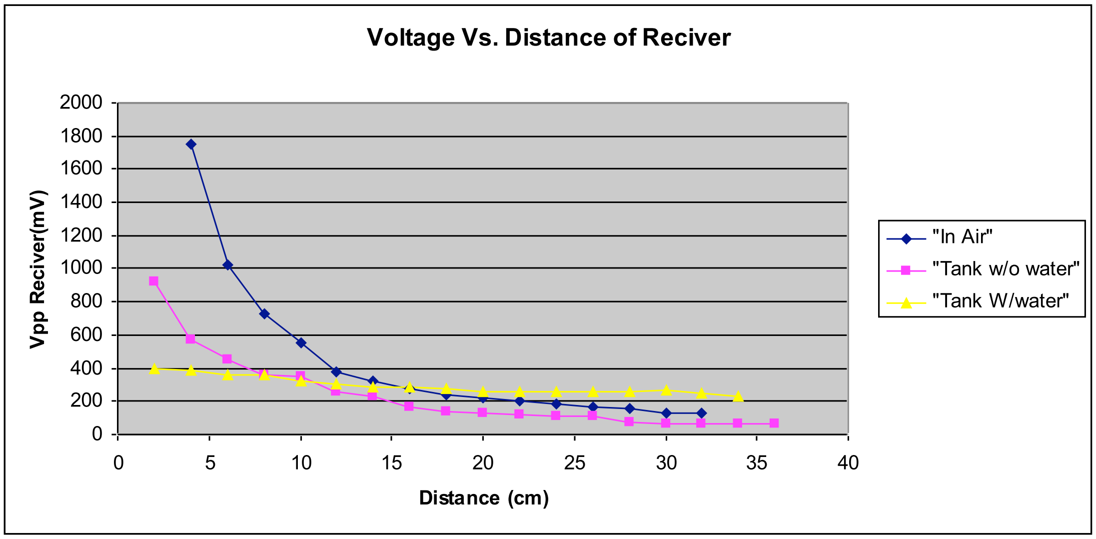
Receiver: L = 5.5m, Rr = 0.48 Ohms

Other Data related to Experiment:

f = 13.56 Mhz, lambda = 22.1 m

We took the measurements of the receiver in air, in the tank without water and in the tank with water with respect to distance between transmitter and receiver. These are the **Vpp** results in mV:

Dist cm (Transmitter to receiver)	In Air	Tank w/o water	Tank w/water
4	1750	575	390
6	1020	456	362
8	730	356	359
10	550	350	321
12	381	256	303
14	318	231	290
16	275	168	282
18	240	137	275
20	220	125	259
22	200	118	256
24	180	112	256
26	168	106	259
28	156	75	256
30	125	69	265
32	125	62.5	253

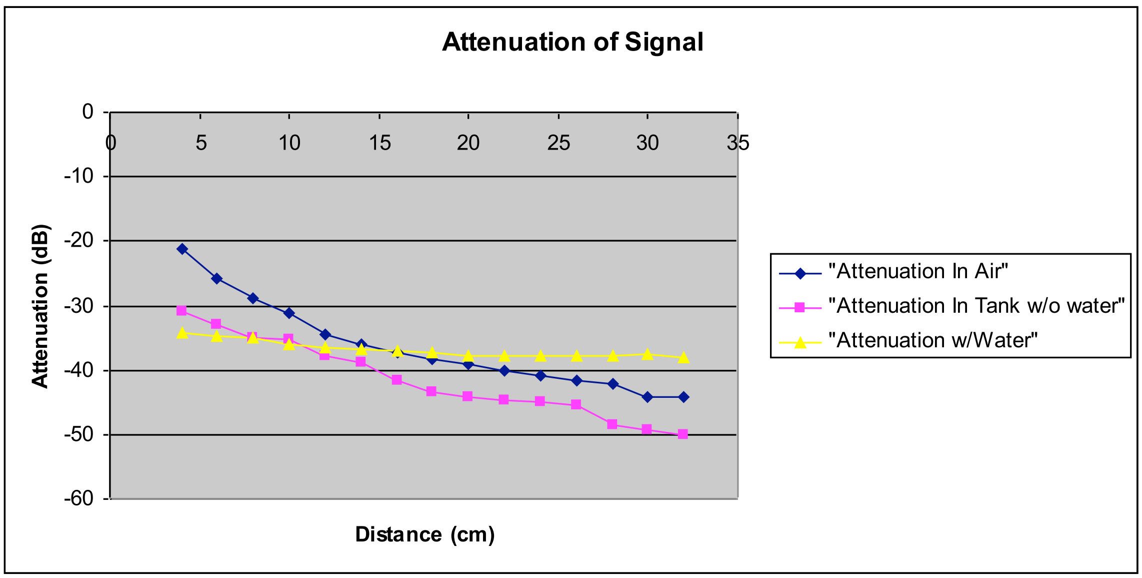


We then calculate the power in mW using the equation V^2/R:

Dist cm (Transmitter to receiver)	In Air	Tank w/o water	Tank w/water
4	60667.591	6549.623613	3013.074485
6	20610.143	4119.175911	2595.958796
8	10556.656	2510.618067	2553.110143
10	5992.4723	2426.703645	2041.224247
12	2875.6141	1298.256735	1818.720285
14	2003.2488	1057.072108	1666.006339
16	1498.1181	559.1125198	1575.356577
18	1141.046	371.8106181	1498.118067
20	958.79556	309.5285261	1328.862916
22	792.39303	275.8320127	1298.256735
24	641.83835	248.4944532	1298.256735
26	559.11252	222.5832013	1328.862916
28	482.09192	111.4302694	1298.256735
30	309.52853	94.31458003	1391.145008
32	309.52853	77.38213154	1268.007132

Then we calculated the **attenuation** in **dB** by using the equation 10*log(Pr/Pt):

Dist cm (Transmitter to receiver)	In Air	Tank w/o water	Tank w/water
4	-21.15135	-30.81874913	-34.19081389
6	-25.8401	-32.83280917	-34.83793462
8	-28.74565	-34.98310607	-34.91021706
10	-31.20485	-35.13074514	-35.88200538
12	-34.39361	-37.84730672	-36.38325346
14	-35.96356	-38.73986643	-36.76414607
16	-37.22545	-41.50592039	-37.00712386
18	-38.40788	-43.27769469	-37.22545215
20	-39.16365	-44.07390577	-37.74611075
22	-39.99151	-44.57446588	-37.84730672
24	-40.90666	-45.02774557	-37.84730672
26	-41.50592	-45.50598872	-37.74611075
28	-42.14961	-48.51088076	-37.84730672
30	-44.07391	-49.23512421	-37.54718855
32	-44.07391	-50.09450568	-37.9496956



The full spread sheet can be seen in the excel file we have turned in with the report.

Analysis:

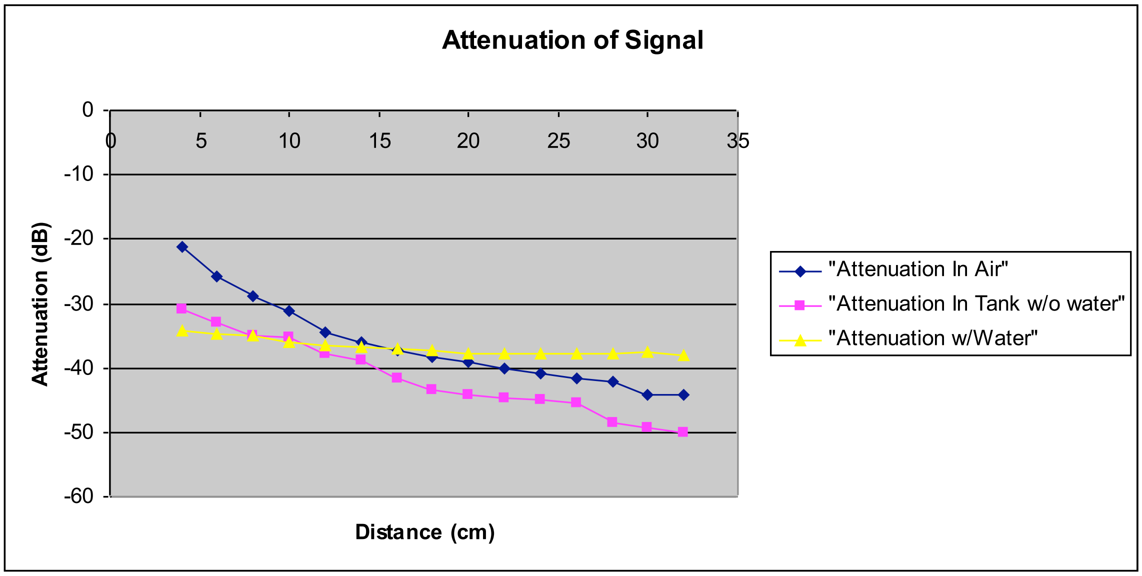
Our predictions stated that the water would highly attenuate the signal, almost to the point where the signal would not be receivable. There are several factors we look at that can affect the signal in this way. These factors include the signal to noise ratio, available power (of output signal to signal received), frequency of the signal and attenuation to depth.

Signal to noise ratio was one of the main factors that caused our signal to deteriorate. In general noise is one of the main causes of signal loss. For our experiment the noise conditions were probably worse that average as there are many wireless signals in the area. We accounted for this by measuring the noise in the room with no signal output applied from the signal generator. This is very much a factor that could affect the reading of an implanted tag. If the signal is not strong enough that it can be lost and wouldn't be able to effectively monitor a patient. We found that noise was a large part of receiving a bad signal, especially when we conducted the experiment with water. The signal picked up mostly noise when we had the receiver in water. We contribute this to the high signal impedance of water in comparison to air.

Available power to the receiving antenna was also a determining factor of signal resolution. In RFID technology the available power will determine how much information can be read. In addition if there isn't enough power the signal is not received by the reader at all. With this information in mind we had to take this into consideration when looking at signal loss. Since our available power was only about 10% of that the transmitter was outputting at the receiver most of the signal loss was due to the available power. We looked into how this could be improved and found it has much to do with inductance and the concept behind transformers and mutual inductance between two coils. Ideally, we should get the same power received as power transmitted. However in a non ideal case, such as our experiment, an amplifier would need to be use in order to get the same amount of power received as transmitted. In that case we would need to use active RFID tags which are only traditionally made for higher frequencies. Another thing that should be done to get a cleaner signal is to use a receiving wire that is at least as long as a quarter of the wavelength of the transmitted signal which we did use in our analysis.

The next thing we took into consideration for signal loss was the frequency. According to our research two signals of different frequency (one higher than the other) will have a different amount of loss inside a medium. This is due to the wavelengths of the signals. A smaller wavelength has an easier time propagating through a medium. We can see this is true through the relative permittivity of a substance. For water the permittivity changes drastically with frequency. In the KHz range (600m wavelength) the relative permittivity for water is 80 while at optical frequencies in the THz range (600nm wavelength) the relative permittivity is around 1.33. The frequency we used (13.56 MHz, about 22.1m wavelength) is closer to the low frequency end of the spectrum which is why so much attenuation was experienced. We also tried using a higher frequency (80MHz) but results looked similar to the results at 13.56MHz.

The last factor we looked at was attenuation in relation to depth of the water, simulating the placement of a tag in the patient's body. Since water attenuates a signal at what is considered a low frequency (13.56 MHz) outside of the RFID world so greatly at any depth, the depth we had the antenna in the water didn't affect the signal much. This can be seen by our graph where the attenuation of water is approximately a straight line in dB.



Theoretical Vs. Measured Comparison:

From our theoretical calculations we speculated that the water would have the most attenuation and that it would have much more attenuation (in magnitude) than the air or the tank only. According to the graph above this is true until we get to around 18cm where the attenuation in water is less than the air and tank only. We came to the conclusion that the reason this happens was due to the noise in the lab and the very high impedance of water. With a more precise oscilloscope and higher power signal generator it would have been possible to get more accurate data. This is the same reason the Vpp of water is higher than our other two sets of measurements after 18cm.

Conclusion:

The main question we were trying to answer was is it possible, based on our data, that we could implant an RFID tag into a person and monitor their health levels from outside the body. We came to the conclusion that yes, it is very possible, with the correct equipment and tools to do so.

Economic Constraints:

RFID technology is still relatively expensive, especially when it comes to medical devices. The ideal case we were considering was using in vivo sensing for diabetes patients. We have to consider the possibility that this may be too expensive compared to current solutions already in place (glucose meters that draw blood). However people would possibly pay more for new technology that didn't require drawing blood. Also it would be a one time cost, compared to currently where diabetes patients have to continually buy strips for blood testing (though these strips are cheap). We would say that economically it is a plausible solution.

Environmental Sustainability:

Based on the history of RFID technology it is easy to say that this technology would have a long lifetime. RFID technology is still in development and being applied in various uses. It has sustained since the idea came about in 1969 and keeps growing. Also it has distinct advantages over current solutions when it comes to glucose reading and other types of in vivo sensing.

Manufacturability:

The ground work for manufacturing this kind of technology is already in place. The tags would need to use nanotechnology which is still in development but at a stable point in its development. Hand held readers and electronics capable of reading out information have already been in use for years. It's just a matter of programming the readers to do what the patients need.

Ethical, Health and Safety Constraints:

This product would be beneficial to the health of society if proper testing is preformed. The FDIC would have to approve the technology before it was widely used to make sure it is indeed safe to implant microchips into humans. The fact that this is already done in animals for animal tracking say that it is probable the FDIC could pass this as safe. Ethically there is not much to consider with this product.

Social and Political Constraints:

In vivo sensing would not really have much affect on the social and political world. The one thing we considered was hacking of the RFID reader. It is known that this technology isn't completely secure (just like any computer system) and could be hacked to give ill readings. However this isn't a main concern.

Final Conclusions

There are technological constraints to consider as well if one was to want to develop an in vivo sensing solution. One thing to consider is the frequency of the tag and transmitter. It would be ideal to use the highest frequency possible within the budget in order to get less signal loss. In RFID technology when long range reading is needed UHF RFID is more ideal, though HF RFID is still used to balance cost. Another suggestion is to use the highest power signal available. 10V amplitude (20Vpp) is not an ideal voltage. The RFID transmitter we purchased had signal amplitude of 24V and a power of 10W. The last thing to take into consideration is the tag and antenna design. Quality of materials should be chosen carefully. Coated copper wire without insulation is ideal for antenna making and is what most companies use for their RFID tags and antenna. Also something that is good to do, but not necessary is to use an antenna that is a quarter wavelength of the frequency of the signal in order to get full signal reconstruction (this means if the transmitter outputs a sine wave the receiver will pick up a sine wave of the same frequency). This is a technique used in signal processing, however none of the tag designs we looked at followed this practice. The transmitting antenna should be a loop 1 full wavelength long or a dipole of half wavelength.

In general there are many factors that can affect the operation of In Vivo RFID technology. Extended research would be needed in order to optimize an acceptable system but in general it is very possible and would be beneficial to have a technology like this to use.