Evaluation of a new radio frequency identification tag for subdermal implantation

by

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Abstract

This research was aimed at examining the readiness of a prototype implantable tag of dimensions 39 mm x 24 mm x 4.1 mm designed to operate at 915 MHz for monitoring the movement of young sea lions and seals. Several issues had to be resolved, and they include developing and testing a suitable communication protocol between the base station and tag, and way of providing power to the tag. Engineering issues related to longevity of the implantable tag, and power radiated by the loop antenna of the implantable tag in its alumina enclosure, under skin and under the fat underlying the skin, also, had to be addressed. Finally issues related to how data from the tag could be best recorded at haul outs and rookeries were examined.

A working prototype of an implantable tag was obtained by reducing the height of the loop antenna by 2 mm and changing the capacitor values in the matching network to 0.2 pF. Field tests using a base station that accepted signal strengths up to -60 dBm indicated that the tag’s range was a maximum of 500 m when it was operated out of a body at a data rate of 1 kbps and the height of the base station antenna was more than 5 m. When the prototype was implanted within its alumina housing under the skin of cavernous tissue, the range of the device fell to an acceptable 180 m. A lifetime model indicated that the longevity of the tag would meet the three year target if it were to be operated using a data rate of 1 kbps, transmission interval of 15 min, packet size of 104 bits and battery capacity of 72 mAh. The lifetime model was verified at the same temperature as a sea lion. A link budget model was developed for the prototype tag, and was used to estimate the performance of the implantable in the sea lion’s environment.
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Glossary

Conductivity: Measure of a material's ability to conduct an electric current.

Co polarization: The polarization which the antenna is intended to radiate. Since the loop antenna is oriented in the horizontal plane, the co polarisation is horizontal polarisation.

Cross polarization: The polarization orthogonal to a specified reference polarization, in a specified plane containing the reference polarization ellipse. The reference polarization is usually the co-polarization. For the loop antenna, the cross polarisation is vertical polarization.

DC: Abbreviation for direct current. Frequency at DC is zero Hz.

Dielectric constant: The relative static permittivity (or static relative permittivity) of a material under given conditions is a measure of the extent to which it concentrates electrostatic lines of flux. Also referred as relative permittivity.

Diffraction: Change in the directions and intensities of a group of waves after passing by an obstacle or through an aperture whose size is approximately the same as the wavelength of the waves.

EMI: Abbreviation for electromagnetic interference.

Haulout: The place or the act of an animal crawling or pulling themselves out of the water and onto land, ice, or other object, such as a buoy.

Horizontal polarisation: Transmission of linear polarized radio waves whose electric field vector is parallel to the earth's surface.

ISM: Abbreviation for the industrial, scientific and medical (ISM) radio bands.

JTAG: Joint Test Action Group (JTAG) is the common name used for the IEEE 1149.1 standard entitled Standard Test Access Port and Boundary-Scan Architecture for test access ports used for testing printed circuit boards using boundary scan.

Line of sight: Refers to a characteristic of certain transmission systems, such as laser, microwave, and infrared systems, in which no obstructions in a direct path between transmitter and receiver can exist.

Link budget: The accounting of all of the gains and losses from the transmitter, through the medium (free space, cable, waveguide, etc.) to the receiver in a communications system.

MMRU: Abbreviation for marine mammal research unit based in University of British Columbia, Vancouver.

Molting: the process of shedding hair, skin, or an outer layer periodically to be later replaced by new growth.
**PCB:** Abbreviation for printed circuit board.

**Permeability:** The degree of magnetization of a material that responds linearly to an applied magnetic field.

**Polymer:** A long or larger molecule consisting of a chain or network of many repeating units, formed by chemically bonding together many identical or similar small molecules called monomers.

**Q factor:** The "Q" or quality factor of the loop antenna will determine its selectivity at resonance (the tuned frequency). Ideally the q factor of the antenna should be between 50 to 300.

**Radiation pattern:** Directional dependence of the radiation of an antenna. Also known as antenna pattern. In the tests carried out, the far field radiation patterns were obtained where the shape of the radiation pattern is independent of the distance.

**Return Loss:** The difference between the power incident upon a discontinuity in a transmission system and the power reflected from the discontinuity.

**RF:** Abbreviation for radio frequency.

**RFID:** Radio frequency identification tag is the use of an object (typically referred to as an RFID tag) applied to or incorporated into a product, animal, or person for the purpose of identification and tracking using radio waves.

**Rookery:** The breeding ground of certain other birds or animals, such as penguins and seals.

Subdermal: Located or placed beneath the skin.

**Uplink:** A transmission path by which radio signals are sent from end user unit to base station unit.

**Vertical Polarisation:** Transmission of linear polarized radio waves whose electric field vector is parallel to the earth's surface.
Acknowledgements

This research was funded by the National Oceanic and Atmospheric Administration (NOAA). I would like to thank Dr. William Dunford for giving me an opportunity to work on this research project. I would like to thank Dr. Royann Petrell for her input throughout the writing process of the thesis and during the skin testing of the implantable tag. I would also like to thank Morgan Davies and Tarek Ward for taking time out of their busy schedules and helping me out with the field and radiation tests respectively.
Dedication

For my family, who offered me unconditional love and support throughout the course of this thesis, all of whom joked with me everyday “When will the thesis be finished?”, and whom will have a joy on their faces after reading the first few pages.
1 Introduction

The application on which this research is focused relates to the development of a new radio frequency identification (RFID) tag for subdermal implantation into endangered seals and sea lions such as Steller sea lion (*Eumetopias jubatus*) and northern fur seal (*Callorhinus ursinus*) [1]. It was designed to assist marine biologists in monitoring the movement of the pups, who, like the young of most wildlife species, are considered most at risk. The intention is to use the tag to monitor the pups on their rocky haulouts (approximately 130 m in diameter) for three to ten years depending on the species. The tag has to function under varying tissue conditions relating to nutritional status, molting status and maturity.

Adult steller sea lions are capable of diving more than 400 m in search of food while pups are known to reach a depth of 250 m [2]. The skin of the animals can be subjected to other forces as well, including those related to impact and shear. The housing of the tag, therefore, must be made of a suitable material which can withstand these forces and protect the animal from any contact with its electrical components. Titanium enclosures filled with polymer that are used to protect pace makers from diving pressure [3] cannot be used because titanium blocks RF signals\(^1\). Alumina was the chosen material for the enclosure because it is very strong and biocompatible [1]. It is also the choice of material for many types of implants including pacemakers and RFID tags that are used in conjunction with active medical implantable devices [4]. The drawback to alumina is the high dielectric constant of about 9\(^2\) from DC to GHz frequencies. The dielectric constant should be closer to one, as higher values tend to negatively affect radiation propagation of the antenna.

Frequencies for active RF implantable device run from as low as 30 kHz to as high as 915 MHz. The application in the highest frequency range constituted of four tiny spiral slot antennae for radiotelemetry capsules for monitoring physiological parameters of the gastrointestinal tract [5]. The lowest frequency tag is often used in wildlife telemetry (for example, to monitor movements of salmons), and often has an antenna that sticks out of the animal’s body [6]. The low frequency tags that have smaller (implantable) antennas are limited in longevity. For example, the LT4 Tlitley tag model\(^3\) used for wildlife monitoring of small creatures such as

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1. Almost all of the RF signal power is reflected back by metals. The signal cannot penetrate the metal layer due to the skin depth effect and signal flow along the surface of the metal layer.

2. The dielectric constant of Alumina depends on the purity level and the frequency of operation.

frogs has a dimension of 12 mm x 8 mm x 4 mm, a expected line of sight range (antenna outside the body) of 1 to 2 km on the ground and 12 to 15 km in the air with the base station antenna at tree height and a lifespan of 10 to 12 days (based on 1.55 V silver oxide cells) [7].

In the current application, 915 MHz was chosen as the frequency of operation after Lea and Vaughan (2005) carried out for the Marine Mammal Research Unit (MMRU) at University of British Columbia (UBC) a study on the radiation efficiencies of small loop antennas and propagation losses at three candidate frequencies i.e., 200 MHz; 433 MHz; and 915 MHz [8]. In that analysis the enclosure material and the longevity of the tag were not considered. A link budget was also developed for the tag that took into account losses associated with tissue (artificial media) but did not take into account the effect of the alumina enclosure. Results of that link budget indicated that the expected range of the tag was theoretically 600 m if the receiver sensitivity of the base station was -119 dBm and the tag operated at a data rate of 1 kbps.

The RF device within the alumina enclosure had never been tested under actual skin and fat tissues that underlay the skin. Implantable antenna propagation behaviour of the loop antenna was modeled and tested using a coax loop antenna inside muscle simulating liquid. The recipe for the muscle simulating liquid was derived from Johansson, 2004 and comprised 52.4% water, 45% sugar, 1.4% salt and 1% Hydroxyethylcellulose (HEC) substance [9]. Also, the effect of the alumina enclosure was observed by placing the antenna inside the alumina enclosure. Modeling and testing results indicated that for a loop antenna operating at 2.25 GHz, a frequency shift of 1.8 GHz and 0.7 GHz occurred respectively. Further, the amount of resonance decreased when: the antenna was placed inside the simulated tissue and the antenna was placed inside the alumina enclosure respectively [10]. Other researchers have also mentioned frequency shifts occurring when the antenna is placed within the body [5], [11]. When the frequency of operation increases, the amount of losses associated with the body increases. These investigations were focused mostly on antenna placed well inside of a body. A matching network for the loop antenna in the current application was developed by Lea, 2007 [12] which would permit the working of the tag in free space outside of the alumina enclosure. This matching network ensured that the antenna could radiate maximum power. This matching network had not been tested under tissues. Another reason why the tag had not been tested under the tissue was that an internal power supply had not yet been fully developed so that it could fit within the enclosure, and magnetic switch had not been added to the board.

The research described herein pertains to readying the prototype for insertion into live adult animals. If found effective and safe, the next step could be tag implantation into pups. To
avoid frequency shifts and detuning; and reduction in transmission power of the loop antenna, the antenna and the matching network were adjusted to take into account the effect of the enclosure and the skin properties. In addition, an internal power system was devised, and a lifetime model was developed to determine device longevity under different operating conditions (such as data rate, battery capacity, number of transmissions). The complete tag was tested under cavernous skin of pig and elephant seal to determine radiation performance of loop antenna; return losses of the matching network; and expected line of sight range of the device. Some of the information obtained was compared to results obtained by testing the Titley tags under the skin of a cadaverous pig. The link budget was modified, compared to data obtained at sea lion haulouts, and used to determine the base station height. The results will be used by marine biologists in the development of experimental designs for the protection of endangered seal and sea lions. This thesis will also provide to bioengineers new information on the performance of alumina as an enclosure for active RFID subdermal devices.

The thesis is organized in the following way: Chapter two is used to describe the electronics of the tag, its power supply and its enclosure as they were at the beginning of this project. As well, in that chapter the propagation model and link budget as developed by A. Lea and R. Vaughan for the MMRU are described in more detail. Background relating to previous research on propagation loss in the body is described more in detail. The third Chapter is used to describe the methods and materials used to carry out the subdermal tests within the cadaverous tissue including a description of the base station and communication protocol and the development of the matching network and modifications to loop antenna. Also, in Chapter three there is a description of the development of the lifetime model including the various protocol options, link budget and the tests previously done on the Titley tag. Chapter four is used to present the performance data of the tag: without the enclosure in free space; inside the enclosure in free space; and subdermally inside the enclosure. Chapter five is used to compare the performance data against literature values and currently available commercial Titley tag, as well as to provide performance and recommendations to marine biologist relating to the use of the tag and the base station. Finally, Chapter six and Chapter seven are used to present conclusions and recommendations for future work respectively.
2 Background

This chapter is used to describe the prototype system including the implantable tag and the base station as they were at the beginning of the project. As well, the pre-existing propagation model and link budget are described in detail. Previous research on propagation losses in the body are described more in detail.

2.1 Antenna description

The antenna of the implantable tag is used to radiate the RF signal that will be received by the receiver. Initially, two different antenna configurations for the tag were examined, namely the microstrip patch antenna and loop antenna.

A patch antenna consists of an electronic signal feed, a microstrip patch placed on top of a substrate and ground plane. The ground plane is usually rectangular in shape, but could also be circular. Three different transmitting frequencies in the ISM band were considered for the antenna: 5.8 GHz, 2.4 GHz and 915 MHz. Initially the transmission frequency of 5.8 GHz was chosen as the antenna size would be extremely small. Research by Olawale et al [13] on the dielectric properties of the steller sea lion’s skin indicated that the dielectric constant (20-40) varies with individuals between 0.1 and 10 GHz, and within this range conductivity increases from much less than 1 to 5 S/m. A patch antenna designed for 5.8 GHz did not perform well under the skin, although the dielectric properties of the skin would have assisted in further reduction of the overall size of the antenna. The patch antenna design was discarded as it had several issues relating to its performance and size: the antenna size was considerably larger at lower frequencies (i.e., 915 MHz); the operating frequency of the patch antenna tended to shift in tissues even after being tuned (very sensitive) and the radiation efficiency significantly decreased after implantation under the skin of a cavernous young pig. The range was considered to be too short for monitoring sea lions and seals at their haulouts.

A loop antenna consists of a wire loop as the radiation elements. It is normally in a circular shape. Due to the small dimensions of the loop antenna, it is suitable for very low power applications where size is of importance. The inductance of the loop antenna can be determined as
\[ L_{\text{Loop}} \approx \mu_0 b \left[ \ln \left( \frac{8b}{a} \right) - 2 \right] \]  \hspace{1cm} (2.1)

Where \( a \) is wire radius, \( b \) is loop radius and \( \mu_0 \) is permeability in free space.

The radiation resistance and loss resistance of the loop antenna can be defined as:

\[ (R_r)_{\text{Loop}} = 320\pi^4 \left( \frac{\Delta A}{\lambda^2} \right) \]  \hspace{1cm} (2.2)

\[ (R_l)_{\text{Loop}} = \left( \frac{\pi b}{a} \right) \sqrt{\frac{f\mu_0}{\pi\sigma}} \]  \hspace{1cm} (2.3)

Where \( \Delta A \) is area of loop, \( f \) is frequency of operation, \( \lambda \) is wavelength, and \( \sigma \) is conductivity of the material of the loop antenna.

The efficiency of the loop antenna is given as

\[ \text{Efficiency} = \frac{R_r}{R_r + R_l} \]  \hspace{1cm} (2.4)

For a particular size of loop antenna, as frequency increases, the radiation resistance of the loop antenna reduces resulting in higher efficiency of the loop antenna. Antenna length can be less than optimal at a given frequency, but smaller than optimal antennas would suffer radiation inefficiencies. Loop antennas that are normally implanted are considered on the smaller side and their radiation efficiencies (about 1%) are often less than the radiation efficiency of a quarter wave monopole (90% above small ground) [15]. In the design of the prototype antenna, it was assumed that the tissues would have little effect on an already inefficient radiating short loop antenna [8]. Three initial frequencies i.e., 200 MHz, 433 MHz and 915 MHz were considered for the loop antenna design out of which 915 MHz was chosen as it favored better antenna radiation efficiency, i.e., radiation efficiency at 915 MHz was about -3 dB while at lower frequencies it was more than -10 dB. However, lower frequencies would have been better for the application as they have lower signal propagation loss in human and animal’s body and higher bodyworn radiation efficiency as compared to 915 MHz [11]. The dimension of the loop antenna of the tag was 24 mm x 21.2 mm with a trace width of 2 mm and was fabricated on a FR-4 PCB substrate. This substrate is not well suited for microwave applications as it dissipates energy (around 2 dB loss occurs from the substrate) [12].
2.2 Tag description

Figure 2.1 illustrates the schematic of the implantable RFID tag at the start of this research [15]. The board consists of an IA 4420 transceiver for RF transmissions and a MSP 430 mixed signal microcontroller that commands the transceiver chip. The lower limit of the system data rate is 1 kbps (limited by the base station), and the upper limit is 15 kbps (limited by the rate at which the microprocessor can pass data to the transceiver chip). The small JTAG interface is used for programming the microcontroller chip and is removed prior to implanting the tag inside the animal’s skin. Two types of crystal are implemented in the tag:

1) 10 MHz oscillator for the transceiver chip operation.
2) 32.768 kHz crystal as an alternative for the micro internal clock.

The output power of the transceiver chip is +4 dBm. The matching network of the antenna was matched for the loop antenna to perform efficiently at 915 MHz in free space without the enclosure [12]. The overall dimension of the tag (without the JTAG interface) is 24 mm x 39 mm.

Figure 2.1: Schematic of implantable RFID tag
Figure 2.2: Implantable tag with (left) and without (right) the JTAG interface

The tag is encapsulated inside a tapered alumina enclosure of thickness 4 mm to 5.1 mm. The tapered shape is intended to ease insertion under the skin. One side of the enclosure has a porous layer to aid enclosure attachment to surrounding tissues [1]. Alumina was selected as the choice of material for the enclosure as it is bio-compatible, provides more ruggedness to the tag and can withstand more force without breaking as compared to implantable devices covered just with epoxy. One porous layer is preferred over a porous layer on both sides, as one porous layer would make the tag easier to revive from the tissues [1]. The major drawback of this material was that it had a high dielectric constant (9 around 915 MHz based on 99.5% purity [16]). High dielectric materials tend to affect the radiation pattern and efficiency of a loop antenna i.e., frequency detuning of the loop antenna occurs and the radiation pattern worsens [10].
A complete test program covering the tests and measurements were done to evaluate the tag’s power consumption (in different states such as active [transmission] mode, sleep mode) and requirements [15]. The objective of the test was to determine the best supply voltage for the tag and its maximum current at this bias point. DC power consumption of the tag is illustrated by equation 2.5 while equation 2.6 shows the power efficiency of the tag which is the ratio of RF power to the power consumption of the implantable tag.

\[ P_{DC} = V_{DD} \times I_{DC} \]  
\[ \eta = \frac{P_{out}}{P_{DC}} \]

Where \( V_{DD} \) and \( I_{DC} \) is the voltage and current consumed by the tag respectively, \( \eta \) is the power efficiency and \( P_{out} \) is the RF power.
The current consumed by the tag for transmission of a radio packet during its active mode is about 25 mA. Figure 2.8 demonstrated that the tag would work if the supply voltage was greater than 2 V while the best DC biasing point for the tag was obtained for $V_{DD} = 2.2$ V. Taking into account the action of battery voltage diminishing over time, a margin of 0.3 V was considered. Thus a supply voltage of at least 2.5 V was considered for the tag.

2.3.1 Battery choice

After power requirements were identified, a suitable battery choice and configuration was investigated by Sun, 2005 to power the device [17]. For this application, an implantable and non-intrusive approach was required, so the primary battery type was preferred over secondary battery type. The primary battery produces current immediately on assembly whereas the
secondary battery consists of rechargeable secondary cells acting as a unit (also called storage battery). Due to the extremely limited space for the battery inside the alumina enclosure of the tag, the shape of the battery had to be coin type or low in profile and the volumetric energy density would have to be as large as possible. The battery would also require a long shelf life (about ten years), perform well at temperature of 35 °C (internal body temperature of sea lion) and under high pressure (due to the diving activities of the sea lions). The shelf life of the battery is the time an inactive battery can be stored before it becomes unusable. Once the lid of the alumina enclosure is sealed, the battery cannot be replaced. By using a battery with a longer shelf life, there would be no need to replace the battery of the tag if it was inactive for long periods.

Several kinds of implant primary battery (non-rechargeable battery) technology were considered. Lithium and Silver oxide batteries were found to have the characteristics of high energy density with small weight and implantable size, high reliability, long shelf life (up to 10 years), low self-discharge and prediction for battery end of life. Lithium batteries have been utilized in biomedical implant application for the last 30 years. They have been used in implantable devices such as cardiac pacemaker, drug pump, neurostimulators and cardiac defibrillators [18]. Silver oxide batteries also have high energy density, implantable size and low cost. It is mainly used in watch and camera. It is also found in devices used for wild life tracking [7]. Research and investigations on these two kinds of implant battery were conducted to explore the features and feasibility for the sea lion RF tag application. Table 2.1 lists the commercially available batteries that could meet the sea lion RF tag application [19].
### Table 2.1: Comparison of widely used primary batteries

<table>
<thead>
<tr>
<th>Type</th>
<th>Silver oxide battery</th>
<th>Coin type lithium battery</th>
<th>Zinc air battery</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nominal voltage</strong></td>
<td>1.55 V</td>
<td>3 V</td>
<td>1.4 V</td>
</tr>
<tr>
<td><strong>End voltage</strong></td>
<td>1.2 V</td>
<td>2 V</td>
<td>1 V</td>
</tr>
<tr>
<td><strong>Positive electrode</strong></td>
<td>Silver oxide</td>
<td>Manganese dioxide</td>
<td>Air</td>
</tr>
<tr>
<td><strong>Electrolyte solution</strong></td>
<td>Sodium hydroxide</td>
<td>Organic electrolyte</td>
<td>Potassium hydroxide</td>
</tr>
<tr>
<td><strong>Negative electrode</strong></td>
<td>Zinc</td>
<td>Lithium</td>
<td>Zinc</td>
</tr>
<tr>
<td><strong>Self-discharge rate at 20 °C, % percent loss per year</strong></td>
<td>5</td>
<td>1-2</td>
<td>3</td>
</tr>
<tr>
<td><strong>Discharge characteristic</strong></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td><strong>Energy density</strong></td>
<td>370-470 Wh/l</td>
<td>440-850 Wh/l</td>
<td>1150 Wh/l</td>
</tr>
<tr>
<td><strong>Volumetric density</strong></td>
<td>120 Wh/kg</td>
<td>230-380 Wh/kg</td>
<td>390 Wh/kg</td>
</tr>
<tr>
<td><strong>Temperature range</strong></td>
<td>-10 to 60 °C</td>
<td>-20 to 85 °C</td>
<td>-10 to 60 °C</td>
</tr>
</tbody>
</table>
| **Features**              | • Flat discharge curve  
                          • Superior long-term reliability  
                          • High energy density | • High 3 V voltage  
                          • Stable discharge curve  
                          • High energy density  
                          • Wide usable temperature.  
                          • Superior long-term reliability | • For heavy and continuous use  
                          • Stable discharge curve  
                          • Excellent anti-leakage  
                          • High energy density |
| **Limitations**           | Expensive, but cost-effective on button battery application | Available in small sizes | Drying out, flooding Limited power output |

The Zinc/air battery has the highest volumetric energy density (1150 Wh/l) among the listed types of batteries. However, the positive electrode of this type of battery is air. An inexhaustible supply of air was necessary to be present within the battery, which was not suitable for this implantable application. The silver oxide battery was chosen over the coin type lithium battery as they could easily fit with the space allocated for the battery in the enclosure, despite having a lower energy density as compared to the lithium battery. After looking at different types
of silver oxide battery, GP348 silver oxide battery model was chosen as the primary battery for the tag. A capacitor must be included in the power supply as high transient loads such as the transmitter cannot be supplied directly by the battery.

2.3.2 Configuration of battery

The chosen battery was configured as outlined below to meet the power requirements of the tag. Two batteries of the same voltage and capacity were connected in series to increase the voltage of the bank as shown in Figure 2.9. The negative terminal of the first battery is connected to the positive terminal of the second battery to obtain voltage of 3.2 V. At this stage, the battery capacity remains unchanged.

![Series Connection](image)

**Series Connection**

\[
1.55 \text{ V} @ 12 \text{ mAh} \quad 1.55 \text{ V} @ 12 \text{ mAh}
\]

![Figure 2.9: Series connection of battery to form a bank](image)

To increase the battery capacity, nine of these banks were connected in parallel as shown in Figure 2.10. The positive terminals of all the nine banks were connected to a common conductor i.e., EMI shielding tape (smooth copper type), and all the negative terminals were connected in the same manner. The final voltage of this arrangement remains unchanged while the total battery capacity is the sum of the capacities of the individual banks of this connection. Thus, a battery pack of dimension 24 mm x 4.3 mm; total voltage of 3.2 V; and battery capacity of 108 mAh was obtained.

![Parallel Connection](image)

**Parallel Connection**

\[
3.1 \text{ V} @ 108 \text{ mAh}
\]

![Figure 2.10: Parallel connection of nine banks to form final battery pack](image)
2.3.3 Problems associated with current battery

There are several drawbacks of the initial battery configuration. The first issue is with the size, i.e., the dimensions of the total battery size did not satisfy the required dimensions of the allocated battery space in the alumina enclosure (the height of the battery pack was more than the allocated height). Thus, the case could not be properly sealed. The second issue relates to the electrical contacts. The EMI shielding tape electrical contacts did not ensure the individual packs were firmly held in place. Another drawback was there was no magnetic switch, so once the tag was wired up, it would start transmitting. If the tag is not instantly subdermally implanted in the animal, it would decrease the longevity of the tag.

2.3.4 Effect of number of transmissions and data rate on the longevity of the device

The longevity of the tag is a crucial parameter for any implantable device. Ideally, an implantable tag with an expected longevity of three to ten years would be suitable depending on the animal species as there would be no need to replace the battery in the tag once it is subdermally implanted. The number of packet transmissions from the tag and the data rate has to be appropriately chosen to ensure the battery can last as long as possible. Research carried out by Valdastri et al, 2004 on implantable telemetry system demonstrates the relationship between the longevity of the device and number of transmissions [20]. For a battery with fixed capacity, the battery life decreases with increase in number of transmissions. Data rate is important for determining the number of transmissions. If the data rate of the tag is high, it will take less time to transmit a packet, as well as consume less amount of power per packet transmission, thus increasing the longevity. On the onset of this research, there was no way of determining suitable working conditions of the device to predict the longevity of the battery unit.

2.4 Range model

The range of the RFID tag is dependent on several factors such as: height of base station antenna; data rate of the tag; power transmitted from the tag; power received at the base station; polarization mismatch; impedance mismatch; and gain of transmit and receive antenna. The foundation of any link budget can be estimated by the Friis transmission equation. Using it the range of the system can be determined.
\[ P_D = \left( \frac{\lambda}{4\pi} \right)^2 P_T G_T(\theta, \phi) G_R(\theta, \phi) q p \] (2.7)

Where \( P_D \) is power delivered to the receive antenna, \( P_T \) is power transmitted from the implantable tag, \( G_T \) and \( G_R \) are the gain of the transmit and receive antennas respectively, \( p \) is polarization mismatch factor, \( q \) is Impedance mismatch factor, \( \lambda \) is Wavelength at the frequency of operation and \( r \) is Distance between transmitter and receiver antenna.

This equation does not take into account losses associated with the animal tissue and alumina enclosure. The term in the bracket is known as inverse square-law path loss [21], and applies to line-of-sight propagation without multi-path reflection. The two path ray model as shown in Figure 2.11 was chosen as a realistic model for the environment in which the tag will be located i.e., a rocky terrain.

![Figure 2.11: Two-path ray model](image)

The distance of the direct ray is
\[ r_1 = \sqrt{d^2 + (h_a - h_m)^2} \] (2.8)

and the distance of the reflected ray is
\[ r_2 = \sqrt{d^2 + (h_a + h_m)^2} \] (2.9)

Where \( d \) is distance between the transmitter and receiver antenna, \( h_a \) and \( h_m \) are height of base station antenna and loop antenna of tag respectively.

The Friis equation for this scenario can be derived as
\[ P_D = P_T \left( \frac{\lambda}{4\pi} \right)^2 \frac{\exp(-j\beta r_1)}{r_1} - \rho \frac{\exp(-j\beta r_2)}{r_2} \left| G_T(\theta, \phi) G_R(\theta, \phi) q p \right| \] (2.10)
The path loss is taken as the product of the two terms in brackets. The reflection coefficient ($\rho$) requires the factor

$$\chi = \frac{1.8 \times 10^{10} \sigma}{f}$$

(2.11)

and is defined for horizontal polarization as

$$\rho_h = \frac{\sin \theta - \sqrt{\varepsilon_r - j \chi - \cos^2 \theta}}{\sin \theta + \sqrt{\varepsilon_r - j \chi - \cos^2 \theta}}$$

(2.12)

And for vertical polarization as

$$\rho_h = \frac{(\varepsilon_r - j \chi) \sin \theta - \sqrt{\varepsilon_r - j \chi - \cos^2 \theta}}{(\varepsilon_r - j \chi) \sin \theta + \sqrt{\varepsilon_r - j \chi - \cos^2 \theta}}$$

(2.13)

Where $\sigma$ is electrical conductivity of the signal propagation environment, $\varepsilon_r$ is the dielectric constant of the signal propagation environment and $\beta$ is phase delay.

Three carrier frequencies were considered for the tag: 200 MHz, 433 MHz and 915 MHz out of which 915 MHz was chosen as most appropriate because of large improvements in the antenna radiation efficiency relative to the other frequencies. Propagation over seawater with dielectric constant of 72 and electrical conductivity of 4 S/m was considered [7]. Figure 2.12 shows the path loss over seawater for a base-station antenna height of 2 m and tag height of 0.4 m. This tag height implies that the sea lion head is just above the waterline. This application implies that the base station antenna is on a boat or moored in the sea.

![Figure 2.12: Path loss over sea water for 915 MHz](image)

Free-space path loss and inverse fourth-power path loss given by
\[ PL_{dB} = 20 \log \left( \frac{h_a h_m}{d^2} \right) \]  \hspace{1cm} (2.14)

are included for reference. Note the breakpoint located at
\[ d_{bk} = \frac{4 h_a h_m}{\lambda} \]  \hspace{1cm} (2.15)
beyond which both polarizations show similar path loss.

Figure 2.13 shows the path loss over seawater for horizontal polarization at the three candidate frequencies. Based on equation 2.14, it was assumed that the path loss was effectively independent of frequency. However, by observing equation 2.7, it could be observed that the path loss is dependent on frequency, i.e., the path loss increases with increase in frequency of operation. The breakpoint where inverse fourth power fading begins is less than 10 m for all of the frequencies. The frequency of operation was chosen as 915 MHz because the radiation efficiency of the loop antenna of size 24 mm x 21.2 mm with a trace width of 2 mm was higher as compared to the other two frequencies, despite the path loss associated with 915 MHz being higher than the other two frequencies.

![Figure 2.13: Path loss over seawater for horizontal polarization at three ISM band frequencies](image)

2.4.1 Range of system

Before the research began, no measurements on the uplink (transmission of signals from the tag to the base station) range of the system were conducted. Using the Friis formula, the range was theoretically calculated. To estimate the uplink range of the system, the Friis equation is rearranged to solve for the minimum allowable path loss.
\[ PL_{\text{min}} = P_{\text{min}} - G_T(q,f) - G_R(q,f) - P_T \]  

(2.16)

Where all of the variables are expressed in decibels. The polarization mismatch and matching loss factors were omitted from the equation. The antenna gains were estimated at -20 dB for the tag antenna and 10 dB for the base-station antenna. The RF output power of the IA4420 is +4 dBm and the receive sensitivity of the base-station transceiver is shown in Table 2.2.

<table>
<thead>
<tr>
<th>Bit rate</th>
<th>Receiver sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kbps</td>
<td>-119 dBm</td>
</tr>
<tr>
<td>9.6 kbps</td>
<td>-112 dBm</td>
</tr>
</tbody>
</table>

The range was calculated assuming inverse fourth power path loss, and re-arranging (equation 2.14) as

\[ d = \sqrt{h_a h_m \cdot 10^{\frac{PL_{dB}}{20}}} \]  

(2.17)

The resulting estimated uplink range for the embedded system at different rates is given in Table 2.3.

<table>
<thead>
<tr>
<th>Bit Rate</th>
<th>Estimated range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kbps</td>
<td>600 m</td>
</tr>
<tr>
<td>9.6 kbps</td>
<td>400 m</td>
</tr>
</tbody>
</table>

2.4.2 Base station board

ADF7020 base station board from Analog Devices was selected for the base station application. It consisted of two components: EVAL ADF702XXMB2 mother board that provided an interface between the daughter board and the computer; and ADF7020 daughter board that operated in 862-928 MHz frequency band. The board could be powered either via a USB cable or 2.3 V to 3.6 V battery external battery. It has a low power consumption in receive mode (about 19 mA), can support data rates of 0.3 to 200 kbps in FSK mode and 0.3 to 75 kbps in ASK mode, receiver sensitivity of -117.5 dBm at 1 kbps in FSK mode and -110.5 dBm at 9.6 kbps in FSK mode respectively [22]. The unit came along with an evaluation software that could be used to program the base station according to the requirements and monitor transmissions between the tag and the base station unit.
2.4.3 Effect of height on base station antenna

To ensure maximum line of sight range of the tag, the base station antenna has to be set at an appropriate height. Several studies have been conducted on investigating the effect of different heights on the signal range in cellular mobile systems [23], [24]. From those studies, it could be observed that the height of the base station antenna had a strong influence on the range of the system i.e., base station antennas at lower height had less range as compared to higher placed base station antennas. This is due to the fact that when the antenna is close to ground, the range decreases as the signal can easily get blocked by obstructions in between the path of the device and the base station. To maximize line of sight range of the system, the base station antenna should be placed at a height greater than the obstructions in the surrounding environment. The studies also showed that the number of signal transmissions had no effect on the variability of the received signal, as well as the range of the system.

Sea lions are normally found in rookeries and haulouts (rocky terrains). Figure 2.16 shows a sample haulout location. The base station antenna of the intended implantable tag system has to be placed at a height greater than the rocks. If the base station antenna is placed at a height lower than the rocks, no signal coverage will be obtained if the animal is lying behind the rocks. If the base station antenna is placed on a boat, there would be difficulty in obtaining signal transmissions, if the tag is behind a large rock or it is located on a rock greater than the height of the base station antenna. The analysis for the different frequencies of the loop antenna mentioned earlier assumed that the base antenna would be placed on the boat.
2.4.4 Effect of data rate on the range of the system

One of the crucial parameters in obtaining the best coverage distance of the tag system is the data rate. The range of the system is inversely proportional to the data rate of the tag i.e., other things being equal, a higher data rate system will not transmit as far as a lower data rate system. RF signals of a given carrier frequency lose power as they propagate. Path loss increases with the square of the distance and is relatively easy to estimate when the path is unobstructed and can be given by the path loss equation:

\[ PL = \frac{\lambda}{4\pi r^2} \]  

(2.18)

Where \( \lambda \) is wavelength and \( r \) is the distance between transmitter and receiver.

To determine whether the base station can hear the tag over a given range, two other variables i.e., transmit power of the tag and base station receiver sensitivity should be considered. Transmit power is simply how “loud” the signal is, is expressed in dB and is normally a positive number. The receiver sensitivity is the ability of the base station to hear the signal and indicates what level of signal strength must be present to correctly receive data at a specified bit error rate. The data rate, the rate at which the base station and the tag communicate, is a component in determining the receive sensitivity of a radio. In 802.11b radio, for every
doubling of the data rate, the receiver sensitivity reduces by 3 dB. In free space, every 6 dB reduction in receiver sensitivity results in halving of the range of the system [25].

2.4.5 Link budget

A simple link budget model (Table 2.4) for the three different candidate frequencies having crude gain estimates was constructed by Vaughan in April, 2005 to justify the chosen frequency of operation i.e., 915 MHz. The diffraction estimate shows the amount of signal propagation loss expected in the sea lion’s environment i.e. rocky terrain.

### Table 2.4: Link budget (boat to haulout)

<table>
<thead>
<tr>
<th>Gain estimate</th>
<th>915 MHz</th>
<th>433 MHz</th>
<th>200 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Path gain over 1km in free space (square of frequency)</td>
<td>-92 dB</td>
<td>-85 dB</td>
<td>-78 dB</td>
</tr>
<tr>
<td>1a Path gain over 1km over ground plane (fourth power)</td>
<td>-122 dB</td>
<td>-122 dB</td>
<td>-122 dB</td>
</tr>
<tr>
<td>2 Tag antenna efficiency</td>
<td>-3 dB</td>
<td>-12 dB</td>
<td>-23 dB</td>
</tr>
<tr>
<td>3 Tag antenna directivity</td>
<td>2 dB</td>
<td>2 dB</td>
<td>2 dB</td>
</tr>
<tr>
<td>4 Tag antenna gain (2+3)</td>
<td>-1 dB</td>
<td>-10 dB</td>
<td>-21 dB</td>
</tr>
<tr>
<td>5 Harbor seal tissue losses</td>
<td>-5 dB</td>
<td>-4 dB</td>
<td>-3 dB</td>
</tr>
<tr>
<td>6 Embedded gain of antenna plus harbor seal (4+5)</td>
<td>-6 dB</td>
<td>-14 dB</td>
<td>-24 dB</td>
</tr>
<tr>
<td>7 Base station gain</td>
<td>5 dB</td>
<td>3 dB</td>
<td>2 dB</td>
</tr>
<tr>
<td>8 Diffraction (non-line-of-sight)</td>
<td>-20 dB</td>
<td>-17 dB</td>
<td>-15 dB</td>
</tr>
<tr>
<td>9 Total in freespace without diffraction (1+6+7)</td>
<td>-93 dB</td>
<td>-96 dB</td>
<td>-100 dB</td>
</tr>
<tr>
<td>10 Total in freespace with one diffraction (9+8)</td>
<td>-113 dB</td>
<td>-113 dB</td>
<td>-113 dB</td>
</tr>
<tr>
<td>11 Total over groundplane without diffraction (1a+6+7)</td>
<td>-123 dB</td>
<td>-133 dB</td>
<td>-144 dB</td>
</tr>
<tr>
<td>12 Total over groundplane with diffraction</td>
<td>-143 dB</td>
<td>-150 dB</td>
<td>-159 dB</td>
</tr>
</tbody>
</table>

Several unresolved issues arise in the link budget. Study conducted by Zadeh, 2006 on an implantable loop antenna operating at 915 MHz demonstrated that the loop antenna performance worsened when it was placed inside the alumina enclosure and inside simulating tissue liquid [10]. The amount of loss from the sea lion tissue was assumed too low. Finally, the gain of the base station antenna was not reliable as it had not been properly tested. Taking these effects into account, a proper link budget at 915 MHz had to be created. Information obtained by propagation studies on actual haulouts were used to test the link budget.
2.4.6 Propagation loss due to the tissue

The antenna inside its alumina housing will have a different performance inside a body as compared to free space. To get a clearer picture of the range of the tag, propagation losses due to tissue (skin and blubber or fat) have to be taken into account. No study has been conducted so far on the propagation loss of implantable device implanted just under the skin of an animal. Several studies have been carried out to examine implantable devices placed deep within a body or simulating liquid [5], [10], [11], [26]. Results from such studies show that antennas of implantable devices have a better performance at lower frequencies as compared to higher frequencies. For example, a radio telemeter packaged for human vaginal placement placed at a depth of 5 mm inside the body, the loss due to tissues at 418 MHz was about 15.6 dB, whereas at 916.5 MHz the loss increased to 24.4 dB [11]. In addition, when antennas are placed under tissues, frequency detuning occurs, i.e., the resonant frequency of operation of the antenna shifts to a lower frequency. Due to the effects of body tissues on antenna performance, most higher frequency applications are aimed at very moderate pickup distances (< 1 m).

A study conducted by Zhen et al, 2009 illustrated the propagation loss in the different layers of the human body [27]. From that study, it was observed that the propagation loss of the chip antenna operating at 2.45 GHz in the fat layer of dielectric constant 6 was lower than the propagation loss in the skin of dielectric constant of 42.4 or muscle layer of dielectric constant of 48.1. The difference in the propagation loss can be understood by looking at the absorption of the signal by the tissue. An estimate of absorption of the signal by the tissue at a particular frequency is obtained by calculating the penetration depth, as follows:

\[ \delta = \left[ \frac{k^2}{2} \left( \frac{\varepsilon_r^2 + \left( \frac{\sigma}{w\varepsilon_0} \right)^2}{\varepsilon_r} - 1 \right) \right]^{\frac{1}{2}} \]  

(2.19)

Where \( \delta \) is penetration depth of tissue, \( k \) is wave number = \( \frac{2\pi}{\lambda} \), \( \lambda \) is wavelength of signal = \( c/f \), \( c \) is speed of light in vacuum = \( 3 \cdot 10^8 \) m/s, \( f \) is frequency, \( \varepsilon_0 \) is electric constant = \( 8.8 \cdot 10^{-12} \) F/m, \( \varepsilon_r \) is dielectric constant of tissue and \( \sigma \) is conductivity of tissue.

A study conducted by Gabriel, 1996 on the dielectric properties of the skin show how the dielectric properties change with frequency [28]. As the frequency of operation increases, the dielectric constant of the skin decreases while the conductivity of the skin increases.
Since the fat layer of the tissue has less water content than the skin or muscle layer, the dielectric properties of the fat layer tend to be lower than the dielectric properties of skin or muscle [27]. For a fixed thickness of skin and fat, the signal penetration depth in fat will be higher as compared to the penetration depth in skin. As a result, the propagation loss in the skin will be higher than the fat layer.

The thickness of the tissue plays a role in the amount of power loss of the transmitted signal. The power loss in the tissue of a particular thickness can be given by:

\[
\text{Power loss (dB)} = 10 \times \log_{10} \left( e^{-2z/\delta} \right) = -20 \frac{z}{\delta} \log_{10} e = -8.69 \frac{z}{\delta}
\]

(2.20)

Where \( z \) is thickness of tissue and \( \delta \) is penetration depth of tissue.

For a fixed thickness of skin and fat, the power losses in the fat will be lower than the power losses in the skin due to its higher penetration depth. However, if the total thickness of the tissue (thicknesses of the layer above the tissue + thickness of the tissue) is considered, the power loss associated with the fat will be higher than the power loss associated with the skin. From equation 2.20, it can also be observed that the power loss in the tissue is dependent on how deep the device is implanted inside, i.e., if the tag is implanted deeper in the tissue (increase in thickness of that tissue layer), the power loss in that tissue will increase. As a result the propagation loss of the tag from that tissue will also increase. From equation 2.19, it could be seen the frequency of operation of the implantable tag plays a role in the amount of losses in the tissue. When lower frequencies are used, the penetration depth of the signal in the particular tissue is more than penetration depth at higher frequencies, resulting in lower power losses in the tissue at lower frequencies.

The nature of the surface of the tissue plays a crucial factor in its dielectric properties. The dielectric properties of wet tissue are different as compared to the dielectric properties of the dry tissue. Gabriel, 1997 study on the dielectric properties of the skin showed the difference between wet and dry surface of the skin [28]. In that study, it was observed that by wetting the skin, its dielectric properties were similar to those for a high water content tissue. By wetting the surface of the tissue, the dielectric properties increase, resulting in lower skin depth and subsequently higher power losses in the wet tissue as compared to the dry tissue.
3 Methods & procedures

The following sections are used to describe how the antenna and matching network were adjusted and tested. In addition, how a commercially available tag was tested is described. Furthermore, how the internal power source was devised, how the life time model was developed, and how a link budget was devised by taking into account the effect of the terrain are described.

3.1 Antenna and matching network adjustments

The width of the loop antenna was shortened and the capacitors in the matching network were adjusted with selected values in order for the tag to function effectively within its strong alumina enclosure implanted under the skin of an animal. First, the 915 MHz tag was tested in free space to establish a benchmark on the performance. Then the matching network and antenna were modified and tested so that it would function in its alumina enclosure, and then finally they were modified and tested again so that it would function under the skin and fat of a cadaverous animal. Pork bacon (chemically untreated) was selected because its skin properties (skin thickness and dielectric properties) are similar to sea lion pups, and northern elephant seal (*Mirounga angustirostris*) was selected due to its availability in the marine mammal research unit freezer [12]. The seal offered the worst case scenario due to its very thick skin as compared to other marine pinnipeds. Finally, how propagation loss data on a commercial tag was obtained was described. That data was used to determine the differences between this new tag and available tags in terms of novelty and performance.

To evaluate the performance of the tag, two tests were carried out namely the return loss test and the radiation pattern tests. Tests on the new tag were carried out at Webtech Wireless in Burnaby, B.C., and on the commercial tag, Protocol-EMC in Abbotsford was used.

3.2 Return Loss tests

Return loss tests were carried out to determine the effectiveness of the matching network of the tag. This test was carried out on the matching network to determine how much transmitted signal was being reflected back from the matching network. The performance of the tag inside its alumina enclosure and ultimately under the skin was adjusted by trying to improve the return loss of the matching network of the loop antenna.
3.2.1 Equipment

Agilent 8594E spectrum analyzer was used to measure the return loss of the matching network of the tag.

3.2.2 Procedure

Before performing any return loss tests, the spectrum analyzer had to be calibrated. The mechanical calibrations of the spectrum analyzer were performed using the HP 8502B mechanical calibration kit. After the calibration tests were done, one end of the matching network feed was connected to a terminated 50 Ω load while the other end of the matching network feed was connected to the input of the spectrum analyzer. First, the return loss of the original tag in free space was measured. Next, the return loss of the original tag was measured with the tag covered by a hand followed by a plastic enclosure to observe if frequency detuning occurs. Then, the capacitors values in the matching network of the loop antenna were adjusted to increase the amount of return loss from the plastic enclosure and then subsequently from the alumina enclosure. The surface mount capacitors in the matching network on the electronics board were replaced using a soldering gun. Next, another prototype tag was designed to perform better than the first two samples inside the alumina enclosure and under skin, by adjusting the width of the loop antenna and changing the capacitor values of the original tag design. The width of the loop antenna was achieved by cutting the front end of the loop and soldering it back on the tag at different height. Finally, a prototype with a simple wire loop around the electronics was constructed to see if this configuration produces a workable condition (if so, then the tag could be considerably reduced in size).

3.3 Radiation pattern tests

Radiation pattern tests were carried out to obtain radiation pattern of the loop antenna of the tag. The radiation patterns were used in determining the gain of the tag along with the gain of tag in horizontal and vertical polarization states. They were also used to observe the radiation performance of the tag when it was placed inside its alumina enclosure and subsequently under the skin.
3.3.1 **Equipment**

Agilent E-5062A network analyzer and GTEM 750 radiation chamber were used to measure the radiation pattern of the loop antenna. The size of the GTEM 750 radiation chamber is 360 cm x 184 cm x 124 cm and can operate over a frequency range of 0.1 MHz to 18 GHz.

3.3.2 **Procedure**

The tag was placed on a rotating Table inside the radiation chamber. For horizontal polarization, the tag was vertically inclined inside the chamber while for vertical polarization it was horizontally inclined inside the chamber. Signal strength was recorded at every 10° step of the rotating Table for all of the observations excepting tissue tests. For the tissue samples, the signal strength was recorded at every 45° step and only horizontal measurements were taken as it would give an estimate of the gain of the antenna inside the tissue sample at different orientation angles. The choice of step size for the tissue sample was constrained by the length of time it took to complete the measurement process in the different skin samples and the amount of time available for the tests. The tests took a long time as the orientation of the tissue sample had to be done manually and each time it had to be ensured that no mess was created inside the chamber such as blood spilling from the elephant seal meat sample. Additionally it had to be ensured that the loop antenna of the tag was held firmly in place inside the tissue sample. The outcome of the measurements was a listing of the signal strength received at specific angles. The radiation pattern plots were obtained by plotting the signal strengths against the respective angles yield. The chamber introduced about 28 dB loss at 915 MHz and there was about 2 dB attenuation loss in the cable connecting the radiation chamber to the network analyzer. The readings of the signal strengths obtained by the network analyzer were adjusted accordingly, i.e., losses were subtracted from the received signal strengths.

3.4 **Range tests**

Range tests were carried out to determine the line of sight range distance of the tag. As well, several scenarios were considered to evaluate the effective range of the tag: in free space, in its alumina enclosure, inside the alumina enclosure under skin, effect of different data rates, and effect of height of base station antenna.
3.4.1 Equipment

ADF 7020 base station unit and YA 5900 yagi antenna were used for evaluating the range of the tag. At the same time, Tektronix TDS 3032B oscilloscope was also used for monitoring incoming transmissions at the base station unit and verifying the packet sequence. A laptop was used for recording the data received by the base station unit and a power generator was used for powering the equipment.

3.4.2 Procedure

Range tests were carried out at two different locations, i.e., Rhododendron wood area and Thunderbird parkade on University of British Columbia Vancouver campus as shown in Figure 3.1. The base station was set at a height of 1.5 m at Rhododendron wood area, and at 4.5 m and 7 m at Thunderbird parkade, respectively. Markers were placed at 10 m intervals.
The following tests were carried out at Rhododendron wood area of length 200 m: effect of low noise amplifier on the range of the tag; range of the tag and the different prototype tags in free space and inside its alumina enclosure; and effect of different data rates on the range of the tag. Each of the tests was carried out three times and signal strengths up to -62 dBm were recorded at every sampling point. Signal strength did not go lower than -70 dBm as the amount of transmitted power by the tag is limited. Also, taking into account the losses associated the matching network of the loop antenna and the dielectric properties of the material surrounding the loop antenna such as alumina enclosure and the tissue, signal strength signals lower than -70 dBm will not be obtained.

The following tests were carried out at Thunderbird parkade of length 510 m: range of the different prototype tags and inside its alumina enclosure (except the one with the loop around the electronics. This prototype was only tested in free space); and effect of different tissue layers on the range of the final prototype tag. Each of the tests was carried out three times except the tissue sample tests. The tissue sample tests were carried out twice and three signal measurements were recorded at every sampling point. Table 3.1 gives a summary of the type of range tests carried out.
Table 3.1: Summary of range tests

<table>
<thead>
<tr>
<th>Location</th>
<th>Height of base station antenna</th>
<th>Type of test</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhododendron wood area</td>
<td>1.5 m</td>
<td>1. Effect of low noise amplifier on the range.</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Performance of original tag and prototype tag with loop antenna around electronics in free space.</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Performance of original tag and different prototype tags inside alumina enclosure.</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Effect of data rate on the range of the system of different prototype tags.</td>
<td>3</td>
</tr>
<tr>
<td>Thunderbird parkade</td>
<td>4.5 m</td>
<td>1. Performance of prototype tags inside alumina enclosure.</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Performance of prototype with loop antenna around electronics in free space.</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Performance of final prototype tag under non-chemically treated pork bacon piece.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Performance of final prototype tag under elephant seal skin</td>
<td>2</td>
</tr>
<tr>
<td>Thunderbird parkade</td>
<td>7 m</td>
<td>1. Performance of prototype with loop around electronics in free space.</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Performance of prototype tags inside alumina enclosure.</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Performance of the final prototype under non-chemically treated pork bacon piece</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Performance of the final prototype tag inside cavernous elephant seal skin</td>
<td>2</td>
</tr>
</tbody>
</table>

3.4.3 Observations

On the Thunderbird parkade location, the path between the base station antenna and the tag antenna was obstructed by different objects such as tree branches, cars, humans, etc, which caused the signal loss to vary. At other times, signal reception at the base station unit vanished. When this happened and to ensure maximal range was recorded, the orientation of the loop antenna was adjusted to the orientation angle where the tag radiated maximum power in the horizontal plane. This was done by observing the horizontal gain radiation pattern of the loop antenna of the tag.

3.5 Pig tissue sample

A non-chemically treated and uncooked pork bacon sample was obtained from a local butcher. For ease of testing purposes, two pieces of size 22 cm x 35 cm and 22 cm x 31 cm
respectively were cut. The average thickness of each piece was about 25 mm (Figure 3.3). One of the cutted pieces was kept in the refrigerator to preserve it for testing at a later time. The other one was used for testing immediately. In between tests, the bacon was kept on ice within a cooler. Using a scalpel, three skin pockets of roughly the size of the tag inside of its enclosure were made following the procedures as outlined in Hori et al 2009 [1]. The tag in these pockets would be sitting on fat tissue and its upper part would be completely covered with skin. The skin in these areas varied in thickness from 2.1 mm to 3 mm. As a seal lion or seal grows, the fat layer increases in depth. It is possible that a tag that had been initially inserted subdermally would end up below fat. To test the performance of a tag under skin and fat, three additional pockets were made. These were made using a scalpel to cut the fat reachable from outside of the bacon piece. The fat thickness in these areas varied from 3.1 mm to 10 mm, and the total thickness (skin and fat) above the tag varied from 5 mm to 13 mm. The cuts were made deep and wide enough to ensure the enclosure along with the device could easily fit inside the pockets.

Figure 3.3: Non-chemically treated pork bacon showing skin and fat layers
The loop antenna of the tag was covered by the alumina enclosure. The enclosure was sealed at one end using ordinary tape to ensure the lid would not come off. The whole enclosure along with the loop antenna portion was inserted in the different pocket cuts representing skin and fat as shown in Figures 3.5 and 3.6 respectively. The electronics board of the tag was covered by plastic to avoid contact with the meat. The device was externally powered by a 3 V battery.

Figure 3.4: Non-chemically treated pork bacon with different sample markings

Figure 3.5: Testing the loop antenna inside the alumina enclosure in non-chemically treated pork bacon skin
3.6 Seal sample

A frozen adult elephant seal tissue sample was provided by the Marine Mammal Research Unit. This sample was obtained by marine biologists from a dead elephant seal that had accidentally collided against a boat. The size of the piece was 10 cm x 16 cm. The overall thickness of the piece was about 26 mm. Prior to any testing, the sample had to be thawed. Once it was completely thawed, two pocket cuts were made in the piece using a scalpel. The unfrozen sample oozed with blood. The skin was very thick (6 mm). One skin pocket was made 3 mm from the skin surface, while the other was made at a distance of 6 mm from the surface right above the subdermal level. No fat pockets were tested due to the small size of the sample.
The range and radiation pattern tests in the elephant seal meat sample were carried out with the chosen final prototype tag. The prototype tag along with the power source was placed inside the alumina enclosure and the lid was sealed on the case using a normal tape. The whole device was completely inserted into the two pockets, and range and radiation pattern tests as described earlier were conducted.

3.7 Base station characteristics

3.7.1 Base station antenna

The base station antenna was selected using the following criteria:

1. Omni directional or directional.
2. Type of antenna and ease of placing it.

A high gain directional seven element welded yagi antenna (YA 5900W model from Larsen Antennas) was selected for this application. The characteristics of this antenna and the radiation characteristics are available in the Larsen base station antenna brochure [29]. This model was chosen as it had a high gain (11 dBi) in the 890-960 MHz frequency band. Also, this antenna could be easily mounted at any location and the different polarization states could be achieved simply by rotating the antenna. The limitation of this model is that it is a directional antenna and radiates maximum power over a beamwidth of 45° in both the E-plane and H-plane.

3.7.2 Low noise amplifier

To improve the range performance of the tag, a low noise amplifier (LNA) was added to the base station board to amplify the weak signals received by the base station antenna. The main criteria for the choice of a suitable LNA were: high gain at the frequency of operation as it would reduce the noise of the subsequent stages in the base station unit; and low noise figure as the noise of the LNA is directly injected into the received signal. RF3866 Wide bandwidth, high linearity LNA model was chosen for our application. The features of the particular device are:

1. 700 MHz to 3800 MHz operation.
2. Self biased from a single voltage supply (2.5 - 6 V) with 50Ω input and output ports.
3. A 0.8 dB noise Figure, 36 dBm OIP3 performance and gain of 32 dB is achieved with a 5V VDD, 180 mA in the low band (700 MHz – 1200 MHz).
The functional block diagram of the LNA chip along with the evaluation board schematic and component values for the frequency band 700 MHz – 1200 MHz can be obtained from RF 3866 data sheet [30].

### 3.7.3 Base station software

ADF7020Demo software from analog devices was used to configure the base station. This application was written in Visual C++.

![Figure 3.8: Screen shot of the software.](image)

To configure the base station for suitable settings, enter “Edit Protocol Configuration” settings. Here, the PHY and MAC layer of the protocol can be configured. Once the parameters are loaded, the protocol was loaded to the base station using the “Write to EEPROM” button.
Once the protocol is written to the EEPROM of the board, the base station target board must be reset in order for the new configuration to take effect. Figure 3.14 below shows the settings for the base station to operate at a data rate of 1 kbps at 915 MHz with the tag.
Communication between the base station and implantable devices was configured in a star configuration, as shown in Figure 3.15. The base station acts as a master unit, usually referred to as a Base Unit (BS), and the tags are termed End Points (EP). Currently, all communication is from EP to BS. Peer to peer communication between the end points is not supported. The BS was connected to a PC to allow logging of received data from multiple number of tags.
Figure 3.11: Star configuration

The packet structure for communication between the implantable tag and base station was based on the ADlismLink Air interface protocol and is illustrated below.

Table 3.2: Packet structure of the tag based on the ADlismLink protocol

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Sync Word (24 bits)</th>
<th>Header</th>
<th>Variable length payload</th>
<th>16 bit CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>101010...</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The packet begins with a preamble (a 1010… sequence) of user-configurable length in order to allow the ADF7020 AFC and AGC loops to settle and to achieve bit synchronization. Next, there is a sync-word. The ADF7020 is configured to recognize this sequence in hardware to produce a signal that denotes both the correct byte alignment and the start of the packet data area. This sync word is user configurable but the length has been fixed at 24 bits for this protocol.

Then there is a 4-byte packet header:

Table 3.3: Packet structure of the header based on the ADlismLink protocol

<table>
<thead>
<tr>
<th>Source (short) address</th>
<th>Destination (short) address</th>
<th>Flags</th>
<th>Payload length (0-240)</th>
</tr>
</thead>
</table>

Addresses can be anywhere in the range 1 – MAX_ADDRESS (which is defined during the protocol configuration). Address 0 is reserved as an invalid address and address 255 is reserved as a broadcast address.

The flags are defined as follows:
Table 3.4: Flag bits

<table>
<thead>
<tr>
<th>Flag Bit</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit 7(0x80)</td>
<td>Beacon</td>
</tr>
<tr>
<td>Bit 6(0x40)</td>
<td>ACK is required</td>
</tr>
<tr>
<td>Bit 5(0x20)</td>
<td>Further DL traffic pending (currently not implemented in the base station board)</td>
</tr>
<tr>
<td>Bit 4(0x10)</td>
<td>Battery low</td>
</tr>
<tr>
<td>Bits 3-2</td>
<td>2 bit ACK sequence number</td>
</tr>
<tr>
<td>Bits 1-0</td>
<td>2 bit data sequence number</td>
</tr>
</tbody>
</table>

Then there will be a number of payload bytes. The payload length may be anywhere between 0 and 255 bytes, although the current protocol implementation limits the max payload at 240 bytes.

Finally, there is a 16bit CRC. This is calculated using the V41 (CCITT) Kermit type generator polynomial:

\[
G = 1 + X^5 + X^{12} + X^{16}
\]  

(3.1)

This gives a 1:65536 chance that a packet containing errors will slip through undetected. If the packet addresses are still correct then corrupt data will be passed through the MAC to the user application. Corruption of the payload length field has the potential to overrun packet buffer limits so this will need to be checked while each packet is being received. At present, the packet structure consists of 104 bits as shown below.

1. Original Tag with source address 1

Table 3.5: Overall packet structure of original tag

| AAAA | DB5559 | 01050102 | 3333 | AE14 |

Table 3.6: Header structure of original tag

| 01 | 05 | 01 | 02 |

3.8.1 Different packet settings

Different type of packet configurations for communication between the tag and the base station is looked at. If the preamble length or a different sync word is used for the tag packet structure, preamble and sync word settings have to be updated accordingly on the ADF7020 software.

2. Tag with different preamble length

Table 3.7: Overall packet structure of tag with different preamble length

| 55 | DB5559 | 01050102 | 3333 | AE14 |
3. Tag with different sync word length

Table 3.9: Overall packet structure of tag with different sync word length

| AAAA | DB5587 | 01050102 | 3333 | AE14 |

Table 3.10: Header structure of tag with different sync word length

| 01 | 05 | 01 | 02 |

Figure 3.12: Tag with different preamble and sync word configurations

If the tag source address (unique for each tag) is changed, the header value and the CRC value have to be changed accordingly in the tag. No changes are required in the base station settings.

4. Tag with source address 2

Table 3.11: Overall packet structure of tag with source address 2

| AAAA | DB5559 | 02050102 | 3333 | D318 |

Table 3.12: Header structure of tag with source address 2

| 02 | 05 | 01 | 02 |
5. Tag with source address 3

Table 3.13: Overall packet structure of tag with source address 3

<table>
<thead>
<tr>
<th>AAAA</th>
<th>DB5559</th>
<th>03050102</th>
<th>3333</th>
<th>F81C</th>
</tr>
</thead>
</table>

Table 3.14: Header structure of tag with source address 3

| 03 | 05 | 01 | 02 |

Figure 3.13: Software with packets from implantable tags with different source addresses

If the packet size or packet content is modified, again the resulting CRC value and header and the packet byte have to be updated in the tag. No changes are required on the base station side.

6. Tag with different packet value

Table 3.15: Overall packet structure of tag with different payload content

<table>
<thead>
<tr>
<th>AAAA</th>
<th>DB5559</th>
<th>01050102</th>
<th>4354</th>
<th>D3F3</th>
</tr>
</thead>
</table>

Table 3.16: Header structure of tag with different payload content

| 01 | 05 | 01 | 02 |

7. Tag with different packet size

Table 3.17: Overall packet structure of tag with shortened payload content

<table>
<thead>
<tr>
<th>AAAA</th>
<th>DB5559</th>
<th>01050101</th>
<th>33</th>
<th>0F25</th>
</tr>
</thead>
</table>

Table 3.18: Header structure of tag with shortened payload content

| 01 | 05 | 01 | 01 |
Figure 3.14: Software with different payload lengths size

3.9 Power

A suitable battery was chosen to ensure it could fit easily within its allocated space in the alumina enclosure. Proper electrical contact was designed and magnetic switch was added to the tag design to improve the battery performance. A lifetime model was developed to estimate the longevity of the device.

3.9.1 Choice of battery

The battery for the implantable tag was chosen by the criteria outlined below:
1. Voltage: Nominal or operating voltage, maximum and minimum permissible voltages, profile of discharge curve.
2. Temperature Requirements: Temperature range over which operation is required.
3. Physical requirements: Size, shape, weight; terminals.
4. Service Life: length of time operation is required.
5. Environmental Condition: Vibration, shock, spin, acceleration, etc.; atmospheric conditions (pressure, humidity, etc.).
6. Maintenance and Re-supply: Ease of battery acquisition, commercial availability, accessible distribution.

   SR416SW-337 silver oxide round cell model was chosen to power the device. It was a primary battery type of dimension 4.8 mm x 2.15 mm with flat contacts and weight of 0.12 g, operating voltage of 1.55 V and end point voltage of 1.2 V, temperature range of operation between -20 °C to 60 °C. The shelf life of the battery was 10 years. The average service life was 485 hours tested using a discharger resistance of 100 kΩ with a discharge condition of 24 hr/day at room temperature. The chosen battery was readily available in the market. The chosen battery was configured in the similar fashion as mentioned earlier to obtain a battery pack of overall voltage of 3.1 V and overall capacity of 72 mAh.

Figure 3.15: Discharge characteristics of battery [31]

Figure 3.16: Battery location inside the alumina enclosure
3.9.2 Proper electrical contact

V-shaped beryllium copper spring contact was designed to replace the previous positive plate contact made from EMI shielding tape. To make this contact, a beryllium copper piece of size 24 mm x 9 mm x 1.27 mm was used. The particular dimensions were chosen to ensure the contact could easily fit inside the allocated space for the battery compartment of the alumina enclosure. Eight rectangular edges on either side of the piece were marked of size 3 mm x 2 mm. These edges were cut vertically and using a plier they were vertically bended to create the spring effect to the electrical contact.

![V shaped beryllium copper spring contact](image)

Figure 3.17: V shaped beryllium copper spring contact

3.9.3 Magnetic switch

To conserve power when the device was not in use, the magnetic switch was implemented on the tag electronics board. The MDRR-DT magnetic model from HAMLIN was selected due to its size. The dimension of the switch was 14.73 mm x 2.54 mm allowing it to be easily placed between any electrical contacts of the power source and tag on the space available on the electronics board.

3.9.4 Lifetime model

There are several models which can predict the lifetime of a device based on discharge lifetime of battery systems, one-time full cycle voltage measurement of a constant load and usage patterns of wireless devices [32], [33], [34], [35]. However, none of these models were suitable to predict the longevity of the implantable tag as they did not take into consideration the operating conditions of the device and could not specify at what time intervals the device ought to transmit. A suitable lifetime model had to be constructed that could determine the transmission interval rate taking into account key parameters of the implantable tag such as total
battery capacity; data rate of the device; transmission packet size and required longevity for the tag.

The lifetime model calculates the interval required between consecutive transmissions to obtain a desired lifetime of the tag. To determine the transmission interval, the following approach was considered: First, the total capacity of the battery and the required lifetime of the power source were determined and the total packet length of the transmission and the data rate were fixed. Then, the amount of current consumed by the tag during its transmission state was measured. The time per packet was calculated as the packet length divided by the data rate. Next, the current consumed per packet transmission was calculated by multiplying the time per packet with the device current consumption. The total number of transmissions was equal to the battery capacity divided by the current consumed per packet transmission. Finally, the interval span for the transmissions by the device was determined by dividing the required lifetime period of the power source by the total number of transmissions.

3.9.5 Oven chamber tests

Oven chamber tests were carried out to determine the performance of the battery source and validate the proposed lifetime model. The oven was set to 35 °C to replicate the internal body temperature of steller sea lions in which the tag would be placed. Initially, two implantable tags using the EMI shielding tape electrical contacts were placed in the oven and were programmed to operate at 1kbps and transmit after every 20 secs to last for the duration of a month. Subsequent tests were carried out by replacing one of the existing electrical contacts with the v-shaped beryllium copper spring contact. The tests were re-carried out with the same tag settings, this time using three implantable tags. Finally, three tags were configured to transmit with the same interval rate of 2.04 secs but different rates of 1 kbps; 4.8 kbps & 9.6 kbps respectively and were tested inside the oven for the duration of a month to show the model could estimate the life of the tag given different values for the data rate and transmission interval rate.

3.10 Actual rookeries and haulouts – local rocky habitats

Range tests were carried out in actual rookeries and haulout locations by A. Lau (graduate student), D. Michelson (Electrical and Computer Engineering, UBC) and R. Petrell (chemical and Biological Engineering, UBC) in 2004 at two frequencies, namely 2.4 GHz and 5.25 GHz for the MMRU. The purpose of the study was to evaluate how the base station antenna height
along with the environment in which marine pinnipeds are found i.e., rocky terrain would affect the range of the RF signal. These data were used in the current research to test the link budget and in the design of a base station for haulouts and rookeries. As the data is used in this thesis and has not been published, how the data was obtained is described in this section. Measurements were carried out in various locations namely McInnes island (latitude: 52° 15' 35"N, longitude: 128° 43' 15"W), Warriror rocks (54° 03' 51"N, longitude: 130° 51' 11"W), Steele rocks (latitude: 52° 27' 49"N, longitude: 129° 22' 15"W) and Langara rocks (latitude: 54°15'40"N, longitude: 133°01'29"W). Time was of an essence, so only minimal tests were performed. Tests were carried out in similar fashion at all the sites using the same equipment.

3.10.1 Equipment

A Geo Explorer XT 128MB GPS unit was used for measuring the GPS position. The receiver unit was a light weight XL Microwave 2261 Analyze-R Wideband Receiver that had an operating time of 6 hrs and 3 hrs recharge time. Minimum received signal strength by the unit was -100 dBm. It operated over 4 selectable frequency bands: 2.400-2.484 GHz; 5.150–5.250 GHz; 5.250–5.350 GHz; and 5.725–5.875 GHz. The transmitter unit was an XL Microwave 2230 Survey-R Transmitter that had a 4-5 hrs operating time and 3 hrs recharge time. The output power of the transmitter was +10 dBm and it operated over 2 tunable frequency bands: 2.400-2.483 GHz and 5.150-5.999 GHz with 1MHz resolution. The contour XLRic laser gun was used for measuring the distance between the transmitter and receiver unit along with the bearing angle. The dimensions of the antenna at 2.4 GHz and 5.25 GHz were 21.9 cm and 1.9 cm respectively.

3.10.2 Procedure

The crew arrived at a haulout site, unpacked and set up the test equipment. The receiver unit was set up at the highest point in two places: directly on the ground and at a height of 1.5 m. Two to four signal measurements (in dBm); bearing angle; GPS position; inclination angle; and distance between receiver and transmitter at various elevations in ~2m descending increments were recorded at 2.4 GHz and 5.25 GHz respectively. There was always a reading next to the base station and one at the waterline.
3.10.3 Restrictions

RF data collection was a secondary objective of the field trip and was conducted on a non-interference basis. The crew were only permitted to disembark for approximately 30 minutes per site during favourable weather conditions. The transmitter and receiver units could only store a maximum of 200 data points on board.

3.11 Testing of commercial implantable device

Four off-the-shelf implant tags using loop antenna were acquired from Titley Scientific of Australia and tested by Olawale in June 2004. The tests were carried out to evaluate the performance of a commercial tag in free space and in pig cadaver and to compare this data to the prototype tag. As the data have not been published, but were used in this thesis, the methods and materials used to obtain the data are described next. One Titley tag was tested in a testing range in Abbotsford, BC. Another one tag was uncoated so that its return loss could be determined. An antenna testing range was required to conduct radiation pattern measurements of the loop antenna. A company specializing in radio frequency measurements, Protocol-EMC in Abbotsford, BC was contracted for these tests. Test results obtained from the measurements were plotted as radiation patterns.

3.11.1 Materials

The materials required for these measurements were mainly the selected loop antenna and pig cadavers. Testing equipment was provided by Protocol-EMC, the company contracted to take the measurements. The loop antenna came with a small electronic circuit to energize it. A magnetic switch was included for use in turning the electronic circuit on (thereby enabling the loop antenna to radiate). The RF tag was enclosed in sealed package. A sketch of the internal structure of the RF tag is shown in Figure 3.22. It highlights the position of the components mentioned above. A summary of important characteristics of the tag is given in Table 3.21. The dimensions of the loop antenna of the titley tag was 12 mm x 18 mm.
### Table 3.19: Important characteristics of the loop antenna

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall size</td>
<td>$24 \times 22 \times 9$</td>
<td>mm</td>
</tr>
<tr>
<td>Weight</td>
<td>6</td>
<td>g</td>
</tr>
<tr>
<td>Frequency</td>
<td>165</td>
<td>MHz</td>
</tr>
<tr>
<td>Battery</td>
<td>Sanyo 2032</td>
<td></td>
</tr>
<tr>
<td>Battery capacity</td>
<td>200</td>
<td>mAh</td>
</tr>
<tr>
<td>Battery voltage</td>
<td>3.0</td>
<td>V</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>$\sim 14.0$</td>
<td>ms</td>
</tr>
<tr>
<td>Pulse separation</td>
<td>$\sim 1.5$</td>
<td>s</td>
</tr>
</tbody>
</table>

### 3.11.2 Pig test

Three freshly butchered pigs were used to test the performance of this device. Two of the pigs were small, about 22.7 kg each. The third pig was an old female pig (called sow) previously used for breeding. As a whole, the sow was too big for use in the project. Only the head and neck were therefore obtained and used in the measurements. The pigs were acquired from Johnston Packers Limited in Chilliwack, BC. The temperature of the body of each pig was taken just before and after the measurements. Ice blocks were placed inside the small pig to keep the body temperature from rising quickly during measurements. A summary of information on the pigs is presented in Table 3.22.
Table 3.20: Information on pig cadavers

<table>
<thead>
<tr>
<th>Pig</th>
<th>Weight (kg)</th>
<th>Body temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Start</td>
</tr>
<tr>
<td>Small pig 1</td>
<td>~ 22.7</td>
<td>17.2</td>
</tr>
<tr>
<td>Small pig 2</td>
<td>~ 22.7</td>
<td>9.5</td>
</tr>
<tr>
<td>Pig sow</td>
<td>~ 34</td>
<td>11</td>
</tr>
</tbody>
</table>

3.11.2.1 Small pigs

Vertical and horizontal orientations of the Titley RF tag were required during measurements. The horizontal orientation was achieved by placing each of the small pigs on their stomach. The vertical orientation required placing each pig on its side. In both cases, the tail of the pig was pointed towards the 0° mark on the rotary table. Figures 3.23 and 3.24 show the pig orientation on the rotating table.

Figure 3.19: Pig orientation on rotating table (loop antenna is horizontal).
3.11.2.2 Sow

In the sow, the position of the pocket created for the tag was slightly off the center of the back. This is because the neck was not complete. When the tag was placed inside the pocket, it was slanted because the pocket was on one side of the neck. It was therefore considered a vertical orientation, rather than horizontal. To obtain horizontal orientation of the tag, the sow was placed on her side.

3.11.3 Measurements

Six full-circle measurements for each of the three pig subjects were acquired to obtain the results for different antenna polarizations. Signal strength was recorded at every 20° step of the rotating Table for the first small pig. The step size was reduced to every 10° in the other two pigs. The choice of step size was constrained by the length of time it took to complete the measurement process. The outcome of the measurements was a listing of the signal strength received at specific angles. The radiation pattern plots were obtained by plotting the signal strengths against the respective angles yield.
4 Results

4.1 Lifetime model

The lifetime model that was developed was used to predict the packet transmission interval required to achieve a particular lifetime. The battery capacity for the tag is 72 mAh, and it consumes about 25 mA during transmission. Assuming that the tag is required to last for a duration of three years, the transmission interval between successive packets at 1 kbps is 15.82 min. However, if the data rate is increased to 9.6 kbps, the transmission interval reduces to 1.64 min. The calculations showing how these numbers were obtained follow.

1st case: Data rate of 1 kbps

Time per packet = 104 x 1/1000 = 104 msec

Current consumed per packet transmission = time per packet x current consumed

= 25 mA x 104 msec

= 2600 mA msec

Total number of transmissions = battery capacity/Current consumed per packet transmission

= 72mA x (60)^2 / 2600 mA msec

= 99692

Interval span = lifetime of device / total number of transmissions

= 1576800/99692

= 15.82 min

2nd case: 9.6 kbps

Time per packet = 104 x 1/9600 = 10.83 msec

Current consumed per packet transmission = time per packet x current consumed

= 25 mA x 10.83 msec

= 270.75 mA msec

Total number of transmissions = battery capacity/Current consumed per packet transmission

= 72mA x (60)^2 / 270.75 mA msec

= 957341

Interval span = lifetime of device / total number of transmissions

= 1576800/957341

= 1.64 min
The effect of battery capacity and packet size could also be observed from the model. If the tag transmits at a fixed data rate, for a required duration of longevity of the device, more transmissions can be obtained from the tag by increasing the capacity. As well, an increase in the number of transmissions from the tag operating at a fixed capacity and data rate and known required longevity of the device can be obtained by reducing the overall packet size.

4.2 Lifetime results

Initial lifetime tests showed that the two tags operating at 1 kbps and transmitting after an interval of 2.04 sec (to last for the duration of a month) did not last longer than two weeks. The reduced longevity of both the samples was traced to the EMI shielding tape electrical contacts.

The lifetime tests were carried out again after replacing the positive EMI shielding tape electrical contact with the v shaped beryllium copper spring contact. Three samples were configured as per the previous testing. Using this new electrical contact configuration, the lifetime of the devices increased to three and a half weeks as shown in Figure 4.2.
Figure 4.2: Tags operating at data rate of 1 kbps and transmitting after an interval of 1 kbps with beryllium copper spring electrical contacts

The final lifetime test carried out pertained to the tag operating at different data rates. Three implantable tags were programmed to transmit after an interval of 2.04 sec at three different data rates, i.e., 1 kbps, 4 kbps and 9.6 kbps. From Figure 4.3, it could be observed that for a fixed number of transmissions and battery capacity, the longevity of the tag increased with increase in the data rate, and was similar to the findings from the study carried out by Valdastri et Al, 2004 [20].

Figure 4.3: Tags operating at different data rates and transmitting after an interval of 2.04 sec
4.3 Return loss

As previously mentioned, the return loss indicates how much signal power is being reflected back from the matching network of the loop antenna. Figure 4.4 illustrates the return loss of the original tag design in free space. At 915 MHz, the return loss is -6.4 dB. The low return loss figure indicates that almost half of the transmitted signal is being reflected back from the matching network.

![Figure 4.4: Original tag in free space](image)

When the loop antenna was surrounded by a dielectric material i.e., the plastic enclosure or a hand, frequency detuning occurred and return loss at the frequency of operation of the tag decreased as shown in Figure 4.5 to 4.7. A frequency shift of about 200 MHz occurred when the tag was covered by a hand, 65 MHz when the tag was encapsulated within a replicate plastic enclosure and 60 MHz when the tag was encapsulated in the plastic case and surrounded by a hand. The detuning effect of the tag was similar to findings in previous study on the behaviour of the implantable loop antenna inside the plastic enclosure and covered by hand [10].
Figure 4.5: Original tag covered by hand

Figure 4.6: Original tag encapsulated inside plastic enclosure
Figure 4.7: Original tag inside plastic enclosure and covered by hand

Figure 4.8 to 4.10 illustrate the performance of the tag with the matching network tuned to perform efficiently inside the plastic enclosure. The capacitors in the matching network of the loop antenna were changed to 0.5 pF from their initial original values of 0.8 pF.

Figure 4.8: Tag in free space with 0.5 pF capacitors in the matching network
Figure 4.9: Tag with 0.5 pF capacitors in the matching network inside plastic enclosure

Figure 4.10: Tag with 0.5 pF capacitors in the matching network inside plastic enclosure and covered by hand

Figure 4.11 and 4.12 show the performance of the device inside the alumina enclosure. From previous testing, the performance of the loop antenna inside the alumina enclosure could be improved by lowering the capacitor values. The loop antenna had a better return loss with 0.3 pF capacitors in the matching network as compared to 0.2 pF capacitors and resonated close to 915 MHz. This prototype had a better performance inside the alumina enclosure as compared to
the original tag inside the alumina enclosure, yet it was less as compared to the original tag in free space.

Figure 4.11: Tag with 0.2 pF capacitors in the matching network inside the alumina enclosure

Figure 4.12: Tag with 0.3 pF capacitors in the matching network inside the alumina enclosure

When the height of the loop antenna was reduced, the antenna resonated at a lower frequency as compared to the original resonant frequency, i.e., 915 MHz. However, by lowering the capacitor values in the matching network, the frequency of operation of the antenna shifted upwards to a higher frequency. By reducing the height of the loop antenna by 2 mm and
changing the capacitors in the matching network to 0.5 pF, the tag operated more efficiently at 915MHz inside its alumina enclosure. Return loss for this configuration is -21 dB which shows the performance of this prototype inside the case is much better than the performance of the original tag in free space. In this configuration, the amount of transmitted signal reflected back by the matching network reduces to about 40%.

Figure 4.13: Loop antenna in free space with 0.8 pF capacitors in the matching network and loop height reduced by 6 mm

Figure 4.14: Loop antenna in free space with 0.5 pF capacitors in the matching network and loop height reduced by 6 mm
Figure 4.15: Loop antenna inside alumina enclosure with 0.8 pF capacitors in the matching network and loop height reduced by 6 mm

Figure 4.16: Loop antenna inside alumina enclosure with 0.8 pF capacitors in the matching network and loop height reduced by 4 mm
Figure 4.17: Loop antenna inside alumina enclosure with 0.5 pF capacitors in the matching network and loop height reduced by 2 mm

The prototype tag with the height of the loop antenna reduced by 2 mm and capacitors in the matching network changed to 0.5 pF was tested under non-chemically treated pork bacon skin and fat. Figure 4.18 and 4.19 show the return loss of the device under the two skin samples. The return loss increased by 1 dB and the amount of frequency detuning decreased by 20 MHz with an increase in skin thickness of 1mm. However the antenna showed a better performance in both the fat samples. For instance, the return loss increased by 4 dB under fat layer of thickness 10 mm. This implies that about 40 % of the transmitted signal was reflected back by the matching network in the fat layer as compared to the skin samples where about 70% of the transmitted signal was being reflected back. In the other fat sample of thickness 3.1 mm, the return loss increased slightly by 1 dB as compared to both the skin samples.
Figure 4.18: Prototype tag under non-chemically treated pork bacon skin of thickness 2.1 mm

Figure 4.19: Prototype tag under non-chemically treated pork bacon skin of thickness 3 mm
The antenna height was reduced to 3 mm to observe if the performance of the tag under the skin and fat of the pork bacon would improve. From Figure 4.22 and 4.23, there was a very small improvement in the performance of the device under the different layers of the bacon. Hence the configuration was left to 2 mm.
Figure 4.22: Height of the loop antenna reduced to 3 mm inside the alumina enclosure under non-chemically treated pork bacon skin of thickness 2.1 mm

The prototype with the loop antenna around the electronics and 0.5 pF capacitors in the matching network had a return loss of -13.6 dB. It has a better return loss than the original tag in free space but is lower than the prototype tag with reduced antenna height. The alumina enclosure would need to be redesigned for this prototype to fit inside the case.

Figure 4.23: Height of the loop antenna reduced to 3 mm inside the alumina enclosure under non-chemically treated pork bacon fat of thickness 3.1 mm
4.4 Radiation pattern

Figures 4.25 to 4.27 illustrate the far field patterns of the original tag in free space. The tag radiated more power in the horizontal polarization state (about -5 dBm) as compared to the vertical polarization state (about -7 dBm). The power radiated in the vertical polarization state is almost constant whereas in the horizontal polarization state, there is a -10 dB decrease in power at different orientation angles of the horizontal loop antenna of the tag and its shape looks similar to the shape of figure 8. From Figure 4.27, it can be seen the gain of the antenna is about -7 dB if it is horizontally orientated at an angle of 160-180 °. However, when the tag is placed inside the alumina enclosure, the radiation performance of the loop antenna worsens (Figure 4.28 to 4.30). The amount of power radiated in the vertical state increases by 3 dBm as compared to the power radiated in the horizontal polarization state. There is a decrease of about -10 dBm in radiated power in both the polarization states due to the enclosure. From Figure 4.30, the gain of the antenna reduces to about -30 dB with the loop antenna inside the alumina enclosure.
Figure 4.25: Horizontal Polarization in free space of original tag (note: max scale is 0 dB)

Figure 4.26: Vertical Polarization in free space of original tag (note: max scale is -5 dB)
Figure 4.27: Horizontal gain of antenna of original tag in free space (note: max scale is -6.5 dB)

Figure 4.28: Horizontal polarization inside alumina case of original tag (note: max scale is -26 dB)
Radiation patterns of the prototype tag with 0.3 pF capacitors in matching network and loop antenna inside the alumina enclosure (Figures 4.31 to 4.34) showed an improvement in the radiation performance of the loop antenna as compared to the original tag inside the alumina enclosure. The antenna radiated maximum power of -7.8 dB in the horizontal state as compared to -9.7 dB in the vertical state. In the horizontal state, maximum power was obtained when the tag was horizontally orientated between 240-300°, whereas in the vertical polarization state there
was a reduction of about 2 dB in between the different orientation angles. The gain of the antenna in this configuration is -7.5 dBm when it was oriented at 190-300°.

Figure 4.31: Horizontal polarization with 0.3 pF capacitors in matching network in case (note: max scale is -6 dB)

Figure 4.32: Vertical polarization with 0.3 pF capacitors in matching network in case (note: max scale is -8 dB)
Figure 4.33: Horizontal gain of antenna with 0.3 pF capacitors in matching network inside case (note: max scale is -5 dB)

Figure 4.34 to 4.36 shows the radiation patterns of the prototype tag with the loop antenna inside the alumina enclosure, with antenna height reduced to 2 mm and capacitors in the matching network changed to 0.5 pF. The radiation performance of this arrangement was the best as compared to all other prototypes with the gain of antenna around -5 dBm. The power radiated in the horizontal and vertical polarization state was nearly uniform and the gain of the antenna was almost uniform at all orientation angles.
Figure 4.34: Horizontal polarization of tag with antenna height modified by 2 mm and 0.5 pF capacitors in matching network in case (note: max scale is -5 dB)

Figure 4.35: Vertical polarization of tag with antenna height reduced by 2mm and 0.5 pF capacitors in matching network in case (note: max scale is -4 dB)
Figure 4.36: Horizontal gain of antenna of tag with antenna height reduced by 2 mm and 0.5 pF capacitors in matching network in case (note: max scale is -2 dB)

Figure 4.37 to 4.42 illustrate the performance of the prototype with the loop antenna inside the alumina enclosure, with antenna height reduced by 2 mm and 0.5 pF capacitors in the matching network under the non-chemically treated pork bacon (skin and fat) and elephant seal skin. The loop antenna of the tag is rotated in the horizontal plane to observe the gain of the antenna under the different meat samples.

In Figures 4.37 and 4.38, it can be observed that there is a slight decrease in the performance between the two skin samples of the non-chemically treated pork, i.e., the gain of the antenna reduced by 2 dB in the second (thicker) skin sample as compared to the first skin sample. The gain of the loop antenna in the fat samples (Figure 4.39 and 4.40) is about -31 dB, whereas in the skin samples it was about -33 dB. The gain of the antenna was constant at most orientation angles when it was positioned deep under the fat sample. The maximum gain of the antenna in the fat sample was about -30 dB at 90°, while the maximum gain of the antenna in the skin sample was about -32.5 dB at 0°.

Figures 4.41 and 4.42 show the performance of the tag in the skin of elephant seal meat. The gain of the antenna and orientation angles for maximum gain were similar to those obtained from the bacon fat samples, i.e., maximum gain was obtained at 90° orientation. The losses in the elephant seal increased with the increase in thickness of the skin of the elephant seal.
Figure 4.37: Horizontal gain of final prototype in non-chemically treated pork bacon skin sample 1 (thickness 2.1 mm) (note: max scale is -32 dB)

Figure 4.38: Horizontal gain of final prototype in non-chemically treated pork bacon skin sample 2 of thickness 3 mm (note: max scale is -33 dB)
Figure 4.39: Gain of antenna of final prototype in non-chemically treated pork bacon fat sample of thickness of 3.1 mm under a skin layer of 2.1 mm (Note Max scale is -30.5 dB)

Figure 4.40: Gain of antenna in non-chemically treated pork bacon fat sample of thickness 10 mm under a skin layer of 3 mm (Note: max scale is -30 dB)
Figure 4.41: Horizontal gain of antenna of final prototype in the middle of elephant seal skin, approximately 3 mm deep (note: max scale is -30 dB)

Figure 4.42: Horizontal gain of final prototype inside elephant seal skin of thickness 6 mm. The tag was positioned on top of the blubber layer (note max scale is -25 dB)

Figures 4.43 – 4.44 illustrates the radiation patterns for the prototype tag with the loop antenna around the electronics and 0.5 pF capacitors in the matching network in free space. The tag radiates constant maximum power at all angles in the horizontal polarization state, whereas
the power radiated in the vertical state reduces quite considerably at different orientation angles. The gain of the loop antenna in this configuration is about -15 dB, suggesting that the performance of this prototype would be better than the performance of the original tag inside the enclosure, and lower than the performance of the final prototype inside the alumina enclosure.

Figure 4.43: Horizontal polarization with antenna around electronics and 0.5 pF capacitors in matching network in free space (note max scale is -10 dB)

Figure 4.44: Vertical polarization with loop around electronics and 0.5 pF capacitors in matching network in free space (note max scale is -10 dB)
4.5 Range tests

Initial tests carried out with the tag inside the alumina enclosure transmitting at a data rate of 1 kbps, with transmission interval of 2.04 sec showed a range of 100 m with the base station antenna at a height of 1.5 m, and a range of 160 m with the base station antenna height at 4.5 m. Range tests carried out on the three prototypes indicated that by increasing the height of the base station antenna, the line of sight range of the tag increased. Also, the results indicated that by increasing the data rate of the tag, for a given base station height the range of the tag decreased. Out of all the prototypes, the tag with the loop antenna inside the alumina enclosure and the height of the loop antenna reduced to 2 mm and capacitors in the matching network changed to 0.5 pF had the best performance of those tested. The longest distance recorded was when the base station height was more than 7 m and the data rate was 1 kbps.

The range of the system of the prototype tag with loop antenna inside enclosure with reduced antenna height was significantly reduced when placed under skin of non-chemically treated pork bacon and cavernous elephant seal. The range of the system just under the skin layer of the non-chemically treated pork bacon was approximately 160 m, whereas under the fat sample it fell to 120 m, though from the radiation pattern tests it could be observed that the loop antenna performed better in the fat layer than the skin layer. Under the thick and moist elephant seal skin, the range of the device was much lower as compared under the dry pork bacon, i.e., range of the system was about 100 m. The range of the tag system would have been more if the receiver sensitivity of the base station was more than -62 dBm i.e., signals lower than -62 dBm upto -70 dBm were not being displayed by the base station software.

The tag with the loop antenna around the electronics gave an acceptable line of sight range in free space as compared to the performance of the the performance of loop antenna tuned to perform efficiently inside the alumina enclosure. By implementing a proper design for the loop antenna around the electronics, the range performance could be increased to more than the range of the final prototype.
Figure 4.45: Horizontal polarization at 1kbps for tag with capacitors modified to 0.3 pF at base station height of 1.5 m

Figure 4.46: Vertical polarization at 1kbps for tag with capacitors modified to 0.3 pF at base station height of 1.5 m

Figure 4.47: Horizontal polarization at 2.052 kbps for tag with capacitors modified to 0.3 pF at base station height of 1.5 m
Figure 4.48: Vertical polarization at 2.052 kbps for tag with capacitors modified to 0.3 pF at base station height of 1.5 m

Figure 4.49: Horizontal polarization at 4.789 kbps for tag with capacitors modified to 0.3 pF at base station height of 1.5 m
Figure 4.50: Vertical polarization at 4.789 kbps for tag with capacitors modified to 0.3 pF at base station height of 1.5 m

![Graph showing signal strength vs distance for vertical polarization at 4.789 kbps with capacitors modified to 0.3 pF at base station height of 1.5 m.]

Figure 4.51: Horizontal polarization at 1 kbps for tag with loop antenna modified by 2 mm + capacitors modified to 0.5 pF at base station height of 1.5 m

![Graph showing signal strength vs distance for horizontal polarization at 1 kbps with loop antenna modified by 2 mm + capacitors modified to 0.5 pF at base station height of 1.5 m.]

Figure 4.52: Vertical polarization at 1 kbps for tag with loop antenna modified by 2 mm + capacitors modified to 0.5 pF at base station height of 1.5 m

![Graph showing signal strength vs distance for vertical polarization at 1 kbps with loop antenna modified by 2 mm + capacitors modified to 0.5 pF at base station height of 1.5 m.]

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Figure 4.53: Horizontal polarization at 2.052 kbps for tag with loop antenna modified by 2 mm + capacitors modified to 0.5 pF at base station height of 1.5 m

Figure 4.54: Vertical polarization at 2.052 kbps for tag with loop antenna modified by 2 mm + capacitors modified to 0.5 pF at base station height of 1.5 m

Figure 4.55: Horizontal polarization at 4.789 kbps for tag with loop antenna modified by 2 mm + capacitors modified to 0.5 pF at base station height of 1.5 m
Figure 4.56: Vertical polarization at 4.789 kbps for tag with loop antenna modified by 2 mm + capacitors modified to 0.5 pF at base station height of 1.5 m

Figure 4.57: Horizontal polarization at 1 kbps for loop antenna around tag with capacitors modified to 0.5 pF at base station height of 1.5 m
Figure 4.58: Vertical polarization at 1 kbps for loop antenna around tag with capacitors modified to 0.5 pF at base station height of 1.5 m

Figure 4.59: Range of prototype tag under non-chemically treated pork bacon skin sample of thickness 2.1 mm at data rate of 1 kbps and base station height of 7 m

Figure 4.60: Range of prototype tag under non-chemically treated pork bacon skin sample of thickness 3 mm at data rate of 1 kbps and base station height of 7 m
Figure 4.61: Range of prototype tag under non-chemically treated pork bacon fat sample of thickness 10 mm at data rate of 1 kbps and base station height of 7 m

Figure 4.62: Range of prototype tag under non-chemically treated pork bacon fat sample of thickness 3.1 mm at data rate of 1 kbps and base station height of 7 m

Figure 4.63: Range of prototype tag under elephant seal skin sample of thickness 3 mm at data rate of 1 kbps and base station height of 7 m
Figure 4.64: Range of prototype tag under elephant seal skin sample of thickness 6 mm at data rate of 1 kbps and base station height of 7 m.

Figure 4.65: Horizontal polarization at 1 kbps of tag with capacitor values changed in the matching network to 0.3 pF at base station height of 7 m.
Figure 4.66: Vertical polarization at 1 kbps of tag with capacitor values changed in the matching network to 0.3 pF at base station height of 7 m

Figure 4.67: Horizontal polarization at 1 kbps measurement of tag with height of loop antenna reduced by 2 mm and with capacitor values changed in the matching network to 0.5 pF at base station height of 7 m
Figure 4.68: Vertical polarization at 1 kbps measurement of tag with height of loop antenna reduced by 2 mm and with capacitor values changed in the matching network to 0.5 pF at base station height of 7 m

Figure 4.69: Horizontal polarization at 1 kbps for tag with loop antenna around electronics and capacitor values changed in the matching network to 0.5 pF at base station height of 7 m
Figure 4.70: Vertical polarization at 1 kbps for tag with loop antenna around electronics and capacitor values changed in the matching network to 0.5 pF at base station height of 7 m

Figure 4.71: Horizontal polarization at 1 kbps of original tag in case without LNA at base station height of 1.5 m
Figure 4.72: Vertical polarization at 1 kbps of original tag in case without LNA at base station height of 1.5 m

Figure 4.73: Horizontal polarization of original tag in case without LNA at base station height of 4.5 m

Figure 4.74: Vertical polarization of original tag in case without LNA at base station height of 4.5 m
Figure 4.75: Horizontal polarization of tag with capacitors modified to 0.3 pF in case at base station height of 4.5 m.

Figure 4.76: Vertical polarization of tag with capacitors modified to 0.3 pF in case at base station height of 4.5 m.
Figure 4.77: Horizontal polarization of tag with loop antenna height modified by 2mm and capacitors modified to 0.5 pF in case at base station height of 4.5 m

Figure 4.78: Vertical polarization of tag with loop antenna height modified by 2mm and capacitors modified to 0.5 pF in case at base station height of 4.5 m
Figure 4.79: Horizontal polarization of tag with loop antenna around electronics and capacitors modified to 0.5 pF in case at base station height of 4.5 m

Figure 4.80: Vertical polarization of tag with loop antenna around electronics and capacitors modified to 0.5 pF in case at base station height of 4.5 m
Figure 4.81: Loop antenna around electronics + modified capacitors 0.5 pF

Figure 4.82: Final prototype tag
Figure 4.83: Testing the loop antenna inside the alumina enclosure

Figure 4.84: Parts of the prototype tag
Figure 4.85: Assembled prototype tag with magnet to turn the device 'ON'

Figure 4.86: Layout of modified prototype tag
5 Discussion

A prototype tag was designed by taking into account the effect of the alumina enclosure and skin. As compared to free space, the tag performed differently within its enclosure and under skin. To ensure the device could work effectively, different prototypes were designed by retuning the matching network and adjusting the loop antenna. The best performance prototype was compared with the performance of the Titley tag and data from literature. Effect of different data rates and height of base station antenna were examined in regard to choosing ideal configurations for haulouts and rookeries. The link budget that had been developed for the tag and the operating conditions is described and applied.

5.1 Effect of case and animal tissues

The original tag performed efficiently in free space without its alumina enclosure. However, when the tag was placed inside the enclosure and subsequently under the skin, its performance degraded. Although there was degradation, the range of the tag met the range expectations of the application.

To get a better understanding of why the tag is sensitive to the type of material surrounding the loop antenna, the quality factor (Q factor) is taken into consideration. Ideally a high Q factor indicates that the antenna will radiate more efficiently and will be insensitive to surrounding materials [14]. The Q factor of the implantable tag is 20 [12]. Since the Q factor is low, the loop antenna of the tag will be sensitive to any detuning caused by vicinity of surrounding materials. Hence, when dielectric constant of the surrounding materials is higher than free space, and is placed around the loop antenna of the tag, the radiation performance of that antenna worsens. With the increase in the dielectric constant, the radiation performance reduces. When the plastic case was used, for example, the dielectric constant of the housing material increased to 3. This resulted in a frequency shift of 65 MHz. Similar effects of frequency shift of the implantable loop antenna operating at 915 MHz was found in the study conducted by Zadeh, 2006 [10]. Similarly, when the original tag was placed inside the alumina enclosure (dielectric constant of 9), its radiation performance worsened and the frequency shifted by more than 150 MHz. To ensure the tag radiates maximum power when placed inside its alumina enclosure, the values of the capacitors in the matching network were changed to 0.3 pF.
Of all the prototypes designed, the tag with the height of the loop antenna reduced by 2 mm and 0.5 pF capacitors in the matching network had the best performance inside the alumina enclosure in free space. However, when it was placed under the different skin samples, its performance varied. This could be traced to dielectric properties of the skin samples. Research carried out by Fu and Ma, 2009 [36] illustrated a model of the electrical field strength of the signal through a human body at 2.45 GHz. This model can be used to demonstrate the effect of dielectric properties of the animal tissue on the signal propagation through the animal’s body. The electrical field strength of the signal in the human body can be described as function of the propagation distance by

$$E = E_0 \exp[j(wt - kd)] \cdot \exp(-\alpha s)$$  \hspace{1cm} (5.1)

Where $s$ is the propagation distance, $E_0$ is the field amplitude, $k$ is the wave number, and $e^{-\alpha s}$ depicts the attenuation factor in which the constant $\alpha$ is the attenuation constant given as the real part of the propagation constant $\gamma = \alpha + j\beta$. In this case, the relative electrical dielectric constant should be treated as a complex quantity, so that $\varepsilon_r = \varepsilon_r^* - j\varepsilon_r^\prime$, where $\varepsilon_r^\prime = \sigma/\varepsilon_0 w$ and the wavelength changes to

$$\lambda = \frac{\lambda_0 \Re \sqrt{\varepsilon_r^\prime - j\frac{\sigma}{\varepsilon_0 w}}}{\Re}$$  \hspace{1cm} (5.2)

Where $\Re[.]$ denotes real part. Thus the attenuation factor can be expressed as

$$e^{-\alpha s} = \exp\left[-\frac{ws}{2} \frac{\mu_0 \varepsilon_0^\prime \varepsilon_r^\prime}{\varepsilon_0} \left[1 + \left(\frac{\sigma}{\varepsilon_0 w \varepsilon_r}ight)^\mu\right]\right]^{-1}$$  \hspace{1cm} (5.3)

Where $\varepsilon_0 = 10^{-9}/36\pi$ (Fm⁻¹), $\mu_0 = 4\pi \cdot 10^{-7}$ (Hm⁻¹)

As previously mentioned, the dielectric properties of the skin will be higher than the dielectric properties of the fat due to high water content in the skin tissue. Previous studies carried out by Olawale et al, 2006 [13] showed that the dielectric constants of the sea lion and pig skin are fairly constant above 1000 MHz, while the conductivity increases. The dielectric constants tended to vary with individuals in both species (sea lion: 20-40, pig: 20-50). At 1000 MHz, conductivity was very low (<<<1 S/m). Gabriel et al, 1996 measured the dielectric properties of several human tissues to show that between 10 Hz and 20 GHz trends are similar [37]. Since the dielectric constant of the skin of the pork bacon is significantly higher than the permittivity of alumina, a mismatch occurs in the matching network of the loop antenna, as a
result most of the transmitted signal power is being reflected back by the matching network resulting in huge drop in the transmitted power from the tag. As a result, there is a significant reduction in the range and radiation performance of the tag inside the alumina enclosure under the skin of pork bacon as seen by the radiation pattern tests and range tests of the prototype tag.

Since the dielectric properties of the fat of the pork bacon are lower than the dielectric properties of the skin of the pork bacon, the loop antenna of the tag ought to have a better performance when implanted in the fat layer [28]. Radiation pattern results and return loss results of the prototype tag under the fat of the pork bacon demonstrate the loop antenna has a better performance than under the skin. However when the range tests were carried out with the prototype tag under the fat layer, the range of the tag had fallen down by 60 m as compared to the skin layer. This can be attributed to the total thickness of the fat layer of the pork bacon. When the tag is implanted under the fat layer of the pork bacon, the total thickness is the sum of the thickness of the fat layer where the tag is implanted plus the thickness of the skin layer of the pork bacon piece above it. That means, the transmitted signal from the tag in this fat layer will have to pass through both the skin and fat layer. The penetration depth in the fat layer of the pork bacon will be high, resulting in low power loss in the fat layer of the pork bacon piece. However, the penetration depth in the skin of the pork bacon will be much lower than the fat layer, resulting in significant increase in the power loss in the skin layer. Hence, when the tag is implanted under the fat layer, it will encounter more signal losses due to the losses associated in the above skin layer, resulting in reduction of the range of the tag system.

The performance of the prototype tag under the skin of elephant seal was similar to the performance under the fat of pork bacon piece. The properties of the elephant seal skin are discussed in a study conducted by Ling, 1968 on the skin and hair of the Southern Elephant Seal [38]. The elephant skin contains fat (lipids) secreted by the sedum to make the skin water proof. Since fat is considered to be dryer than normal skin without a high lipid content, it has lower dielectric properties as compared to skin with high water content [37]. As a result, the dielectric properties of the skin layer of the elephant seal are similar to the dielectric properties of the fat layer of the pork bacon piece, and the performance is almost similar in those samples.

Of great interest in this research was the change in radiation gain pattern due to tissue type. It was observed that when the antenna was inserted under the skin of the pork bacon, maximum gain was obtained at around 0-30° orientation. However, when the antenna was placed in the fat of the pork bacon and subsequently under the skin of the elephant seal, maximum gain was obtained around 90° orientation. Similar findings were also seen in studies conducted by
Chira et al, 2003 and Rahmat-Samii on the performance of implantable devices inside the body [39], [40]. The change in the orientation angle could be due to the non homogenous nature of the fat layer. Further research needs to be carried out to get a better understanding of the nature of the shift of the orientation of the gain of the loop antenna under the fat layer.

The results relating to performance under tissues shows that the tag will function independent of nutritional status (fat in the tissue or not), molting (loss of epidermis and hair) and position. Care would have to be taken when considering orientation, range and height of the base station. Also it is very important not to insert the tag deeply into the blubber, and to keep it way above 10 mm from the skin surface.

5.2 Loop antenna around electronics

This prototype was created to see if it would be possible to obtain a tag with a smaller size with an improved performance in comparison with the original tag. Return loss and radiation patterns of this prototype showed that the performance was in between: loop antenna matched to perform efficiently inside the alumina enclosure in free space and the final prototype. By redesigning a proper loop around the electronics as compared to the crude version, it could be possible to obtain a tag with a better performance than the final prototype. This design would result in a reduction of the overall size of the tag by 50%. The alumina enclosure would need to be redesigned so that the tag could be placed inside it. If the dimensions of the current enclosure were adjusted, the remaining empty space due to the reduction of the size of the tag could be used to place a better battery i.e., a battery with higher capacity could be placed thus increasing the longevity of the device. At present, thin film rechargeable battery with higher capacity are available from Oak Ridge and could be used to power this arrangement, thus ensuring the total size of the device remains considerably smaller as compared to the final prototype tag.

5.3 Base station characteristics

The low noise amplifier (LNA) helped in improving the range of the overall system. From the range tests, it was observed that when the LNA was not used, the overall range of the system in the two polarization states decreased quite significantly. This is due to the strength of transmitted signal power picked up the base station antenna. Since no power amplifier could be added on the tag electronics board, the transmitted power of the tag is limited. The LNA amplifies the weak received signals from the tag thus helping in effectively increasing the range
of the system. The downside of using the LNA is an external power supply has to be provided for it to function.

5.3.1 Communication protocol

The current packet size of the packet transmission is large i.e., about 104 bits. From the lifetime model, it could be seen that if the size of the packet structure is decreased, the longevity of the device could be increased. If separate software was designed for monitoring communication between the tag and the base station, the packet structure could be shortened to a greater length. For example, the 32 bit header could be reduced in size to an 8-bit source address and the CRC could be removed.

5.3.2 Effect of data rate

Effect of data rates on the range of the tag system were observed by testing the prototype tags at three data rates i.e., 1 kbps, 2.052 kbps and 4.789 kbps with the base station height at 1.5 m and 4.5 m respectively. From the range test results, it could be seen that the range of the tag in the horizontal polarization and vertical polarization states reduced with the increase in data rates. This is due to the effect of the data rate on the receiver sensitivity. When the data rate is increased, the receiver sensitivity gets reduced. With the reduction in the receiver sensitivity, weaker signals will not get picked up by the base station, thus resulting in reduction of the range of the system. The best performance of the range of the tag system was obtained at the lowest data rate i.e., 1 kbps.

5.4 Power source

5.4.1 Battery choice

The SR416SW-337 silver oxide battery model ensured the complete assembled battery pack could easily fit inside the allocated battery compartment size of the alumina enclosure. The major tradeoff of this battery as compared to the original battery model is its capacity. The capacity of the original battery was 12 mAh while the capacity of the chosen model was 9 mAh. Thus the overall capacity of the battery pack reduced from 108 mAh to 72 mAh leading to a major tradeoff with the longevity of the device. From the lifetime model, it could be observed that by increasing the battery capacity and for a fixed data rate and number of transmissions, the
longevity of the device could be increased. Alternatively, for a required longevity of the tag and a fixed data rate, the transmission interval between the packets could have increased with the increase in battery capacity.

5.4.2 Battery contact

The beryllium copper sheet spring contact was effective in comparison to the EMI shielding tape contacts. The EMI tape contacts did not apply any pressure on the battery pack to hold it in its position. Once the lid was sealed on the device, there was a strong possibility the batteries could easily break from the battery pack due to the movements of the pinnipeds. The springiness of the beryllium copper sheet contact ensures equal pressure is applied on all of the battery packs and they are held tightly in place once the lid is closed. Lifetime tests of the tag carried out at 1 kbps with the two different contacts (put in Figure numbers) show the effectiveness of each of the configuration. The performance of the battery pack improved significantly with the beryllium copper contact as compared to the traditional method.

5.4.3 Lifetime model

The lifetime model gave a good estimate on the longevity of the tag taking into consideration its key parameters such as data rate, battery capacity and required longevity of the tag. Battery capacity determines the amount of transmissions possible from the tag. For a packet with fixed data rate and packet size, the total number of transmissions from the battery increase with increase in battery capacity for the tag to work for a specified duration. Data rate determines the amount of time it requires for a single packet transmission and the amount of current consumed per packet transmission. For a fixed battery capacity, the frequency of transmissions increases with use of higher data rates for the device to perform for certain duration. The three examples of the lifetime model at different data rates show the required number of packet transmissions for the device to last for certain duration. It could be observed, the number of transmissions increased with use of higher data rates as well as the number of transmissions reduced at the fixed data rate if the capacity of the battery was decreased. Based on the lifetime model, using higher data rates would be ideal as it would maximize the battery life. However the major tradeoff of using higher data rates is the effect on the range of the tag system i.e., when higher data rates are used, the sensitivity of the base station receiver reduces as
a result the range of the system decreases. Thus lower data of 1 kbps was chosen to maximize range of the tag at the cost of the longevity of the tag.

Oven tests were carried out to validate the lifetime model and also observe the effects of temperature on the battery pack. The oven was set to 35°C to replicate internal body temperature of the sea lions. During the initial life time tests carried out using the EMI shielding tapes, all the battery packs were not being utilized effectively, resulting in the tags lasting only for duration of two weeks than the expected duration of a month. By changing the electrical contact with the beryllium copper spring contact, the longevity of the device increased to about 3 weeks. Tests at different data rates with same time for the frequency of transmissions were done to see if the model could show how long the device would last given the data rate and number of transmissions and also observe the longevity performance at different data rates. In all the scenarios, the life time model gave a reliable estimate on longevity of the tag. Also, the longevity of tag increased with higher data rates i.e., the tag operating at 9.6 kbps lasted nearly a month as per the required longevity of the test.

The longevity of the tag could be slightly improved by changing the packet size of the transmission. At present, transmission packet size is 104 bits. By reducing the packet size, the number of transmissions could be increased for a fixed capacity and fixed data rate for the device to last for certain duration.

5.5 Link budget model

There are very few studies that have been conducted on the reliability of picking up signals from tagged sea lions and seal, and thus far, no link budget studies. One such study conducted by Born, 2002 comprised of monitoring haul out activity of Ringed Seals using satellite telemetry [41]. In that study, satellite-linked radio transmitters were placed at haul out activity of 15 ringed seals. Telemetry data on haul out activity was obtained by using Land Sea Reporter (LSR), Time at Depth (TAD) and Timeline (TIM) systems housed within the satellite transmitters. Based on the data obtained, it could be observed that there was a significant increase in haul out time (from 25% to 57%) on the aerial survey of basking ringed seals around late June period. Also, this study indicated that the haul out activity peaked during the afternoon. A simple link budget model was prepared for the prototype tag knowing the performance parameters and is shown below in Table 5.5.1
Table 5.1: Link budget for prototype tag in sea lions to a base station

<table>
<thead>
<tr>
<th></th>
<th>Gain Estimate</th>
<th>915 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Path gain over 1km in free space (square of frequency)</td>
<td>-92dB</td>
</tr>
<tr>
<td>1a</td>
<td>Path gain over 1km over ground plane (fourth power)</td>
<td>-111dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Tag antenna gain</td>
<td>-30dB</td>
</tr>
<tr>
<td>5a</td>
<td>Sea lion tissue losses</td>
<td>-10dB</td>
</tr>
<tr>
<td>5b</td>
<td>Alumina enclosure loss</td>
<td>-5 dB</td>
</tr>
<tr>
<td>6</td>
<td>Embedded gain of antenna plus alumina enclosure plus sea lion (4+5a+5b)</td>
<td>-45dB</td>
</tr>
<tr>
<td>6a</td>
<td>Propagation loss if other animal is near the implanted tag</td>
<td>-30 dB</td>
</tr>
<tr>
<td>7</td>
<td>Base station gain</td>
<td>11dBi</td>
</tr>
<tr>
<td>8</td>
<td>Diffraction (non-line-of-sight)</td>
<td>-20dB</td>
</tr>
<tr>
<td>9</td>
<td>Total in freespace without diffraction (1+6+7)</td>
<td>-126dB</td>
</tr>
<tr>
<td>10</td>
<td>Total in freespace with one diffraction (9+8)</td>
<td>-146dB</td>
</tr>
<tr>
<td>11</td>
<td>Total over groundplane without diffraction (1a+6+7)</td>
<td>-146dB</td>
</tr>
<tr>
<td>12</td>
<td>Total over groundplane with diffraction</td>
<td>-166dB</td>
</tr>
</tbody>
</table>

For this link budget, the height of the base station antenna was assumed as 7 m, while the height of the implantable tag antenna was 0.4 m. In comparison with Table 2.4.3, this link budget takes into account the effect of the sea lion tissue and alumina enclosure on the gain of the loop antenna. At the same time, it also takes into consideration the propagation loss of the signal from the tag if another animal is obstructing the path between the transmitter of the tag and the receiver of the base station unit.

The path gain over 1 km in free space can be calculated as:

\[
Attenuation(dB) = 92.467 + 20 \log_{10}(f_{GHz}) + 20 \log_{10}(d_{km})
\]  
(5.4)
Where $f_{\text{GHz}}$ is frequency in GHz and $d_{\text{km}}$ is distance between transmit and receive antennas in km. The path gain for 915 MHz at a distance of 1 km turns out as -92 dB.

Path gain over 1km over ground plane can be calculated using (fourth power) as

$$\text{Path gain over ground plane} = \left( \frac{h_{\text{Tag}}^2}{h_{\text{BS}}^2} \cdot \frac{1}{d^4} \right)$$  \hspace{1cm} (5.5)

Where $h_{\text{Tag}}$ and $H_{\text{BS}}$ is height of implantable tag and base station antenna respectively in m, and $d$ is distance between transmit and receive antennas in m. The path gain for 915 MHz over 1km ground plane is -111 dB.

The radiation pattern tests gave an estimate on the gain of the antenna under the different cavernous skin samples. The gain under the skin of the pork bacon sample was about -30 dB. Losses for the sea lion skin and alumina enclosure were considered as -10dB and -5dB.

Studies carried out by Alomainy et al, 2006 [42] illustrated the amount of signal loss if a human body obstructed LOS path between the implanted device and receiver. From the study, the propagation loss at 868 MHz is about 30 dB (the dielectric properties of the dry human skin at 868 MHz is similar to the dielectric properties of the wet sea lion skin at 915 MHz). This Figure can be used as a rough estimate on the propagation loss if multiple sea lions obstruct the path between the implanted tag and the base station.

The gain of the receiver antenna is 11 dBi. The Diffraction loss for the environment is considered as -20 dB. This Figure is a reasonable estimate for the haulout environment and is in line with the range tests carried out at the haulouts where about -24 dB loss occurred when the transmitter was placed behind a large rock. The data rate of the tag is 1 kbps and the transmission interval for successive packet transmissions from the tag is about 15 min for the device to last for the duration of three years. By re-arranging the Friis equation and taking into account losses associated with the alumina enclosure and sea lion tissue, the uplink range of the system can be estimated as

$$PL_{\text{min}} = P_{\text{min}} - G_T - G_R - P_T - \text{loss from Alum, min aEnclosure - loss from Sealion Tissue}$$  \hspace{1cm} (5.6)

Where $P_{\text{min}}$ is the receiver sensitivity at 1 kbps (-119 dBm), $G_T$ and $G_R$ are the gain of the transit and receiver antenna and PT is power transmitted from the tag (-4dBm) and the theoretical range of the system can be calculated as

$$d = \sqrt{\frac{h_a \cdot h_m}{\cdot 10^{-\frac{PL_{\text{min}}}{20}}}}$$  \hspace{1cm} (5.7)

Where $h_a$ and $h_m$ are the height of the loop antenna of the tag and base station respectively.
Using the values from the link budget, the theoretical estimate of the range of the budget is about 167 m which is in line with the range obtained from testing the prototype tag inside the alumina enclosure under the skin.

5.5.1 Issues affecting the detection of tagged sea lions and seals in the field

The base station antenna height is crucial in achieving a suitable line of sight range for the tag system. For tracking seals and sea lions, the base station height will depend on whether the animal will be tracked using a mobile basestation (e.g. plane or boat) or a fixed basestation (fixed to haulout and rookeries). The topography and material make up of the haulouts and rookeries play major roles in the ability of a basestation to pick up radio signals. The range of the animal from its basestation, as well, its orientation and its proximity to other animals, also, play major roles in the ability of the basestation to record the presence of tagged animals.

5.5.1.1 Fixed base station

For fixed basestations, height, nature of the terrain, orientation of the animal and expected range the animal is from the basestation and proximity of other animals are very important. The importance of height and terrain can be seen by inspecting the data obtained from the propagation studies done on haulouts (Appendix A). The haulouts that were sampled were not very large. For example the range from the top of a haulout to its base ranged from 0 to 10 m, and the average height was 6.2 m. This is good news because this range is within the expected propagation range of the tag. Unfortunately, due to the terrain and possibility tag orientation, animals on a haulout may not be picked up by a basestation positioned on top of a haulout. To illustrate this, the following is a description of data obtained on the four haulouts.

The free space path loss for the frequency of operation i.e., 2.4 GHz and 5.25 GHz at each of the haulout are shown in the range graphs. The free space path loss can be calculated as:

\[
\text{Attenuation}(dB) = 92.467 + 20 \log_{10}(f_{GHz}) + 20 \log_{10}(d_{km})
\]  

(5.8)

Where \(f_{GHz}\) is frequency in GHz and \(d_{km}\) is distance between transmit and receive antennas in km.

In the entire haul out graphs, the signal strength of the received signal was close to the free space path loss curve as long as there was a line of sight between the transmitter and receiver. When the transmitter went out of line of sight, the signal strength of the received signal reduced by about -30 dB. Also, if the transmitter was placed behind a rock, the signal strength of the received signals at both the frequencies fell by approximately -20 dB. Reduction in the signal
strength was also observed when the peak was higher than the receiver antenna. In this case, the signal strength fell by -28 dB. By observing the data, the base station antenna should be placed at a height greater than the peak rock on the haulout.

Orientation of the tag with respect to the base station antenna needs to be taken into account. The base station antenna is horizontally polarized. The prototype tag will be horizontally implanted under the skin of the sea lion. In ideal conditions, maximum range of the implantable tag will be obtained if both the transmit and receive antenna are horizontally polarized. However, as the animal’s orientation will never be fixed, the performance range will decrease depending on the orientation of the loop antenna of the implantable antenna with respect to the base station antenna.

From the radiation characteristics of the base station antenna, the beamwidth of the antenna is about 45°. the angle between the half-power (-3 dB) points of the main lobe, when referenced to the peak effective radiated power of the main lobe. If the animal is behind the base station, the gain of the base station antenna will be significantly reduced. As a result, there could be a possibility that there would be signal reception from the tag at the base station.

If there are multiple number of sea lions present around the implantable tag, more propagation losses will occur. As previously mentioned, when the animals block the LOS path, propagation loss of about -30 dB occurs.

By placing the base station higher than the highest peak in the haulout, the line of sight distance between the transmitter and the base station can be increased plus it could help in reducing the diffraction losses due to the nature of the environment (if the animal is located behind a rock). It is not always possible to install a communications link such that there is no obstruction between the transmitting and the receiving antenna. Radiation pattern tests show the performance of the tag in the different polarization states under the skin. As long as the orientation of the angle doesn’t change by more than 40°, an acceptable range performance can be obtained from the tag.

5.5.1.2 Mobile base station

Another method of monitoring the implantable tags is by mounting the base station antenna on top of a boat or a plane. Since the base station antenna in both of these methods is mobile, if the sea lion is located behind the base station antenna, signals will be picked up more effectively as compared to the fixed base station antenna. The base station antenna on top of a
boat could have problems picking up signals from the tag if the sea lion is located behind the rock or the rock peaks are greater in height than the base station height, thus the range performance would be lower than the fixed base station antenna. This is due to the fact the height of the base station antenna at the boat level is lower than the height of the fixed base station antenna, thus reducing the line of sight range between the transmitter and receiver. This problem can be avoided if the base station is placed on a plane. Diffraction losses due to the nature of the environment cannot be completely eliminated, but would be lower than the fixed base station antenna option. Also the problems associated with multiple obstructions between the transmitter and the receiver along with the orientation of the animal cannot be completely eliminated with the mobile methods.

5.6 Performance with titley tags

Radiation pattern and theoretical range performance of the Titley tag is shown in Appendix B. In general, the polarization radiation plots (whether it be horizontal or vertical polarization) is directional and pattern shape resembles closest to a Figure 8 pattern whereas the horizontal gain of the antenna is uniform and has a circular pattern. The polarization radiation pattern plot indicate how the transmit loop antenna of the tag should to be oriented so that the tag radiates maximum power whereas the gain of the antenna indicates the gain of the antenna in the different orientation states. For the meat sample tests, the horizontal gain radiation pattern tests were conducted to get an idea of the gain of the loop antenna under the tissue samples.

Radiation pattern tests for the polarization states of the initial tag in free space and inside alumina enclosure showed shape of pattern close to a Figure 8 pattern and were similar to the ones obtained by Lea, 2007 [12]. When the final prototype was tested, the radiation pattern of the polarization plots inside the alumina enclosure were better than those of the original tag in free space. With proper orientation of the transmit loop antenna with the base station antenna, maximum radiated power by the loop antenna inside the alumina enclosure was about – 5dB. In comparison, the maximum power radiated by the Titley tag in free space is about -18 dB (with proper orientation). The horizontal gain of the loop antenna of the prototype tag is about -5 dB and is mostly uniform throughout at all orientation angles. The horizontal gain of the Titley tag in free space is about -2 dB. When both the devices are placed inside the skin of the pig, the horizontal gain of the loop antenna of the prototype reduces to -32 dB where as in the Titley tag, the horizontal gain of the loop antenna drops down to -12 dB. Though the loop antenna of the
Titley tag has a higher gain as compared to the loop antenna of the prototype tag, the prototype tag radiates more power out from the tag as compared to the Titley tag. Therefore if both these devices were planted just under the skin, more distance would be obtained from the prototype tag rather than the Titley tag. However if both the devices are planted in the fat layer, since the Titley tag is operating at a much more lower frequency than the prototype tag, the penetration depth of the fat layer and penetration depth of the total thickness of the tissue layer will be higher than the prototype tag resulting in lower power losses overall in the fat layer as compared to the prototype tag in the fat layer.

At the same time, effect of the alumina enclosure cannot be neglected. The permittivity of coating of the Titley tag for protection is about 3 whereas the permittivity of alumina is about 9. Due to increase in dielectric material losses associated with the alumina material will be more than the losses from the coating. One advantage of using the prototype in the alumina enclosure is that it ensures biocompatibility whereas the Titley tag is coated by resin to protect the electronics, which could cause harm to the animal over the long term. If the loop antenna of the Titley tag was encapsulated by an alumina enclosure, detuning effects similar to the loop antenna of the prototype tag would be observed.

The Titley tag has a limited longevity of 10 to 12 days if 1.5 V silver oxide cells are used. As well, the number of transmissions from it cannot be changed to suit the requirements of any experimentation. The current prototype tag has a longer longevity as compared to the Titley tag (the prototype tag has longevity of 38-40 days if it configured to the same transmission interval as the Titley that i.e., 1.5 secs at a data rate of 1kbps). As per the requirements of the customer, the prototype tag can be programmed according to transmit at varied intervals and at different data rates, thus giving the customer more options in controlling the longevity of the device. In comparison to other implantable devices operating at 915 MHz such as the four spirals slot antenna for radiotelemetry capsules designed by Biao, 2007, the prototype tag performed effectively under the skin. Also, if the thickness of the overlaying increased, losses associated with the prototype tag were less as compared to these implantable devices. Though the return loss obtained from the four spirals slot antenna inside the human body is higher than the prototype tag under the skin (return loss for the four spiral slot antenna is about -16 dB, whereas for the prototype tag it is about -7 dB), from the radiation pattern plots it could be seen the gain of four spiral slot antenna reduced significantly in the body to about -50 dB whereas in the prototype tag, the gain of the antenna was significantly higher i.e. about -33 dB resulting in increase of range of the prototype tag.
If the device was implanted under the skin of the sea lion, over time as the animal grew the device could shift into the fat layer. From the return loss testings under the fat of cavernous pork bacon, it was observed the loop antenna of the prototype tag performance improved in comparison to its performance under the skin. The less path losses in fat than those in skin can be attributed to less water content in fat. Thus, the performance of the device including the range of the system could potentially increase as the animal grew in time and the device shifted into the fat layer.

The tag must still be filled and sealed with a suitable epoxy, and retested. The new tag must be pressure tested before deployment, as all mechanical tests that have been done on the housing integrity were done without the electronics.
6 Conclusion

A final prototype tag was designed by modifying existing tag design i.e., adjusting the capacitor values in the matching network and reducing the height of the loop antenna. This prototype had a better performance inside the alumina enclosure as compared to the original tag design. The prototype was tested under the skin and fat of pork bacon and skin of cadaverous elephant seal. The range of the tag under skin and fat was measured to be 180 m. (max -60 db detection) A suitable battery and magnetic switch were chosen, and a life time model was derived for the tag based on its key parameters. The life time model indicated that the tag could last three years at a data rate of 1kbps, transmission interval of 15 min, packet size of 104 bits and battery capacity of 72 mAh. The lifetime model was tested by placing tags inside the over set to the internal body temperature of the sea lion. A link budget model was developed for the prototype tag, and was used to estimate the performance of the implantable tag in the sea lion’s environment. The new tag meets the standards relating to size, longevity and range (relative to haulout size) and is ready for implantation into seals and sea lions.
7 Future work

For the future, designs with loop antenna around the electronics can be explored to reduce the overall size of the tag. The software of the base station can be redesigned to reduce the packet size of the transmission between the base station and the tag and increase the received signal strength capability. Radiation pattern tests at further depth under the fat layer could be carried out to get a better understanding for the shift in orientation of the horizontal gain of the antenna. Range tests could be carried out to determine the effect of different types of rocks found in the rocky terrain. The tag should be depth tested for leaks before deployment.
8 References


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Appendices

A. Rocky terrain (sea lion haulout) measurements

Measurements carried out by A. Lau and R. Petrell illustrates the effect of the terrain and base station antenna height on the range of the system at microwave frequency of 2.4 GHz and 5.25 GHz. Using higher frequencies results in increasing the free space signal propagation loss as shown in all of the Figures. Also, the range of the system decreases when the frequency increases. The study also showed that the range of the system would increase if the base station antenna was placed at a higher height. From the Figures of the testing at the haulouts, it could be seen the signal strength fell down considerably if the transmitter was placed behind a rock. As well, the signal strength of the transmitted signal decreased, if the transmitter was out of line of sight of the receiver.

A: 1 McInnes island location (latitude: 52° 15' 35"N, longitude: 128° 43' 15"W)
A: 2: Signal strength vs. distance with the base station at a height of 1.555m (ascending)

A: 3: Steele Rock location (latitude: 52° 27' 49"N, longitude: 129° 22' 15"W)
A: 4: Haulout at steele rock

A: 5: Signal strength vs. distance when base station at 1.555 m (ascending)
A: 6: Signal strength vs. distance when base station at 1.555 m (descending)

A: 7: Warriror rocks location (54° 03' 51"N, longitude: 130° 51' 11"W)
A: 8: Sea lions at warrior rock haul out

A: 9: Signal strength vs. distance when base station at 0 m (ascending)
A: 10: Signal Strength vs. distance when base station at 1.555 m (ascending)

A: 11: Signal strength vs. distance when base station at 0 m (descending)
A: 12: Signal strength vs. distance when base station at 1.555 m (descending)

A: 13: Langara rocks location (latitude: 54°15'40"N, longitude: 133°01'29"W)
A: 14: Haulout at langara rocks

A: 15: Signal Strength vs distance when base station at 0 m (ascending)
A: 16: Signal strength vs. distance when base station at 1.555 m (ascending)
B. Performance of Titley tag

The following section illustrates the performance of the LT4 Titley tag. The loop antenna is of size 24 mm x 22 mm and operates at 165 MHz. Figure B:1 illustrates the performance of the Titley tag in free space while Figures B:2 to B:4 illustrate the performance of the Titley tag in the two small pig samples and the sow sample respectively. Co-polarization plot is the polarization in which the antenna is intended to radiate. For the loop antenna, horizontal polarization is represented by the co-polarization plot. Cross-polarization plot is the measure of discrimination to oppositely polarized electromagnetic waves (i.e., the discrimination that a vertically polarized antenna has to horizontally polarized radio waves). Isotropic plot is the performance of an isotropic antenna operating at 165 MHz.

B: 1: Free space measurements
B: 2: Radiation patterns of tag in small pig no. 1

B: 3: Radiation pattern of tag in small pig no. 2
The horizontal polarization for the tag in free space is about -2 dB. The horizontal polarization gain of the loop antenna of the Titley tag reduces to about -5 dB in the two pig samples while in the sow sample it reduces to -6 dB.

**Estimated range**

From the foregoing radiation patterns, the transmission range of the loop antenna was estimated. Projected transmission range for the first small pig (at maximum radiation) is shown in Figure B:5.
B: 5: Coverage estimates for loop antenna implanted into small pig no. 1 (at maximum radiation)

In the Figure, the path-loss exponent, \( n \), is used to indicate how cluttered the transmission environment is. \( n = 2 \) represents free-space (no obstructions between the transmitter and receiver), the theoretical ideal. Sea lion habitats would likely have values of \( n \) from 3 to 5. It also indicates that perfect reception is expected up to 50 m, regardless of the path-loss exponent, \( n \). For \( n = 5 \), coverage drops below 50% at 175 m. Statistically, if a base station is located at the center of a circle with radius 175 m, less than 50% of the loop antennas transmitting from the perimeter of the area will be received.
C. Receive register settings

The Receive Register Settings can be entered for registers 1-6, 9 and 11 of the ADF7020. The register map can be found on the ADF7020 data sheet. To calculate the register settings it is best to use ADF7020Registers.exe. It is also possible to save the receive register settings in ADF7020Registers.exe and load them into ADF7020Demo.exe using the Import Rx Registers button.

Transmit Register Settings

It is required to program only 3 registers (register 0, 1 & 2) to set the ADF7020 up in transmit mode (and register 1 is the same in transmit or receive). It is advisable to use the ADF7020 datasheet in conjunction with ADF7020Register.exe to choose these values. The transmit register values should also correlate with the PHY parameters.

Xtal Freq and R Divider

These values are only used when frequency hopping is enabled to calculate the synthesiser integer and fractional N values at run-time.

Baud Rate (and Use Tx Clk From ADF7020)

This is used to calculate some protocol timing values from known numbers of bits and to set the rate of timer 2 in the ADuC847 for when an external Tx clock from the ADF7020 is unavailable.

In GFSK mode, the ADF7020 outputs a reference clock at bit-rate and this should ALWAYS be used, as the timing of when bits are delivered to the ADF7020 is critical. Use Tx Clk From ADF7020 should be ticked. In non-GFSK modes, the ADF7020 does not output a clock so the PHY layer must be configured to use its internal timer-derived clock. Use Tx Clk From ADF7020 should be un-ticked.

In Rx mode the reference clock is always taken from the ADF7020, since this performs the task of bit timing recovery in all modes.

The minimum value for the baud rate in GFSK mode is dictated by the ADF7020 xtal + register configuration.

When using the internal clock reference, the minimum baud rate is 96baud. (Note that the minimum bit rate of the ADF7020 in receive mode may still be higher than this.)

The maximum baud rate supported by the MAC and PHY is somewhere in excess of 50k baud with a CPU clock of 6.23MHz on the ADuC847. It is possible that ACP restrictions in the band of operation will limit the usable baud rate to a value lower than this.
**Preamble Byte and Length**

The packet preamble is comprised of a number of repetitions of the preamble byte. A typical preamble would be 4 bytes of 0x55 giving a 32bit 1010 sequence (bytes are transmitted MSbit first dictated by the SPI port). A preamble of at least 24bits of 1010 is recommended to give the ADF7020 AFC, AGC and bit recovery systems time to lock.

**Tx Sync Word**

For this protocol, this has been fixed at 3 bytes (24 bits). If the sync word detector in the ADF7020 is set to tolerate 0 errors then the sync word pattern is arbitrary since only an exact match will satisfy the Rx and yield the correct bit/byte synchronisation. If the number of Rx errors is set to 1 or more then the sync word should be chosen to have an auto-correlation function that is not less than this error threshold at any position other than at the 0 bit-shift case.

The Rx sync word programmed into the ADF7020 must match this value output by the Tx so there is a button in the ADF7020Demo configuration panel to load this into R5 with the correct bit-shift. (Note that this button also sets the error tolerance to 0. To counter the effect of the 1 bit delay observed between the ADF7020 detecting a sync-word match and outputting a 1 on the sync detect pin, the sync-word loaded into the R5 is right-shifted by 1 bit. A knock-on of doing this is that the last preamble bit becomes part of the sync-word pattern but this is known and is accounted for.)

**Base RF Freq / 100**

This value sets the RF freq when hopping is not enabled and sets the lowest frequency of the band when hopping is enabled. Units are 100 Hz.

**PA Level**

This sets the Tx power. See ADF7020 datasheet for power levels in dBm.

**RSSI Threshold**

This sets the level in dBm above which the protocol assumes the channel is occupied. Its value should be -ve.

This will be a difficult parameter to optimise when rolling out a network as it will be influenced by interference and other received signals local to the node in question. If this is set too low then the unit will often be too scared to Tx. Set it too high and it will trample over other transmissions in the network. In both cases network throughput will be reduced.

**TxRx Turnaround Time**
This sets the time between the end of the CRC in a packet (this is the end of the packet itself excluding the 1-byte end-amble) and the start of the next packet on the channel. Units are 40.69us (1/Fcore of 6.29MHz). A 5ms turnaround time would therefore require a value of 122. The gap between the end of one packet and the start of the next is important in this protocol: It must be long enough to allow some critical processing to be performed (CPU speed dependent) and short enough not to allow other nodes to get in on the channel. (Its impact on network throughput efficiency is minimal.) The CCA measurement window must be sufficiently wider than this turnaround gap in order for CCA to work properly.

**CCA Number Of Measurements and Measurement Time**

Clear Channel Assessment looks at the channel RSSI a number of times at the spacing specified. If the RSSI is above the specified threshold at any of these reading instants then the channel is deemed to be occupied. The measurement period is in units of are 40.69us (1/Fcore of 6.29MHz).

The total CCA measurement window is the product of the CCA measurement period and the number of readings. It is currently set to 7.8ms which is safely larger than the 5ms TxRx turnaround time.

**Unit Address**

This sets the short address for the unit. Addresses must be between 1 and Max Address (which has its own configuration box). This address must match the Associated BS address when the unit is configured as a BS.

**Associated BS Address**

This is the address of the BS with which an EP will communicate. (See Unit Address)

**Unit Is BS**

This sets the unit to be the BS. Only 1 BS should be enabled in a network (i.e., using the same sync word and unit address values).

**Max Address**

Limits on this parameter have been set at 4 and 254. Reducing the address range used in a network has the small benefit of reducing the amount of RAM required at the BS to manage packet duplicate rejection.

**Max Payload**

Limits on this parameter have been set at 2 and 240. The only benefit in reducing the max payload size is that it permits more Tx holding buffers to be allocated in the BS where RAM may be tight.
Num BS Tx Buffers

This sets the number of Tx holding buffers that are allocated within the BS. The number of buffers that will fit within the available heap space depends on the size of the memory heap and the Max Payload parameter. The heap is currently set at 1k bytes in the demo build.

Max Retries

This sets the number of times a packet will be repeated ONCE ACCESS HAS BEEN GAINED TO THE CHANNEL. E.g. An EP will perform CCA with random back-off until it finds the channel clear. It will then transmit the data this many times, separated by the time taken for the EP to know that the BS will not be replying.

A typical value is 4 retries. If the channel was indeed clear and the BS has still not responded then there’s little point in flogging the dead horse and performing a random back-off would more sensible.

Return To CCA After Max Retries

Once the max number of retries has been exceeded, what happens next depends on whether this flag is enabled.

If it is, then the MAC will perform another random back-off, followed by a CCA and a further #Max Retries transmissions. This will continue until Max CCA attempts have been exhausted. If it is not, then the MAC will give up after one burst of Max Retries and return TX_FAILED to the user application.

Use CSMA

Generally this should be enabled. If it is disabled then EPs will Tx as soon as the user code passes a packet to mac_tx_packet(). This may be useful for systems requiring a fast response time but it bypasses the primary channel multiple access system and will therefore impact channel capacity (unless only a very few EPs have this feature turned off).

Max CCA Attempts

This limits the number of times an EP will attempt to access the channel when it is busy (RSSI above the supplied threshold). When this limit is exceeded the MAC will return TX_FAILED to the user application which will in turn have to decide whether to try again or give up.

CCA Back-off Min and Back-off Range

These define the random back-off used when CCA detects that the channel is occupied. The min value is specified in ticks (1/128 sec = 7.8125ms units). The range allowed by the config GUI is
50 to 32767 ticks (0.39s to 4.2 mins). The range is specified in seconds and must be between 1 and 255.

The random back-off time is uniformly distributed between these two limits.

**Enable Hopping**

Does what it says. Use this mode for the 902-928MHz ISM band (FCC 15.247).

The frequency hopping mode operates with a slot period of 48 ticks (0.375s) and hops over 128 frequencies starting at Base RF freq and separated by Hop Delta Freq.

**Debug Hopping**

This prevents the PHY from actually changing frequency so network activity may be analysed in the time domain using a spectrum analyser set to zero-span. (Be aware that since the transceivers will not be re-tuning to different frequencies, nodes will still hear one another even when there is a slot synchronisation error.)

**Hop Delta Freq / 100**

This sets the spacing of the hop frequencies and is not used when hopping is disabled. Units are 100 Hz.

**Hopping Code**

The RF Channel Number (RFCN) is selected according to the following algorithm:

![Hopping code algorithm](image)

The hopping code (network code) provides a means of changing the hopping sequence and may be used to reduce interference between multiple networks operating in the same air space.

**BS Beacon Spacing**

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In hopping mode the BS transmits a beacon every N slots. This beacon contains flags to distinguish it from normal traffic and the full 13-bit slot number at the BS. An EP is able to completely (re)synchronise itself with a single beacon packet. Since there are no duty cycle limits in FCC15.247 and there are probably no power consumption limits at the BS, it is sensible to make the beacon spacing reasonably regular. Making beacons more frequent will reduce the time that an EP needs to acquire sync. On the other hand beacons use up channel capacity so a trade-off between acquisition time and lost capacity must be made for each particular application.

Hop synchronisation is nominally achieved within 128 beacon periods. Since this is a statistical value based on the probability that the EP Rx frequency coincides with the BS beacon frequency, actual lock times may be longer or shorter. (If the beacon spacing = 5 slots then this average period is 240 seconds.)

**EP Re-Sync Period**

This is the period in minutes after which an EP attempts to re-synchronise to the next available beacon subject to the constraint that the MAC is not busy. New Tx traffic is blocked from entering the MAC until resynchronization is complete. This period is in minutes and should be between 1 and 32767.

If re-synchronisation has NOT been achieved by the time the re-sync period has passed a second time, the EP will resort to performing a full re-synchronisation. In this case any outstanding traffic in the MAC is dumped and a CALLBACK_TX_FAILED message passed to the user application.

**Beacon Length Offset**

This is the offset between the start-of-slot-period in the BS and the end of beacon (CRC detection) in an EP. This could be calculated within the MAC from known parameters but has been included as a configuration parameter for the time being. Units are ticks.

The value for this offset is nominally:

$$\text{TxRx turnaround} + 8*(\text{preamble} + 3\text{byte sync-word} + 4\text{byte header} + 2\text{byte payload} + 2\text{byte CRC})/\text{baud_rate}.$$