Link Analysis of a Prototype Wireless Implanted Tracking Tag

Andrew Lea and Rodney Vaughan
School of Engineering Science,
Simon Fraser University,
Burnaby, BC, Canada
leadag@ieee.org,

W. G. Dunford
Department of Electrical and Computer Engineering,
University of British Columbia,
Vancouver, BC, Canada

Royann J. Petrell
Department of Chemical and Biological Engineering,
University of British Columbia,
Vancouver, BC, Canada

Andrew Trites
Marine Mammal Research Unit,
Fisheries Centre,
University of British Columbia,
Vancouver, BC, Canada

***Abstract* — A team of graduate students from Simon Fraser University and the University of British Columbia have designed and built a prototype implanted wireless tag for monitoring Steller sea lions. This paper reviews the system level RF design aspects, and estimates the RF link range.**

Keywords - Implanted antenna, corner reflector, tissue loss, RFID, loop antenna, sensor network.

I. Introduction

The authors are part of a collaboration[1] that has developed a prototype implantable RFID tag for monitoring Steller sea lions.

The goal of this project was to achieve a communications range of one kilometre, under line-of-sight conditions, at very low data-rates (1kbps to 15kbps), and have an active lifespan of at least three years. These requirements exceed the performance of any commercially available tracking system, and present a challenging design process.

This paper begins with a brief overview of the system architecture. We review path loss estimates and present simulated far-field patterns of both the embedded tag antenna and base-station antenna. Finally, a link budget is used to estimate the range of the RF link.

II. Architectural Overview

The prototype tag wakes up at a regular interval and transmits an ID packet to the base-station. The communications link is binary FSK in an unlicensed ISM (Industrial, Scientific, and Medical) frequency band at 915MHz.

The base-station is not subject to the same size constraints as the tag, and is key to realizing the desired RF link performance. High transmit power will maximize the downlink (base-station to tag) range, and high receive sensitivity is needed to achieve similar performance in the uplink direction. A high gain antenna will increase the communications range.

Analog Devices' AD7020 transceiver evaluation board is used as a prototype base-station. This device was chosen because it uses a correlator demodulator which yields optimum receive sensitivity. This device is unique because most ISM band transceiver ICs use simplified demodulation structures to save on size and power at the cost of reduced sensitivity. The AD7020 evaluation board uses ADIismLINK protocol, developed by Analog Devices, which requires the packet structure shown in fig. 1.

24 bit Preamble (1010 …)	**24 bit Synch Pattern**	**32 bit Header**	**8 bit Payload**	**16 bit CRC**

Figure 1. ADIismLink packet structure.

This packet contains more overhead than is needed for our system, but is ideal for prototype purposes. The source code for the evaluation board software is available from Analog Devices, so the packet structure can be changed in the future without any hardware modifications. In future iterations, the CRC can be omitted and the 32-bit header reduced to an 8-bit source address. These simplifications reduce the packet to a more reasonable length of 64 bits.

The tag electronics and antenna are located on a multi-layer printed circuit board (PCB), shown in fig. 2, which fits into a housing designed specifically for this project.

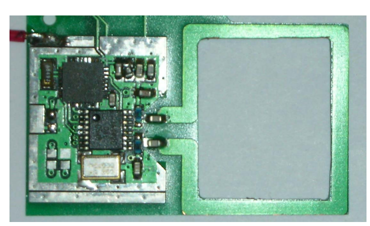

Figure 2. Prototype RFID tag

Space for batteries is reserved in the housing adjacent to the left-hand side of the PCB. Because of the size restrictions

[1] The authors wish to acknowledge the following team members who contributed valuable work to the project: Hamid Meghdadi (SFU), Robert Virtue (UBC), and Maryam Soltanzadeh (SFU).

0840-7789/07/$25.00 ©2007 IEEE

of the housing, the tag electronics are quite simple. A low-power RISC microprocessor with onboard memory (Texas Instruments, MSP1232) controls the tag, and an ISM band transceiver (Integration Associates, IA4420) handles the radio frequency communications.

The lower limit of the system data-rate is 1kbps (limited by the AD7020), and the upper limit is 15 kbps (limited by the rate at which the microprocessor can pass data to the IA4420 on the tag). The tag consumes as much power in receive mode as it does in transmit mode, so for now, communication is limited to the uplink direction.

III. Path Loss Calculations

The foundation of any link budget is the Friis transmission equation

$$P_D = \left(\frac{\lambda}{4\pi r}\right)^2 P_T G_T(\theta,\phi) G_R(\theta,\phi) qp, \tag{1}$$

which expresses the power delivered to the receive antenna (P_D) in terms of transmitted power (P_T), gain of the transmit and receive antennas (G_T and G_R), a polarization mismatch factor (p), and an impedance mismatch factor (q). The term in brackets is known as inverse square-law path loss [1], and applies to line-of-sight propagation without multi-path reflection.

Three carrier frequencies were initially considered for the tag: 200 MHz, 433 MHz and 915 MHz. The lower frequencies are more favourable for tissue loss and path loss; however, the antenna radiation efficiency favours the higher frequencies. To determine the optimum frequency, we need the increase in free-space path loss relative to the lowest frequency, given by

$$\Delta PL_{dB} = 20\log\left(\frac{f, MHz}{200MHz}\right). \tag{2}$$

TABLE I. Relative Increase in Path Loss

Frequency, *f*	**Increase in path loss, Δ*PL***
200 MHz	0 dB
433 MHz	6.7 dB
915 MHz	13.2 dB

The two-path ray model in fig. 3 describes classical two-path fading - a more realistic model for our environment.

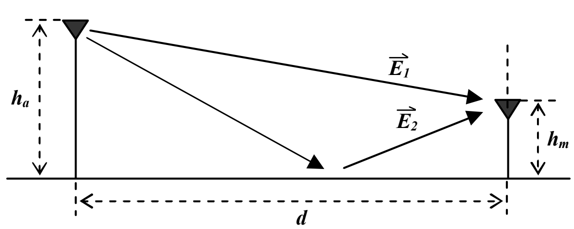

Figure 3. Two-path ray model

The distance of the direct ray is $r_1 = \sqrt{d^2 + (h_a - h_m)^2}$, and the distance of the reflected ray is $r_2 = \sqrt{d^2 + (h_a + h_m)^2}$.

The Friis equation can be derived for this scenario as

$$P_D = P_T\left(\frac{\lambda}{4\pi}\right)^2 \left|\frac{\exp(-j\beta r_1)}{r_1} - \rho\frac{\exp(-j\beta r_2)}{r_2}\right|^2 \cdot G_T(\theta,\phi) G_R(\theta,\phi) qp, \tag{3}$$

and the path loss is taken as the product of the two terms in brackets. The reflection coefficient (ρ) requires the factor $\chi = \left(1.8\times10^{10}\right)\sigma/f$, and is defined for horizontal polarization

$$\rho_h = \frac{\sin\theta - \sqrt{\varepsilon_r - j\chi - \cos^2\theta}}{\sin\theta + \sqrt{\varepsilon_r - j\chi - \cos^2\theta}}, \tag{4}$$

and for vertical polarization

$$\rho_v = \frac{(\varepsilon_r - j\chi)\sin\theta - \sqrt{\varepsilon_r - j\chi - \cos^2\theta}}{(\varepsilon_r - j\chi)\sin\theta + \sqrt{\varepsilon_r - j\chi - \cos^2\theta}}. \tag{5}$$

We consider propagation over seawater with electrical permittivity (ε) of 72 and electrical conductivity (σ) of 4 Siemens per metre [4]. Fig. 4 shows the path loss over seawater for a base-station antenna height of 2 metres and tag height of 0.4 metres.

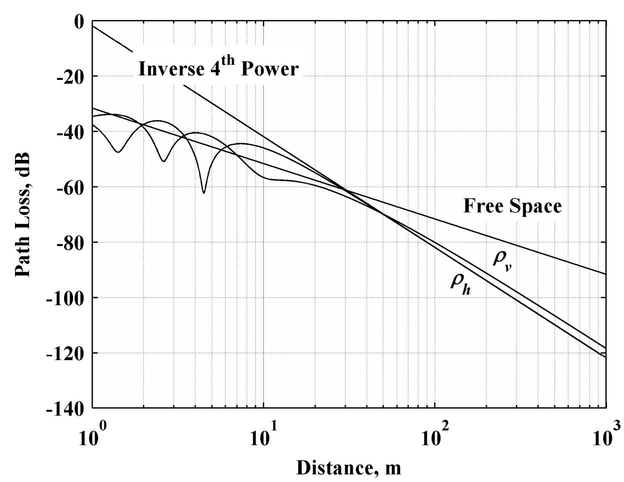

Figure 4. Path loss over seawater for 915MHz

Free-space path loss and inverse fourth-power path loss given by

$$PL_{dB} = 20\log\left\{\frac{h_a h_m}{d^2}\right\}, \quad (6)$$

are included for reference. Note the breakpoint, located at

$$d_{bk} = \frac{4h_a h_m}{\lambda}, \quad (7)$$

beyond which both polarizations show similar path loss.

Fig. 5 shows the path loss over seawater for horizontal polarization at the three candidate frequencies. The breakpoint where inverse fourth power fading begins is less than 10 metres for all of the frequencies. This means path loss is effectively independent of frequency.

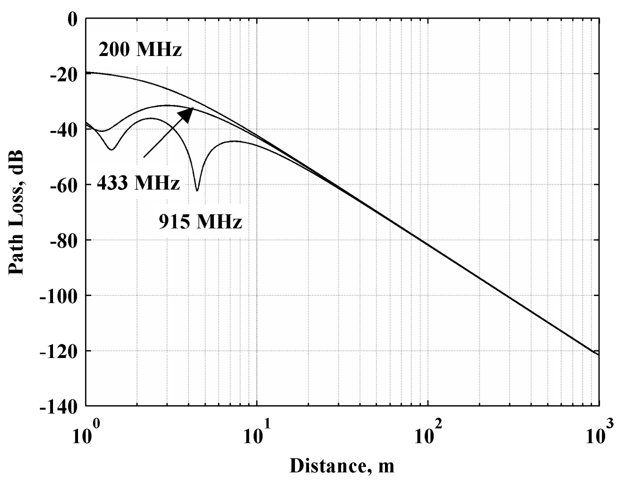

Figure 5. Path Loss over seawater for horizontal polarization at three ISM band frequencies.

As a result of these estimates, the highest frequency (915 MHz) was chosen as most appropriate because of a large improvement in the tag antenna radiation efficiency relative to the other frequencies.

IV. Base-Station Antenna

A single high gain antenna that can be aimed manually is adequate for the prototype base-station. We designed and built a monopole antenna with a corner-reflector, shown in fig. 6.

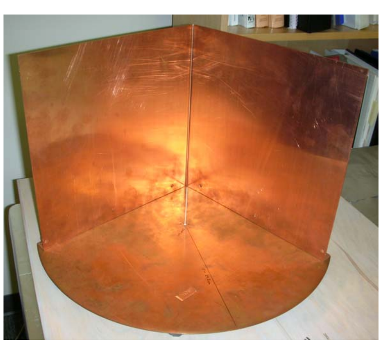

Figure 6. Corner Reflector Antenna built for prototype base-station.

Kraus [2] outlines the design and performance of a dipole antenna with a corner reflector. The polarization can be changed simply by rotating the antenna 90 degrees.

The measured and simulated return loss of the antenna is shown in fig. 7. The impedance match at 915 MHz is very good, and the simulated results agree well with the measurement.

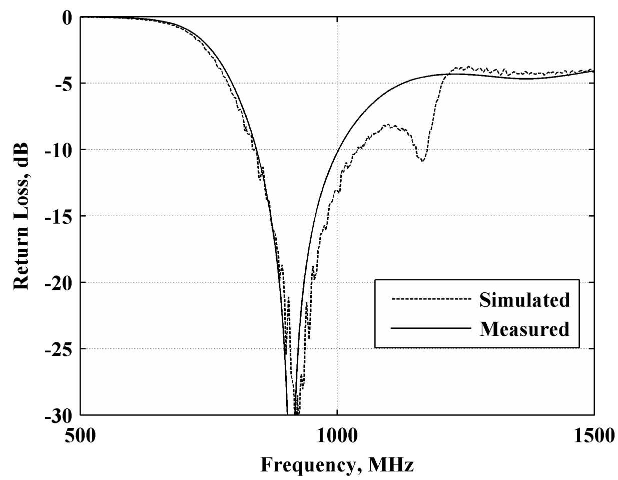

Figure 7. Measured return loss of the base-station antenna.

A vertical cut of the main lobe of the antenna gain pattern is shown in fig. 8. This lobe is centered horizontally halfway between the reflecting plates. The maximum gain of 11 dB occurs 25 degrees above the horizon and has a 3 dB beam-width of 50 degrees.

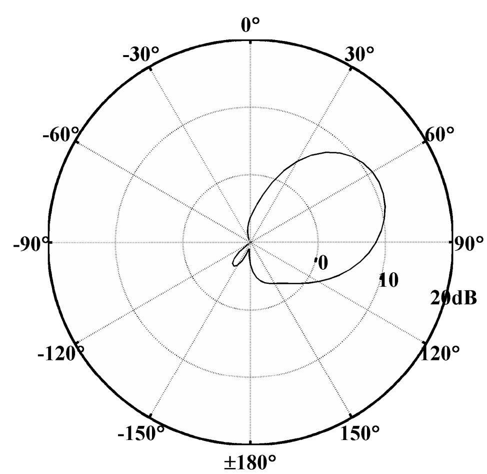

Figure 8. Simulated vertical gain pattern of the main lobe of the base-station antenna

Fig. 9 shows the horizontal cut of the same lobe. The 3 dB bandwidth in this direction is 56 degrees. As previously mentioned, the lobe is centered mid-way between the reflecting plates at 45 degrees.

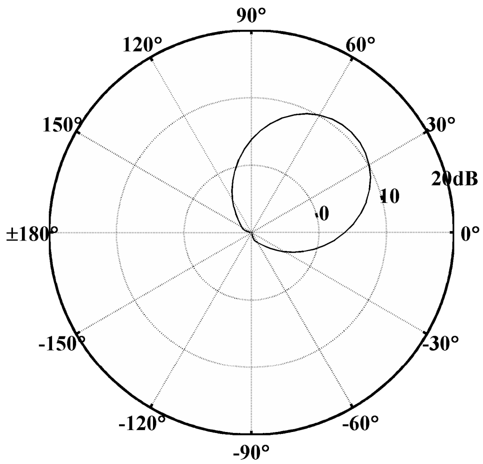

Figure 9. Simulated horizontal gain pattern of the base-station antenna.

V. TAG ANTENNA RADIATION PATTERN AND GAIN

We are concerned primarily with the tag antenna radiation in the horizontal direction.

The antenna and housing were modeled as embedded beneath the skin of a sea lion. A study of the electrical properties of sea lion tissue [3] was used to construct the tissue model. The horizontal cut of the embedded tag antenna gain pattern is shown in fig. 10.

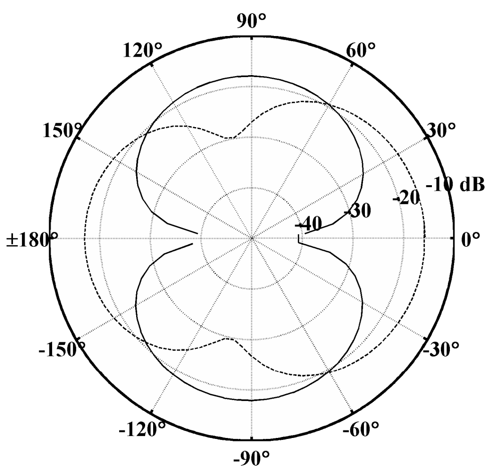

Figure 10. Simulated horizontal gain pattern of embedded tag antenna. The solid line is vertical polarization and the dashed line is horizontal polarization.

The embedded tag far-field contains both horizontal and vertical polarization. The horizontally polarized field has lobes in the front and rear of the tag (90 degrees and 180 degrees respectively), and the vertically polarized field has lobes on the sides of the tag (located at 90 degrees and -90 degrees).

VI. RANGE ESTIMATES

To estimate the uplink range of the system we re-arrange the Friis equation to solve for the minimum allowable path loss

$$PL_{min} = P_{min} - G_T(\theta,\phi) - G_R(\theta,\phi) - P_T \quad (8)$$

where all of the variables are expressed in decibels. The polarization mismatch and matching loss factors have been omitted.

The antenna gains are estimated at -20 dB for the tag antenna and 10 dB for the base-station antenna. The receive sensitivity of the base-station transceiver is given in table 2, and the RF output power of the IA4420 is 4dBm.

TABLE II. AD7020 BASE-STATION RECEIVE SENSITIVITY

Bit-Rate, *R*	**Receive Sensitivity**
1 kbps	- 119 dBm
9.6 kbps	- 112 dBm

The range is calculated assuming inverse fourth power path loss, and re-arranging (6) as

$$d = \sqrt{h_a h_m \cdot 10^{-\frac{PL_{dB}}{20}}}. \quad (9)$$

The resulting estimated uplink range for the embedded system is given in table 3.

TABLE III. ESTIMATED RF LINK RANGE

Bit Rate, *R*	**Estimated Range, *d***
1kbps	600 m
9.6 kbps	400 m

VII. CONCLUSION

A range of 1km is very difficult to achieve with the prototype tag configuration. This range is limited primarily by tissue losses and the low transmit power of the tag.

To increase the range, more output power or sophisticated coding must be added to the tag; however, there is not enough room in the tag housing for the additional electronics required by either of these options. The best option may be to deploy multiple, low-cost base-stations, similar to the prototype base-station, to achieve the desired coverage.

REFERENCES

[1] R. Vaughan and J.B. Anderson, "Channels, Propagation and Antennas for Mobile Communications", The Institution of Electrical Engineers, London, 2003

[2] J. D. Kraus and R. J. Marhefka, "Antennas for All Applications, Third Edition", McGraw Hill, New York, 2002

[3] Kassim O Olawale1, Royann J Petrell, David G Michelson and Andrew W Trites, "The dielectric properties of the cranial skin of five young captive Stellar sea lions (*Eumetopias jubatus*) and a similar number of young domestic pigs (*Sus scrofa*) and sheep (*Ovis aries*) between 0.1 and 10 GHz." *Physiological Measurement*, 26:626-637.

[4] "Propagation of Radiowaves", M. P. M. Hall, L. W. Barclay and M. T Hewitt, Editors, The Institute of Electrical Engineers, London, 1996