RF Tag Antenna Performance on Various Materials Using Radio Link Budgets

Joshua D. Griffin, *Student Member, IEEE*, Gregory D. Durgin, *Member, IEEE*, Andreas Haldi, and Bernard Kippelen, *Senior Member, IEEE*

***Abstract*—Passive radio frequency (RF) tags in the UHF and microwave bands have drawn considerable attention because of their great potential for use in many radio frequency identification (RFID) applications. However, more basic research is needed to increase the range and reliability of a passive RF tag's radio link, particularly when the RF tag is placed onto any lossy dielectric or metallic surface. This paper presents two new useful forms of the radio link budget that describe the power link of an RF tag system when the tag is attached to an object. These radio link budgets are dependent upon the *gain penalty*, a term which quantifies the reduction in RF tag antenna gain due to material attachment. A series of measurements, or *radio assay*, was used to measure the far-field gain pattern and gain penalty of several flexible 915 MHz antennas when attached to cardboard, pine plywood, acrylic, deionized water, ethylene glycol, ground beef, and an aluminum slab. It is shown that the gain penalty due to material attachment can result in more than 20 dB of excess loss in the backscatter communication link.**

***Index Terms*—Antenna gain patterns, antenna measurements, link budget, material properties, radio frequency identification (RFID), radio frequency (RF) tag.**

I. INTRODUCTION

PASSIVE modulated backscatter RF tags are transponders that communicate with an interrogator, or reader, using far-field electromagnetic waves. These tags operate in the UHF and microwave frequency bands and typically modulate the radiation scattered from the tag antenna using load modulation. Though the basic operating principles of backscatter RF tags can be traced to 1948 [1], only recently has the use of RF tags for radio frequency identification (RFID) found application in inventory management, access control, toll collection, animal tracking and a host of other applications [2]. Though RFID tag usage is expected to significantly increase in coming years, the high cost and poor performance of passive RFID tags have limited their implementation thus far. For their widespread use to become reality, much research is needed to lower the tag cost, decrease the tag footprint, and improve the tag performance and reliability.

RF tag performance is affected by many factors, including the electromagnetic properties of objects near or in contact with the tag antenna. Although little literature has been published on this topic, Foster and Burberry [3] have performed basic measurements of an antenna near several objects. Raumonen *et al.* [4] have studied a similar problem through simulation. Dobkin and Weigand [5] have also experimentally shown a decrease in the read range of several RF tags near a metal plate and a water filled container along with changes in the RF tag antenna input impedance near metal.

This paper presents new forms of the power and backscatter communication radio link budgets that allow the RF tag designer to quantify the effects of RF tag material attachment. An important term in these radio link budgets is the *gain penalty*, or the decrease in RF tag antenna gain from its free space value when attached to a material. Using a *radio assay*, or series of tests, the gain penalty and gain pattern of several flexible, 915 MHz folded dipole RF tag antennas are measured on materials with varying electromagnetic properties.

II. RADIO LINK BUDGETS

Equation (1) is the power radio link budget that describes the amount of power available to the RF tag for operation. It is a modification of the Friis transmission equation and assumes that the antennas have an impedance and polarization match

$$P_{\text{tag}} = P_{\text{reader-tx}} - L_{\text{sys}} + G_{\text{reader-tx}} + G_{\text{tag}} - \text{GP} - 20\log_{10}\left(\frac{4\pi}{\lambda}\right) - 20\log_{10}(d) \quad (1)$$

where

P_{tag} (dBm)	power at the RF tag antenna terminals;
$P_{\text{reader-tx}}$ (dBm)	power input to the reader transmit antenna;
L_{sys} (dB)	system losses in both the tag and reader;
$G_{\text{reader-tx}}$ (dBi)	gain of the reader transmit antenna;
G_{tag} (dBi)	RF tag antenna gain in free space;
GP (dB)	gain penalty due to material attachment;
$20\log_{10}(4\pi/\lambda)$	a loss dependent upon the free space wavelength, λ;
$20\log_{10}(d)$	free space path loss referenced to 1 m.

The backscatter communication radio link budget, a modification of the monostatic radar equation [6] shown in (2), describes the amount of modulated power that is scattered from the RF tag to the tag reader:

$$P_{\text{reader-rx}} = P_{\text{reader-tx}} - L_{\text{sys}} + G_{\text{reader-tx}} + G_{\text{reader-rx}} + 10\log_{10}\left(\frac{\sigma}{4\pi}\right) - 20\log_{10}\left(\frac{4\pi}{\lambda}\right) - 40\log_{10}(d) \quad (2)$$

Manuscript received January 26, 2006; revised February 28, 2006. This material is based upon work supported in part by the STC Program of the National Science Foundation (NSF) under Agreement Number DMR-0120967, the Center for Organic Photonics and Electronics (COPE), the Georgia Research Alliance (GRA), and the Georgia Tech Foundation.

J. D. Griffin and G. D. Durgin are with The Propagation Group, Georgia Institute of Technology, Atlanta, GA 30332 USA (e-mail: griffinj@ece.gatech.edu; durgin@ece.gatech.edu).

A. Haldi and B. Kippelen are with the Center for Organic Photonics and Electronics, the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA.

Digital Object Identifier 10.1109/LAWP.2006.874072

where

$P_{\mathrm{reader-rx}}$ (dBm)	power at the reader receive antenna;
$P_{\mathrm{reader-tx}}$ (dBm)	power input to the reader transmit antenna;
$G_{\mathrm{reader-tx}}$ (dBi)	the gain of the reader transmit antenna;
$G_{\mathrm{reader-rx}}$ (dBi)	the gain of the reader receive antenna;
σ	the radar cross section of the RF tag.

All other terms are defined in (1) and all antennas are assumed to have an impedance and polarization match. The radar cross section (RCS) of the RF tag is primarily due to scattering by the RF tag antenna and can be written as the sum of a structural mode and an antenna mode [6]. The scattered fields due to the structural mode are radiated by currents induced by the incident field on the surface of the antenna. The structural mode is not dependent upon the RF tag antenna load and therefore, power scattered due to this term is not modulated. The modulated scattered power, or modulated backscatter, is proportional to the antenna mode of the RCS and can be written (in the linear scale) as

$$\sigma_{\mathrm{antenna}} = \frac{G_{\mathrm{tag}}^2 \lambda^2 |\Gamma|^2}{4\pi} \tag{3}$$

where $\Gamma = (Z_{\mathrm{load}} - Z_{\mathrm{antenna}}^*)/(Z_{\mathrm{load}} + Z_{\mathrm{antenna}})$ where * denotes the complex conjugate. By neglecting the structural mode (which cannot be electrically modulated) and substituting $\sigma_{\mathrm{antenna}}$ into (2), the backscatter communication radio link budget (in the logarithmic scale) becomes

$$\begin{aligned} P_{\mathrm{reader-rx}} = {} & P_{\mathrm{reader-tx}} - L_{\mathrm{sys}} + G_{\mathrm{reader-tx}} \\ & + G_{\mathrm{reader-rx}} + 20\log_{10}|\Gamma| + 2G_{\mathrm{tag}} \\ & - 2\mathrm{GP} - 40\log_{10}\left(\frac{4\pi}{\lambda}\right) - 40\log_{10}(d) \end{aligned} \tag{4}$$

III. METHODS

A. The Radio Assay

A radio assay,[1] shown in Fig. 1, was used to measure the gain of several RF tag antennas attached to materials with varying electromagnetic properties. The gains were calculated using P_{avg}, the power received by the horn antenna (see Fig. 1) averaged over region one[2]

$$P_{\mathrm{avg}} \equiv \frac{1}{180} \sum_{k=-90^\circ}^{+90^\circ} P_{\mathrm{tag}}(\theta = k) \quad \text{(in the linear scale)}. \tag{5}$$

Using these measured gains, the gain penalty was calculated from the following definition:

$$\mathrm{GP(dB)} \equiv G_{\mathrm{tag,freespace}}(\mathrm{dBi}) - G_{\mathrm{tag,material}}(\mathrm{dBi}) \tag{6}$$

where $G_{\mathrm{tag,material}}$ and $G_{\mathrm{tag,freespace}}$ are the gains of the RF tag antenna with and without a material present, respectively.

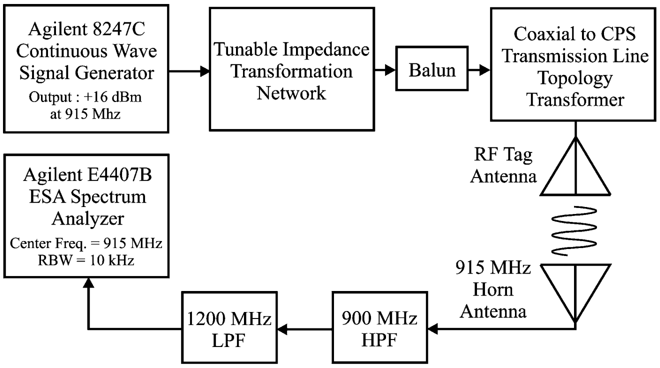


Fig. 1. The radio assay experimental setup for measurement of GP, the RF tag antenna gain penalty when attached to a material.

Since the impedance of an antenna varies when placed on a material, a tunable impedance transformation network, shown in Fig. 1, was used to achieve a conjugate match between the RF tag antenna and the 50 Ω coaxial feed line [7]. All other devices in Fig. 1 were impedance matched and the antennas were oriented for a polarization match. To ensure accurate measurements, the experimental setup was calibrated by removing the the antennas and measuring the losses in the transmitting and receiving portions of the system.

The quarter wave coaxial balun and coplanar strip (CPS) transmission line used to feed the RF tag antennas are shown in Fig. 2(a), [7]. Each RF tag antenna was connected to the CPS line using a clamp to press the antenna against the two conducting strips of the CPS line. Every effort was made to reduce coupling of the antenna to surrounding objects: the clamp fixture was made from unplated FR4 and nylon, the quarter wave coaxial balun was $\approx 0.03\lambda_o$ in diameter (where λ_o is the free-space wavelength at 915 MHz) and was oriented orthogonally to the plane of the pattern measurements, the metal box housing the tunable impedance transformation network was separated from the antenna by $\approx 1.25\lambda_o$, and the antennas and materials were suspended on a PVC mount as shown in Fig. 2(b).

B. RF Tag Antennas

The RF tag antennas tested in the radio assay were half-wave, planar folded dipoles, as shown in Fig. 3. Each RF tag antenna was designed for an estimated input impedance of 233 Ω at 915 MHz. Two of the RF tag antennas were made using an electroless silver and an electroless copper plating process on flexible, 25.4 μm thick polyethylene terephthalate (PET) substrates. The conductor thicknesses of these antennas were 202 ± 19 nm and 195 ± 17 nm while their ohmic losses (measured at dc) were 36 Ω and 49 Ω, respectively. Since these prototype antennas were very thin and lossy, a baseline antenna was also tested for comparison. The baseline antenna was milled on 1 oz. copper-clad FR4 and had negligible ohmic losses (measured at dc).

C. Radio Assay Materials

Seven materials, listed in Table I, were tested in the radio assay. These materials were chosen because they are commonly

---

[1] The term *assay* is borrowed from chemistry and refers to a series of tests applied to an unknown material to determine its properties. Hence, the radio assay is a series of tests to determine the unknown gain penalties resulting from material attachment.

[2] Region one and region two denote the half-spaces enclosing air and the material, respectively, as shown in Fig. 4(b)–(f)

TABLE I
MEASURED AVERAGE GAIN PENALTIES FOR 915 MHz HALF-WAVE FOLDED DIPOLE PLACED ON OBJECTS WITH VARYING ELECTRICAL PROPERTIES AND DIMENSIONS

	Cardboard Sheet	Acrylic Slab	Pine Plywood	De-ionized Water	Ethylene Glycol†	Ground Beef††	Aluminum Slab
Average Gain Penalty, AGP (dB)	0.9	1.1	4.7	5.8	7.6	10.2	10.4
Relative Permittivity*, ϵ_r	≈ 1**	2.6	1.7	77.3	33	50	-
Loss Tangent*, $\tan\delta$	≈ 0**	0.0061	0.036	0.048	0.4	0.7	-
L x W x H*** (cm)	31 x 65 x 4	15 x 61 x 3	30 x 57 x 3	22 x 10 x 10	22 x 10 x 10	11 x 22 x 1.0	46 x 58

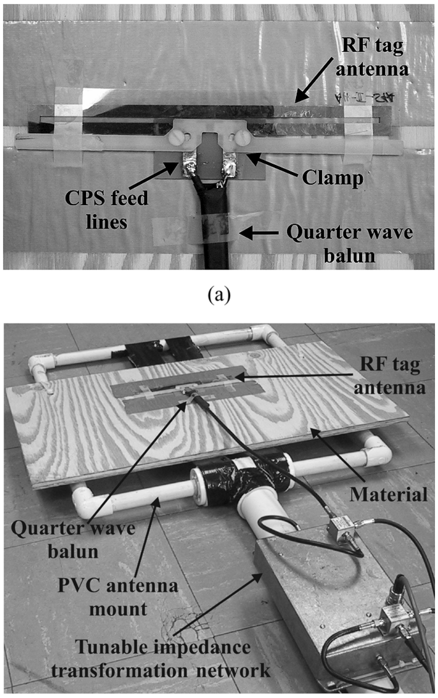
†Undiluted antifreeze containing at least 90% ethylene glycol

**Assumed to be approximately equal to free space.

††At approximately room temperature.

***L x W are the surface dimensions and H is the height/depth of the material

*These values were interpolated to 915 MHz from data of similar materials given by Von Hippel [8]



(a)

(b)

Fig. 2. (a) The feed of the silver RF tag antenna composed of a quarter wave balun, CPS transmission line, and clamp fixture. (b) The PVC antenna mount holding an RF tag antenna attached to pine plywood, the quarter wave balun and the tunable impedance transformation network.

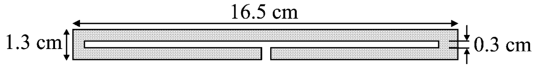


Fig. 3. A planar folded dipole RF tag antenna for use in the radio assay at 915 MHz. It has an estimated free space input impedance of 233 Ω.

used, are likely candidates for RF tag attachment, and provide a variety of complex permittivities and loss tangents. In each test, the block of material to which the RF tag antenna was attached was composed of several layers of the material. The dimensions in Table I are the approximate dimensions for each material block. The electromagnetic properties of these materials were estimated from the permittivity and loss tangent values of similar materials given by Von Hippel [8]. These estimates, given in Table I, were interpolated to 915 MHz from Von Hippel's data at 300 MHz and 3 GHz and are presented as "rules of thumb", recognizing that the actual material properties may vary slightly. The RF tag antennas were attached to each of these materials using thin adhesive tape. For the liquid materials, the antenna was attached to a waxed cardboard carton containing the liquid. Due to the CPS transmission line feed and the clamp fixture, the antennas were not able to lie perfectly flat against each material. However, since the distance that they were separated from the material or bent to touch the material was electromagnetically small $(\approx 1/50\lambda_o)$, this irregularity was neglected.

IV. RADIO ASSAY RESULTS

A. Gain Patterns

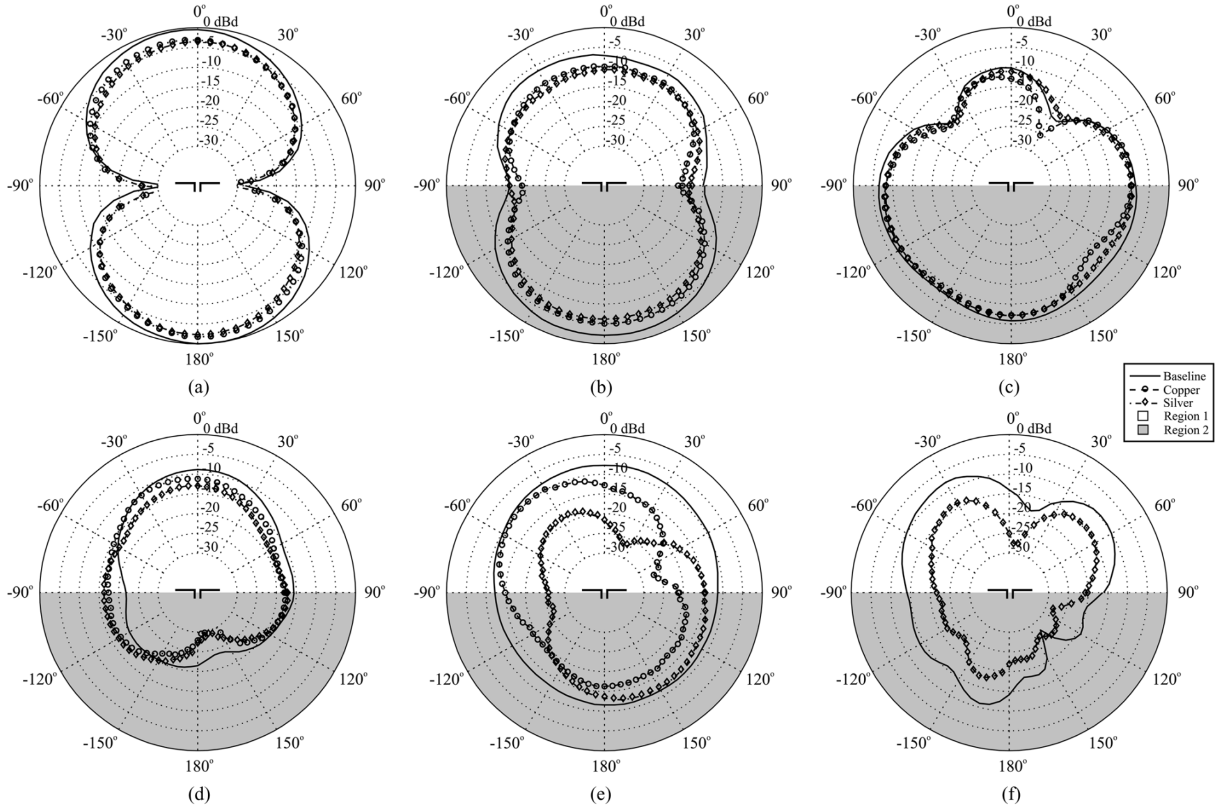
The free-space gain pattern measurements, shown in Fig. 4(a), closely resemble those of an ideal dipole: the patterns contain no spurious lobes or distortion and are free from the effects of multi-path fading. For each gain pattern test, the tunable impedance transformation network achieved a return loss greater than 46 dB and had an insertion loss of less than 2 dB. These parameters were measured to ensure a proper impedance match was reached. The gain patterns measured on the radio assay materials are shown in Fig. 4(b)–(f). The cardboard gain patterns (not shown) are almost identical to the free space patterns. The acrylic and pine plywood gain patterns both display a pattern that is slightly larger in region two than in region one. This pattern enlargement is attributed to an increase in the near field power coupled into the material due to its high permittivity relative to air [9]. The gain patterns measured on the aluminum slab[3], ethylene glycol, and ground beef all show a decrease in the nulls and are more omnidirectional. The de-ionized water patterns are unique, with three distinct lobes centered at 0° and pattern enlargement in region two. These gain pattern distortions cannot be attributed to a single phenomenon. The surface waves in the material, the diffraction around the material, the permittivity of the material, and the loss tangent of the material all have an effect.

B. Gain Penalties

Table I shows the average RF tag antenna gain penalty, AGP, calculated for each material. The AGP was found by averaging, in the linear scale, the GP values measured for each antenna on the particular material. As Table I shows, the AGP increases with the increasing loss tangent of each material. The individual GP measurements exhibit high precision for the dielectric materials with a small loss tangent (i.e., cardboard, acrylic, pine plywood, and deionized water), varying at most by 0.9 dB. However, for the highly conductive materials, the GP for each antenna varies by 2.1, 8.4, and 4.2 dB on ethylene glycol, ground

---

[3] The copper RF tag antenna was not tested on the aluminum slab.



(a) (b) (c)

(d) (e) (f)

Fig. 4. The measured E-plane gain patterns of each half-wave folded dipole in (a) free space, attached to (b) pine plywood, (c) de-ionized water, (d) ethylene glycol, (e) ground beef, and (f) aluminum sheet metal at 915 MHz. Each pattern was normalized to the maximum of the free space baseline gain pattern.

beef, and the aluminum slab, respectively. Although measurements indicate that an excellent impedance match was achieved, the impedance matching network may have reached its tuning limit on the highly conductive materials. In this case, the AGP values are pessimistic since mismatch losses would have been included with pattern and efficiency losses due to material attachment. In addition, the AGP values are dependent upon the dimensions of the material. Hence, the AGP values are intended for use as a "rule of thumb" to allow the RF tag designer to make educated decisions in the design of the RF tag system radio link. The AGP values presented in Table I, when substituted for GP in (1) and (4), show that the effects of material attachment can be significant. In the case of the aluminum slab with an AGP of 10.4 dB, material losses cause 20.8 dB of excess loss in the backscatter communication radio link budget.

V. SUMMARY

This paper presents two new forms of the radio link budget that allow the RF tag designer to quantify the reduction in RF tag antenna performance due to material attachment. A radio assay was used to measure the AGP and gain patterns of three 915 MHz, folded dipole RF tag antennas attached to seven different materials. The measured gain patterns show significant distortion due to the permittivity and loss tangent of the material, surface waves, and diffraction. The measured AGP increases with the increasing loss tangent of the material from 0.9 dB on cardboard to 10.4 dB on the aluminum slab. It is shown that the gain penalty due to the aluminum slab can cause more than 20 dB of excess loss in the backscatter communication link.

ACKNOWLEDGMENT

The authors would like to thank Y. Lu, J. Prothro, and C. Durkin for their assistance in this research.

REFERENCES

[1] H. Stockman, "Communication by means of reflected power," *Proc. IRE*, vol. 36, pp. 1196–1204, 1948.

[2] *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification*, 2nd ed., John Wiley and Son Ltd., New York, NY, 2003. K. Finkenzeller.

[3] P. R. Foster and R. A. Burberry, "Antenna problems in RFID systems," *IEE Colloq. RFID Technol.*, pp. 31–35, 1999.

[4] P. Raumonen *et al.*, "Folded dipole antenna near metal plate," in *Proc. IEEE Antennas Propagat. Soc. Int. Symp.*, vol. 1, 2003, pp. 848–851.

[5] D. M. Dobkin and S. M. Weigand, "Environmental effects on RFID tag antennas," in *Proc. IEEE Int. Microw. Symp.*, Jun. 2005.

[6] *Radar Cross Section Handbook*, vol. 1–2, Plenum, New York, 1970. G. T. Ruck .

[7] J. D. Griffin, "A Radio Assay for the Study of Radio Frequency Tag Antenna Performance," Master's Thesis, Georgia Institute of Technology, Atlanta, 2005.

[8] A. R. V. Hippel, *Dielectric Materials and Applications*. New York: Wiley, 1954.

[9] G. S. Smith, "Directive properties of antennas for transmission into a material half-space," *IEEE Trans. Antennas Propagat.*, vol. AP-32, pp. 232–246, 1984.