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RF Magnetic Field Coupling Analysis

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Prepared by
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Abstract

This letter addresses the radiation from a loop antenna especially RuBee LW RFID technology coupling to systems that may have sensitive EEDs that may be as low as *45 mW* no-fire device. The magnetic field coupling from a RuBee loop antenna to an exaggerated area of a shorted lead loop that an idealized unshielded wire configuration is shown to be negligible. Hazard from use of a lithium coin battery in RuBee tag is also addressed.

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subject: RF Magnetic Field Coupling Analysis

INTRODUCTION

In the original discussion of V-curve [1], Paul Mohrbach, et al. discussed a shorted wire lead type that is essentially a loop antenna responding to the magnetic field. Therefore, V-curve is equally valid for electric field or magnetic field coupling configurations. The important condition is that the loop is small and either the magnetic field or the electric field is uniform on the antenna.

The analysis in this memo directly relates to the RuBee LW RFID technology [2]. There have been many discussions on how to perform electromagnetic radiation evaluation on the loop antenna coupling to weapons [3], [4]. Reference 3 took the lead to address the issue: The magnetic field coupling to the connecting lead was identified as the loop antenna that couples to an EED. Only difference between [1] and [3] is that, in [3], the key step of obtaining antenna effective area is not pursued (Appendix 1). Reference [4] essentially re-derived the result in [1].

It is the purpose of this letter to address the special problem introduced by electromagnetic fields generated by a transmitting loop antenna at such low frequencies that the field varies significantly on the connecting lead to a system. Note that the RuBee RFID system (Appendix 2) operates at 131 kHz.
Because, at such a low frequency, the loop antenna generates 99.99% of its energy in the magnetic field, the magnetic field from the transmitting loop antenna determine what is coupled to the weapon circuit and eventually to the EED.

ELECTRIC AND MAGNETIC FIELDS FROM A LOOP ANTENNA

Traditionally, the loop antenna with a constant circulating current is treated as a magnetic dipole. Most EM textbooks gave derivation of fields from a magnetic dipole by using the Hertz Vectors or Polarization Potentials [5]. Reference [6] obtained far fields from a loop antenna using a simplified derivation. We give the fields of a magnetic dipole by following a simple methodology♠ used in [6].
The electric and magnetic fields of a magnetic dipole can be derived using a magnetic scalar potential ψ and an electric vector potential $\underline{F}$

$$\underline{E} = -\frac{1}{\varepsilon}\nabla \times \underline{F} \qquad (1)$$

$$\underline{H} = -\nabla\psi - j\omega\underline{F}. \tag{2}$$

On the other hand, the electromagnetic fields of an electric dipole can be derived using an electric scalar potential V and a magnetic vector potential $\underline{A}$:

$$\underline{E} = -\nabla V - j\omega\underline{A} \tag{3}$$

$$\underline{H} = -\frac{1}{\mu}\nabla \times \underline{A} \tag{4}$$

Note that Maxwell's equations with both electric and magnetic sources can be written as:

$$\nabla \times \underline{E} + j\omega\mu\underline{H} = -\underline{J_m} \qquad \nabla \cdot \underline{H} = \frac{\rho_m}{\mu} \tag{5}$$

$$\nabla \times \underline{H} - j\omega\varepsilon\underline{E} = \underline{J} \qquad \nabla \cdot \underline{E} = \frac{\rho}{\varepsilon} \tag{6}$$

Currents and charges of both types are related by continuity equations:

$$\nabla \cdot \underline{J} + j\omega\rho = 0, \quad \nabla \cdot \underline{J_m} + j\omega\rho_m = 0 \tag{7}$$

Imposing the Lorentz conditions:

$$\nabla \cdot \underline{F} + j\omega\mu\varepsilon\psi = 0, \quad \nabla \cdot \underline{A} + j\omega\mu\varepsilon V = 0$$

the governing equations for scalar and vector potentials can be given as:

$$\nabla^2\underline{F} + k^2\underline{F} = -\varepsilon\underline{J_m}, \quad \nabla^2\psi + k^2\psi = -\frac{\rho_m}{\mu} \tag{9}$$

$$\nabla^2\underline{A} + k^2\underline{A} = -\mu\underline{J}, \quad \nabla^2 V + k^2 V = -\frac{\rho}{\varepsilon} \tag{10}$$

The analogy between the electric dipole field and magnetic dipole field can be drawn [6]: The magnetic dipole moment is $q_m l$ which is the pole strength of the fictitious magnetic current I_m. Since the time rate of increase in q_m must equal the magnitude of the magnetic current flowing toward it (7), the magnetic current is related to the magnetic charge by:

$$q_m = \frac{I_m}{j\omega} \tag{11}$$

and the magnetic moment of the loop is given by:

$$m = IA = \frac{q_m \ell}{\mu} = \frac{I_m \ell}{j\omega\mu} \tag{12}$$

♠ Equations 11 and 12 given below differ from their corresponding equations given in [6]. [6] has μ in an equation corresponding to (11). A corresponding equation to (12) in [6] does not include a factor of μ between magnetic dipole moment defined by current loop and magnetic charge.

where I is the electric current circulating the loop and A is the loop area. As noted by Sommerfeld [5] that the dipole moment defined with magnetic charges differs from the current loop by a factor μ [7].

Choosing the magnetic dipole along the z-direction, the electric vector potential can be written as

$$\underline{F} = \underline{k}F_z \approx \underline{k}\frac{\varepsilon}{4\pi}e^{j\omega\left(t-\frac{r}{c}\right)}\int_{-\frac{\ell}{2}}^{\frac{\ell}{2}}\frac{I_m}{r}dz = \underline{k}\frac{j\omega\varepsilon q_m\ell}{4\pi r}e^{j\omega\left(t-\frac{r}{c}\right)} = \underline{k}\frac{j\omega\mu\varepsilon IA}{4\pi r}e^{j\omega\left(t-\frac{r}{c}\right)} \quad (13)$$

$$F_r = F_z cos\theta, \quad F_\theta = -F_z sin\theta \quad (14)$$

The magnetic scalar potential can also be derived as

$$\psi = -\frac{1}{j\omega\mu\varepsilon}\nabla\cdot\underline{F} = j\omega\frac{IAcos\theta e^{j\omega\left(t-\frac{r}{c}\right)}}{4\pi c}\left(\frac{1}{r}+\frac{c}{j\omega r^2}\right) \quad (15)$$

and

$$H_r = \frac{IAcos\theta e^{j\omega\left(t-\frac{r}{c}\right)}}{2\pi}\left(\frac{j\omega}{cr^2}+\frac{1}{r^3}\right) \quad (16)$$

$$H_\theta = \frac{IAsin\theta e^{j\omega\left(t-\frac{r}{c}\right)}}{4\pi}\left(-\frac{\omega^2}{c^2r}+\frac{j\omega}{cr^2}+\frac{1}{r^3}\right) \quad (17)$$

$$E_\emptyset = \frac{j\omega\mu IAsin\theta e^{j\omega\left(t-\frac{r}{c}\right)}}{4\pi}\left(\frac{j\omega}{cr}+\frac{1}{r^2}\right) \quad (18)$$

MAGNETIC FIELD FROM RUBEE PORTAL'S LOOP ANTENNA

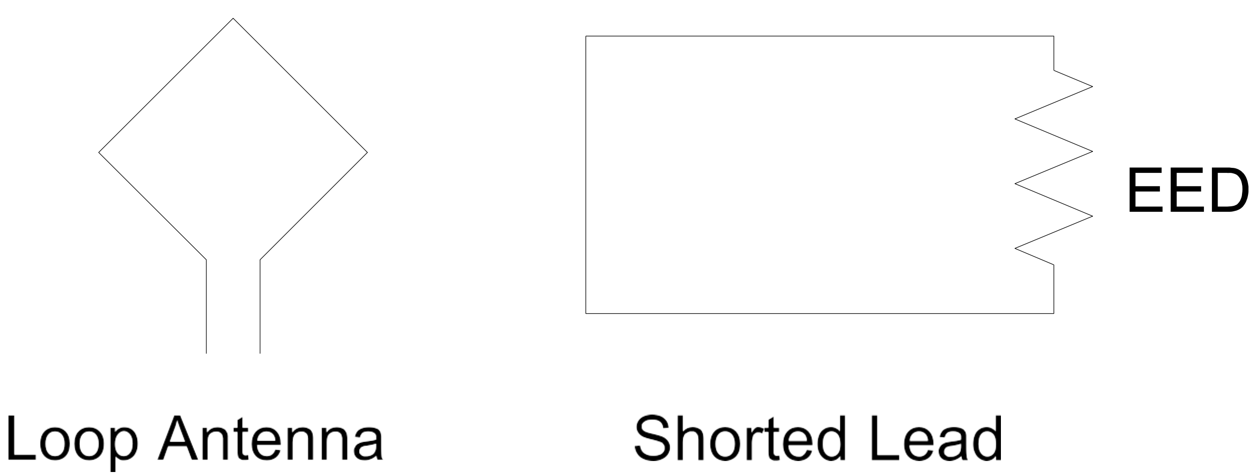


Figure 1. A Hypothetical Configuration of RuBee Loop Antenna Coupling to an EED through a Shorted Lead.

Figure 1 depicts a worst-case coupling configuration that the portal transmitting loop is lying on the plane as the shorted lead loop. Note that the θ component of the magnetic field from a loop antenna derived previously is a maximum when $\theta = 90°$ (i.e. when the magnetic field is perpendicular to the loop. Also, the radial component does not contribute to the coupling because (1) no flux links to the shorted lead loop and (2) the field has a null when $\theta = 90°$.

Since the detailed source parameters are not available, the following analysis makes use of the RuBee specification (Appendix 2): Note that the relative magnitude of the three contributing terms to the θ component of the magnetic field can be numerically evaluated:

$$\frac{\omega}{c} = \frac{2\pi f}{c} = \frac{2\pi \times 131000}{3\times 10^8} \approx 2.74 \times 10^{-3}\ m^{-1} \tag{19}$$

The terms inside the parenthesis of the θ component of the magnetic field can be given as:

$$-\frac{7.5\times 10^{-6}}{r} + \frac{j2.74\times 10^{-3}}{r^2} + \frac{1}{r^3} \tag{20}$$

At a distance of up to 30 ft, only the last term is needed in the numerical calculation.

The magnetic field value at *10 ft* (Appendix 2) is exclusively used to derive an approximate fit function (in MKS units):

$$H \approx \frac{5.66}{r^3} A / m\ .$$

The derived formula is consistent with the single-digit value given for the magnetic field at 20 ft. The 0 ft value is irrelevant for our analysis.

An exaggerated area of the shorted lead loop is assumed to have a lead separation of *a=2 cm* [3] and is assumed to be extended to infinity for convenience. The coupling to actual wire bundle configuration is considerably less than assumed because (1) wires in the bundle might be twisted and (2) a significant portion of the incident magnetic field is cancelled by the reflected wave from the floor in order to satisfy the vanishing normal magnetic field on the floor. The nearest point of the shorted lead is assumed to be *10 ft*. The voltage induced on the shorted lead loop is

$$V = -\oint \frac{\partial B}{\partial t} \cdot ds = -j\omega\mu a \int_{3.048}^{\infty} \frac{5.66}{r^3} dr = \left.\frac{j2.83\omega\mu a}{r^2}\right|_{3.048} = j0.3048 \times 2\pi \times 131000 \times 12.56 \times 10^{-7} \times 0.02\ V \tag{21}$$

The induced voltage is approximately *6.3 millivolts*. When this voltage is applied to *4.5Ω* (a *100 mA, 45 mW* no-fire EED), the current is only *1.4 mA*. There is no safety concern for the EEDs in a system.

SAFETY CONCERN FROM RUBEE TAG BATTERY

Another safety concern is that the coin battery in RuBee tag battery somehow could short to an EED. Here the short-circuit current can be estimated from the Panasonic CR2016 specification sheet (Appendix 3):

For voltage vs. load resistance curves given in the spec sheet, the internal resistance for the battery at *60°C* is *71.5 ohms* (*2.8V* with *1 k*Ω load), resulting in a short circuit-current of *42 mA*; at *20*°C the internal resistance is *120 ohms* (*2.68V* with *1 k*Ω), resulting in a short-circuit current of *25 mA*.

CONCLUSIONS

A simple analysis for treating RF coupling from a low frequency loop antenna is discussed. The derived formulas are applied to the RuBee portal loop antenna coupling to a worst-case shorted lead configuration at a distance of 10 ft from the loop antenna. The worst-case coupling current is found to be safe. A further analysis based on the internal resistance of the RuBee tag battery give its short-circuit current of no more than 42 mA. Neither the magnetic field from the RuBee portal nor the short-circuit current of the RuBee Tag battery poses any safety concern for EEDs in a system.

APPENDIX 1 A BRIEF DERIVATION OF V-CURVE BASED ON MAGNETIC FIELD COUPLING

Starting from the first equation for the induced voltage V_L on a loop, the power received by the matched EED load can be written as [6]

$$P_{eed} = \frac{V_L^2}{4R_{rad}}$$

where R_{rad} and V_L are the radiation resistance of and the induced voltage on the loop:

$$R_{rad} = \frac{\eta}{6\pi}\left(\frac{2\pi}{\lambda}\right)^4 A^2$$

and

$$V_L = 2\pi f A \mu H$$

The effective area of a small loop is the same as a short dipole [6]

$$A_{eff} = \frac{3}{8\pi}\lambda^2$$

The power density is

$$P_d = \eta H^2$$

Therefore,

$$P_{eed} = P_d A_{eff}$$

APPENDIX 2 RUBEE DOE PORTAL SPECIFICATION

Table 1. RuBee DOE Portal V20 Electromagnetic Power Specification.

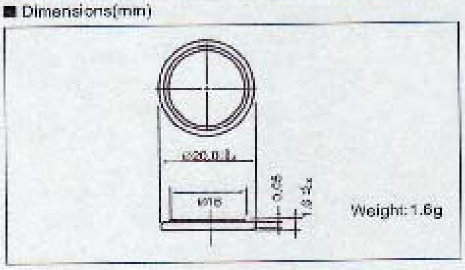
Spec.	Value	Units	Value		Units
1		Communication frequency	131	kHz	
2		3dB bandwidth at 10ft	5	Khz	
3		30dB bandwidth at 10ft	20	kHz	
4		Data Protocol		IEEE P1902.1	
5		Maximum RF peak power (far field)	1.E-08	Watts	
6			Maximum RF TX magnetic field strength amplitude:		
7	0 ft	50	A/m	628	mGauss
8	10 ft	0.2	A/m	2.5	mGauss
9	20 ft	0.03	A/m	0.37	mGauss
10		40 ft		***Not Detectable***	
11		Power Consumption	100	Watts	
12		Infrared motion sensor (portal wake up sensor) range	2-10	Feet	
RuBee Tag Electromagnetic Power Specification.					
13		Communication frequency	131	kHz	
14		3 dB bandwidth	20	kHz	
15		Data Protocol		IEEE P1902.1	
16		Maximum RF peak power (far field)	1E-18	Watts	
17			Maximum RF TX magnetic field strength amplitude:		
18	0 ft	1.1	A/m	14	mGauss
19	10 ft	0.00015	A/m	0.0019	mGauss
20		20 ft		***Not Detectable***	
21		40 ft		***Not Detectable***	
22	The RF magnetic minimum field response sensitivity	0.12	A/m	1.5	mGauss
23		Tag battery CR 2016 Panasonic	90	mAh	
24		Normal Voltage	3	Volts	
25		Minimum Voltage	2	Volts	
26		No Read Tag Life	4	Years	
27		Number of Possible Reads	500,000.00	Reads	
28		Tag microcontroller		EPSON SIC60A08	

APPENDIX 3 RUBEE TAG SPECIFICATION SHEETS

Manganese Dioxide Lithium Coin Batteries: Individual Specifications

CR2016

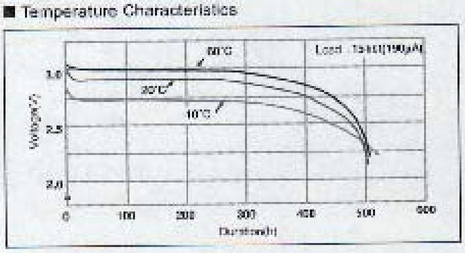
■ Dimensions(mm)



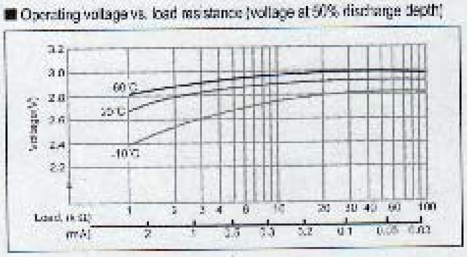
■ Specification

Nominal voltage (V)	3
Nominal capacity (mAh)	90
Continuous standard load (mA)	0.1
Operating temperature (C)	-30 ~ +60

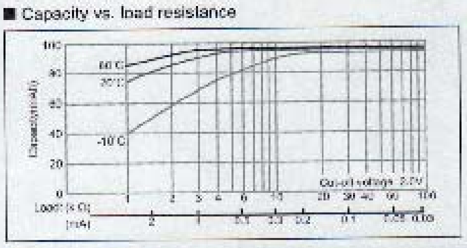
■ Temperature Characteristics



■ Operating voltage vs. load resistance (voltage at 50% discharge depth)

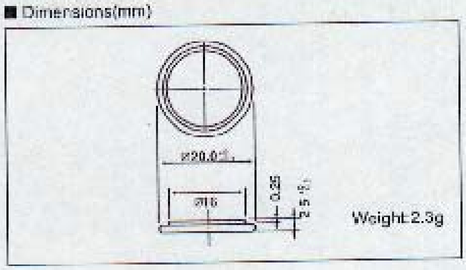


■ Capacity vs. load resistance



CR2025

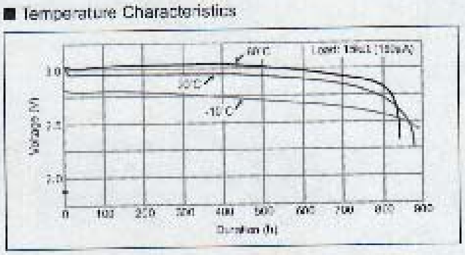
■ Dimensions(mm)



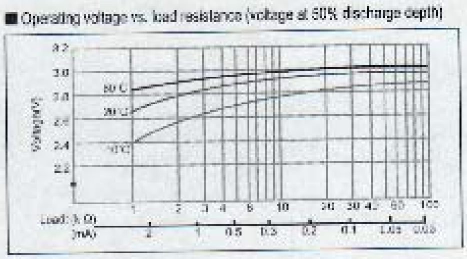
■ Specification

Nominal voltage (V)	3
Nominal capacity (mAh)	165
Continuous standard load (mA)	0.2
Operating temperature (C)	-30 ~ +60

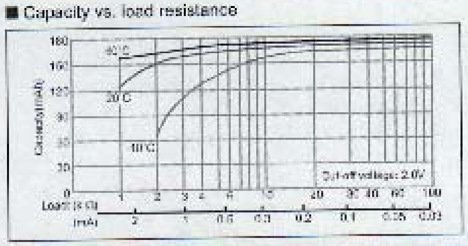
■ Temperature Characteristics



■ Operating voltage vs. load resistance (voltage at 50% discharge depth)



■ Capacity vs. load resistance



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