Analysis of a Simple RFID System Design

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The history and basic architecture of simple Radio Frequency Identification (RFID) systems are discussed. We describe various constraints on designs imposed by governmental regulation and by requirements of users. We review the theoretical basis of inductively coupled RFID antenna operation and calculate the expected performance of a simple antenna design. We discuss how varying antenna parameters can affect overall system design.

Introduction

The idea behind Radio Frequency Identification (RFID) systems can be traced to a military technology that appeared during World War II known as Identification Friend or Foe (IFF). These military systems used coded radar signals from an interrogator to send a challenge message that triggered a transponder in an aircraft to reply with a code that identified them as friendly. This same idea is used in RFID systems today – an RFID transponder is queried by an interrogator device (called a reader), and the transponder responds with some form of data specific to its application.

There are two broad classifications of RFID based on the transponder power strategy: active and passive. Active RFID transponders require an attached power source and are typically used for longer range applications such as electronic toll collection. Passive RFID transponders use the power from the incoming reader signal to provide the energy required to power the devices.

The list of applications of RFID systems is impressive, ranging from the implantable "microchips" used to identify your pets to so-called 1-bit RFID transponders that are used as security devices in stores. The physical mechanisms used to implement RFID systems are almost equally varied. If you can imagine a physical process that can communicate information over space, there is probably an RFID system that exploits that process.

Regulatory Constraints on RFID Designs

Some of the most important constraints on the design of RFID systems are regulatory in nature. Since most RFID devices emit radio frequency signals they are classified as radio devices. The functioning of other radio services must not be disrupted by RFID systems so the range of available and suitable operating frequencies is severely limited by regulation.

In practice this generally means that the frequencies from 9-135 KHz are available, as are the worldwide Industrial-Scientific-Medical (ISM) frequency ranges. Among the other users of the ISM frequencies are remote control systems, pagers, Citizen's Band and Amateur (HAM) radio, and motion detectors.[1]

In addition to frequency band constraints, the permissible transmission power and/or field strengths in the main carrier and sidebands are regulated as well. Historically, the frequency band below 135 KHz is attractive for RFID operation because it is permissible to work with high magnetic field strengths in that range, which is critical to passive RFID operation.

Basic Operation of Inductively Coupled RFID Systems

By far, the most popular RFID systems are inductively coupled low-frequency (LF) systems. There are two broad classifications within this category: the so-called 1-bit systems; and multi-bit systems. The transponders used in 1-bit systems do not use an electronic "chip" and can be made for a fraction of a cent. More sophisticated multi-bit systems do use on-board logic and have memory capacities measured in kilobytes.

1-Bit Systems

The simplest form of RFID system is the inductively coupled 1-bit system. This system has only two states, typically called "transponder in interrogation zone" and "no transponder in interrogation zone." Although seemingly limited, these systems are very widespread, used as anti-theft devices and referred to collectively as Electronic Article Surveillance (EAS) systems.

An EAS system is composed of an interrogator unit (typically called the reader), a security element/transponder (referred to colloquially as an RFID tag) and a deactivation device. The reader unit generates an alternating magnetic field in the LF radio frequency range. The coil used to generate and sense the magnetic field (the generating coil) is usually found in frame-like structures one finds in the doorways of stores (see figure seven). Optionally a separate sensor coil may be used to detect the changes in the magnetic field due to the transponder.

When an RFID transponder is moved into the vicinity of the reader magnetic field, a voltage is induced in a coil built into the transponder. The field generated by the inductor in this circuit acts in opposition to the generating field which causes a drop in the overall strength of the magnetic field. This drop in field strength is detected by the reader. Since this signal can be quite small, the generator frequency is often swept between two cutoff frequencies around the resonant frequency of the tag to make detection of this effect easier.

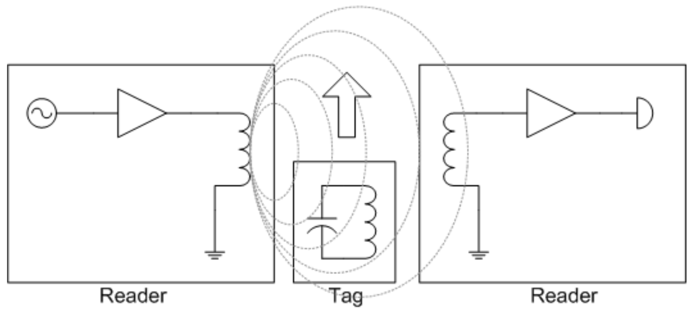

FIG 1: Basic architecture of a 1-Bit RFID system. The reader detects the presence of the RFID tag in the magnetic field generated by the generating coil in the reader. The sensor coil may actually be the generating coil itself.

Figure one shows the electrical configuration of such a 1-Bit system. The reader generates a magnetic field into which the RFID transponder (tag) at the center moves (presumably as an article is carried through the system). The presence of the coil in the tag results in a mutual inductance coupling between the generating coil and the tag coil. This mutual inductance reduces the overall field strength which can be detected by a sensor coil. Alternatively the mutual inductance results in a voltage drop in the generator coil which can also be detected.If the presence of an RFID tag is detected an alarm is sounded.

RFID tags can be deactivated by passing them through a very high intensity magnetic field which induces a voltage that destroys the transponder device.

Multi-Bit RFID Systems

Often there is a need for the RFID transponder to return some form of information when it is interrogated. For example, the RFID transponder used in animal identification returns a six byte code uniquely identifying the animal when it is interrogated. In these cases there is a need for on-board electronics to store and return the data, and therefore a need to power the devices on the tag. So-called active RFID tags include a battery for this purpose. Passive RFID systems use the voltage induced in the transponder antenna coil to power the electronics. The architecture of such a system is shown in figure two.

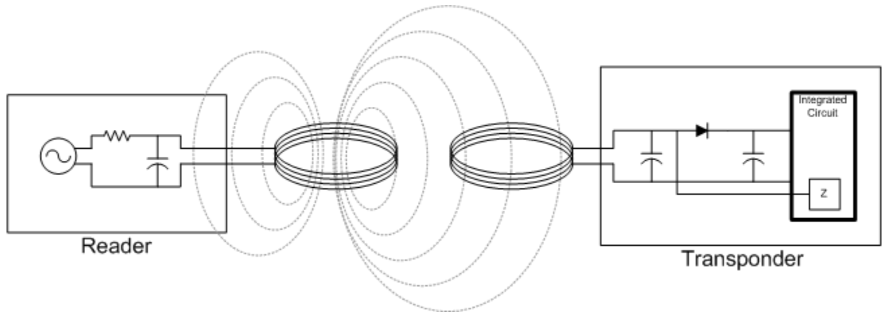

FIG 2: Passive RFID tags use power derived from the reader antenna signal to power onboard logic. The integrated circuit detunes the resonant circuit in order to modulate the signal coupled back to the reader.

The magnetic field generated by the reader is coupled to an LC resonant circuit in the transponder where the resulting signal is rectified and used to charge a capacitor. This capacitor is used as an energy storage device. When the voltage on the capacitor reaches a predefined value, the integrated circuit (IC) turns on and data stored in the IC is returned to the reader. The data communication is accomplished by varying the impedance of the resonant circuit by switching a parallel load in and out (see the component labeled "Z" in figure two). This technique is called load modulation and results in amplitude changes which are detectable at the reader generating coil.

RFID Antenna Physics

As described above, the interaction between the magnetic field of the transponder and that of the reader is used to communicate information from the transponder back to the reader. This means that a system of this type cannot use electromagnetic radiation to communicate with the transponder.

Consider the formation of electromagnetic waves by an antenna. At a distance of $\lambda/2$ EM waves begin to detach from the antenna and propagate into space. Once the wave has detached from the antenna it can no longer interact with the antenna via inductive coupling. The area of interest in RFID antenna design is therefore the near field of the antenna where $r << \lambda$. In RFID systems, the maximum range over which a transponder can successfully communicate with a reader is called the read range. In the case of a magnetic field oscillating at 135 KHz a typical read range of roughly 1 meter in EAS systems is certainly much less than the wavelength of over 2 kilometers.

It can be shown that the vector potential of a localized oscillating source with sinusoidal time dependence is given by

$$\vec{A}(\vec{x}) = \frac{\mu_0}{4\pi} \int \vec{J}(\vec{x}) \frac{e^{ik|\vec{x}-\vec{x}'|}}{|\vec{x}-\vec{x}'|} d^3x' \qquad (1)$$

In the case of near zone, $r << \lambda$ (or $kr \ll 1$) the exponential in (1) can be taken as unity. In this case, the vector potential is quasi-stationary[2] and is given by

$$\vec{A}(\vec{x}) = \frac{\mu_0}{4\pi}\int \frac{\vec{J}(\vec{x})}{|\vec{x}-\vec{x}'|} d^3x' \tag{2}$$

Assume that the generating antenna of the reader is a single current loop of radius a lying in the x-y axis, as shown in figure three.

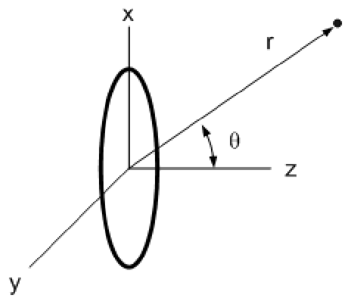

FIG 3: Configuration of a single current loop used as a reader generating antenna. In an EAS system the z direction would be parallel to the floor pointing across the doorway at "package carrying height" and the antenna loop would be mounted in a frame next to the doorway.

In this case the geometry is cylindrically symmetric and the vector potential can be written as,[3]

$$A_\phi = -\frac{\mu_0 I_0 e^{-i\omega t} a}{4\pi}\int_0^{2\pi} \frac{\cos\phi'}{\left(a^2 + r^2 - 2ar\sin\theta\cos\phi'\right)^{1/2}} d\phi' \tag{3}$$

For $\theta \ll 1$ an expansion of (3) in powers of $a^2 r^2 \sin^2\theta / \left(a^2 + r^2\right)^2$ leads to the following expressions for the components of the magnetic induction,

$$B_r = \frac{\mu_0 I_0 e^{-i\omega t} a^2 \cos\theta}{2\left(a^2 + r^2\right)^{3/2}}\left[1 + \frac{15a^2 r^2 \sin^2\theta}{4\left(a^2 + r^2\right)^2} + \cdots\right] \tag{4}$$

and

$$B_\theta = -\frac{\mu_0 I_0 e^{-i\omega t} a^2 \sin\theta}{4\left(a^2 + r^2\right)^{5/2}}\left[2a^2 - r^2 + \frac{15a^2 r^2 \sin^2\theta\left(4a^2 - 3r^2\right)}{8\left(a^2 + r^2\right)^2} + \cdots\right] \tag{5}$$

If the approximation is taken to lowest order, the harmonic oscillation is suppressed, and the field is considered along the z-axis, the formula for a circular current loop calculated using the law of Biot-Savart is recovered.

$$B_z = \frac{\mu_0 I a^2}{2\left(a^2 + r^2\right)^{3/2}} \tag{6}$$

This proves to be a reasonable approximation since, given the geometry of the application and the nature of the movement in the system, the RFID transponder will pass close to the z-axis and remain there for a relatively long period of time as a person walks through a detector transporting an article with an attached transponder.

Considering (6), it can be seen that there is an optimal radius *a* for a generating antenna given a desired read range *r*. Figure four shows a plot of the function $a^2 / \left(a^2 + r^2\right)^{3/2}$ with $r = 1$.

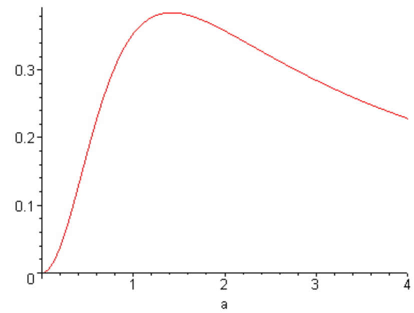

FIG 4: The strength of the magnetic induction at a given read range is influenced by the radius of the reader generating antenna. There is an optimum radius of reader generating antenna for a given range.

The maximum can be calculated by differentiating the term in (6) involving *r* and *a* with respect to *a* and solving the resulting expression for zero.

$$\frac{\partial}{\partial a} B_z \propto \frac{2a}{\left(a^2 + r^2\right)^{3/2}} - \frac{3a^3}{\left(a^2 + r^2\right)^{5/2}} = 0 \Rightarrow a = \pm\sqrt{2} r \tag{7}$$

Therefore the optimal radius for a reader generating coil is approximately 1.4*r* where *r* is the read range of an EAS system.

In an inductively coupled RFID system, the magnetic induction produced by the reader generating coil must be coupled to the transponder antenna, and the presence of the transponder coil must be communicated back to the reader. Mutual inductance is the physical process that is used to enable this communication. This can be easily understood if one considers the reader generating coil as the primary and the transponder antenna coil as the secondary of a transformer as illustrated in figure five.

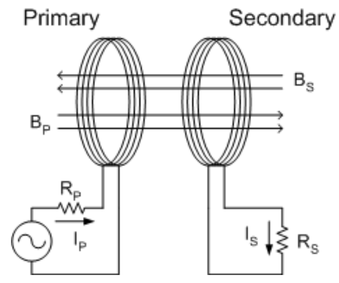

FIG 5. The generating coil of an RFID reader can be understood as the primary winding of a transformer. Likewise the antenna coil of an RFID transponder can be viewed as the secondary.

Application of Kirchoff's voltage law to the primary and secondary circuits results in,

$$V_P = I_P R_P + L\frac{dI_P}{dt} - M\frac{dI_s}{dt} \tag{8}$$

$$M\frac{dI_P}{dt} = I_S R_S + L\frac{dI_S}{dt} \tag{9}$$

where *L* is the self-inductance of an antenna coil and *M* is the mutual inductance between the coils for the given geometry.

In the equation for the primary circuit (8) the negative mutual inductance term represents the load "felt" in the primary circuit due to the presence of the secondary circuit. It can then be easily seen that when a secondary circuit (an RFID transponder antenna coil) is brought within the magnetic field of a reader antenna, the voltage in the reader (primary) circuit will be reduced due to the mere physical presence of the secondary. This is the mechanism used by 1-bit RFID systems to determine the state "transponder in interrogation zone."

Notice that the mutual inductance term communicates changes in the current of the secondary circuit back to the primary via the presence of the derivative of the secondary current. This is the mechanism used by load modulation schemes to communicate data back to the reader – typically a load is switched in and out of the secondary circuit thereby changing its impedance and communicating a signal back to the primary.

The equation for the secondary circuit (9) shows that the mutual inductance term acts as a voltage source. In a passive RFID transponder, the current induced in the secondary circuit is used to charge a capacitor that is used as the energy source for the integrated circuit that performs the load modulation.

Faraday's law in integral form states,

$$\mathcal{E} = \oint \vec{E} \bullet d\vec{l} = -\frac{d}{dt}\int \vec{B} \bullet d\vec{S} \tag{10}$$

If (6) is substituted into (10) and evaluated along the z-axis, it is easy to see that the voltage induced by a reader coil of radius *a* with N_1 windings on a circular tag antenna of radius *b* with N_2 windings is given by,

$$\mathcal{E} = -\frac{d}{dt}\frac{\mu_0 I_1 N_1 a^2 N_2 \pi b^2}{2\left(a^2 + r^2\right)^{3/2}} = -\frac{\mu_0 N_1 a^2 N_2 \pi b^2}{2\left(a^2 + r^2\right)^{3/2}}\frac{dI_1}{dt} = -M\frac{dI_1}{dt} \tag{11}$$

The coefficient of the derivative in (11) is taken as the mutual inductance, *M*, of this geometrical configuration.

In practice, the generator antenna coil and the transponder antenna coil are components of resonant circuits. Therefore the frequency, self-inductance and capacitance of the components composing the primary and secondary circuits must respect the resonance condition,

$$\omega = \frac{1}{\sqrt{LC}} \tag{12}$$

This provides a significant improvement in the efficiency of the transponder circuit as will be seen below.

There is a great deal of freedom in the generator antenna coil design since the form factor for this coil must be quite large due to (7). The primary constraints on the bulk of the reader are going to be based on design (in the sense of fashioning artistically). A typical design is shown in figure six.

FIG 6. Reader generating and sensing antennas for EAS systems are optimally of quite large size. This reader system is scaled to cover a doorway of roughly one meter in width. Since the reader is large, and there is one per-system, there is a great deal of design freedom with respect to the components, size, weight and cost.

Because of the many degrees of design freedom in the reader, the effort put into the design of RFID systems is predominantly spent on the design of the transponders where there are considerable cost, size, material, durability, and usability constraints.

Two of the most commonly seen form factors for RFID transponders are called smart cards and smart labels. The antenna designs for these devices range from small circular copper screened coils of radius 9mm (figure seven left) to those used in the smart labels of hospital identification bracelets (figure seven center), to the RFID tags used in smart cards (figure seven right).

FIG 7. Transponder antennas are of small size and have stringent manufacturability and cost constraints. Typically the conductors are screen printed onto a flexible substrate.

Analysis of a Prototypical RFID Transponder Antenna

A very common design for an RFID transponder antenna is seen in figure seven (right). The coil on this device is called a rectangular planar spiral inductor. A simplified version is shown schematically in figure eight.

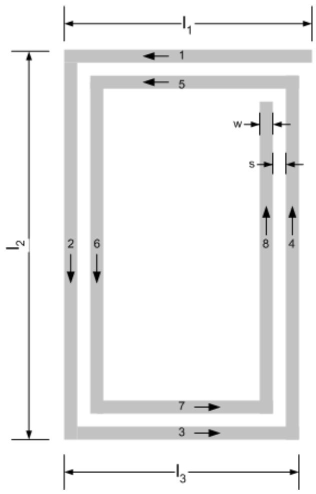

FIG 8. A schematic representation of a rectangular planar spiral inductor of two loops. It is composed of eight straight conductor segments that are typically printed onto a flexible backing.

The inductor is composed of eight straight conductor segments labeled with indices $1,2\cdots8$. Each straight conductor segment has an associated length $l_1, l_2 \cdots l_8$ and there is a segment width W, a segment spacing S, and a segment thickness t. Each conductor segment is shown with a relative current flowing in the direction of the arrow.

The usual method used for calculating the inductance of an inductor such as the prototypical planar spiral is due to Greenhouse and Grover.[4] The Greenhouse method states that the overall inductance of a geometric configuration of conductors can be found by summing the self-inductance of each wire segment along with the positive and negative mutual inductance contributions of each possible wire pair. Wires that are orthogonal in orientation have negligable mutual inductance. The direction of current flow in a wire segment determines the sign of the coupling – the sign is positive if current flow in two segments is in the same direction.

Calculating the inductance of the simple two-turn spiral inductor illustrated above involves eight self-inductance terms,

$$L_{self} = \sum_{i=1}^{8} L_i \tag{13}$$

eight positive mutual inductance terms,

$$M_+ = M_{15} + M_{51} + M_{26} + M_{62} + M_{37} + M_{73} + M_{48} + M_{84} \tag{14}$$

and sixteen negative mutual inductance terms

$$\begin{aligned} M_- = & -M_{17} - M_{13} - M_{57} - M_{53} - M_{28} - M_{24} - M_{68} - M_{64} \\ & -M_{71} - M_{75} - M_{31} - M_{35} - M_{82} - M_{86} - M_{42} - M_{46} \end{aligned} \tag{15}$$

Inductance of current carrying elements can be estimated by considering magnetic energy.[5] Given the relation between self-inductance and magnetic energy,

$$L = \frac{1}{I^2} \int \frac{\vec{B} \bullet \vec{B}}{\mu} d^3x \tag{16}$$

it can be shown that an estimate of the magnetic induction can provide an estimate of the self-inductance of a circuit element. For a wire of radius *a* the form of the self-inductance is on the order of

$$\frac{dL}{dl} = \frac{\mu_0}{4\pi}\left(\ln\left(\frac{\rho_{\max}^2}{a^2} \right) + \frac{1}{2} \right) \quad (17)$$

Applying this approach to straight thin film circuit elements of length *l*, width *w* and thickness *t* measured in cm results in the formula,[6]

$$L = .002l\left(\ln\left(\frac{2l}{w+t} \right) + 0.50049 + \frac{w+t}{3l} \right) uH \quad (18)$$

Using $w = 3mm, s = 3mm, t = 50\mu m$ and the lengths for the individual conductor segments given in table 1, the self-inductance term of the total inductance of the spiral is estimated to be 4.13 uH (micro-Henries).

index	**length (mm)**
1	60
2	95
3	57
4	89
5	51
6	83
7	44
8	77

TABLE 1. The lengths of the individual conductor segments of the Antenna as defined in figure nine. The dimensions roughly reflect a credit card-sized antenna with very much wider than normal conductors.

The mutual inductance terms may be found using,[7]

$$M = 2\ln\left\{ \left(\frac{l}{d} \right) + \left[1 + \left(\frac{l}{d} \right)^2 \right]^{\frac{1}{2}} \right\} - \left[1 + \left(\frac{l}{d} \right)^2 \right]^{\frac{1}{2}} + \left(\frac{d}{l} \right) nH \quad (19)$$

In this case, d is the center-to-center spacing between the conductors in question. In the case of unequal length conductors (as is the case here) the smaller of the two lengths is used.

Summing the eight positive and sixteen negative mutual inductance terms results in a correction of approximately 73 nH (nano-Henries). Therefore, the prototypical smart card antenna described above will have an expected total impedance of 4.06 uH.

Since the downward corrections due to mutual inductance effects are much smaller than the addition of self-inductance realized by adding conductors, it is clear why one finds spiral planar inductors with many turns just as one finds circular loop coils with many turns.

If the transponder spiral planar inductor is approximated as a number of square loops of given area, an approximate mutual inductance between the reader coil and the transponder coil can be found as in (11),

$$M = \frac{\mu_0 N_1 a^2 N_2 lw}{2\left(a^2 + r^2\right)^{3/2}} \tag{20}$$

where *lw* is the area of one of the reader coil loops.

One important consideration is the orientation of the transponder antenna with respect to the magnetic induction. Typically the antenna will be attached to some purchased article which may be carried in some random orientation by the purchaser. This introduces a function of the orientation angle as shown in figure four.

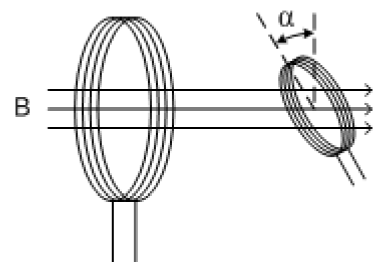

FIG 9. The RFID transponder coil introduces an angular dependency as it is moved through the generator magnetic field in various orientations.

From (9) and (20), along with the orientation dependence angle α, the voltage induced in the transponder antenna can be shown to be

$$M\frac{dI_P}{dt} = \frac{\mu_0 N_1 a^2 N_2 lw}{2\left(a^2 + r^2\right)^{3/2}} \frac{dI_P}{dt} \cos\alpha \tag{21}$$

In a typical transponder circuit, the addition of a resonant circuit allows improvement of the voltage transfer efficiency to be increased[8] so that,

$$V = \frac{\omega}{\left(\left(\frac{\omega L}{R_L}\right)^2 + \left(1 - \omega^2 LC\right)^2\right)^{1/2}} \frac{\mu_0 N_1 a^2 N_2 lw}{2\left(a^2 + r^2\right)^{3/2}} \frac{dI_P}{dt} \cos\alpha \tag{22}$$

If we change to a more realistic inductance for a smart card transponder coil to be 30 uH, then by the resonance condition C must be roughly 300 nF at 135,000 KHz. If the load resistance (in this case the input impedance of the integrated circuit) is taken at 1000 Ω, the first term in (22) represents a gain in efficiency of 161,270 realized by the addition of a resonant circuit.

Some quick back-of-the-envelope calculations can be made to illustrate some important points about the design space of RFID systems. If a read range of one meter is desired, the optimal reader antenna radius will be roughly 1.4 meters. This corresponds to a rather imposing structure, so the range is typically split in half and two reader antenna coils are used, leading to a design looking somewhat like that shown in figure six. The optimal reader coil size for a desired read range is going to dictate the form factor for the reader.

If *r* is defined as 0.5 meters, *a* as 0.7 meters, N_1 arbitrarily set to 400 (four hundred loops in the reader antenna), N_2 is set to 8 (eight loops in the transponder antenna – as in figure seven right) and all transponder coil dimensions are taken to be 50 x 80 mm for simplicity (roughly credit card sized), there will be one volt generated at the RFID transponder for every ampere of current in the reader generator coil at the maximum read range. Since some RFID transponder integrated circuits turn on at 2.4 volts, it would require a current of roughly 2.4 A in the reader coil to operate such a system.

If the transponder antenna design was changed to a wire loop antenna of the same dimensions, but with 400 turns, the resulting system would involve more expensive reusable RFID transponders known as hard tags. This type of transponder (an example of which is shown in figure ten) is typically seen in the retail clothing industry, where they are attached to clothing using pins.

FIG 10. Reusable hard tag transponder antennae are more expensive to produce but can contain antenna coils of many windings. This increases the mutual inductance of the reader and transponder antenna system and increases the read range, or reduces the current requirements of the reader antenna.

For a hypothetical 400 turn hard tag, it would require that the reader antenna would be driven at about 50 mA for an identical read range. Alternatively, the generating coil current could be held constant resulting in an increase in read range.

Conclusion

RFID systems use simple physical principles as the basis of their operation. Overall system design is, however, a fairly complex process. There are many often conflicting constraints applied to the design of a system derived from governmental regulations, cost-benefit analyses, return-on-investment issues, ease of use, and even style. Freedom to choose between many alternatives, however, allows for a virtually unlimited design space even within the small subset of RFID technologies we examined here.

Understanding the physics of inductively coupled RFID systems is the easy part. The hard part of RFID systems design is finding the combination of physical properties, processes and components that satisfy the requirements placed on the overall system.

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[1] Klaus Finkenzeller, *RFID Handbook*, 2nd edition (John Wiley & Sons, Inc., West Sussex, 2003), Chap. 5, p.161.

[2] John David Jackson, *Classical Electrodynamics*, **3**rd edition (John Wiley & Sons, Inc., Hoboken, 1999), Chap. 9, p.408.

[3] John David Jackson, *Classical Electrodynamics*, **3**rd edition (John Wiley & Sons, Inc., Hoboken, 1999), Chap. 5, p.182.

[4] Frederick Grover, *Inductance Calculations*, (D. van Nostrand Company, New York, 1946), Chap. 2, p.6.

[5] John David Jackson, *Classical Electrodynamics*, **3**rd edition, (John Wiley & Sons, Inc., Hoboken, 1999), Chap. 5, p.216.

[6] Youbok Lee, *Antenna Circuit Design for RFID Applications*, (Microchip Technology, 2003) p.12.

[7] Youbok Lee, *Antenna Circuit Design for RFID Applications*, (Microchip Technology, 2003) p.15.

[8] Klaus Finkenzeller, *RFID Handbook*, **2**nd edition (John Wiley & Sons, Inc., West Sussex, 2003), Chap. 4, p.75.