

Tutorial overview of inductively coupled RFID Systems

Introduction

There are two main categories for RFID systems on the market today. These are *near field* systems that employ inductive coupling of the transponder tag or *Smart Label* to the reactive energy circulating around the reader antenna, and *far field* systems that couple to the real power contained in free space propagating electromagnetic plane waves. Near field coupling techniques are generally applied to RFID systems operating in the LF and HF bands with relatively short reading distances well within the radian sphere defined by $\lambda/2\pi$, while radiative far-field coupling is applicable to potentially longer read range UHF and microwave RFID systems. This short technical paper is confined to the case of inductively coupled near-field RFID systems operating in the internationally available 13,56 MHz ISM frequency band.

Basic system components

All RFID systems comprise of two main components which create the wireless data link: The transponder, or tag, and the interrogator, or reader. The third essential part is the host computer system that manages the information sent to and received from the tag.

The reader contains a radio frequency (RF) transceiver module (transmitter and receiver), a signal processor and controller unit, a coupling element (antenna) and a serial data interface (RS232, RS485) to a host system. The tag acts as a programmable data carrying device and consists of a coupling element (resonant tuned circuit) and a low-power CMOS integrated circuit (IC). The IC chip contains an analogue RF interface, antenna tuning capacitor, RF-to-DC rectifier system, digital control and EEPROM memory, and data modulation circuits.

The smart label tag is passive, i.e. it does not require any internal power supply or battery energy source. The necessary power required to energise and activate the tag's microchip is drawn from the localised oscillatory magnetic field created by the reader unit's antenna. In the case of synchronous tags, the energising RF field also provides the necessary timing pulses for the microchip's internal system clock and label reply subcarrier generation circuits.

Tag as a resonant circuit

The tag's ability to efficiently draw energy from the reader field is based on the well known electrical resonance effect. The coupling or antenna element of the tag is really an inductor coil and capacitor connected together and designed to resonate at the 13,56 MHz system operating frequency (see Figure 1). The tag's resonant frequency is determined by choosing the inductive and total capacitive values so that equation 1 comes true:

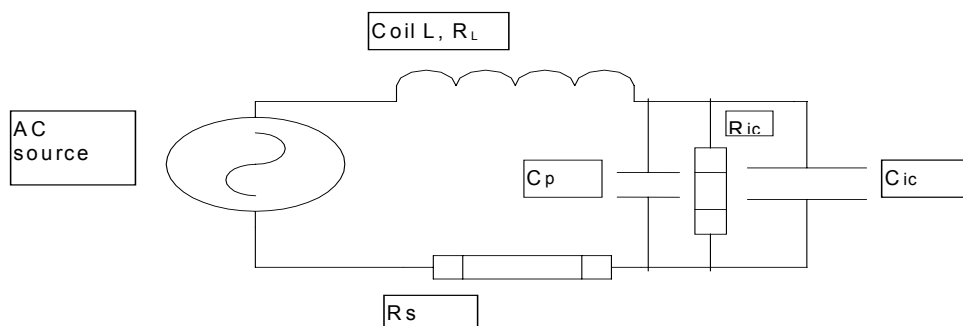


Figure 1. Smart label tag: simplified equivalent circuit.

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

In practice, equation 1 means that when the tuned circuit is resonating, the sum of its capacitive and inductive reactances is zero. In this situation, the impedance is minimized and the circulating RF current flow in the circuit is desirably maximised for best sensitivity.

The Quality Factor, or Q value of the coupling element defines how well the resonating circuit absorbs power over its relatively narrow resonance band. In smart label RFID applications, the Q value demanded is reasonably high. Since most of the resonant circuit's tuning capacitance is located within the IC microchip where high capacitor Q can be realised, the effective circuit Q value is determined mainly by the antenna coil losses. The coil Q is usually calculated (without taking into account additional parasitic interwinding capacitance losses) according to equation 2.

$$Q = \omega L/R_s \quad (2)$$

Where R_s is the coil's total effective series loss resistance taking into account both the DC resistance and the ac resistance due to high frequency current flow concentration caused by skin-effect phenomena in the conductor windings.

Practical smart label systems usually operate with a coupling element resonator Q within the range of 30 to 80. Higher Q values than this are generally not feasible because the information bearing amplitude modulated reply sidebands are undesirably attenuated by the resonator's bandpass frequency response characteristic.

At resonance, the induced RF voltage produced across the tuned tag and delivered to the microchip will be Q times greater than for frequencies outside of the resonant bandwidth.

As a resonant application, the smart label tag can be vulnerable to environmental detuning effects that may cause a reduction in transponder sensitivity and reading distance. Undesirable changes in the tag's parasitic capacitance and effective inductance can happen easily. The presence of metal and different dielectric mediums can cause detuning and introduce damping resulting from dissipative energy losses. Such permeable materials can also distort the magnetic flux lines to weaken the energy coupling to the tag. However, these effects can largely be overcome when they are taken into account during the label and system design phase. Clusters of tagged objects that sometimes come together in close physical proximity to each other can also exhibit significant detuning effects caused by their mutual inductances.

This shift in tuning is called "resonance splitting" and occurs whenever resonant circuits, such as near-field tags, come in close physical proximity to each other. It is an expected outcome when two or more tags are brought too close to one another. They become coupled tuned circuits and the degree of coupling (called the coupling coefficient, k) determines the amount of frequency shift. The value of k depends on the coil geometry (size and shape) and spacing distance. Bigger area coils are inherently more susceptible to deleterious mutual coupling effects.

When in close proximity, the magnetic flux lines of the individual coils overlap and the coils exhibit

mutual inductance. This mutual inductance generally adds to the coil's normal inductance and produces a downward shift in the effective resonant frequency. This in turn results in the tag receiving less energy from the reader field and hence the reading distance decreases accordingly. The higher the tag Q, the more pronounced is the effect. Closely coupled tags can also have problems with commands signalled from the reader being misinterpreted due to cross-coupling between tags.

Inductive coupling and operating frequency

The transfer of energy and data in smart label applications is based on vicinity inductive coupling. Inductive coupling is a means of conveying radio frequency energy via an oscillatory high-frequency (HF) magnetic field. In near-field inductive coupling, the reader antenna loop and the tag coil windings establish a loosely connected "space transformer" resulting in power transfer across short bidirectional reading distances that are comparable to the actual physical dimensions of the field creation or transmitting antenna loop. Such coupling is deemed to be predominately magnetic if the physical dimensions of the transmitting loop are small compared to the system's operating wavelength. Magnetic flux linkage and thus energy exchange occurs between the two resonant coil windings having the small but finite coefficient of coupling between them. The HF magnetic field is generated by the reader antenna from its connection to the RF power source of the reader. The chosen AC-current frequency determines the operating frequency of the reader system. With smart labels this RF carrier frequency is 13,56 MHz, an internationally allocated ISM band in all regulatory jurisdictions.

The efficiency of power transfer between the reader antenna coil and the tag coil is proportional to the operating frequency f , the number of coil windings / turns n , the area A enclosed by the tag coil, the presentation angle of the two coils relative to each other, and the distance between the two coils. Maximum power transfer occurs when the two coupled coils are placed or aligned in the same plane. As the label is rotated with respect to the transmit coil, the coupling is reduced by the cosine of the angle of rotation, i.e. a $\cos \theta$ variation.

However, as a result of the inverse cube law discussed in a later section of this paper, inductively coupled tag systems are relatively immune to misorientation of the tag with respect to the reader. This is because the reduction in range of a label from the transmit coil for a given operating power threshold level will be the inverse cube of the cosine of the angle. A quite significant rotation away from optimum alignment will therefore result in only a modest reduction in reading distance. Even as θ tends to 90° there will still be coupling, albeit at reduced range until the null is reached. The inherent curvature of the magnetic flux lines also facilitates coupling to the label under such unfavourable label orientations.

It can be shown that the relationship between the actual received power in the tag, P_{tag} and transmitted power, P_{int} from the interrogator Tx antenna is given by:

$$P_{tag} / P_{int} = (Q_{tag} Q_{int} V_c) / V_d \quad (3)$$

Where,

V_c is the *coupling volume*

V_d is the *dispersal volume*

Q_{tag} and Q_{int} is the Q of the tag resonator and Q of the transmitting antenna respectively

It can be readily seen that to obtain efficient coupling for a given reader output power and quality factors of both tag and reader antennas, the coupling volume should be made as large as possible and the dispersal volume as small as possible. The above power transfer relationship also shows that the Tx and tag antenna Q should also be made as high as information bandwidth and environmental detuning considerations will allow.

The concept of coupling and dispersal volumes is useful for the optimisation of antenna sizes when the tag antenna couples to the magnetic field of the reader antenna in the near field. In this weak coupling situation the magnetic field at the tag position can be regarded as uniform over the comparatively small volume of the tag. The field is determined only by the parameters of the interrogator antenna and is not affected by the small amount of power in the tag. The real power delivered to the tag's microchip circuit can be approximated to be proportional to the reactive power density of the Tx antenna's energy storage field at the tag position.

The effective driving power of a tag is the reactive power density $\mu_0\omega H^2$ established at the tag position by the interrogator.

The coupling volume, which is defined in (4), is a figure of merit for the tag's ability to couple to a field at the position of the tag and is determined only by the tag antenna characteristics.

$$V_c = \frac{\text{peak stored magnetic energy in tag self-inductance when shorted}}{\text{peak magnetic energy density at tag position produced from interrogator}} \quad (4)$$

Increasing the largest dimension and hence the area of the label antenna increases the coupling volume. This is why larger sized labels work better with a larger reading distance.

The dispersal volume, which is defined in (5), is determined by the dimensions of the antenna and on the position of the tag.

$$V_d = \frac{\text{Peak stored magnetic energy in interrogator antenna}}{\text{Peak magnetic energy density at tag position produced by interrogator}} \quad (5)$$

It is as though the field at the tag position is uniformly spread over a volume equal to the dispersal volume. There is an optimum size for an antenna such that the RF field does not cover more volume than necessary. As examples of the sizes required for the interrogator antenna, the commonly deployed loop structure requires a radius equal to the desired tag interrogation distance, and a solenoidal antenna (of length $L \gg \text{Diam}$) requires a lineal length equal to the interrogation distance. It is of interest to note that the use of ferrite in the core of a solenoid increases the coupling volume or decreases the dispersal volume by a factor equal to the effective permeability, μ_{eff} which in turn depends on the size, shape, and grade of ferrite material used.

Electromagnetic fields

When electromagnetic fields are deliberately created, as they are in an RFID reader system, it is generally the case that the reader antenna is primarily intended to create either an electric E or a magnetic H field. When either one of these is created, the laws of electrodynamics automatically ensure that the other field is also created, but how much of the other field is created is dependent on an interplay between the operating frequency and the physical size and design of the field creation system (antenna structure).

In this interplay one can distinguish what is called a near field situation and a far field situation. Whether or not a tag is in the near or far field depends upon how close it is to the field creation system and the operating frequency or wavelength. There is a distance, commonly known as the *radian sphere*, inside which one is said to be in the near field and outside of which one is said to be in the far field.

The concept of the radian sphere, which has a value for its radius of $\lambda/2\pi$, aids in the visualisation of whether the tag coupling is in the near or far field. If the tag is inside this sphere, the reactive energy storage fields (dipolar field terms) dominate and near-field coupling volume theory is used. If the tag falls outside the sphere then propagating plane wave EM fields dominate and the familiar antenna engineering concepts of gain, effective area or aperture, and eirp are used. These often more familiar electromagnetic concepts whereby real power is radiated into free space are relevant to the cases of UHF and microwave tagging technologies.

Distinction between near and far field

At the 13,56 MHz operating frequency, the wavelength is about 22 m which is much more than the conductor length in any standard reader antenna. It is also several times greater than the operating distance between the reader antenna and the tag. This means that inductive coupling takes place in the antenna's near field region and the radio frequency field created may be treated as a simple alternating magnetic field. So the energy coupling mechanism is purely magnetic if the physical dimensions of the reader transmitting antenna and tag operating distance are small compared to the wavelength, as is the case for systems at 13,56 MHz. Since the operating wavelength is very much greater than the distance between the tag and reader, the coupling elements are not really antennas in the true sense because no real power is being radiated. Power transfer to and from the tag is by coupling of reactive near-field energy in the immediate vicinity of the antenna structure.

The space surrounding any antenna can be divided into two parts, depending on the properties of the created radiation. Because changes in electromagnetic fields occur gradually, the boundary is not exactly defined. The primary magnetic field begins at the antenna and induces electric field lines in space. This area is termed the near field of an antenna. The zone where the electromagnetic field separates from the antenna and propagates into free space as a plane wave is termed the far field where the ratio of electric field E to magnetic field H has the constant value of 120π or 377Ω . The approximate distance where this transition zone happens is $\lambda/2\pi$. At 13,56 MHz, this places the near field-far field boundary at 3.5 m.

Note that when one is in the near field, the 120π relationship between E and H that applies in the far field is no longer valid. In the near field it is possible to have electric field with very little magnetic field, or magnetic field with very little electric field. The choice between these two alternatives being determined by the design of the interrogation antenna. RFID systems are generally designed to minimise any incidental electric field generation.

When separated from the antenna, the electromagnetic plane wave can no longer have a direct effect by inductive coupling. For inductively coupled RFID systems this means that when the far field has begun,

inductive coupling is no longer possible. The radius $r = \lambda/2\pi$ around the antenna therefore represents an insuperable range limit for inductively coupled systems. Note that in practice, the magnetic field strength has reduced to a relatively small amplitude at this boundary region.

In the near field, the magnetic field strength attenuates according to the relationship $1/d^3$ which corresponds to a damping characteristic of 60 log (d) or 60 dB per decade (the distance), i.e. the magnetic field intensity decays rapidly as the inverse cube of the distance between the reader antenna and the tag. In power terms, this equates to a dramatic $1/d^6$ reduction with distance of the available power to energise the tag. The magnetic field strength is thus high in the immediate vicinity of the "transmitting" coil, but a very low level exists in the distant far field; hence a spatially well-confined interrogation region or localised tag reading zone is created. Note that magnetic loop reader antennas can also be designed that exhibit good electrical symmetry and balance to eliminate stray electric E-field pick-up.

This rapid attenuation of the energising and data communication field with increasing distance is the fundamental reason why 13,56 MHz passive RFID systems have a maximum reading distance of the order of 1 metre. Through the principle of antenna reciprocity and the minimisation of stray E-field susceptibility, it is also the reason why well designed near field RFID systems have good immunity to environmental noise and electrical interference. All these characteristics are particularly well suited to many smart label applications.

Data transfer between a tag and a reader

When a tag is placed within the alternating magnetic field created by the reader, it draws energy from the magnetic field. This additional power consumption can be measured remotely as a voltage perturbation at the internal impedance of the reader antenna. The periodic switching on and off of a load resistance at the tag therefore effects voltage changes at the reader's antenna and thus has the effect of an amplitude modulation of the antenna voltage by the remote tag. If the switching on and off of the load resistor is controlled by the tag's stored data stream, then this data is transferred from the tag to the reader. This type of data transfer is called *load modulation*. The process of load modulation creates amplitude modulated sidebands symmetrically placed around the 13,56 MHz interrogation carrier frequency.

Because the coupling between reader antenna and tag is relatively weak and the voltage change created by the tag leads to relatively poor signal-to-noise ratios, reply code modulation with a subcarrier is utilized in most RFID chips. In this improved signalling method, the tag's data reply information is contained in a pair of backscattered sidebands which are subsequently demodulated in the RF and baseband signal processing sections of the reader to recover the tag's data stream. In ISO 15693 chips, the subcarrier frequency is equal to 423.75 kHz ($F_c/32$) with either FSK or OOK modulation and Manchester data coding. The achievable label data transfer rate is up to a relatively fast 26.48 Kbps.

Advantages of using 13.56 MHz frequency

- Frequency band available worldwide as an ISM frequency
- ISO 15693 and ISO 14443 and HF ePC standardisation for the air interface
- Robust reader-to-tag communication
- Excellent immunity to environmental noise and electrical interference
- Well defined and localised label interrogation zones
- Minimal shielding effects from adjacent objects and the human body
- Water's damping effects relatively small, field penetrates dense materials
- Freedom from environmental reflections that can plague UHF and microwave systems



- Good data transfer rate
- High clock frequency and synchronous subcarrier
- On-chip capacitors for tuning transponder coil can be easily realised
- Cheap IC's, disposable tags
- Cost effective antenna coil manufacturing
- Low RF power transmission so EM regulation compliance cause no problems
- No user licenses for reader systems required (ISM band)
- Possible to use the systems in industrial and in hazardous environments with potential for explosive substances