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DETERMINING AND IMPROVING THE READ RANGE OF RFID TAGS IS ESPECIALLY IMPORTANT AS THESE TAGS BECOME MORE COMMONPLACE.

Optimizing read range in RFID systems

Increasingly available, low-cost RFID (radio-frequency identification) tags can track and tag just about any object you can think of. Costs have come down, and performance has risen to the point that tagging applications that were out of reach only two years ago are now common. But one of the most basic questions is how far away the reader can read data from these tags.

This article provides a brief tutorial on the factors affecting read range and a real-time, real-life design example. The tutorial and design example are based on passive, 125-kHz to 13.56-MHz, inductively coupled RFID systems. The article focuses primarily on the interface between tag and reader, because a detailed discussion of reader-datapath designs could fill an entire textbook—or at least another article.

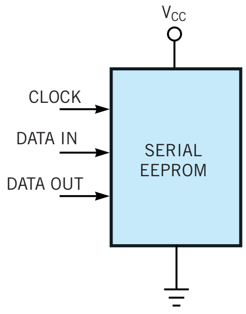
In contact systems, such as reading the data from a serial EEPROM over a two-wire (I^2C) or three-wire SPI or Microwire bus, the power, clock, and data lines are connected separately (**Figure 1**). Passive RFID devices also use a serial bus, but the power, clock, and data are all in the same signal (**Figure 2a**). But, other than separating these components into their separate uses on the tagging IC, the principles are much the same. You need dc power to bias the CMOS circuits, and binary data in a memory is clocked out to the communication bus serially.

The carrier is separated into usable signals in the tagging IC (**Figure 2b**). For dc power, you rectify the reader's carrier signal using any of a number of common rectifier circuits, usually incorporating one or more diodes inside the IC. In synchronous systems, you derive the data clock by dividing the carrier down through several stages of divide-by-2 blocks to arrive at the baseband clock rate. In asynchronous systems, you derive the data clock from an on-chip oscillator. In read/write systems, the reader transmits amplitude-modulated data as well, so the tagging IC must also peak-detect (or gap-detect in 100%-modulation systems) the signal to extract the envelope that contains the command or data ("command detector" in **Figure 2b**).

Inductively coupled systems, as all passive 125-kHz and 13.56-MHz systems are, behave much like loosely coupled transformers (**Figure 3**). The magnetic coupling between the primary winding (reader antenna coil) and secondary winding (tag antenna coil) conveys power from reader to tag. You use tuned LC circuits at these frequencies to maximize coupling between the primary and secondary winding, because you cannot use an iron core when reading at a distance.

A time-variant H-field from the reader, which current I_1 generates and the tag coil intercepts, induces current I_2 and voltage across the tag coil. The

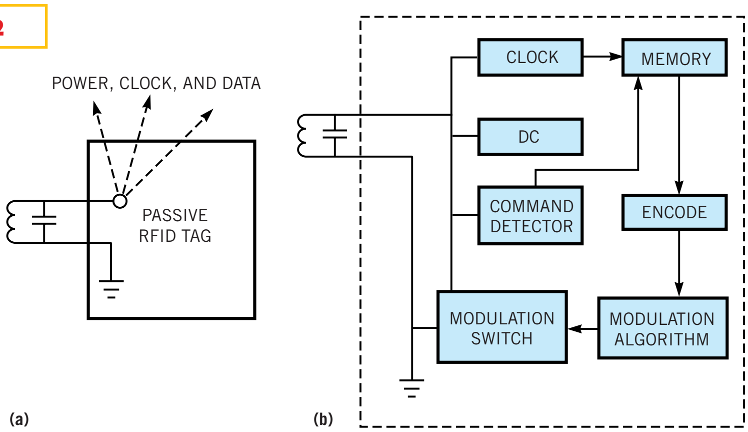
Figure 1



A traditional EEPROM IC requires two contacts for power and ground and three contacts for data and control.

mere presence of a tuned circuit causes a slight dip in p-p voltage at Node A, just as loading the secondary of a transformer causes a resulting effect in its primary. If you place a switch across the tag coil and close it, then the tag coil is shorted, and it is no longer resonant and is no longer loading the reader's coil. Therefore, the voltage at Node A again increases to its prior level. In an RFID tagging IC, the switch is a transistor (**Figure 4**). Modulation of the switch on and off then provides a corresponding AM envelope at Point A, which circuitry can extract via analog or digital means. After filtering and squaring, the pulse train at Node B looks exactly like the one clocked out of the tag memory at Node C.

Figure 2

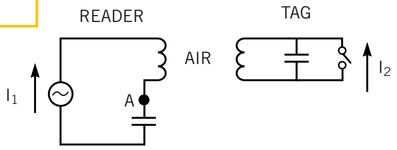


An RFID tag must accomplish the EEPROM interface using just one signal path (a). A typical RFID IC encompasses a significant array of functional blocks plus power-recovery functions (b).

PRIMARY FACTORS AFFECTING READ RANGE

With all these ideas in mind, then, what factors would you expect to contribute or detract from read range? First, consider power. The reader must generate energy in a manner that meets government limits, such as the FCC (Federal Communications Commission) in the United States, the ETSI (European Telecommunications Standards Institute) in Europe, and the MPT (Ministry for Post and Telecommunications) in Japan. This energy must be coupled from the reader to the tag, and the tag must use it efficiently. Therefore, maximum reader power output, the coupling of the energy from reader to tag, and tag power consumption are all important factors of the design. At these carrier frequencies, available voltage is falling off as $1/r^3$ (inverse cube of the distance from the reader), and power is falling off as $1/r^6$ (**Figure 5**).

Figure 3



The transfer of signals and power between the reader and tag and vice versa is conceptually similar to the simple case of a pair of loosely coupled transformer windings.

Next, the tag must "speak" loudly enough for the reader to "hear" it. Although this factor relates to modulation depth, it also depends on the amount of perturbation the tag can cause in the reader's local magnetic field. The perturbation is related to coupling of energy between the two coils, which the antenna aperture (diameter) and Q affect. Finally, the reader must "listen" well. This factor relates to the quality of the reader's noise rejection, SNR, filtering, and processing.

When designing for optimum read range, you should primarily consider the reader's power, the tag's power consumption, the tag's quality factor (Q), the tag's tuning, the reader's antenna aperture, and the tag's antenna aperture. Secondary considerations include the tag's modulation depth, the reader's SNR, the tag's power-conversion efficiency, the reader's antenna tuning and carrier accuracy, the reader's filter quality, how well the reader's driver matches the antenna, the microcontroller's speed and code efficiency, and the tag's data rate.

Sometimes, the modulation type also affects read range. PSK (phase-shift-keying) and FSK (frequency-shift-keying) systems are inherently more immune to noise than ASK (amplitude-shift-keying) systems, because PSK and FSK systems use a subcarrier that noise cannot easily duplicate. In ASK systems, any sufficiently wide noise spike can look like data and corrupt a bit, so you must use checksums, parity schemes, or CRC (cyclic-redundancy checking) to counteract the noise.

In PSK and FSK systems, highs and lows in the AM modulation do not represent binary data. Instead, in PSK systems, 0° or 180° phase shift represents a binary bit (1 or 0) during the entire bit time; in FSK systems, two different subcarrier frequencies represent 1 or 0. However, in a passive system, the tag does not transmit anything, so there is no true subcarrier, only variations of AM. Therefore, your use of checksums or CRCs and the range factors mentioned affect read range so dramatically that any benefit you gain by using FSK or PSK is usually insignificant.

The application environment can also affect read range. Key factors include the proximity of the metal to the tag or reader antennas, the presence of in-band noise sources, whether the tag and reader are stationary or moving, and the angle of the tag with regard to the reader's H-field. Another environmental factor is whether the system is enclosed; a system in a shielded tunnel, for example, can use more power than one in the open air.

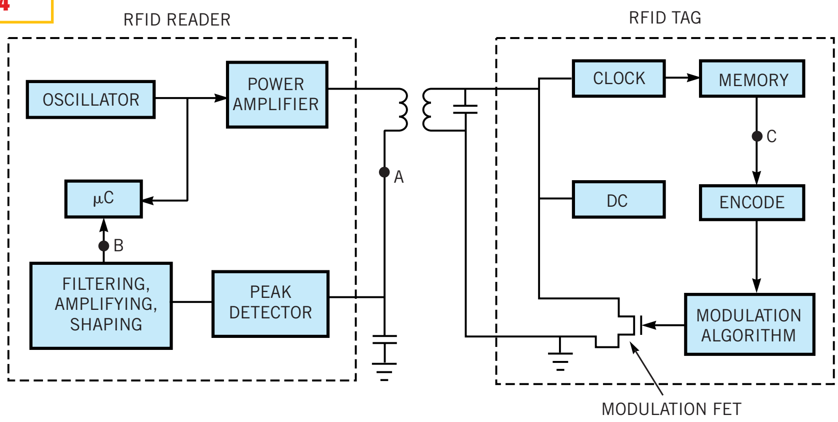
DEVICE SELECTION ALSO CRITICAL

Tag power consumption, turn-on voltage, and modulation depth vary dramatically from model to model and manufacturer to manufacturer. For example, the 13.56-MHz MCRF355 and MCRF-

450 RFID tagging devices from Microchip Technology Inc power-up at 4V p-p and typically draw 7 μA, whereas the company's 125- to 134-kHz MCRF200 powers up at 9V p-p and draws 10 μA.

Power-consumption differs widely for systems operating at 13.56 MHz, because CMOS devices consume more current proportionally as their clocking frequency increases. This frequency-dependent consumption is not a problem in synchronous tags operating at 125 kHz; however, a tag that is deriving its clock from a 13.56-MHz carrier has at least one gate that consumes 100 times more current than its counterpart in the 125-kHz tag. The rest of the divider chain draws as much or more than the fastest gate.

Figure 4



An on/off switch, built from a MOSFET, acts as the amplitude-modulating element in an RFID tagging IC.

You can see the result in two similar 13.56-MHz devices. The MCRF450 consumes 16.7 μW from dc through the V_{CC} pin and 28 μW p-p through its coil pads. A competitive device consumes 200 μW; documentation does not specify whether this figure is p-p or dc.

The power-consumption advantage of the MCRF355 translates into a read-range improvement of at least 30%, which third parties tested using similar tag apertures and reading on the same third-party multiprotocol reader. Because the device has an asynchronous design, its low-power, on-chip oscillator has to switch only at the baseband frequency of 70 kHz instead of 13.56 MHz. Such switching at 1/200th the frequency means that at least a few gates consume 1/200th the current.

READER CONSIDERATIONS ALSO COUNT

Reader designs are as diverse as the items they tag. Prices for readers range from less than $100 for a short-range, low-performance unit to more than $1000 for long-range, high-speed versions. RFID-reader designers must consider the regulatory agencies' maximum allowable limits on radiated energy. They should also consider physical constraints, including dimensions, weight, and power source—whether an ac line or a 9V battery, for example. Read-range requirements are also important; some applications require only a few inches or centimeters, whereas others may need 3m. Designers should also decide whether signal directivity or maximum reading volume is more important in an application because increasing one decreases the other.

Regulatory agencies express limits in power or voltage levels at distances of tens of meters from the source, and passive tags in this frequency range generally can be read at a distance of only 1 to 2m. This difference exists because the regulatory limits relate to the electric-field component of the generated EM carrier, whereas the inductively coupled tag requires a significant magnetic field. Some reader manufacturers use creative design techniques to maximize the magnetic field near the reader while canceling the electrical field farther away to optimize read range in the near field but minimize emissions in the far field.

Within these limits, you can enhance the range by increasing the power, which requires increasing the current drive into the tuned LC circuit and improving the impedance match between the driver and antenna. But there is a limit to the improvement you can achieve in this way, because the aperture, or diameter, of the reader antenna coil and the quality of the detection circuit affect range more than reader power level does.

For example, doubling the aperture diameter of the tag or reader can double the read range, but doubling the power does not necessarily double the read range. You can see this by modeling the flux lines around the reader's antenna coil (**Figure 6**). The smaller the aperture, the shorter the flux lines, because they wrap back around the coil. A larger diameter allows the flux lines to extend further in the Z direction before wrapping around, providing both distance and more flux density for the tag's antenna to intercept.

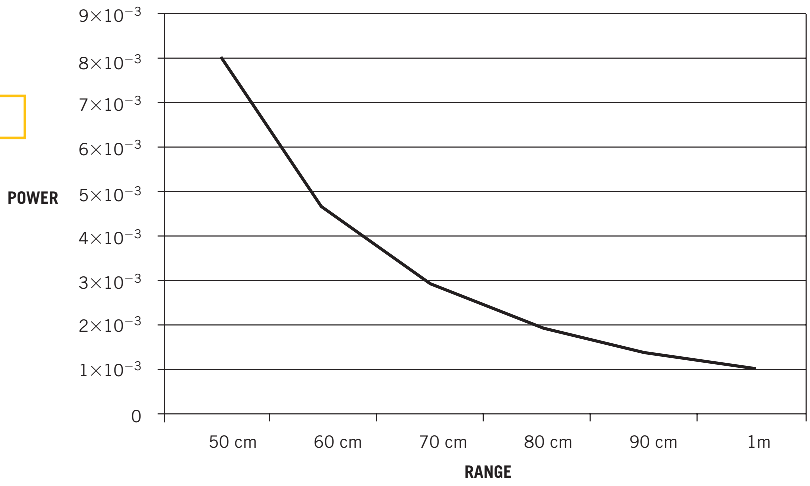
This approach also has limits, because beyond a certain diameter, the flux lines are no longer additive. This situation occurs when the flux density in the center of the coil and its projection into the tag's antenna aperture decrease; therefore, range also decreases. At this point, increased power may enhance read range.

A good rule of thumb is that the maximum read range in a low-frequency, inductively coupled, passive, back-scatter RFID system is one to two times the reader antenna's diameter. Exceptions to this rule can occur with clever design techniques, antenna shape, or signal processing, but a basic reader has these limits.

One way to increase range in a space-constrained application requiring a small reader antenna is to wind the reader antenna around a ferrite rod. This approach makes the reader more directional but increases its range along the axis of the ferrite by concentrating the magnetic flux in one direction.

Once you select a device, you still must design the tag antenna for your application. The primary factors you must con-

Figure 5



Available RF power rapidly falls off with the tag-to-reader distance, proportional to the inverse sixth-power of the distance between them.

sider are aperture, Q, and tuning. You may also need to consider other issues, such as flexibility, mechanical robustness, thinness, permeability to water or chemicals, shape, and size, but those requirements affect read range only if they affect aperture, Q, or tuning.

The tag's antenna aperture relates to read range almost linearly. In other words, doubling the tag's coil diameter may double read range to as much as twice the reader's antenna diameter, as noted previously, as long as Q and conductor surface area remain relatively constant. However, if you use the same wire gauge for a 4-in. (10-cm)-diameter tag as for a 2-in. (5-cm)-diameter tag, the Q suffers because of increased resistance of the windings. You should use a larger diameter wire to keep Q constant or even improve it. Similarly, a tag implementation using conductive traces rather than wire has the same problem. The traces need to be wider to maintain the same Q when you expand a tag to a larger diameter.

Increasing the tag's antenna diameter increases read range because a larger diameter allows the tag to intercept more lines of flux from the reader's antenna; these intercepted lines develop current in the tag coil. Note that at these frequencies, you are using a tuned-LC circuit, not a fractional-wavelength antenna.

For applications that require tags with less than ½-in. (1-cm) aperture, you must wind the tag antenna around a ferrite rod. This approach concentrates the available lines of flux into the tag's antenna, effectively magnifying or focusing the lines of flux through the coil so that they can generate current in the coil. This situation highlights the fact that powering up the tag is the primary barrier to maximizing read range.

Such rods are available in many combinations of length, diameter, and permeability μ and are common in 125-kHz tags used for animal tagging and key-fob applications. You can also use ferrite rods for 13.56-MHz systems, but you must choose them with the carrier frequency in mind. A winding around a ferrite rod makes the tag directional, with its best range where the ferrite's axis is in line with the reader's antenna axis.

Quality factor, Q, is the ratio of stored energy to dissipated energy. It is also reactance divided by resistance, so a higher resistance of the coil winding corresponds to a lower quality factor. Q also relates to the 3-dB corners of the transfer function of the LC circuit in the tag. It is therefore a double-edged sword: The higher the Q of the tag's tank circuit, the longer the read range, because the higher Q allows the extraction and storage of more energy from the reader's field. But, because high Q also means a narrower transfer function, it causes the tag to be more sensitive to changes in tuning.

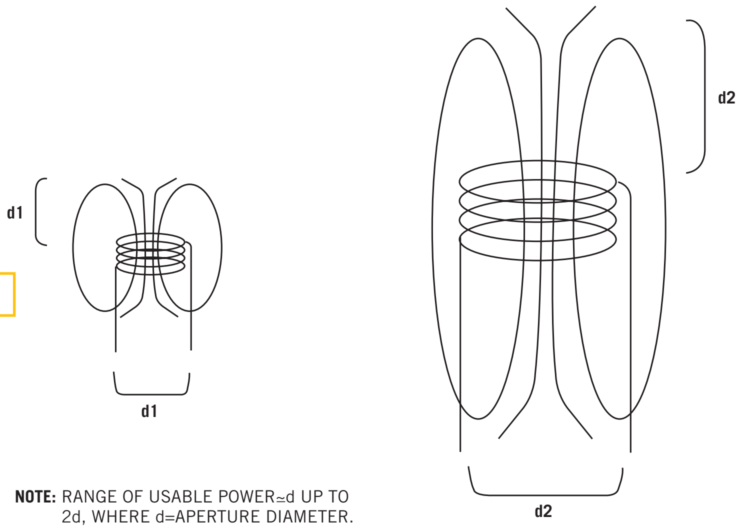
These changes can result from manufacturing tolerances on the coil and capacitor or the tag's environment, such as a tag that is directly on top of another tag or near a metallic surface. The environmental changes result when the two inductors in close proximity to each other create a mutual inductance L_M which causes the tuned frequency of both tags to shift. Even a metallic surface can cause a tuning shift because the resulting eddy currents also look like a nearby inductor. The tuning shift is the same for low Q and high Q tags but results in dramatic differences in the resulting received power and, therefore, the read range for each tag. (**Figure 7**).

Some applications do not require a long read range but may need to read many tags in close proximity, possibly even stacked on top of one another. Optimizing read range in that application, then, involves controlling, not maximizing, the read range. By intentionally limiting the Q of the tags, you effectively limit each tag's read range. However, you also limit their effect on one another by limiting the amount of power loss due to tuning shift caused by the proximity of other inductors.

Some applications require the tagging of metallic objects, which can be a problem for any passive tag at any frequency if you don't know about the metal beforehand. Metal causes detuning due to eddy currents in the case of the ferrous metal. You cannot enclose a passive tag or any other RF device with which you want to communicate inside an enclosed conductive container; no electromagnetic energy can enter or leave such a container or Faraday shield.

Depending on the orientation of the tag to the reader and their orientation to the metallic objects to be tagged, you can control or compensate for the resulting effects. If you know the objects to be tagged beforehand, you can pretune the tags such that their open-air tuning is offset from the carrier frequency, yet their tuned frequency, when attached to the metallic objects, is precisely centered on the carrier. If you do not know the objects, then you must solve the problem with more reader power, perhaps in a shielded tunnel, and reduce the Q of the tags to minimize the power drop due to frequency shift.

Figure 6



NOTE: RANGE OF USABLE POWER≃d UP TO 2d, WHERE d=APERTURE DIAMETER.

A model of the field-flux lines shows how antenna aperture (diameter) is directly related to potential read range.

A DESIGN EXAMPLE ILLUSTRATES CONCEPTS

There is no "typical" item-level tagging application, and each application has different—sometimes dramatically different—requirements. A medium-range application shows how you might approach the problem if the requirements were different. This sample application requires a tag measuring 2.5 cm in diameter and 25 mm thick and a reader measuring 20×20×4 cm. The required read range is 40 cm, and the application requires 760 bits of rewritable memory. Only 25 tags can be in the reader's field at any time, and the application involves water and chemicals, but no metal.

Because the read range is twice the maximum aperture for the reader antenna and the tag diameter is small, a high-Q tag is the best choice. It is easier to manufacture a high-Q tag at 13.56 MHz than 125 kHz, because a 13.56 MHz a tag requires only four to five windings compared with 200 to 300 windings for 125 kHz. The high bit count and need to update information further limit your selection. One device, the MCRF450, holds as much as 1 kbit of data, some of which are in its unique ID Code and other control registers, but still leaving 864 bits of user-rewritable, user-write-protectable memory. Because the role of the 760 bits is unspecified, the engineer may have intended to include a serial number in these bits. If that were the case, it would reduce the required number of user bits. The MCRF450 also includes an advanced anticollision algorithm, which enables it to address more than the required 25 tags in the reader field.

You have several options. For example, you could use a 125-kHz device if you could make its Q high enough and turn-on power levels sufficient for reading at 40 cm. If the tags were to come in contact with a lot of metal surfaces in this application, 125 kHz might be a better choice than 13.56 MHz, because of their lower Q which makes them a little more impervious to tuning shift.

In that case, however, the read-range requirement would have to decrease because a low Q would be mandatory. Incidentally, you can make 13.56-MHz devices into low-Q tags by using one of several available conductive inks rather than metal windings for the antenna. Conductive inks have much higher resistance and, therefore, low Q. You could also make the devices into low-Q tags by using small-diameter wire in the windings or by connecting a discrete or thick-film resistor across the LC circuit.

This example does not specify read speed. For applications requiring high speed, such as a conveyor belt moving at 400 ft (130m)/minute, a TTF (Tag-Talk-First) device, such as the MCRF355, might be necessary, but the memory requirement would have to decrease because the MCRF355 has only 154 bits of user space. This difference highlights what is essentially a trade-off between the "central-database" and the "distributed-database" schools of thought. The MCRF355 holds a serial number and so acts as a pointer, similar to a bar code, into a central database; the MCRF450 has much deeper memory, so you can use it as a distributed database.

You could use a printed bar code for less nasty environmental conditions requiring the reader to read the tags one at a time. A 2-D bar code holds plenty of information for a distributed database. The design example has no cost requirements, but a ruggedized and protected industrial bar code can meet the needs of lists with severe cost requirements.

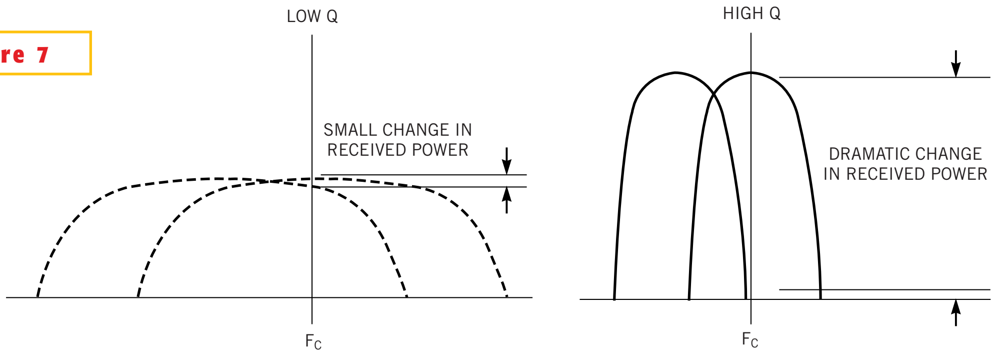
For installations in regions or countries in which either 13.56-MHz noise is present or government regulations significantly limit radiated power in this band, you can use the MCRF355 and MCRF450 at another carrier frequency, such as 3, 6, or 22 MHz. Their asynchronous design means that the device uses the carrier only for power, not for timing. As long as the LC-circuit is tuned for the new frequency, both devices operate correctly. The trade-off, though, is that if you use a lower frequency, you may need to use more windings to achieve the higher inductance the tag requires, or you may need to use a larger capacitor.

The requirements for this design example do not specify tag spacing. If the 25 tags in the reader field are lateral with respect to one another or spaced at least one diameter apart in any direction, then a high-Q tag would work. But if the tags are stacked on top of each other, then using a high-Q tag would be a detriment due to detuning, or mutual-inductance, effects. In that case, consider a low-Q design, which you can implement by moving to 125 kHz or by using one of the techniques mentioned. Note that reducing Q also reduces read range, because trade-offs always exist.

PACKAGING

Due to the rather harsh environment, you cannot use an open, label-type tag in this application. Instead it requires a water-tight, chemical-resistant seal, such as an epoxy, PVC, or plastic disk. A number of manufacturers provide this type of packaging in a variety of shapes and sizes, such as Cross Technology, Amatech USA, MC Davis, and Checkpoint Systems. You can make the windings inside the tag using on air-wound copper coil, etched aluminum or copper, or deposited conductive ink. Because this read range requires high Q, you should use heavy-gauge copper wire or etched copper inlet in this application.

Figure 7



Q factor causes a trade-off. Although higher Q improves energy recovery and read range, it makes the system more sensitive to manufacturing tolerances and to external factors, such as proximity to metallic surfaces.

If the environmental conditions would allow, you could use a less expensive label-type tag. In this approach, you etch or deposit a four- or five-turn coil onto a thin, flexible dielectric. Both single- and double-sided processes result in paper-thin, flexible "inlets," which you can bond inside a human-readable label or barcode label or attach directly to an object. Manufacturers of this type of inlet include Checkpoint Systems, Poly Flex, Leema Pharmed and Cool Tech.

If read range were not an issue and the size constraints were more severe, you could use a glass-encapsulated tag the size of a grain of rice. This would include a wound-ferrite core antenna, which can work with 125-kHz and 13.56-MHz systems.

LC-CIRCUIT DESIGN

All inductively coupled, passive RFID tagging systems need good coupling and maximum energy transfer from reader to tag. For these reasons, they use parallel LC-circuits in the tag antenna and series LC circuits in the reader antenna. To generate the maximum H field from the reader, the design should achieve maximum coil current at the resonant frequency, because current through a coil generates the magnetic field, which is the reason you use a series LC circuit, whose impedance is zero at resonance. Conversely, you want to maximize the voltage gain at resonance in the tag. Thus, you would use a parallel LC circuit because its impedance goes to infinity at resonance. You achieve tuning for both circuits by:

$$f=\frac{1}{2\pi\sqrt{LC}}. \qquad (1)$$

For the tag, it is usually best to start with a readily available production value of C and then calculate and wind L according to this equation. For this example, you choose 100 pF for the capacitor. Solving for L yields $L=1/(2^2\,\pi^2 Cf^2)=1.38$ µH.

Winding a spiral inductor, you use:

$$L=\frac{(aN)^2}{(8a+11b)}. \qquad (2)$$

where a is the distance from the center of the coil to the center of the windings in centimeters, b is the width of the windings in centimeters, N is the number of turns, and L is in microhenries.

Solving for N using a=1 cm and b=0.5 cm, which will fit the tag-dimension limits, you find that N=4.3 turns. This equation changes when you use a flat conductor, such as an etched or deposited inlet. The antenna almost always involves some trial and error due to the spacing of the windings, and it is difficult to make the last turn equal 0.3 turn, but this equation is a good starting point.

The reader design often involves some special techniques to maximize local magnetic field and minimize electrical-field emissions at 30m. In this example, you make a simple, single-loop antenna which can be etched on the reader's pc board. In this case you choose the inductor's dimensions before you choose the capacitor.

To maximize the read range, you must use all the available circumference on the reader's pc board. Once you solve for L using **Equation 3**, you calculate C using **Equation 1**. The equation for this simpler antenna is more complex than **Equation 2**, which you use for a multiturn, wire-wound inductor.

$$L=0.0467aN^2(\log_{10}(2a^2/(t+w))-\log_{10}(2.414a))+0.02032aN^2(0.914+((0.2235/a)(t+w))), \qquad (3)$$

where a is the length of one side of the square loop in inches, t is the thickness of the material in inches, N is the number of turns, w is the width of the trace in inches, and L is in microhenries.

Using the dimensions of your pc board and assuming some margin for the case, use a=7 in., w=0.25 in., t=0.002 in. (2-mil-copper-clad board), and N=1. Then solving for L, L=0.576 µH. Solving for C in **Equation 1**, you find C=239 pF. Note that 220 pF is a standard capacitor value; adding 22 pF in parallel gives 242 pF total, which, solving for f, yields 13.48 MHz, close to your target of 13.56 MHz. L is not exactly accurate because of the inductance of connection points, detours around assembly bosses, separation of the two connection points, and tolerance in manufacturing, so you often need a variable capacitor or selected value of capacitor for tuning in production.

You could use a flat rather than a wound inductor for the tag coil. In this case, you would use **Equation 3** for a square inductor or **Equation 2** for a round one. Alternatively, you could use a wire-wound coil for the reader antenna instead of a copper trace on the pc board. Because of the inductance and resistance of a large loop of wire, this frequency still usually limits you to using only one turn. **Equation 4** represents a single-turn, circular-loop antenna:

$$L=0.01257a(2.303\log_{10}(16a/d-2)), \quad \textbf{(4)}$$

where a is the mean radius of the loop in centimeters, d is the wire diameter in centimeters, and L is in microhenries.

Note that **Equation 4** does not calculate Q for coil and capacitor values, because resistivity, which controls Q, is independent of the reactive parameters in the tuning equations. However, the materials you select for the windings dramatically affect Q, because every material has a characteristic resistance per unit length. For this reason, you must carefully choose the material, considering all the application requirements.

WHEN USING AN RFID TAG AND READER, OPTIMIZING FOR READ RANGE IS A SYSTEM ISSUE.

STEP BACK AND REASSESS

When designing an RFID tag and reader, remember that optimizing for read range is a system issue; no single component determines the entire read range. A tagging IC has no read range; it can only maximize or minimize its part of the system. Only a total system can have a read range. Also, keep in mind the different semiconductor devices, materials, and techniques available for use in RFID tags and systems, because careful selection by application is critical. And, although optimizing read range is more complicated than you imagine, optimizing read range is simpler than you imagine if you use these hints, guidelines, and equations.□

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