5

Components of the RFID System

5.1 Engineering Challenges

An RFID system consists of an RFID reader, RFID tag, and information managing host computer. The reader contains an 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 IC. The IC chip contains an analog RF interface, antenna tuning capacitor, RF-to-dc rectifier system, digital control and electrically erasable and programmable read-only memory (EEPROM), and data modulation circuits. RFID involves contactless reading and writing of data into an RFID tag's nonvolatile memory through an RF signal. The reader emits an RF signal and data is exchanged when the tag comes in proximity to the reader signal. Tags can be categorized as follows:

1. Active tag, which has a battery that supplies power to all functions;
2. Semipassive tag, which has a battery used only to power the tag IC, and not for communication;
3. Passive tag, which has no battery on it. The absence of a power supply makes passive tags much cheaper and more reliable than active tags.

Given the increase in RFID usage, many new challenges face design engineers. Currently, these challenges include multiple tag standards, 20% tag failure rate, installation and placement issues, the need for cost-effective management and maintenance of readers, the need for reductions in the reader size that allows them to be imbedded into structures and handheld devices, and intellectual property protection and secure access control protocols. A number of different parameters will influence the quality and reliability of the RFID system: tag size, reader/writer antenna size, tag orientation, tag operating time, tag movement velocity, effect of metallic substances on operating range, multiple-tag operating characteristics, and the effect of the number of tags on operating success rate, tag overlapping, and so forth.

5.2 Near- and Far-Field Propagation

RFID systems on the market today fall into two main categories: *near-field* systems that employ inductive (magnetic) coupling of the transponder tag 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 [1]. Near-field coupling techniques are generally applied to RFID systems operating in the LF and HF bands with relatively short reading distances, whereas far-field coupling is applicable to the potentially longer reading ranges of UHF and microwave RFID systems. Whether or not a tag is in the near or far field depends on 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. 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 (the *near field*).

The zone where the electromagnetic field separates from the antenna and propagates into free space as a plane wave is called the *far field.* In the far field, 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 given as follows:

$$r = \frac{\lambda}{2\pi} \tag{5.1}$$

It is also important to notice that this expression is valid for small antennas where $D << \lambda$.

The reactive near-field region is a region where the E- and H-fields are not orthogonal; anything within this region will couple with the antenna and distort the pattern, so the antenna gain is not a meaningful parameter here. Using (5.1), at 13.56 MHz ($\lambda = 22$m), this places the near-field–far-field boundary at about 3.5m (10 feet).

It has been estimated that the far-field distance for the case in which $D > \lambda$ is given as follows:

$$r = \frac{2D^2}{\lambda} \tag{5.2}$$

where D is the maximum dimension of the radiating structure and r is the distance from the antenna. Note that this is only an estimate, and the transition from near field to far field is not abrupt. Typically D for reader antennas is 0.3m (1 foot.) The far-field distance in the UHF ISM band in the United States (915 MHz, $\lambda = 0.33$m) is estimated to be 0.56m.

Generally speaking, the radiating near-field or transition region is defined as a region between the reactive near field and a far field. In this region, the antenna pattern is taking shape but is not fully formed, and the antenna gain measurements will vary with distance:

$$\frac{\lambda}{2\pi} < r < \frac{2D^2}{\lambda} \tag{5.3}$$

The solution of Maxwell's equations for the fields around an antenna consists of three different powers of the range $1/r$, $1/r^2$, and $1/r^3$. At very short ranges, the higher powers dominate the solution, while the first power dominates at longer ranges. This can be interpreted as the electromagnetic wave breaking free from the antenna. The near field may be thought of as the transition point where the laws of optics must be replaced by Maxwell's equations of electromagnetism.

5.2.1 Far-Field Propagation and Backscatter Principle

RFID systems based on UHF and higher frequencies use *far-field communication* and the physical property of backscattering or "reflected" power. Far-field communication is based on electric radio waves where the reader sends a continuous base signal frequency that is reflected back by the tag's antenna. During the process, the tag encodes the signal to be reflected with the information from the tag (the ID) using a technique called *modulation* (i.e., shifting the amplitude or phase of the waves returned) [2].

The concept of the radian sphere, which has a value for its radius of $\lambda/2\pi$ helps in the visualization 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 EM concepts whereby real power is radiated into free space are relevant to the cases of UHF and microwave tagging technologies.

Most theoretical analyses, at least in the first approximation, assume the so-called free-space propagation. *Free space* simply means that there is no material or other physical phenomenon present except the phenomenon under consideration. Free space is considered the baseline state of the electromagnetic field. Radiant energy propagates through free space in the form of electromagnetic waves, such as radio waves and visible light (among other electromagnetic spectrum frequencies). Of course, this model rarely describes the actual propagation situation accurately; phenomena such as reflection, diffraction, and scattering exist that disturb radio propagation. In the wireless industry, most models and formulas we use today are semiempirical, that is, based on the well-known radio propagation laws but modified with certain factors and coefficients derived from field experience. RFID is definitely an area where this practice is required; short distances cluttered with multiple tags and/or other objects are potential obstacles to radio propagation and will cause serious deviations, predictable or not, from the theoretical calculations.

A backscatter tag operates by modulating the electronics connected to the antenna in order to control the reflection of incident electromagnetic energy. For successful reading of a passive tag, two physical requirements must be met:

1. *Forward power transfer:* Sufficient power must be transferred into the tag to energize the circuitry inside. The power transferred will be proportional to the second power of the distance.
2. *The radar equation:* The reader must be able to detect and resolve the small fraction of energy returned to it. The power received will be reduced proportional to the fourth power of the distance.

5.2.1.1 Forward Power Transfer

A typical RFID tag consists of an antenna and an integrated circuit (chip), both with complex impedances. The chip obtains power from the RF signal transmitted by the base station, called the RFID reader. The RFID tag antenna is loaded with the chip whose impedance switches between two impedance states, usually high and low. At each impedance state, the RFID tag presents a certain *radar cross section* (RCS). The tag sends the information back by varying its input impedance and thus modulating the backscattered signal.

In Figure 5.1, $Z_A = R_a + jX_a$ is the complex antenna impedance and $Z_C = R_c + jX_c$ is the complex chip (load) impedance; chip impedance may vary with the frequency and the input power to the chip. The power scattered back from the loaded antenna can be divided into two parts. One part is called the *structural*

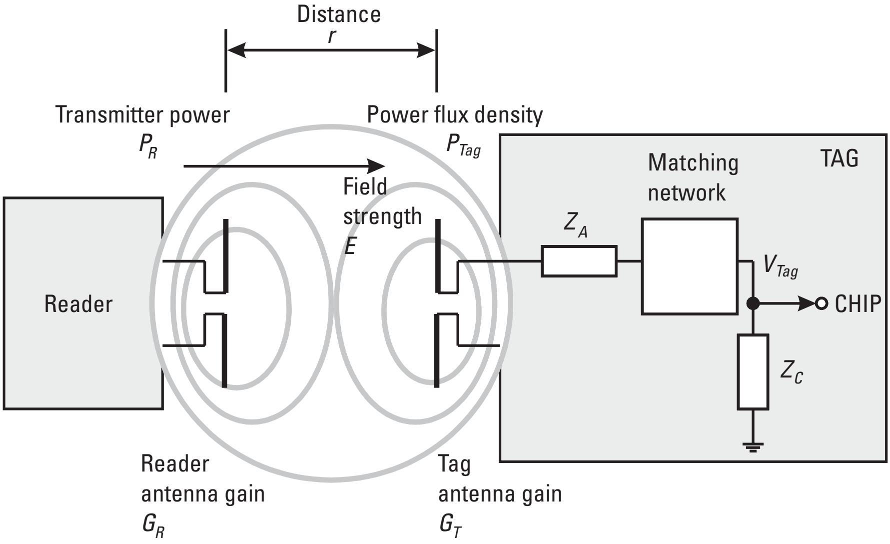


Figure 5.1 Forward power transfer.

mode and is due to currents induced on the antenna when it is terminated with complex conjugate impedance. The second part is called the *antenna mode* and results from the mismatch between antenna impedance and load impedance.

The separation between the antennas is r, which is assumed to be large enough for the tag to be in the far field of the reader. E is the electric field strength of the reader at the tag location. The efficiency of the matching network will be taken as unity and ignored (losses in the network may also be accounted for in the value of G_T). Antenna gains G_R and G_T are expressed relative to an isotropic antenna. From considerations of power flux density at the tag, with λ as the wavelength, we get:

$$P_{Tag} = \left(E^2/120\pi\right)\left(\lambda^2/4\pi\right)G_T = V_{tag}^2/R_c \tag{5.4}$$

and

$$E^2/120\pi = P_R G_R/4\pi r^2 \tag{5.5}$$

After some manipulation of these equations, we obtain:

$$P_{Tag} = \left(P_R G_R/4\pi r^2\right)\left(\lambda^2 G_T/4\pi\right) = P_R G_R G_T \lambda^2/(4\pi)^2 r^2 \tag{5.6}$$

The typical maximum reader output power is 500 mW, 2W (ERP, CEPT), and 4W (EIRP, FCC). Converted to dBm, the permitted maximum limits are about 29 dBm (500 mW ERP, 825 mW EIRP), 35 dBm (2W ERP, 3.3W EIRP), and 36 dBm (4W EIRP). The gain of the transmitter (reader) antenna (typical value) is assumed to be 6 dBi. Therefore, the maximum output power from the power amplifier should be 23, 29, and 30 dBm, respectively. The tag available power versus distance can be seen in Figure 5.2. From the industrial experience, the minimum RF input power of 10 μW (–20 dBm) to 50 μW (–13 dBm) is required to power on the tag. The power received by the tag is then divided in two parts: the reflected power and the available power used by the chip. The distribution of these two parts is very critical for a maximum distance. For dipole antennas presented in the best orientation, G_T may be taken as 2 dBi (gain over isotropic with allowance for losses, approximately 1.6).

We can also say that:

$$V_{Tag} = (\lambda/4\pi r)\sqrt{P_R G_R G_T R_c} \tag{5.7}$$

Note that $P_R G_R$ is the EIRP of the reader. The maximum practical value of R_c is 600Ω. The received voltage V_{Tag} must be large enough to be rectified and power the tag; a voltage in excess of 1.2 V_{rms} may be required. This is with the tag presented to the interrogating field in the ideal orientation and with no power margin.

Using (5.9), at 915 MHz (λ = 0.33m), for example, it can be seen that with 1.6 V_{rms} tag voltage (assuming both the gain of the reader and the tag to be

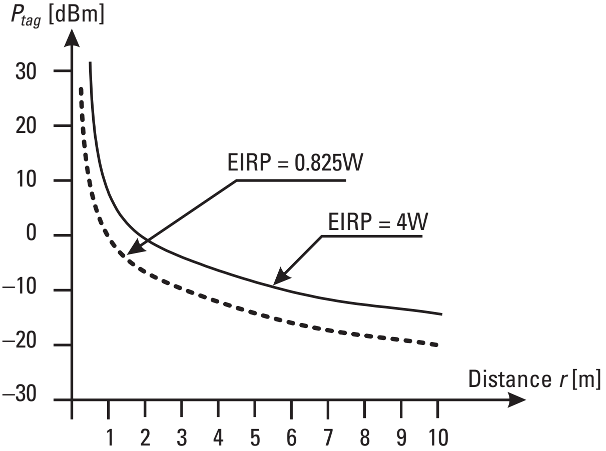


Figure 5.2 Tag-received power versus distance.

2 dBi), the required reader power at 1m distance is 2.416W or EIRP reader power of 3.96W.

$$P_{Tag} = V_{Tag}^2 / R_c = 1.6^2 / 600 = 0.0043\ [\mathrm{W}] \tag{5.8}$$

$$\begin{aligned} P_R &= \left(4\pi r V_{Tag} / \lambda\right)^2 \left(1/(G_R G_T G_c)\right) \\ P_R &= \left(4\pi \cdot 1 \cdot 1.6/0.33\right)^2 \left(1/(1.6 \cdot 1.6 \cdot 600)\right) \\ P_R &= 2.416\ [\mathrm{W}] \end{aligned} \tag{5.9}$$

$$P_{\mathrm{REIRP}} = P_R \cdot 1.64 = 2.416 \cdot 1.64 = 3.96\ [\mathrm{W}] \tag{5.10}$$

The relationship between the electrical field strength and the power flux density is the same as that between the voltage and the power in an electrical circuit; from (5.4) we can say that the electric field strength of the reader at the tag position ($P_R G_R$ is the EIRP of the reader) is equal to:

$$\begin{aligned} E &= \sqrt{30 \cdot P_R G_R} / r \\ E &= \sqrt{30 \cdot 3.96} / 1 = 10.9\ [V/m] \end{aligned} \tag{5.11}$$

Note that the gain of 2 dBi is approximately equivalent to the gain of 1.6 and can be calculated as follows:

$$G[\mathrm{dBi}] = 10 \log G \rightarrow G = 10^{\frac{G[\mathrm{dBi}]}{10}} \tag{5.12}$$

5.2.1.2 The Radar Equation

Radar principles tell us that the amount of energy reflected by an object is dependent on the reflective area of the object—the larger the area, the greater the reflection. This property is referred to as the radar cross section (RCS). The RCS is an equivalent area from which energy is collected by the target and retransmitted (backscattered) back to the source. For an RFID system in which the tag changes its reflectivity in order to convey its stored identity and data to the reader, this is referred to as *differential radar cross section* or ΔRCS. Calculations of the complete return signal path are conveniently conducted in terms of the ΔRCS of the backscatter device.

For the antenna to transfer maximum energy to the chip, the impedance of the chip must be a conjugate of the antenna impedance. However, it is important to remember that the logic circuits of a chip used in a tag draw very little power relative to the amount of power consumed by the chip RF input circuits. As the modulator switches between two states, the load impedance of the chip Z_C will switch between two states. The reflection due to a mismatch between antenna and load in a backscatter tag is analogous to the reflection found in transmission lines and may be expressed in terms of a coefficient of reflection. The coefficient of reflection ρ will therefore change as the modulator switches between two states. When the tag modulator is in the off state, the chip input impedance will be closely matched to the antenna impedance; therefore, the reflectivity will be low and hence the SWR will approach 1 (5.13). When the modulator is in the on state, the tag antenna impedance will be mismatched and so the reflectivity will be high, and the SWR will tend to infinity, causing the maximum amount of power to be reflected:

$$\rho = \frac{Z_C - Z_A^*}{Z_C + Z_A} \tag{5.13}$$

The tag varies its RCS by changing the impedance match of the tag antenna between two (or more) states. The ratio between the states is called the *differential coefficient of reflectivity,* represented by the symbol $\Delta\rho$, and it can be calculated using well-known transmission line theory, a summary of which is provided next. Signal propagation follows the well-known Friis transmission formula; analytical approaches such as the Friis equation assume undisturbed near-field conditions (i.e., no proximity of dielectric and metal objects), known antenna characteristics, and no diffraction and reflection effects.

An antenna of gain G has an effective aperture as calculated here:

$$A_e = \lambda^2 G_T / 4\pi \ \left[m^2\right] \tag{5.14}$$

The $\Delta\rho$ is the differential reflection coefficient of the tag modulating circuitry and can be calculated as shown:

$$\Delta\rho = p_1\left(1 - |\rho_1|^2\right) + p_2\left(1 - |\rho_2|^2\right) \tag{5.15}$$

where the IC in states 1 and 2 for a fraction of and of time, p_1 and p_2 of time, respectively [3].

It is worth mentioning that if the tag modulator switches from a perfectly matched state ($\rho_2 = 0$) to a short circuit state or to an open circuit state ($\rho_1 = 1$), $\Delta\rho$ will be approximately 0.5. Lower (and more realistic) modulation ratios will result in $\Delta\rho < 0.5$. However, in those cases where the modulator switches from a state where the chip has an impedance higher than the antenna impedance, to a condition where it is lower than the antenna impedance, $\Delta\rho$ will represent the difference between the two states, in which case $\Delta\rho$ could be greater than 0.5 (but never higher than 1).

In modulation schemes, where one of the two states is active most of the time (e.g., $p_1 < p_2$), this is a good choice in terms of power efficiency, but these schemes require a much larger bandwidth (due to the short gaps), which is often prohibited by national authorities' regulations. Assuming that both states are active an equal amount of time (as it is in ASK with total mismatch in one state), that is, $p_1 = p_2 = 0.5$, and assuming there are no antenna losses, 50% of the available input power is actually available for rectification, 25% is used as backscattered modulated power, and the remaining 25% is wasted.

The σ is the ΔRCS of the tag and P_{Ret} is the power returned to the reader. The ΔRCS of the tag antenna is equivalent to the antenna effective aperture A_e, when the tag is matched. For the ΔRCS) when the tag antenna is mismatched, theoretically speaking, we can say that:

$$\sigma = \Delta_{\mathrm{RCS}} = A_e \cdot G_T \cdot (\Delta\rho)^2 = \frac{\lambda^2 G_T^2 (\Delta\rho)^2}{4\pi} \; \left[m^2\right] \qquad (5.16)$$

where G is the gain of the tag antenna (G is squared because the signal is received and reradiated), λ is the wavelength, and ρ is the differential reflection coefficient of the tag modulator.

First we assume that electromagnetic waves propagate under ideal conditions, that is, without dispersion. If high-frequency energy is emitted by an isotropic radiator, then the energy propagates uniformly in all directions. Areas with the same power density therefore form spheres ($A = 4\pi r^2$) around the radiator (Figure 5.3). The same amount of energy spreads out on an incremented spherical surface at an incremented spherical radius. That means that the power density on the surface of a sphere is inversely proportional to the radius of the sphere.

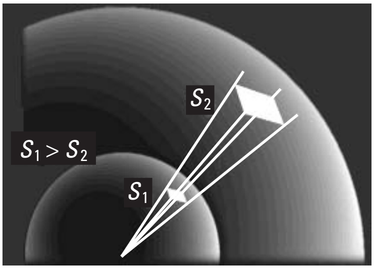


Figure 5.3 Illustration of the power-flux density.

So we obtain the formula for calculating the nondirectional power-flux density:

$$S = \frac{P_R}{4\pi r^2} \; [W/m^2] \tag{5.17}$$

where P_R is the power transmitted from the reader.

Because a spherical segment emits equal radiation in all directions (at constant transmitting power), if the power radiated is redistributed to provide more radiation in one direction, an increase of the power density in direction of the radiation results. This effect is called *antenna gain* and it is obtained by directional radiation of the power. So, from the definition, the directional power flux density is:

$$S_D = S \cdot G_R \tag{5.18}$$

The target (tag in our case) detection is not only dependent on the power density at the tag's position, but also on how much power is reflected in the direction of the radar (reader in our case). To determine the useful reflected power, it is necessary to know the radar cross section σ. This quantity depends on several factors, but it is true to say that a bigger area reflects more power than a smaller area. That means that a jumbo jet offers more RCS than a sporting aircraft in the same flight situation. Beyond this, the reflecting area depends on design, surface composition, and materials used. With this in mind, we can say that the returned (reflected) power P_{Ret} toward the RFID reader depends on the power density S_D, the reader's antenna gain G_R, and the variable RCS σ:

$$P_{Ret} = \frac{P_R}{4\pi r^2} \cdot G_R \cdot \sigma \; [W] \tag{5.19}$$

Because the reflected signal encounters the same conditions as the transmitted power, the power density yielded at the receiver of the reader is given by:

$$S_{REC} = \frac{P_{Ret}}{4\pi r^2} = \frac{P_R \cdot G_R}{(4\pi)^2 r^4} \cdot \sigma \tag{5.20}$$

The backscatter communication radio link budget, a modification of the monostatic radar equation, describes the amount of modulated power that is scattered from the RF tag to the reader (5.21):

$$P_{REC} = S_{REC} \cdot A_e = \frac{P_R \cdot G_R \cdot \sigma}{(4\pi)^2 r^4} \cdot \frac{\lambda^2 \cdot G_R}{4\pi} = \frac{P_R G_R^2 \lambda^2 \sigma}{(4\pi)^3 r^4} \tag{5.21}$$

For successful operation, we require both that the signal at the reader's receiver be above the noise floor and that the ratio of the power received and transmitted from the reader not be too small. The spreadsheet shown in Table 5.1 shows the return signal ratio for various situations. Ratios below 100 dB are both manageable in terms of signal processing and ensure that the return signal is significantly above the thermal noise floor.

Noise is the major limiting factor in communications system performance. Noise can be divided into four categories: thermal noise, intermodulation noise, crosstalk, and impulse noise. For this analysis, we consider only thermal noise and neglect other potential sources of noise. Now, we have to calculate the power of the reflected signal at the receiver of the reader and compare it with the thermal noise threshold.

Thermal noise results from thermal agitation of electrons; it is present in all electronic devices and transmission media and is a function of temperature and the channel bandwidth. Thermal noise is independent of any specific frequency. Thus, the thermal noise power in watts present in a bandwidth of B hertz can be expressed as shown here:

$$N = kTB \tag{5.22}$$

where Boltzmann's constant $k = 1.3803 \times 10^{-23}$ J/K and T is the temperature in kelvin ($T = 273.16 + t$ [°C]).

In dBW, (5.22) would look like this:

$$N = -228.6 + 10 \log T + 10 \log B \tag{5.23}$$

It is also possible to define rms noise voltage across some resistance R by applying Ohm's law to (5.22):

$$E_N = \sqrt{4RkTB} \tag{5.24}$$

The *noise figure* or *noise factor* (NF) is a contribution of the device itself to thermal noise. It is commonly defined as the signal-to-noise ratio at the input divided by the signal-to-noise ratio at the output and is usually expressed in decibels. Typical noise figures range from 0.5 dB for very low noise devices, to 4 to 8 dB.

Table 5.1

Received UHF RFID Power for Various Distances

f [MHz]	λ [m]	r [m]	P Reader [W]	P Reader [dBm]	Reader Antenna Gain	Tag Antenna Gain	$\Delta\rho$	σ [m^2]	P Received [μW]	P Received [dBm]	Power Ratio [dB]
915.00	0.33	1.00	2.00	33.01	1.60	1.60	0.50	0.0055	1.5185	–28.19	–61.20
915.00	0.33	2.00	2.00	33.01	1.60	1.60	0.50	0.0055	0.0949	–40.23	–73.24
915.00	0.33	4.00	2.00	33.01	1.60	1.60	0.50	0.0055	0.0059	–52.27	–85.28
915.00	0.33	8.00	2.00	33.01	1.60	1.60	0.50	0.0055	0.0004	–64.31	–97.32
433.00	0.69	1.00	2.00	33.01	1.60	1.60	0.50	0.0244	30.2793	–15.19	–48.20
433.00	0.69	2.00	2.00	33.01	1.60	1.60	0.50	0.0244	1.8925	–27.23	–60.24
433.00	0.69	4.00	2.00	33.01	1.60	1.60	0.50	0.0244	0.1183	–39.27	–72.28
433.00	0.69	8.00	2.00	33.01	1.60	1.60	0.50	0.0244	0.0074	–51.31	–84.32

For a 500-kHz bandwidth, at room temperature, we can use (5.22) to calculate a thermal noise of −117 dBm; with addition of the 3-dB receiver noise factor, total noise is −114 dBm, leaving enough reader signal margin to the noise threshold.

We can see that the return power ratio conditions are met at relatively longer ranges and that forward power transfer is the limiting factor in UHF backscatter tags. Battery-powered backscatter tags overcome this limitation and can be read at significantly greater ranges.

5.2.2 Near-Field Propagation Systems

5.2.2.1 Magnetic Field Calculations

At low to mid-RFID frequencies, RFID systems make use of near-field communication and the physical property of inductive coupling from a magnetic field. The reader creates a magnetic field between the reader and the tag and this induces an electric current in the tag's antenna, which is used to power the integrated circuit and obtain the ID. The ID is communicated back to the reader by varying the load on the antenna's coil, which changes the current drawn on the reader's communication coil. In the near field, it is possible to have an electric field with very little magnetic field, or magnetic field with very little electric field. The choice between these two alternatives is determined by the design of the interrogation antenna, and RFID systems are generally designed to minimize any incidental electric field generation.

In the near field, the magnetic field strength attenuates according to the relationship $1/r^3$, that is, 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 drastic $1/r^6$ reduction with distance (60 dB/decade) of the available power to energize 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 localized 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 pickup.

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 (Figure 5.4). The current passing through the inductor creates a surrounding magnetic field according to Ampere's law. The created magnetic field B is not a propagating wave [4], but rather an attenuating carrier wave, with its strength given as illustrated in Figure 5.5 and described by formula (5.25):

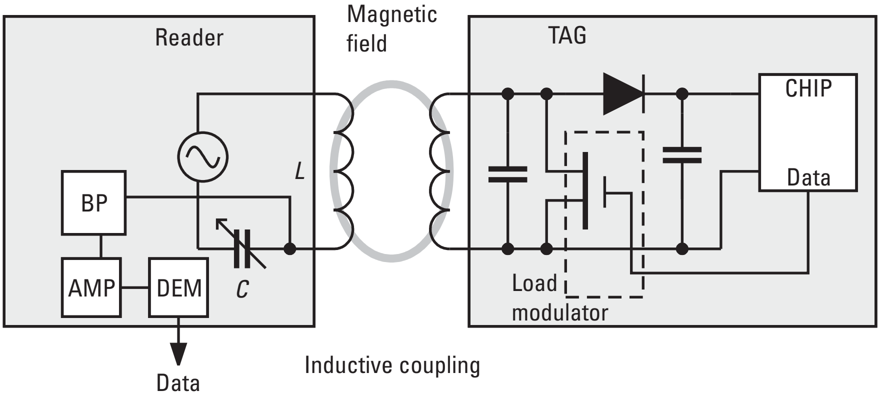


Figure 5.4 Principle of inductive (near-field) coupling.

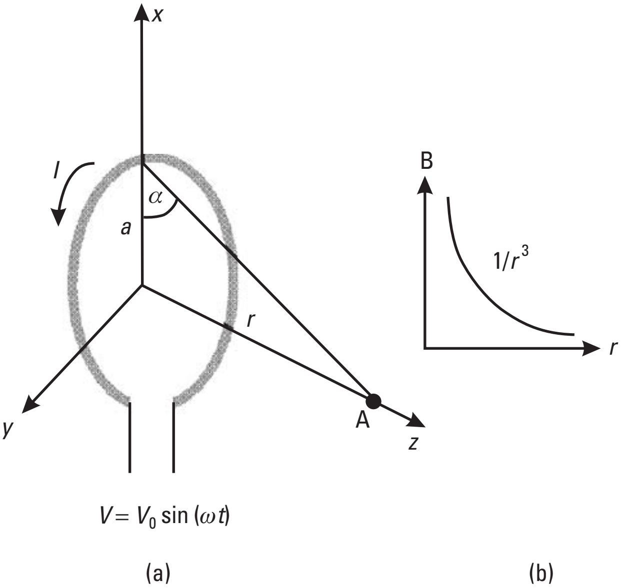


Figure 5.5 Calculation of the magnetic field away from the coil: (a) coil in 3D space, and (b) magnetic field decay with distance.

$$B = \frac{\mu_0 I N a^2}{2r^3} \left[\text{Weber/m}^2 \text{ or tesla}\right] \tag{5.25}$$

where:

I = current through the coil;

N = number of windings in the coil;

a = radius of the coil;

μ_o = permeability of free space ($4\pi \times 10^{-7}$ H/m);

r = perpendicular distance from antenna to point A and $r >> a$.

As one moves away from the source with $r >> a$, the simplified (5.25) shows the characteristic $1/r^3$ attenuation. This near-field decaying behavior of the magnetic field is the main limiting factor in the read range of an RFID device.

We use Ohm's law for ac circuits:

$$I = \frac{V}{Z_L} = \frac{V}{\omega L} \tag{5.26}$$

and assume that L can be approximated as follows:

$$L \approx \mu_0 \pi a N^2 \tag{5.27}$$

We can then rewrite (5.25) as shown here:

$$B = \frac{Va}{2\omega N \pi r^3} \tag{5.28}$$

From (5.28) with a given coil voltage at some distance from the coil, we can now see that B is inversely proportional to N. This is due to the fact that the current increases at the rate of $1/N^2$ with a given coil voltage V. Only the case of an air-coiled inductor has been described, but a ferrite-cored inductor could be used as well. Adding a core has the effect of increasing the effective surface area, enabling one to reduce the physical size of the coil.

To maximize the magnetic field, given fixed antenna dimensions, (5.25) dictates that the current delivered to the antenna must be maximized. Additionally, to maximize current, the antenna must resonate at the excitation frequency provided by the reader circuit. Resonance frequency (f_0) of the reader is determined by the inductance (L) of the antenna (determined by the radius of the coil, the number of windings, the thickness of the windings, and the length of the coil) and a tuning capacitor (C) and is calculated as follows:

$$f_0 = 1/2\pi\sqrt{LC} \tag{5.29}$$

The same formula is used to calculate a tag's resonant frequency, which is determined by choosing the inductive and total capacitive values, so that the value for the tag's resonant frequency f_0 is achieved. In the case of a tag's resonant frequency:

L[H] = inductance of tag antenna coil
C[F] = capacitance of a tag's tuning capacitor

$$Z(j\omega) = R + j(X_L - X_C) \tag{5.30}$$

In practice, when the tuned circuit is resonating, the sum of its capacitive and inductive reactance is zero ($X_L = X_C$), and the impedance shown in (5.30) becomes purely resistive.

Total resistance is thereby minimized and current through the antenna is maximized, yielding a maximized magnetic field strength. Passive tags utilize the energy provided by the carrier wave through an induced antenna-coil voltage. The voltage is proportional to the product of the number of turns in the tag antenna and the total magnetic flux through the antenna. The ASIC within the tag must receive a minimum voltage (threshold voltage or power) to operate.

5.2.2.2 Voltages Induced in Antenna Circuits

Faraday's law states that a time-varying magnetic field through a surface bounded by a closed path induces a voltage around the loop. Figure 5.6 shows a simple geometry for an RFID application. When the tag and reader antennas are in proximity, the time-varying magnetic field B that is produced by a reader antenna coil induces a voltage (called electromotive force or simply EMF) in the closed tag antenna coil. The induced voltage in the coil causes a flow of current on the coil. The induced voltage on the tag antenna coil is equal to the time rate of change of the magnetic flux Ψ:

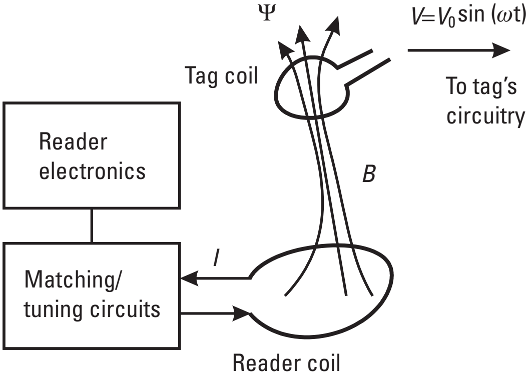


Figure 5.6 Basic reader and tag configuration.

$$V = -N\frac{d\Psi}{dt} \tag{5.31}$$

where N is the number of turns in the antenna coil and Ψ is the magnetic flux through each turn. The negative sign indicates that the induced voltage acts in such a way as to oppose the magnetic flux producing it. This is known as Lenz's law, and it emphasizes the fact that the direction of current flow in the circuit is such that the induced magnetic field produced by the induced current will oppose the original magnetic field. The magnetic flux Ψ in (5.31) is the total magnetic field B that is passing through the entire surface of the antenna coil, and it is found by:

$$\Psi = \int B \bullet dS \tag{5.32}$$

where:

B = magnetic field given in (5.21).

S = surface area of the coil.

$\bullet$ = inner product (cosine angle between two vectors) of vectors B and surface area S. Both magnetic field B and surface S are vector quantities.

The presentation of the inner product of two vectors suggests that the total magnetic flux Ψ that is passing through the antenna coil is affected by the orientation of the antenna coils. The inner product of two vectors becomes minimized when the cosine angle between the two is 90°, or the two (B field and the surface of coil) are perpendicular to each other and maximized when the cosine angle is 0°. The maximum magnetic flux that is passing through the tag coil is obtained when the two coils (reader coil and tag coil) are placed in parallel with respect to each other. This condition results in maximum induced voltage in the tag coil and also maximum read range. The inner product expression also can be expressed in terms of a mutual coupling between the reader and tag coils. The mutual coupling between the two coils is maximized in the preceding condition.

Combining expressions given so far, the voltage across the tag antenna, at the resonant frequency, can be calculated as in the following equation:

$$V_{Tag} = 2\pi fNQB(S\cos\alpha) \tag{5.33}$$

where:

f = frequency of the carrier signal;

S = area of the coil in square meters;

Q = quality factor of the resonant circuit;

B = strength of the magnetic field at the tag;

α = angle of the field normal to the tag area.

The (S cos α) term in (5.33) represents an effective surface area of the antenna that is defined as an exposed area of the loop to the incoming magnetic field. The effective antenna surface area is maximized when cos α becomes unity ($\alpha = 0°$), which occurs when the antennas of the base station and the transponder units are positioned in a face-to-face arrangement. In practical applications, the user might notice the longest detection range when the two antennas are facing each other and the shortest range when they are facing orthogonally.

Voltage is built up in an onboard storage capacitor, and when sufficient charge has accumulated to reach or surpass the circuit operating threshold voltage, the electronics power up and begin transmitting data back to the reader. Both the reader and the tag must use the same transmission method in order to synchronize and successfully exchange data. Two main methods of communication occur between the reader and tag; full duplex and half-duplex. In a full-duplex configuration, the tag communicates its data by modulating the reader's carrier wave by applying a resistive load. A transistor (load modulator) within the tag shorts the antenna circuit in sequence to the data, removing the antenna from resonance at the excitation frequency, thereby removing its power draw from the reader's carrier wave. At the reader side, the loading and unloading are detected and the data can be reconstructed. In a half-duplex RFID system, the carrier wave transmits power and then pauses. Within the pause, the tag transmits the data back to the reader.

For a given tag, the operating voltage obtained at a distance r from the reader is directly proportional to the flux density at that distance. The magnetic field emitted by the reader antenna decreases in power proportional to $1/r^3$ in the near field. Therefore, it can be shown that for a circularly coiled antenna, the flux density is maximized at a distance r (in meters) when:

$$a = \sqrt{2} \cdot r \tag{5.34}$$

where a is the radius of the reader's antenna coil. Thus, by increasing a the communication range of the reader can be increased, and the optimum reader antenna radius a is 1.41 times the demanded read range r.

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. Because most of the resonant circuit's tuning capacitance is located within the IC microchip where high capacitor Q can be realized, 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 capacitance losses) according to this equation:

$$Q = \frac{\omega L}{R_S} = \frac{1}{\omega CR} = \frac{\omega}{\omega_2 - \omega_1} \tag{5.35}$$

In general, the higher the *Q*, the higher the power output for a particular size of antenna. Unfortunately, too high a *Q* may conflict with the bandpass characteristics of the reader, and the increased ringing could create problems in the protocol bit timing. In (5.35), 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 20 to 80. The *Q* of the LC circuit is typically around 20 for an air-core inductor and about 40 for a ferrite-core inductor. 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.

Figure 5.7 shows the frequency response curve for a typical serial resonant tank circuit. A good rule of thumb is to stay within the –3-dB limits; the individual manufacturing tolerances for capacitance and inductance of 2%, a *Q* of 30, can be used. Lower tolerance components may be used at the expense of

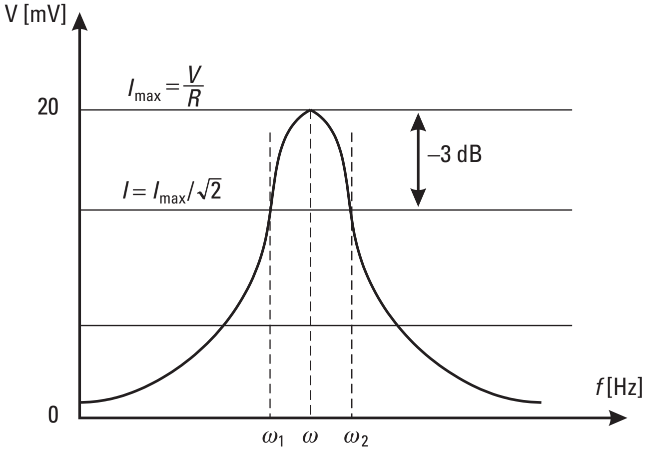


Figure 5.7 Frequency response curve for resonant tank circuit.

sensitivity and, thus, yield a lower range. The corresponding final design must accommodate a wider bandwidth and will, therefore, have a lower response.

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 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 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 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 the effect. Closely coupled tags can also have problems with commands signaled from the reader being misinterpreted due to cross-coupling between tags.

This rapid attenuation of the energizing and data communication field with increasing distance is the fundamental reason why 13.56-MHz passive RFID systems have a maximum reading distance on the order of about 1m (3 feet). This is also the reason why well-designed near-field RFID systems have good immunity to environmental noise and electrical interference. All of these characteristics are particularly well suited to many smart-label applications.

The efficiency of power transfer between the antenna coil of the reader and the transponder is proportional to the operating frequency, the number of windings, the area enclosed by the transponder coil, the angle of the two coils relative to each other, and the distance between the two coils. As frequency increases, the required coil inductance of the transponder coil—and thus the number of windings—decreases. For 135 kHz it is typically 100 to 1,000 windings, and for 13.56 MHz, typically 3 to 10 windings. Because the voltage induced in the transponder is still proportional to frequency, the reduced number of windings barely affects the efficiency of power transfer at higher frequencies.

5.3 Tags

5.3.1 Tag Considerations

There really is no such thing as a typical RFID tag. The read range is a balancing act between a number of engineering trade-offs and ultimately depends on many factors: the frequency of RFID system operation, the power of the reader, and interference from other RF devices. Several general RFID tag design requirements whose relative importance depends on tag application are discussed here. These requirements largely determine the criteria for selecting an RFID tag antenna:

- *Frequency band:* Desired frequency band of operation depends on the regulations of the country where tag will be used.
- *Size and form:* Tag form and size must be such that it can be embedded or attached to the required objects (cardboard boxes, airline baggage strips, identification cards, and so on) or fit inside a printed label (Figure 5.8).
- *Read range:* Minimum required read range is usually specified.
- *EIRP:* EIRP is determined by local country regulations (active versus passive tags).
- *Objects:* Tag performance changes when it is placed on different objects (e.g., cardboard boxes with various content) or when other objects are present in the vicinity of the tagged object. A tag's antenna can be designed or tuned for optimum performance on a particular object or designed to be less sensitive to the content on which the tag is placed.

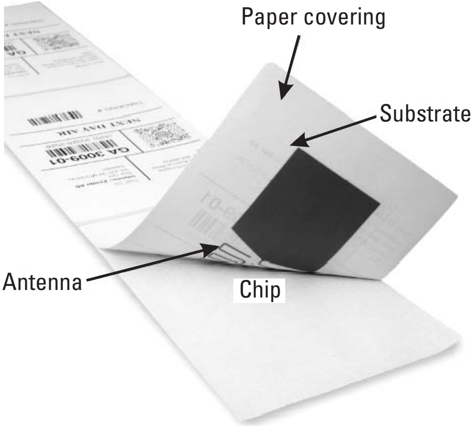


Figure 5.8 RFID label cross section.

- *Orientation (also called polarization):* The read range depends on antenna orientation. How tags are placed with respect to the polarization of the reader's field can have a significant effect on the communication distance for both HF and UHF tags, resulting in a reduced operating range of up to 50%, and in the case of the tag being displaced by 90° and not being able to read the tag at all. The optimal orientation for HF tags is for the two antenna coils (reader and tag) to be parallel to each other (Figure 5.9). UHF tags are even more sensitive to polarization due to the directional nature of the dipole fields. Some applications require a tag to have a specific directivity pattern such as omnidirectional or hemispherical coverage.

- *Applications with mobility:* RFID tags can be used in situations where tagged objects, such as pallets or boxes, travel on a conveyor belt at speeds up to either 600 feet/minute or 10 mph. The Doppler shift in this case is less than 30 Hz at 915 MHz and does not affect RFID operation. However, the tag spends less time in the read field of the RFID reader, demanding a high-read-rate capability. In such cases, the RFID system must be carefully planned to ensure reliable tag identification.

- *Cost:* The RFID tag must be a low-cost device, thus imposing restrictions both on antenna structure and on the choice of materials for its construction including the ASIC used. Typical conductors used in tags are copper, aluminum, and silver ink. The dielectrics include flexible polyester and rigid PCB substrates, such as FR4.

- *Reliability:* The RFID tag must be a reliable device that can sustain variations in temperature, humidity, and stress and survive such processes as label insertion, printing, and lamination.

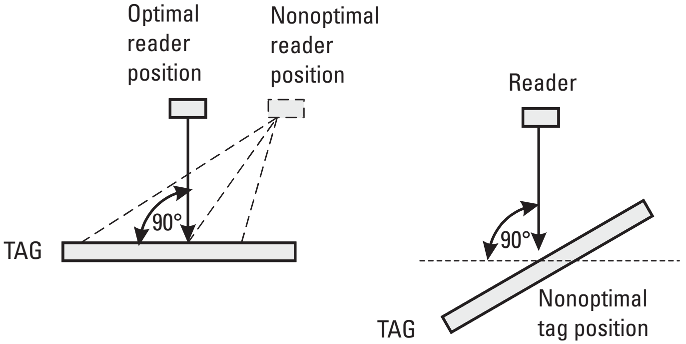


Figure 5.9 Optimal and nonoptimal tag and reader position.

- *Power for the tag:* An active tag has its own battery and does not rely on the reader for any functions. Its range is greater than that of passive tags. Passive tags rely on the reader for power to perform all functions, and semipassive tags rely on the reader for powering transmission but the battery for powering their own circuitry. For comparison, see Table 5.2.

5.3.2 Data Content of RFID Tags

5.3.2.1 Read-Only Systems

Read-only systems can be considered low end; these tags usually only contain an individual serial number that is transmitted when queried by a reader. These systems can be used to replace the functionality of barcodes. Due to the structural simplicity of read-only tags, costs and energy consumption can be kept down.

More advanced tags contain logic and memory, so they support writing and information can be updated or changed remotely. High-end tags have microprocessors enabling complex algorithms for encryption and security. More energy is needed for these than for less complex electronics.

One-bit tags can be detected, but they do not contain any other information. This is very useful for protecting items in a shop against shoplifters. A system like this is called electronic article surveillance (EAS) and has been in use since the 1970s. In practice, this system can be identified by the large gates of coils or antennas at the exits of shops.

Different principles of operation can be used for the one-bit tags. For example, the principle of the microwave tag is quite simple; it uses the generation of harmonics by diodes, that is, frequencies that are an integer times the original frequency. The tag is a small antenna that has a diode in the middle. Because the diode only lets current pass one way, the oscillations that get trapped behind the diode generate a frequency that is twice that of the original one. The system sends out a microwave signal, for example, 2.45 GHz, and listens for the first harmonics, that is, 4.90 GHz. If a tag is present, it generates harmonics that can be detected. However, false alarms may be caused by other

Table 5.2
Power for the Tag

Tag Type	Power Source	Memory	Communication Range
Active	Battery	Most	Greatest
Semipassive	Battery and reader	Moderate	Moderate
Passive	Reader	Least	Least

sources of this particular frequency. To avoid such false alarms, a modulation signal of, for example, 100 kHz is added to the interrogation signal. This means that the same modulating signal can also be found in any reflections from the tags. Microwave EAS tags are usually used to protect clothing. They are removed at the checkout and reused.

Read-only tags that contain more than 1 bit of data are simple ones that only contain a unique serial number that it transmits on request. The contents of the read-only chips are usually written during manufacturing. The serial number can, for example, be coded by cutting small bridges on the chip. Usually these simple chips also contain some logic for anticollision; that is, they allow multiple tags to be read simultaneously.

5.3.2.2 Read/Write Systems

Read/write systems specify what is possible in terms of read-only and read/write capability. It is worth remembering that many read-only tags are factory programmed and carry an identification number (tag ID). Other tags, including read/write devices, can also carry a tag identifier that is used to unambiguously identify a tag. This identifier is distinct from user-introduced identifiers for supporting other application needs.

Read-only devices are generally less costly and may be factory programmable as read only or one-time programmable (OTP). One-time programmability provides the opportunity to write once then read many times, thus supporting passport-type applications, in which data can be added at key points during the lifetime or usage of an item, and thus provide an incorruptible history or audit trail for the item data.

Some chips allow writing only once, and they are often referred to as write once/read many (WORM). These tags are versatile because they can be written with a serial number when applied to an item, instead of linking a predefined serial number to an item. More advanced chips allow both reading and writing multiple times, and the contents of a tag can be altered remotely by a scanner.

Read/write data carriers offer a facility for changing the content of the carrier as and when appropriate within a given application. Some devices will have both a read-only and a read/write component that can support both identification and other data carrier needs. The read/write capability can clearly support applications in which an item, such as a container or assembly support, is reusable and requires some means of carrying data about its contents or on what is being physically carried. It is also significant for lifetime applications such as maintenance histories, where a need is seen to add or modify data concerning an item over a period of time. The read/write capability may also be exploited within flexible manufacturing to carry and adjust manufacturing information and item-attendant details, such as component tolerances. A further important use of read/write is for local caching of data as a portable data file, using it as and when required, and selectively modifying it as appropriate to meet process needs.

Additionally, the chip must be able to resolve who can access it and prevent the wrong people from altering its contents. For secure data transmission, some kind of encryption is added as well.

Time to read is the time it takes to read a tag, which of course is related to the data transfer rate. For example, a system operating at a 1-Kbps transfer rate will take approximately 0.1 second to read a 96-bit tag, with a bit of time for the communication management. Various factors can influence read time, including competing readers and tags (reader access and multiple tags).

5.3.3 Passive Tags

5.3.3.1 About Passive Tags

Passive RFID devices have no power supply built in, meaning that electrical current transmitted by the RFID reader inductively powers the device, which allows it to transmit its information back. Because the tag has a limited supply of power, its transmission is much more limited than an active tag, typically no more than simply an ID number. Similarly, passive devices have a limited range of broadcast, requiring the reader to be significantly closer than an active one would. Uses for passive devices tend to include things such as inventory, product shipping and tracking, use in hospitals and for other medical purposes, and antitheft, where it is practical to have a reader within a few meters or so of the RFID device. Passive devices are ideal in places that prevent the replacement of a battery, such as when implanted under a person's skin.

Tags consist of a silicon device (chip) and antenna circuit (Figure 5.10). The purpose of the antenna circuit is to induce an energizing signal and to send a modulated RF signal. The read range of a tag largely depends on the antenna circuit and size. The antenna circuit is made of an LC resonant circuit or E-field dipole antenna, depending on the carrier frequency. The LC resonant circuit is

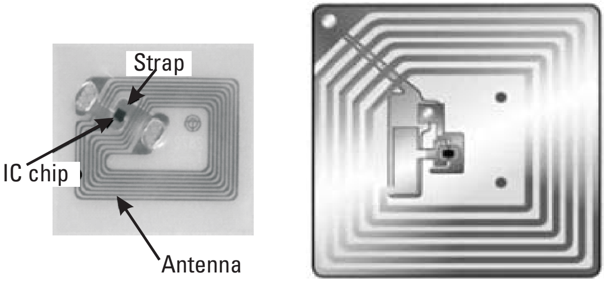


Figure 5.10 13.56-MHz RFID tags.

typically used for frequencies of less than 100 MHz. In this frequency band, the communication between the reader and tag takes place with magnetic coupling between the two antennas through the magnetic field. An antenna utilizing inductive coupling is often called a *magnetic dipole antenna*. The antenna circuits must be designed in such a way as to maximize the magnetic coupling between them. This can be achieved with the following parameters:

- The LC circuit must be tuned to the carrier frequency of the reader.
- The *Q* of the tuned circuit must be maximized.
- The antenna size must be maximized within the physical limits of application requirements.

The passive RFID tags sometimes use backscattering of the carrier frequency for sending data from the tag to the reader. The amplitude of the backscattering signal is modulated with modulation data from the tag device. The modulation data can be encoded in the form of ASK (NRZ or Manchester), FSK, or PSK. During *backscatter modulation*, the incoming RF carrier signal to the tag is loaded and unloaded, causing amplitude modulation of the carrier corresponding to the tag data bits. The RF voltage induced in the tag's antenna is amplitude modulated by the modulation signal (data) of the tag device. This amplitude modulation can be achieved by using a modulation transistor across the LC resonant circuit or partially across the resonant circuit. Changes in the voltage amplitude of the tag's antenna can affect the voltage of the reader antenna. By monitoring the changes in the reader antenna voltage (due to the tag's modulation data), the data in the tag can be reconstructed. (See Chapter 6 for more details on modulation.)

The RF voltage link between the reader and tag antennas is often compared to weakly coupled transformer coils; as the secondary winding (tag coil) is momentarily shunted, the primary winding (reader coil) experiences a momentary voltage change. Opening and shunting the secondary winding (tag coil) in sequence with the tag data is seen as amplitude modulation at the primary winding (reader coil).

5.3.3.2 RFID Chip Description

An RFID tag consists of an RFID chip, an antenna, and tag packaging. The RFID circuitry itself consists of an RF front end, some additional basic signal processing circuits, logic circuitry to implement the algorithms required, and EEPROM for storage. The RFID chip is an integrated circuit implemented in silicon [5]. The major blocks and their functions of the RFID front end are as follows:

- *Rectifier:* Generates the power supply voltage for front-end circuits and the whole chip, as well from the coupled EM field;
- *Power (voltage) regulator:* Maintains the power supply at a certain level and at the same time prevents the circuit from malfunctioning or breaking under large input RF power;
- *Demodulator:* Extracts the data symbols embedded in the carrier waveforms;
- *Clock extraction or generation:* Extracts the clock from the carrier (usually in HF systems) or generates the system clock by means of some kind of oscillator;
- *Backscattering:* Fulfills the return link by alternating the impedance of the chip;
- *Power on reset:* Generates the chip's power-on reset (POR) signal;
- *Voltage (current) reference:* Generates some voltage or current reference for the use of front-end and other circuit blocks, usually in terms of a bandgap reference;
- *Other circuits:* These include the persistent node or short-term memory (or ESD).

Figure 5.11 is a block diagram for RFID IC circuits and lists many of the circuit's associated function blocks. The RF front end is connected to the antenna, and typically, at UHF, an electric dipole antenna is used, while HF tags use a coil antenna. The front-end circuitry impacts the semiconductor process by requiring a process that allows for mixed-mode fabrication. Passive RF tags have no power source and rely on the signal from the reader to power up; thus, the RF front end implements modulators, voltage regulators, resets, and connections to an external antenna. RFID chips have control logic that typically consists of a few thousand gates. The lowest level chip uses very few gates, on the order of 1,500 gate equivalents. Functions in the logic include the error and parity/CRC checkers, data encoders, anticollision algorithms, controllers, and command decoders. More complex RFID chips may include security primitives and even tamperproofing hardware. The size of the circuit affects the number of mask, metal, and poly layers required in the semiconductor process, and RFID systems usually use CMOS.

A certain amount of information is stored on-chip in an EEPROM. The size of this EEPROM increases as more information is required to be on the RFID chip. The size of the required EEPROM is a factor in determining the number of mask, metal, and poly layers required in the semiconductor fabrication process. It is also a factor in determining the size of the final semiconductor die. Silicon cost is directly proportional to both the die size and the number of

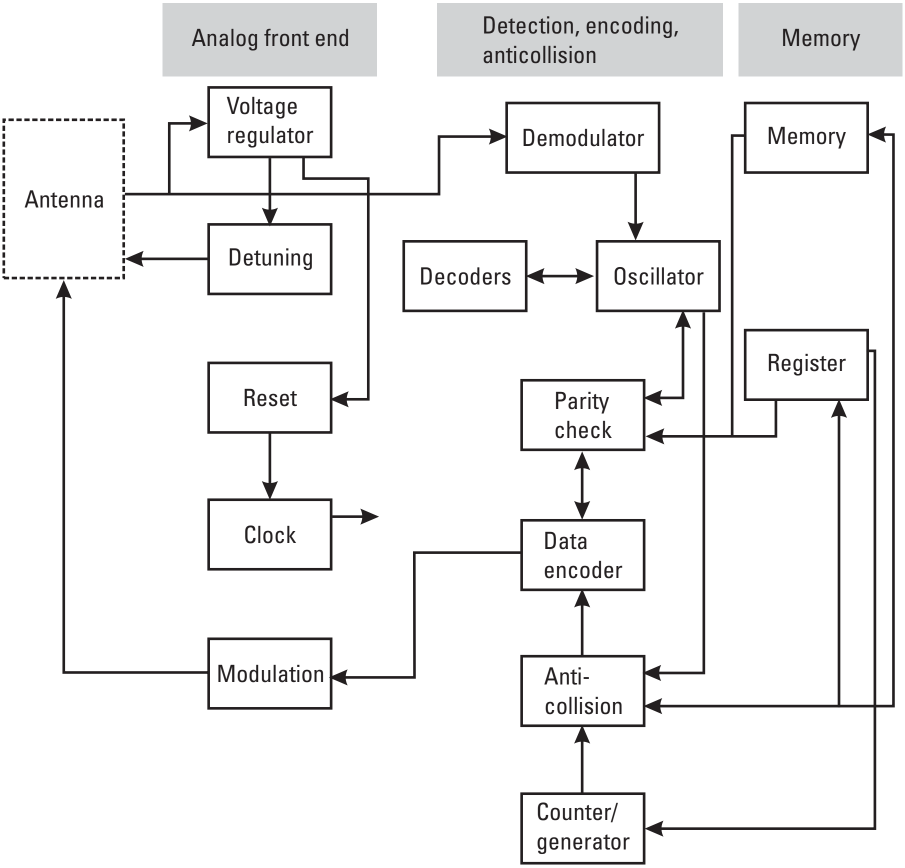


Figure 5.11 RFID tag circuit block diagram.

mask, metal, and poly metal layers. The IC in an RFID tag must be attached to an antenna to operate. The antenna captures and transmits signals to and from the reader. The coupling from the reader to the tag provides both the transmission data and the power to operate the passive RFID tag. Typically, antennas for passive RFID systems can be either simple dipole, 915-MHz RFID tags or more complex coiled shapes for 13.56-MHz systems.

The digital anticollision system is one of the major and most important parts of the tag chip, because it not only implements the slotted ALOHA random anticollision algorithm, but also executes the read/write operation of memory. As we know, the power consumption of memory is very difficult to reduce. Even more, besides the power consumption, the efficiency of the RF front-end rectifier prefers lower output dc voltage. So it is very important to design a low-power, low-voltage digital anticollision system to achieve maximum operating range.

Currently, antennas are made of metals or metal pastes and typically cost as much as 12 cents per antenna to manufacture. However, new methods that range from conductive inks to new antenna deposition and stamping techniques are expected to reduce costs below 1 cent.

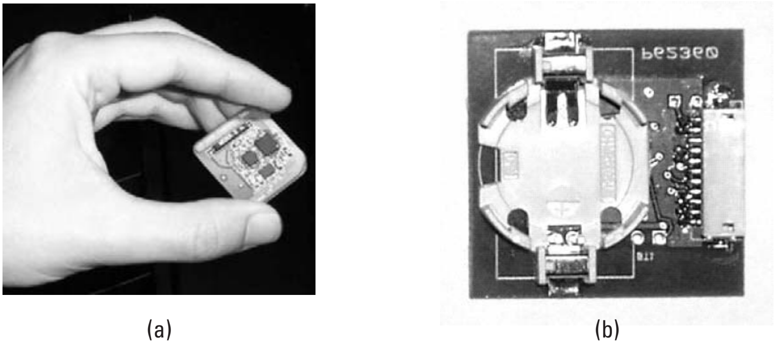
5.3.4 Active Tags

5.3.4.1 Active Tag Description

An active tag usually performs a specialized task and has an on-board power source (usually a battery). It does not require inductions to provide current, as is true of the passive tags. The active tag can be designed with a variety of specialized electronics, including microprocessors, different types of sensors, or I/O devices (Figure 5.12). Depending on the target function of the tag, this information can be processed and stored for immediate or later retrieval by a reader. Active RFID tags, also called *transponders* because they contain a transmitter that is always on, are powered by a battery about the size of a coin and are designed for communications up to 100 feet from the RFID reader. They are larger and more expensive than passive RFID tags, but can hold more data about the product and are commonly used for high-value asset tracking. A feature that most active tags have and most passive tags do not is the ability to store data received from a transceiver.

Active tags are ideal in environments with electromagnetic interference because they can broadcast a stronger signal in situations that require a greater distance between the tag and the transmitter.

The additional space taken up by a battery in an active device necessitates that the active devices be substantially larger than the passive devices. To date, commercially available passive tags are as small as 0.4 mm square and thinner than a sheet of paper. In contrast, commercially available active tags are still only



(a) (b)

Figure 5.12 Active tag (a) front and (b) reverse sides.

as small as a coin, which means that active tags are around 50 times the size of passive ones.

For the *read-only device*, the information that is in the memory cannot be changed by an RF command once it has been written. A device with memory cells that can be reprogrammed by RF commands is called a *read/write device*. The information in the memory can be reprogrammed by an interrogator command.

Although passive tags can only respond to an electromagnetic wave signal emitted from a reader, active tags can also spontaneously transmit an ID. There are various types of unscheduled transmission types, such as when there are changes in vibration or temperature or when a button is pushed.

A semiactive or semipassive (depending on the manufacturer) tag also has an on-board battery. The battery in this case is only used to operate the chip. Like the passive tag, it uses the energy in the electromagnetic field to wake up the chip and to transmit the data to the reader. These tags are sometimes called battery-assisted passive (BAP) tags.

5.3.4.2 Active Tag Classification

Two types of tag systems can generally be recognized within active RFID systems:

- *Wake-up tag systems* are deactivated, or asleep, until activated by a coded message from a reader or interrogator. In the sleep mode, limiting the current drain to a low-level alert function conserves the battery energy. Where larger memories are accommodated, there is also generally a need to access data on an object or internal file basis to avoid having to transfer the entire amount of data so held. These are used in toll payment collection, checkpoint control, and in tracking cargo.
- *Awake tag or beacon systems* are, as the term suggests, responsive to interrogation without a coded message being required to switch the tag from an energy conservation mode. However, they generally operate at lower data transfer rates and memory sizes than wake-up tags, so they conserve battery energy in this way. (A greater switching rate is generally associated with higher energy usage.) This type of tag is the most widely used of the two, and because of lower component costs it is generally less expensive than a wake-up tag system. Beacons are used in most real-time locating systems (RTLS), where the precise location of an asset needs to be tracked. In an RTLS, a beacon emits a signal with its unique identifier at preset intervals, every 3 seconds or once a day, depending on how important it is to know the location of an asset at a particular moment in time.

5.3.5 Active Versus Passive Tags

Active RFID and passive RFID technologies, while often considered and evaluated together, are fundamentally distinct technologies with substantially different capabilities. In most cases, neither technology provides a complete solution for supply chain asset management applications; rather, the most effective and complete supply chain solutions leverage the advantages of each technology and combine their use in complementary ways. Passive RFID is most appropriate where the movement of tagged assets is highly consistent and controlled and little or no security, sensing capability, or data storage is required. Active RFID is best suited where business processes are dynamic or unconstrained, movement of tagged assets is variable, and more sophisticated security, sensing, and/or data storage capabilities are required.

Passive and active tagging systems present very different deployment issues. Active tags contain significantly more sophistication, data management, and security concerns. Active tags generally cost from \$10 to \$50, depending on the amount of memory, the battery life required, any on-board sensors, and the ruggedness.

5.3.6 Multiple Tag Operation

If many tags are present, then they will all reply at the same time, which at the reader end is seen as a signal collision and an indication of multiple tags. The reader manages this problem by using an anticollision algorithm designed to allow tags to be sorted and individually selected. The many different types of algorithms (Binary Tree, ALOHA, and so on) are defined as part of the protocol standards. The number of tags that can be identified depends on the frequency and protocol used, and can typically range from 50 tags per second for HF up to 200 tags per second for UHF. Once a tag is selected, the reader is able to perform a number of operations, such as reading the tag's identifier number or, in the case of a read/write tag, writing information to it. After finishing its dialogue with the tag, the reader can then either remove it from the list, or put it on standby until a later time. This process continues under control of the anticollision algorithm until all tags have been selected.

When containers of freight are moved on a conveyor or similar equipment in a tag reader system, the reader/writer must read and write data to and from moving tags (Figure 5.13). For successful access, the following conditions must be satisfied (5.32):

$$T_c = A_{cn} \times \left(D_t / D_r \right) \tag{5.36}$$

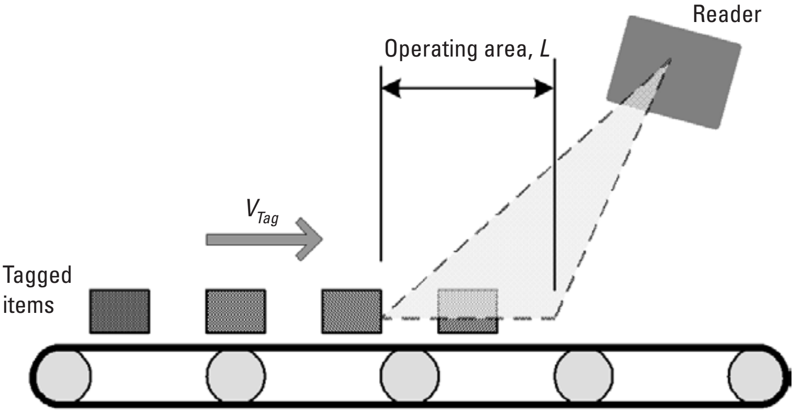


Figure 5.13 Reading moving tags.

This formula shows that when the data transfer volume of the tag D_t increases and the data transfer rate D_r decreases, the tag-reader/writer operation time T_c increases, and operation may fail.

$$T_r = L/V_{Tag} \tag{5.37}$$

Equation (5.37) shows that when the reader/writer operating area decreases, the distance the tag moves (L) decreases, and the tag movement velocity V_{Tag} increases, the amount of time the tag is in the operating area (T_r) decreases, and the operation may fail.

$$T_r \geq T_c + T_d \tag{5.38}$$

Last, (5.38) states that the total amount of time spent in the operating area must be more than the total time taken by the reader/writer and the detection of all tags. If only one type of tag can be used when reading/writing RFID tags attached to freight on a conveyor belt, the reader/writer antenna must have a large operating area to cope with the conveyor belt's speed:

T_r [seconds] = amount of time tag is in operating area;

T_c [seconds] = tag-reader/writer operation time;

D_r [bps] = data transfer rate;

D_t [bit] = data transfer volume;

A_{cn} [count] = average number of tag-reader/writer operations;

V_{Tag} [m/second] = tag movement velocity;

L [m] = distance tag moves within operating area;

T_d [seconds] = amount of time for detecting existence of all tags.

Virtually all high-volume RFID applications require the ability to read multiple tags in the reading field at one time. This is only possible if each RFID tag has a unique ID number. One numbering method is the EPC code, which contains both an item ID number and a serial number. A unique number is the basis for implementing anticollision in any RFID technology. In a multiple-tag operation, where multiple RFID tags are in the reader/writer's operating area, the reader/writer must detect the presence of these multiple tags and read/write each of them consecutively (Figure 5.14). This operating method is generally referred to as the *anticollision protocol* and is different from the single-tag operation protocol.

The effects of operating range, tag orientation, tag movement velocity, and the presence of metallic substances on multiple-tag operating characteristics are basically the same as those on single-tag operating characteristics. One problem with multiple-tag operating characteristics is that the operating time is several times longer than for single-tag operation. Because the reader/writer must read/write each tag, the time increases in proportion to the number of tags. Also,

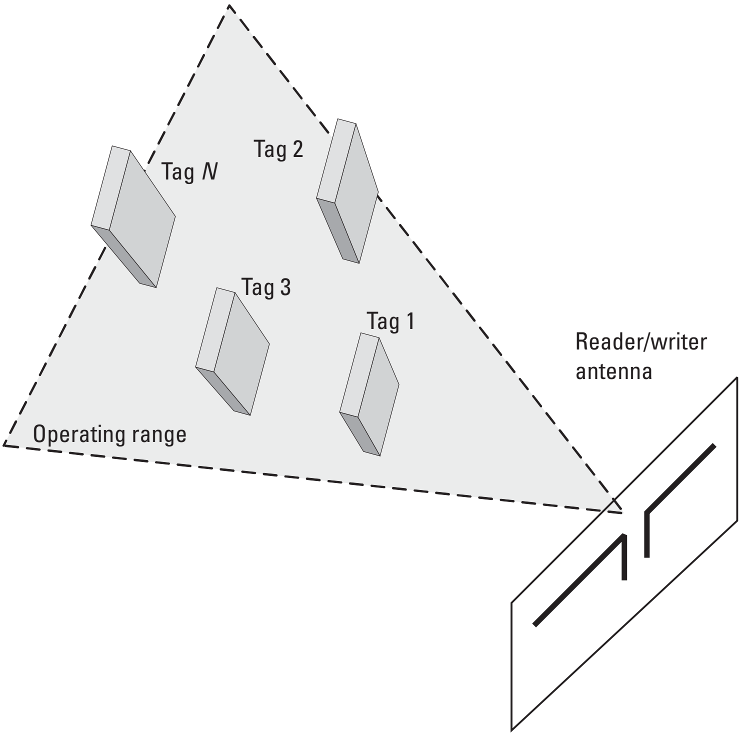


Figure 5.14 Multiple-tag operation.

because multiple tags are used, tags sometimes come into contact or overlap with each other. When there are N tags in the operating area and N_{tag} is the number of tags, the amount of time for which the tags must be in the operating area (T_r) is described by (5.39):

$$T_r \geq \left(T_c + T_{tag}\right) \times N_{tag} \tag{5.39}$$

Although the reader/writer may sometimes read/write stationary tags, in most cases, the tag will be moving. The reader/writer will generally have to read/write RFID tags attached to containers or freight being transported on a conveyor belt or trolleys. When T_c is the operating time for a single tag and T_d is the time required to check for the existence of N multiple tags in an anticollision protocol, (5.40) gives an approximation of the maximum time required for the reader/writer to read/write all N tags (T_N):

$$T_N = (T_c + T_d) \times N_{tag} \tag{5.40}$$

Example:

Tag information volume = 16 bytes;

Data transfer rate (D_r) = 7.8 Kbps;

$T_c = 0.057$ second;

$T_d = 0.055$ second;

$N = 10$;

$T_N = (0.057 + 0.055) \times 10 = 1.12$ seconds.

Therefore, roughly 1.1 seconds are needed for the reader/writer to finish reading/writing all 10 tags. When the tag information volume is 100 bytes, T_N becomes roughly 7 seconds. For the reader/writer to read/write all the tags, the time required for the tags to pass through the operating area (T_r) must be greater than T_N.

One unfortunate but real fact about RFID tags is that the quality of tags is currently not consistent, and therefore performance is not consistent. Considerable variations are seen in performance from one tag to the next, even among tags from the same manufacturer and model.

5.3.7 Overlapping Tags

In inductive frequency band RFID, the resonance characteristic of the tag antenna coil is used for reader/writer operation. As discussed earlier, a tag's resonant frequency f_0 is calculated by (5.41):

$$f_0 = 1/2\pi\sqrt{LC} \tag{5.41}$$

where L [H] is the inductance of tag antenna coil and C [F] is the capacitance of the tag's tuning capacitor.

If tags overlap, the inductance of their antenna coils is obstructed, and L increases. In this case, the resonant frequency expressed by the formula becomes lower ($f_1 < f_0$). As a result, the electromagnetic waves (current i) generated by the tag's coil become smaller, and the operating area decreases (Figure 5.15).

5.3.8 Tag Antennas

5.3.8.1 Antenna Selection

An antenna is a conductive structure specifically designed to couple or radiate electromagnetic energy. Antenna structures, often encountered in RFID systems, may be used to both transmit and receive electromagnetic energy, particularly data-modulated electromagnetic energy. In the low-frequency (LF) range

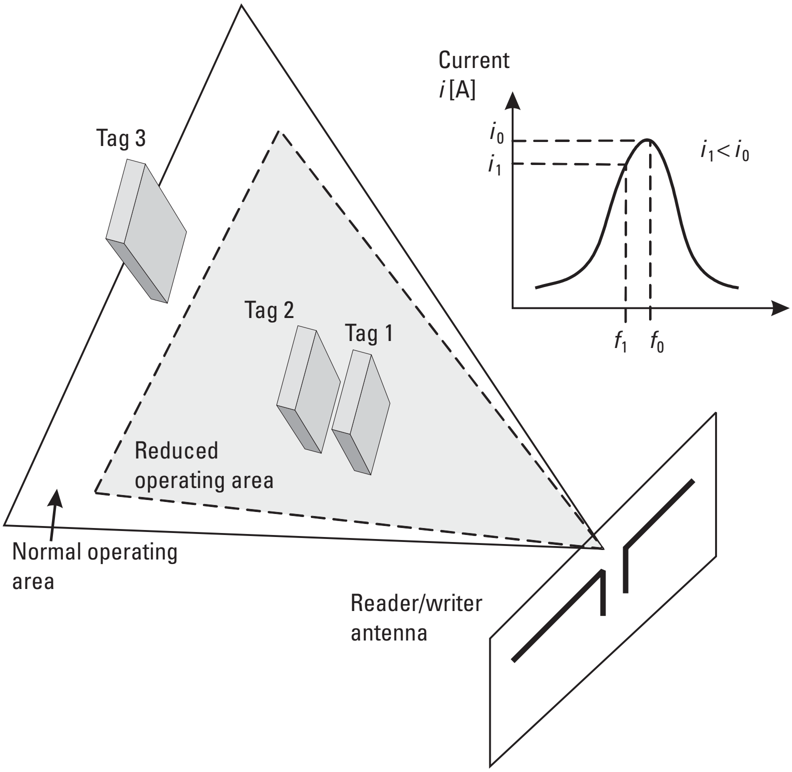


Figure 5.15 Overlapping tags.

with short read distances, the tag is in the near field of the reader antenna, and the power and signals are transferred by means of a magnetic coupling. In the LF range, the tag antenna therefore comprises a coil (inductive loops) to which the chip is attached. In the UHF range, in cases where the read distances are larger, the tag is located in the far field of the reader antenna. The reader and tag are coupled by the electromagnetic wave in free space, to which the reader and tag are tuned by means of appropriate antenna structures.

Good antenna design is a critical factor in obtaining good range and stable throughput in a wireless application. This is especially true in low-power and compact designs where antenna space is less than optimal. It is important to remember that, in general, the smaller the antenna, the lower the radiation resistance and the lower the efficiency. The tag antenna should be as small as possible and easy to produce.

Printed antennas are really very easy to produce. The antenna is attached as a flat structure to a substrate. The next stage in the production process often involves attaching the chip to the substrate and connecting it to the antenna. This assembly is called an inlay. An inlay becomes a tag or transponder when it is fixed to an adhesive label or a smart card. Note, however, that the electromagnetic properties of the materials surrounding the inlay affect the tag's ability to communicate. In extreme cases, tags cannot be read if unsuitable reader antennas are selected.

Another type of usage involves integration into the object that is to be identified. Parts of the object can be shaped to form an antenna and the antenna can be adjusted optimally to suit the object. This significantly increases readability, while simultaneously protecting against counterfeiting.

The size and shape of the tag antenna have a significant effect on tag read rates, regardless of the coupling used for communication. Various types of antennas are available, among which the most commonly used are dipole, folded dipole, printed dipole, printed patch, squiggle, and log-spiral. Among these, the dipole, folded dipole, and squiggle antennas are omnidirectional, thus allowing them to be read in all possible tag orientations, relative to the base antenna. On the other hand, directional antennas have a good read range due to their good resistance to radiation patterns. Care must be taken while choosing an antenna because the antenna impedance must match to the ASIC and to free space. The four major considerations when choosing an antenna are as follows:

- Antenna type;
- Antenna impedance;
- Nature of the tagged object;
- Vicinity of structures around the tagged object.

When individual system performance is not satisfactory, it is advisable to bring redundancy to the system. Low read rates of RFID systems make the deployment of redundant antennas and tags to identify the same object an imperative. Redundant tags are those tags that carry identical information performing identical functions. Dual tags are tags connected to each other that have one or two antennas and are with or without individual or shared memory; *n* tags serving the same purpose as that of dual tags can be used for beneficial use of multiple tags in product identification. It has been observed that both the inductive coupling and backscatter-based tags are dependent on the angle of orientation of the tag relative to the reader. The placement of two tags in two flat planes, three tags in the three-dimensional axes, four tags along the faces of a regular tetrahedron, and so on, can help in achieving the above-mentioned goals.

The choice of an etched, printed, or stamped antenna is a trade-off between cost and performance. For a 13.56-MHz tag, the *Q* factor of the antenna is very important for long read range applications. The *Q* factor is inversely proportional to the resistance of the antenna trace. It has been determined that the etched antenna is less resistive and inexpensive than the printed antenna with conductive material. However, for a very large antenna size (greater than 4 × 4 inches), both etching and stamping processes waste too much unwanted material. Therefore, printed or wired antennas should be considered as an alternative.

As previously stated, reducing antenna size results in reduced performance. Some of the parameters that suffer are reduced efficiency (or gain), shorter range, smaller useful bandwidth, more critical tuning, increased sensitivity to component and PCB spread, and increased sensitivity to external factors. Several performance factors deteriorate with miniaturization, but some antenna types tolerate miniaturization better than others. How much a given antenna can be reduced in size depends on the actual requirements for range, bandwidth, and repeatability. In general, an antenna can be reduced to half its natural size with moderate impact on performance.

5.3.8.2 Loop Antennas

RFID tags extract all of their power to both operate and communicate from the reader's magnetic field. Coupling between the tag and reader is via the mutual inductance of the two loop antennas, and the efficient transfer of energy from the reader to the tag directly affects operational reliability and read/write range. Generally, both 13.56-MHz and 125-kHz RFID tags use parallel resonant LC loop antennas tuned to the carrier frequency. The RFID circuit is similar to a transformer in which loop inductors magnetically couple when one of the loops, in the case of the reader antenna, is energized with an alternating current, thus creating an alternating magnetic field. The tag loop antenna acts like the secondary winding of a transformer, where an alternating current is induced in the antenna, extracting energy from the magnetic field. Generally, the larger the diameter of the tag's antenna loop, the more magnetic flux lines that are passing through the coil and increasing the transfer of energy from the reader to the tag.

Loop antennas can be divided in three groups:

1. Half-wave antennas;
2. Full-wave antennas;
3. Series-loaded, short-loop antennas.

where *wave* refers to the approximate circumference of the loop.

The *half-wave loop* consists of a loop approximately one-half wavelength in circumference with a gap cut in the ring. It is very similar to a half-wave dipole that has been folded into a ring, and most of the information about the dipole applies to the half-wave loop. Because the ends are very close together, some capacitive loading exists, and resonance is obtained at a somewhat smaller circumference than expected. The feedpoint impedance is also somewhat lower than the usual dipole, but all of the usual feeding techniques can be applied to the half-wave loop. By increasing the capacitive loading across the gap, the loop can be made much smaller than one-half wavelength. At heavy loading, the loop closely resembles a single-winding, LC-tuned circuit. The actual shape of the loop is not critical, and typically the efficiency is determined by the area enclosed by the loop. The half-wave loop is popular at lower frequencies, but at higher frequencies, the tuning capacitance across the gap becomes very small and critical.

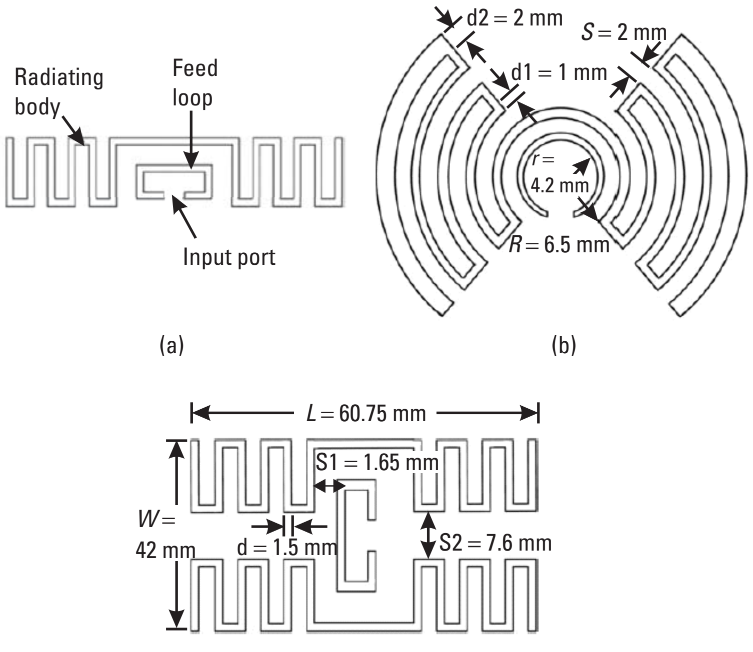
As the name implies, the *full-wave loop* is approximately one wavelength in circumference. Resonance is obtained when the loop is slightly longer than one wavelength. The full-wave loop can be thought of as two end-connected dipoles. Like the half-wave loop, the shape of the full-wave loop is not critical, but efficiency is determined mainly by the enclosed area. The feed impedance is somewhat higher (approximately 120Ω) than the half-wave loop. Loading is accomplished by inserting small coils or hairpins in the loop, which reduces the size. Like the dipole and half-wave loop, numerous impedance-matching methods exist, including gamma matching and tapering across a loading coil or hairpin. The main advantage of the full-wave loop is that it does not have the air gap in the loop, which is very sensitive to load and PCB capacitance spread.

Loaded-loop antennas are commonly used in remote control and remote keyless entry (RKE) applications. The loop is placed in series with an inductor, which reduces the efficiency of the antenna but shortens the physical length.

5.3.8.3 UHF Antennas

A typical inductively coupled feeding structure is shown in Figure 5.16(a) where the antenna consists of a feeding loop and a radiating body. Two terminals of the loop are connected to the chip, and the feed is combined with the antenna body with mutual coupling. For example, if the measured impedance of the selected IC is 73 − *j*113, the load antenna impedance should be 73 + *j*113 for conjugate matching. To achieve this, the proposed antenna structure is shown in Figure 5.16(b), with the dipole arms bent into an arc shape [6].

Another way to achieve high resistance with an inductively coupled feeding structure is to introduce extra radiating elements. A dual-body configuration is presented in Figure 5.16(c). Two meandering line arms are placed in each side of the feeding loop. The slight decrease of mutual coupling is due to the shorter coupling length. However, strong mutual coupling is now introduced between the two radiating bodies, which can be similarly regarded as being in a parallel connection seen from the feeding loop. In this way, resistance of the radiating body is significantly reduced, resulting in high resistance with meandering line arms.



(a) (b)

(c)

Figure 5.16 UHF antennas: (a) typical configuration, (b) arc configuration, and (c) dual-body configuration.

This antenna can be easily tuned by trimming. Lengths of meander trace and loading bar can be varied to obtain optimum reactance and resistance matching. The trimming is realized by punching holes through the antenna trace at defined locations. Such a tunable design is desirable when a solution is needed for a particular application with minimal lead time.

5.3.8.4 Fractal Antennas

Short reading distances and the fact that the cost per tag is still too high are the major reasons that passive RFID systems have not made their breakthrough yet. One key to greater reading distances is improvements in the tag antenna. Because a passive tag does not have its own power supply, it is important that the tag antenna is able to absorb as much of the energy, radiated from the reader, as possible. Another important parameter to minimize is the size of the tags. Small tags and hence small tag antennas will increase the range of areas in which RFID devices can be employed. The trade-off to designing small, effective antennas is that small antennas are generally poor radiators. A factor that affects the size of the tags is the frequency that is used. Different frequency bands are allocated for RFID and these bands differ in different regions of the world. From an economic point of view, it is highly desirable to be able to use only one type of tag in all of the different regions.

In the study of antennas, fractal antenna theory is a relatively new area. However, fractal antennas and their superset, fractal electrodynamics, are a hotbed of research activity these days. The term *fractal* means linguistically broken or fractured and is from the Latin *fractus.* Fractals are geometrical shapes, which are self-similar, repeating themselves at different scales [7]. Many mathematical structures are fractals, for example, Sierpinski's gasket, Cantor's comb, von Koch's snowflake, the Mandelbrot set, and the Lorenz attractor. Fractals also describe many real-world objects, such as clouds, mountains, turbulence, and coastlines that do not correspond to simple geometric shapes. The terms *fractal* and *fractal dimension* come from Mandelbrot, who is the person most often associated with the mathematics of fractals [8].

Fractal antennas do not have any characteristic size; fractal structures with a self-similar geometric shape consisting of multiple copies of themselves on many different scales have the potential to be frequency-independent or at least multifrequency antennas. For example, it has been shown that a bow-tie antenna can operate efficiently over different frequencies and that the bands can be chosen by modifying the structure. Examples of wideband antennas are the classical spiral antennas and the classical log-periodic antennas, which can also be classified as fractal antennas.

Fractal antennas are convoluted, uneven shapes, and sharp edges, corners, and discontinuities tend to enhance the radiation of electromagnetic energy from electric systems. Fractal antennas, therefore, have the potential to be efficient. This is particularly interesting when small antennas are to be designed, because small antennas are not generally good at radiating electromagnetic energy. Some fractals have the property that they can be very long but still fit in to a certain volume or area. Because fractals do not have a dimension that is an integer (e.g., it can be something between a line and a plane), they can more effectively fill some volume or area at deposal. Small antennas generally have a very small input resistance and a very significant negative input reactance. This means that small antennas are poor radiators. It has been shown that many small fractal antennas have greater input resistance and smaller input reactance than small traditional antennas. Also, the *Q* factor of small antennas depends on how effectively the antenna occupies a certain radian sphere. Small fractal antennas can thus be expected to have lower *Q* factors than their regular counterparts and, hence, higher bandwidths.

Small input resistance and large input reactance also mean that it is difficult (and expensive) to match the antenna input impedance with a matching network. It has been shown that many fractal antennas can even resonate with a size much smaller than the regular ones. Hence, it is possible to reduce or even eliminate the cost associated with input impedance matching. By shaping antennas in certain ways, the directivity can be improved. Fractal antennas are shaped antennas. In some RFID applications where the tag orientation can be controlled, it is possible that antennas with high directivity would be preferred to achieve long reading distances and/or to avoid problems associated with scanning several tags simultaneously. It is also possible that in some applications a small handheld reader with a high directivity antenna would be desirable.

Because frequency-independent antennas and wideband antennas tend to be insensitive to deformations like cutting in the structure and bending of the structure, one might expect some fractal antennas to be resistant against deformations, too.

5.3.9 UHF Tag Circuits

5.3.9.1 Tag DC Supply Voltage Circuitry

The voltage multiplier converts a part of the incoming RF signal power to dc for power supply for all active circuits on the chip (Figure 5.17). The specially designed Schottky diodes with low series resistance allow for high-efficiency conversion of the received RF input signal energy to dc supply voltage.

The voltage multiplier circuit shown here is sometimes also called a *charge pump* in the context of memory ICs. A charge pump is a circuit that when given an input in ac is able to output a dc voltage typically larger than a simple rectifier would generate. It can be thought of as an ac-to-dc converter that both rectifies the ac signal and increases the dc level. It is the foundation of power converters such as the ones that are used for many electronic devices today. In this case, for

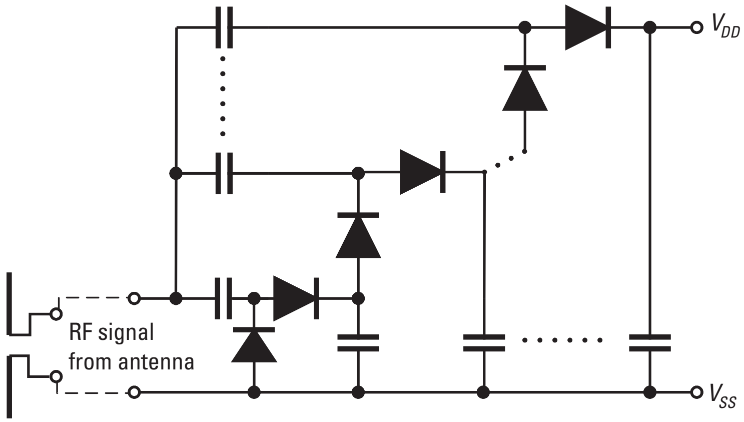


Figure 5.17 Input signal conversion to dc supply voltage.

the RF signal, all of the diodes are connected in parallel (or antiparallel) by the capacitors. For dc, however, they are connected in series to allow a dc current flowing between terminals. The voltage generated between these nodes is approximately equal to:

$$V_{DD} = n(V_{\mathrm{RF}} - V_D) \tag{5.42}$$

where n is the number of diodes, V_{RF} is the amplitude of the RF input signal, and V_D is the forward voltage of the Schottky diodes (approximately 200 mV at 7 μA).

The input impedance is mainly determined by the junction and substrate capacitances of the Schottky diodes. The real part of the impedance is much lower than the imaginary part and is strongly dependent on the dc current taken from the output. For a typical operating point, the real part of the impedance is approximately 30 times lower than the imaginary (capacitive) part. In other words, the IC's input capacitance has a quality factor of 30, placing high demands on the antenna, which needs to be matched to the IC's input impedance for sufficiently good power efficiency. The design parameters of the voltage multiplier are a trade-off between power efficiency, useful impedance, and operating point (load). Optimization parameters include the number of stages, the size of the Schottky diodes, and the size of the coupling capacitors.

5.3.9.2 Tag Wake-Up Circuit Principles

The interrogation of active RFID tags will inevitably involve the development of a mechanism for turning on the tags because power conservation is an important factor that requires the tags to be turned off when not being interrogated. This will also be true for active sensors and sensor networks [9]. There are two practical options for turn-on circuit design:

- Rectifier circuits that can produce, from the RF field, a rectified voltage of the order of 1V, which will turn a CMOS transistor from fully off to fully on;
- Rectifier circuits that can produce, from the RF field, a rectified voltage on the order of 5 mV, which when compared to an internal reference voltage can be used to trigger a transistor from the fully off to the fully on state.

Schottky diodes have been widely used in microwave networks because of their excellent high-frequency behavior. For microwave applications, these Schottky diodes are usually fabricated in specialized processes where barrier heights, capacitances, and other parameters can be fully controlled. However, the RFID application demands a low-cost solution, which would tend toward using the standard CMOS processes. However, the problem is that most of the standard CMOS processes do not support the Schottky diode. We have to modify the processes so as to incorporate the Schottky diodes; several research works have been published on standard CMOS processes that are compatible with Schottky diodes. A Schottky junction is relatively delicate and sensitive to excessive RF power, and RFID applications may work in poorly controlled environments where high power may cause the diode to burn out. Hence, in an application it is important to use power limiters to protect the sensitive Schottky diode.

The battery powering active transponders must last for an acceptable time, so the electronics of the label must have very low current consumption in order to prolong the life of the battery. However, due to circuit complexity or the desired operating range, the electronics may drain the battery more rapidly than desired, but use of a turn-on circuit allows the battery to be connected only when communication is needed, thus lengthening the life of the battery. The turn-on circuit shown in Figure 5.18 is adequate and cost effective for a backscattering active tag.

Here, a *p*-channel FET was used as a switch to control the power supply to a label control circuits and can be triggered by the incident RF 915-MHz radiation on the antenna. Thus, the power generated and amplified by the diode resonance can be utilized to turn a *p*-channel FET from an off state to an on state. The turn-on circuit performs adequately at a minimum power of –43 dBW at the resonant frequency of 915 MHz.

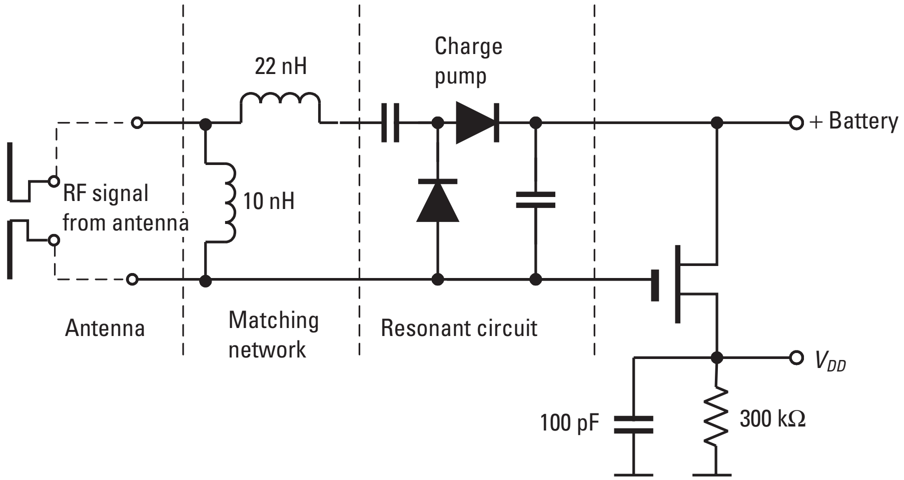


Figure 5.18 Turn-on circuit for the active UHF tag.

5.3.10 Tag Manufacturing Process

The major processes involved in the manufacture of RFID tags are the antenna production process and chip assembly. Both of these activities have gone through serious development in the last few years with the purpose of increasing the throughput and reducing the final cost of the tag.

5.3.10.1 Antenna Production Process

The most popular processes currently on the market for the production of bidimensional antennas are chemical etching and conductive ink printing. *Chemical etching* is an established technology used for the realization of printed electronic circuit boards. To reach the necessary volume requirement, the technology has been modified, adopting a roll-to-roll process where copper tape roll, typically 20 to 40 μm thick, is glued to a polymeric roll substrate, typically PET (polyethylene terephthalate). The copper film is then masked with a photoresist mask and inserted in a chemical bath where the exposed copper is chemically attacked and removed, thereby creating the desired pattern. The photoresist mask is then be removed using a standard process. The strongest advantage of this process, originally invented for the development of flexible circuits, is its availability and well-known manufacturing cost parameters. The currently estimated cost for copper etching is $10 per square meter of produced material that, for 600 antennas per square meter, is equivalent to 1.6 cents per antenna.

Conductive ink printing is certainly the most approachable process on the market. Based on flexographic equipment, the antennas can be printed on a polymer roll in a single step with no need for masking. The major drawback for this technology is the inherent cost of the material used in the process, usually a conductive ink loaded with 30% silver flake particles, and the higher surface resistivity of the conductive layer, a feature inversely proportional to the final performance of the antenna. Perhaps of even greater concern is the inherent environmental impact of using silver. As RFID tags are used and disposed of, their increasing density within landfills around the world will eventually jeopardize groundwater supplies, leading to requirements for recycling as is presently done for electronics.

5.3.10.2 Chip Assembly

The major challenge in assembling the active component onto the antenna circuit is represented by the small size of the chip itself, the need for a low-temperature attachment process, and the required throughput capacity. Chips for passive RFID tags had their size reduced to submillimeter dimensions in order to optimize the cost of the component, thus increasing the number of chips per wafer. This, of course, creates technical problems when the chip, whose pads are now below the 100-μm size, needs to be connected to the antenna at high speed. To overcome this problem, pick and place (PnP) equipment manufacturers have developed innovative technology enabling the attachment of the chip to the antenna roll using standard flip chip technology and dispensing of a quickly curing conductive adhesive at high speed. The process is quite simple and is capable of attaching about 10,000 components per hour, equivalent to about 70 million tags per year.

Some tag manufacturers have approached the problem from a different point of view, focusing their attention on the production capacity and thus purposefully adopting another process, the *strap attach*. In this solution, the chip is attached to a polymeric carrier film in roll form at high density and high velocity using roll-to-roll equipment. This polymeric carrier has previously been prepared with small caves on the surface to receive the chip, which corresponds to large conductive pads. Proper geometry of the cave and chip die guarantees the proper positioning of the chip on the film. Once this step is completed, it is possible to couple the roll containing the straps with the roll containing the antennas and accomplish the final assembly by using dispensed adhesive. Of course, due to the different density and location of the chip on the strap carrier, each strap needs to be singulated before attachment. The advantage of this process, as stated by its major supporters, is the possibility of assembling chips at a very high velocity. The disadvantage is that the process consists of two-step phases and that the singulation of the strap causes a reduction in the speed of the process. Although it is possible to load the straps at incredible speed, the final assembly of the strap on the antenna is still a process regulated in its throughput by the curing of the adhesive used for attachment.

5.4 Readers

5.4.1 Principles of Operation

RFID tags are interrogated by readers, which in turn are connected to a host computer. In a passive system, the RFID reader transmits an energy field that wakes up the tag and powers its chip, enabling it to transmit or store data. Active tags may periodically transmit a signal, much like a lighthouse beacon, so that data can be captured by multiple readers distributed throughout a facility. Readers may be portable handheld terminals or fixed devices positioned at strategic points, such as a store entrance, assembly line, or toll booth (gate readers.) In addition, readers/interrogators can be mobile; they can have PCMCIA cards to connect to laptop PCs, usually are powered from their own power source (battery) or by the vehicle they are mounted on, and typically have wireless connectivity. The reader is equipped with antennas for sending and receiving signals, a transceiver, and a processor to decode data. Companies may need many readers to cover all of their factories, warehouses, and stores. Readers typically operate at one radio frequency, so if tags from three different manufacturers used three different frequencies, a retailer might have to have multiple readers in some locations, increasing the costs further.

Handheld or portable readers are a very useful resource to supplement fixed readers. Handheld readers can be used instead of a portal reader to record boxes loaded and identify boxes as they are removed; little efficiency is gained relative to barcoded labels, but customer mandates can be accommodated with minimal initial expense.

Handheld readers are also very useful for exception handling of boxes that fail to read at a portal or on a conveyor or that have misplaced or misoriented labels or when identifying boxes of unknown provenance, and so forth. Handheld readers can be useful for inventory cycle counts in storage areas or temporary staging locations, for locating specific cartons in storage, for verifying manifests during assembly, and for specialized applications such as tail-to-tail baggage transfer (moving baggage from one airplane to another in an airport without routing it through the terminal).

RFID readers are used to activate passive tags with RF energy and to extract information from the tag. For this function, the reader includes an RF transmission for receiving and data decoding sections. In addition, the reader often includes a serial communication (RS-232, USB, and so on) capability to communicate with a host computer. Depending on the complexity and purpose of applications, the reader's price range can vary from $10 to a few thousand dollars worth of components and packaging. Typically, the reader is a read-only device, whereas the reader for a read/write device is often called an *interrogator*. Unlike the reader for a read-only device, the interrogator uses command pulses to communicate with a tag for reading and writing data.

The *carrier* is the transmitted radio signal of the reader (interrogator). This RF carrier provides energy to the tag device and is used to detect modulation data from the tag using a backscattering. In read/write devices, the carrier is also used to deliver the interrogator's commands and data to the tag.

The RF transmission section includes an RF carrier generator, an antenna, and a tuning circuit. The antenna and its tuning circuit must be properly designed and tuned for the best performance. Data decoding for the received signal is accomplished using a microcontroller. The firmware algorithm in the microcontroller is written in such a way to transmit the RF signal, decode the incoming data, and communicate with the host computer.

The main criteria for readers include the following:

- *Operating frequency (LF, HF, UHF):* some companies are starting to develop multifrequency readers;
- *Protocol agility:* support for different tag protocols (ISO, EPC, proprietary);
- *Different regional regulations (for example, UHF readers):*
    - UHF frequency agility 902 to 930 MHz in the United States and 869 MHz in Europe;
    - Power regulations of 4W in the United States and 500 mW in some other countries;
    - Manage frequency hopping in the United States and duty cycle requirements.
- *Networking to host capability:*
    - TCP/IP;
    - Wireless LAN (802.11);
    - Ethernet LAN (10base T);
    - RS 485.
- Ability to network many readers together (via concentrators or via middleware);
- Ability to upgrade the reader firmware in the field;
- *Management of multiple antennas:*
    - Typically four antennas per reader;
    - How antennas are polled or multiplexed.
- Adapting to antenna conditions (dynamic auto-tuning);
- Interface to middleware products;
- Digital I/O for external sensors and control circuits.

Certain readers also provide connection options to enable simple process control mechanisms to be implemented, such as digital inputs and outputs with 24V, which can be used to control traffic lights or gates that are released once the tag data has been checked at the goods issue/receipt point. PLC couplings can also be realized using this technology. The higher protocol layers have not been standardized yet, resulting in additional time and effort when it comes to integrating readers across different manufacturers. In addition, readers and antennas at loading gates must be highly tolerant with regard to temperature and must be protected against dust and damp.

Up until the recent surge in developments for the supply chain and EPC tags, readers were used primarily in access control systems and other low-volume RFID applications, which meant that the problem of treating very large numbers of tags and high volumes of data was not such a serious issue. Of course, this is now changing, and many reader manufacturers are starting to develop next generation products to handle the application problems that will be specific to the supply chain and EPC/ISO infrastructure.

5.4.2 Reader Antenna

The reader antenna establishes a connection between the reader electronics and the electromagnetic wave in the space. In the HF range, the reader antenna is a coil (like the tag antenna), designed to produce as strong a coupling as possible with the tag antenna.

In the UHF range, reader antennas (like tag antennas) come in a variety of designs. Highly directional, high-gain antennas are used for large read distances. Regulatory authorities usually limit the maximum power emitted in a given direction; as a result, the transmission power emitted from the reader to the antenna must also be regulated accordingly. One advantage of highly directional antennas is that the reader power often has to be emitted only to the spaces in which the tags that are to read are located.

Generally speaking, physical interdependencies mean that the antenna gain is linked to the antenna size. The higher the gain (or the smaller the solid angle into which the antenna emits), the larger the mechanical design of the antenna will be. It follows, therefore, that highly directional antennas are not used for handheld readers. Antennas typically used for handheld readers include patch antennas, half-wave dipoles, and helix antennas. Larger antenna structures can be used for stationary readers; in the UHF range, they usually take the form of arrays.

All other things being equal, a high-gain antenna will transmit and receive weaker signals farther than a low-gain antenna. Omnidirectional antennas, such as dipole antennas, will have lower gain than directional antennas because they distribute their power over a wider area. Parabolic antennas usually have the highest gain of any type of antenna but are not really usable in typical RFID applications, except maybe for microwave RFID readers where a long range and narrow radiation pattern is required. A half-wave dipole antenna will have a gain of near unity, or nearly equal the isotropic antenna.

Reader antennas may have different requirements depending on whether they are fixed, portable, or handheld readers. For example, the choice of an antenna for portable devices is dominated by size and weight constraints. Read range and polarization are generally less significant than in the case of fixed readers. Efficient use of RF power to maximize battery life is critical. Highly directive antennas are useful to reduce power consumption, but are generally physically large and thus may not fit in the restricted form factors allowed for portable applications. The fact that handheld reader antennas are small and light constrains the antenna gain.

Antennas that are less than about one-quarter of a wavelength in all dimensions (a quarter wave is about 80 mm [3.2 inches] for UHF operation in the United States) cannot achieve more than about 4 dB of gain. Slightly larger antennas allow up to about 6 dBi of gain, but make the reader somewhat bulky and awkward to carry. The trade-off is important because handheld and portable applications benefit from high antenna gain. The reader is likely to employ less than the maximum allowed transmitting power to improve battery life, so read range is impacted if antenna gain is low. A narrow antenna beam will improve the ability of the user to locate the tag being read by changing the reader orientation and noting the results. The narrow beam of a high-gain antenna, which is undesirable in a stationary-reader application, is often beneficial for a handheld reader, because the user can readily move the beam to cover the area of interest.

5.4.3 Software-Defined Radios in RFID Systems

The problem of continuous change in the EPC market is a vitally important one for all RFID users, and especially those responsible for buying and installing an RFID reader infrastructure. While tags are the consumables of RFID systems, constantly varying, iterating, and regenerating, the RFID reader infrastructure is a deployed capital expense that cannot easily or cost effectively be replaced every time a new tag variant appears. Further, the comings and goings of tags are not neatly synchronized. Generation 1 will not turn into Generation 2 instantaneously; the two generations will coexist, perhaps for as long as few years, and the reality (and hype) surrounding Generation 3 will begin, as well as the introduction of new classes of tag. This type of change is good for the RFID user because it will deliver ever-improving performance and decreasing costs.

Software-defined radio (SDR) uses software for the modulation and demodulation of radio signals. An SDR performs the majority of its signal processing in the digital domain, most commonly in a digital signal processor (DSP), which is a type of microprocessor specifically optimized for signal processing functions. The advantage of an SDR-based RFID reader is that it can receive and transmit a new form of RFID communication protocol simply by running new software on existing SDR hardware. A software-defined RFID reader consists of an RF analog front end that converts RF signals to and from the reader's antennas into an analog baseband or intermediate frequency signal, and analog-to-digital converters and digital-to-analog converters, which are used to convert these signals to and from a digital representation that can be processed in software running on the reader's digital signal processor.

SDR technology has long been important in the military context, where new radio equipment must interoperate with legacy equipment, much of which is used for many years beyond its design lifetime. Additionally, the U.S. military is often called on to work together with allies that have old, outdated equipment that is incompatible with the more modern U.S. communication hardware. This is exactly analogous to the Generation 1 to Generation 2 (and beyond) transition in RFID. Military SDR projects date back to the early 1990s, and several were fielded in that time frame. Aware of these developments, in 1999 the MIT Auto-ID Center began exploring the idea of using SDR in RFID readers.

5.4.4 Data Transfer Between a Tag and a Reader

5.4.4.1 Signal Transmission

For an RFID system to work, we need three processes: energy transfer, downlink, and uplink. According to this we can divide RFID systems into three groups: full duplex, half-duplex, and sequential. During full duplex and half-duplex operation, the energy is transferred constantly, compared to sequential operation when energy is first transferred by the reader and then the tag responds. In half-duplex systems the information is sent in turns either transferred inductively through load modulation or as electromagnetic backscatter, such as with radar.

In full-duplex systems uplink information is sent on a separate frequency, either a subharmonic or not, so the flow of information can be bidirectional and continuous.

Sequential transfer consists of two phases: First energy is sent to the tag that stores it in a capacitor, then, utilizing the power received, it can function for some time and send its reply. This has the advantage that by extending the charging time and enlarging the capacitor it is possible to acquire more energy for the electronics.

5.4.4.2 Data Transfer Rate

A further influence of carrier frequency is with respect to data transfer, for which it is very important to understand the bit rate (data rate) concept. Whereas in theory it is possible to transfer binary data at twice the carrier frequency, in practice it is usual to use many cycles of the carrier to represent a binary digit or group of digits. However, in general terms, the higher the carrier frequency, the higher the data transfer rate that can be achieved. So, a low-frequency system operating at 125 kHz may transfer data at a rate of between 200 and 4,000 bps depending on the type of system, while rates up to greater than 100 Kbps (but typically less than 1 Mbps) are possible for microwave systems. It should also be appreciated that a finite bandwidth is required in practice to transfer data, this being a consequence of the modulation that is used. Consequential to transfer capability is the data capacity of the tag. Loosely speaking, the lower the frequency, the lower the data capacity of the tags, simply because of the amount of data required to be transferred in a defined time period. Keep in mind that the capacity can also be determined by the manner in which the tag is designed to be read or written to (for read/write tags), be it in total or part. The choice of data transfer rate has to be considered in relation to system transfer requirements—this is determined by the maximum number of tags that may be expected to be read in a unit interval of time multiplied by the amount of data that is required to be read from each tag. Where a write function is also involved, the number of tags and write requirements must also be considered.

ISO 15693 is an ISO standard for *vicinity cards*, that is, cards that can be read from a greater distance as compared to *proximity cards*. ISO 15693 systems operate at the 13.56-MHz frequency, and offer a maximum read distance of 3 to 4 feet. In ISO 15693 chips, the subcarrier frequency is equal to 423.75 kHz (RF/32) with FSK or OOK modulation and Manchester data coding. The achievable label data transfer rate is up to a relatively fast 26.48 Kbps. Most typical bit rate values in bits per second are RF/8, RF/16, RF/32, RF/40, RF/50, RF/64, RF/80, RF/100, and RF/128. Every tag sends back information with some predefined, usually fixed bit rate. Once a manufacturer programs the data rate, it usually cannot be changed. This data rate is clocked by internal tag frequency. For LF transponders the range is from 100 to 150 kHz, depending on the manufacturer. Consider, for example, a transponder type for which the bit rate is RF/32. This means that the data rate is 32 field clocks (FC) per logic 1 or 0 data bit. The data (bit) rate is a bit time duration and it is defined as field clocks per bit. Taking a field clock equal to 125 kHz and a tag bit rate equal to RF/32, the data rate is 125 kHz/32 = 3.9062 Kbps, so receiving 64 bits of information would take $8\ \mu s \times 32 \times 64 = 16.384$ ms.

The manner in which the tags are interrogated is also important. It can be done singularly (one at a time in the interrogation zone) or as a batch (a number of tags in the interrogation zone at the same time). The latter requires that the tags and associated system have anticontention (anticollision) facilities so that collisions between responses from tags in the zone at the same time can be resolved and contention avoided. Various anticontention protocols have been devised and applied with various levels of performance with respect to the number of tags that can be handled and the time required to handle them. So, the anticontention performance may be an important consideration in many applications.

5.4.4.3 Read/Write Range

The read/write range is the communication distance between the reader (interrogator) and tag. Specifically, the read range is the maximum distance to read data out from the tag, and the write range is the maximum distance to write data from the interrogator to the tag. The read/write range is, among other effects, mainly related to:

- Electromagnetic coupling of the reader (interrogator) and tag antennas;
- The RF output power level of reader (interrogator);
- Carrier frequency bands;
- The power consumption of the device;
- Antenna orientation;
- The distance between the interrogator and the tag;
- Operating environment conditions (metallic, electric noise, multiple tags, multiple readers, and so on);
- The tag and the tag's dwell time.

The tag's dwell time is the time a tag is in the interrogator's RF field. An RFID interrogator's read range is the distance between the interrogator and the RFID tag at which the signals from the tag can be read properly. Similarly, an RFID interrogator's write range is the maximum distance at which information within the RF signal from the interrogator can be received correctly and stored within the memory of the tag's microchip. More power is needed to write to a tag than to read it; as a result, the tags need to be closer to the antenna to write than to read. The general rule is that the write range is 50% to 70% of the read range of a particular interrogation zone.

Power limitations, as listed in Table 5.3, are imposed by local authority and cannot be chosen arbitrarily. The standardization of RFID technology and the requirements of the local governing bodies are still in progress and change constantly. For that reason, some of the information provided in this book that was correct during the preparation of the manuscript might change by the time it reaches the reader.

The electromagnetic coupling of the reader and tag antennas increases, using a similar size of antenna with high Q on both sides. The read range is improved by increasing the carrier frequency. This is due to the gain in the

Table 5.3
RFID Power Limitations Based on the Region and Frequency

Frequency Band	Power, Limitations, and Region
125 kHz	Inductively coupled RF tags
1.95, 3.25, and 8.2 MHz	Inductively coupled theft tags, worldwide
13.56 MHz	Inductively coupled RFID tags, worldwide
27 and 40 MHz	0.1W ERP, Europe
138 MHz	0.05W ERP, duty cycle < 1%, Europe
402–405 MHz	Medical implants, 25 μW ERP (–16 dBm)
433.05–434.79 MHz	25 mW ERP, duty cycle < 10%, Europe
468.200 MHz	0.5W ERP, Europe
869.40–869.65 MHz	0.5W ERP, duty cycle < 10%, Europe*
902–928 MHz	4W EIRP, America
2400–2,483.5 MHz	ISM band, 0.5W EIRP Europe; 4W America, Bluetooth
5,725–5,875 MHz	25 mW EIRP

Note: EIRP = equivalent isotropic radiated power; ERP = equivalent radiated power.
*To accommodate concerns over the ability of Gen 2 RFID systems to perform under the European regulations, Europe has already increased its available frequency spectrum from 2 to 8 MHz, allowable power output level from 0.5W to 2W, and replaced its 10% duty-cycle restriction with a listen-before-talk requirement. Even with these improvements, work is still under way to further alleviate European regulatory constraints.

radiation efficiency of the antenna as the frequency increases. However, the disadvantage of high-frequency (900-MHz to 2.4-GHz) application is shallow skin depth and narrower antenna beam width causing less penetration and more directional problems, respectively. Low-frequency application, on the other hand, has an advantage in the penetration and directivity, but a disadvantage in the antenna performance. Read range increases by reducing the current consumption in the silicon device. This is because the LC antenna circuit couples less energy from the reader at further distances. A lower power device can make use of less energy for the operation.

For LF and HF (near-field) systems, to increase the magnetic field at the tag's position, the reader/writer antenna coil's radius must be increased, or the current in the antenna coil must be increased, or both. The strength of the magnetic field is attenuated in proportion to the inverse of the cube of distance. By increasing the diameter of the RFID tag's antenna coil, the signal induced in the tag's coil can be increased. Accordingly, for applications that require long-range operation, the reader/writer antenna coil's radius and tag antenna coil's dimensions must be increased. In tests comparing coin-sized and IC card-sized tags using the same reader/writer, the IC card-sized tag had an operating area several times larger than the coin-sized tag.

The read range of a UHF-based RFID (propagation) system can be calculated by the Friis free-space equation as follows:

$$r = \frac{\lambda \cos\theta}{4\pi}\sqrt{\frac{P_R G_R G_T\left(1-(\Delta\rho)^2\right)}{P_{th}}} \quad \text{for} \quad 0 \le (\Delta\rho)^2 \le 1 \qquad (5.43)$$

where, G_T is the gain of the tag antenna, $P_R G_R$ is the EIRP for the reader, λ is the wavelength, P_{th} is the minimum threshold power required to power an RFID tag, θ is the angle made by the tag with the reader plane, and $(\Delta\rho)^2$ is the power reflection coefficient, which is the ratio of reflected power to incident power by the tag. Note that the power received by the tag is inversely proportional to the square of the distance between the tag and the reader's antenna. Studies reveal that the orientation of the tag in the RF field affects its read range. In the specific context of a directivity pattern, a perfectly parallel tag, relative to the reader's antenna, yields the maximum read range, whereas a tag perpendicular to the base station antenna's field has minimum to zero read range. Thus, efforts are made to make the tag parallel to the reader antenna by deploying one or more of the following measures:

- Change in orientation of the reader antenna to suit the orientation of the tag antenna;
- Use of redundant antennas for ensuring proper alignment of at least one reader antenna to the tag antenna;
- Increase reader antenna power (of course, within the limits allowed by the local authorities) to reduce the effect of tag orientation;
- Increase the polling rate of the antenna to make more reads in the same sampling time.

The far-field formula is correct, subject to the assumption that the polarization of the reader antenna and the polarization of the tag antenna are perfectly matched. However, in fact, the polarization mismatch is essential and required in most RFID applications. The point is that in the majority of applications the tag is allowed to appear in an almost arbitrary position in the field of the reader antenna while the polarization of the tag antenna is usually linear because of the prerequired small size of the tag. In such a situation, the only way to fulfill a system requirement is to use a circularly polarized reader antenna. Thus, a sacrifice of 3-dB power loss (at least, although it can be even much higher; see the discussion on polarization mismatch in Chapter 2) due to a polarization mismatch between a circularly polarized reader antenna and a linearly polarized tag antenna overcomes the problem of tag orientation. This is why, nowadays, the major vendors offer mainly circularly polarized reader antennas. At the same time, the linearly polarized antennas are also available in the market for limited RFID applications. In the case of linearly polarized reader and tag antennas, the substantial polarization misalignment may cause a severe power loss, which in its turn can potentially lead to a fault on the part of the RFID system. In the case of a circular-to-linear polarization mismatch the read range r will be $\sqrt{2}$ times shorter than the one calculated by (5.43).

As we can see from the Table 5.4, systems operating in the 915-MHz band may achieve read ranges of 20 feet (6m) or more under current FCC regulations.

5.4.4.4 Environment and Proximity to Other Objects

Up to now, our considerations have focused on data transfer across an uncluttered air interface. However, free-space propagation in which the reader and tag are distanced from any obstructions or other tags, and perfectly aligned relative to each other, is not a realistic situation. In practice, the region between the tag and the interrogator may contain obstacles and materials that can influence the performance of the system. The carrier frequency is one of significance with respect to the effects that the prevailing conditions and clutter factors (obstacles and physical structures) can have. In low- and high-frequency inductive RFID systems, the magnetic field is effectively used to couple data, and such fields are largely unaffected by dielectric or insulator materials (papers, plastics, masonry, and ceramics, for example); the field simply penetrates the materials. Where metals are involved, they can distort the field, depending on how ferrous they are. This will weaken the field strength in the regions of the interrogation zone, in some cases to the extent that system performance is impaired. The range capability may be impaired or the ability to read or write to a tag may be impaired. For uncompensated tag designs operating at resonant frequencies, the presence of metals can often detune the device, in some cases preventing its operation.

At higher frequencies (UHF and above), where, for propagation RFID, the electric component of a field becomes more significant; the higher the frequency the more easily they can penetrate dielectric materials. However, for some materials where energy exchange mechanisms can be identified at or near the carrier frequency, this can result in energy absorption from the propagating wave, hence causing an impairment of range performance. One of the challenges with UHF RFID tags is efficient operation in the presence of water or metal.

Table 5.4

Read Range for Different UHF Reader Powers and Reflection Coefficients

f [MHz]	λ [m]	P Reader [W]	P Reader [dBm]	Reader Antenna Gain	Tag Antenna Gain	$\Delta\rho$	Angle [°]	Tag Threshold Power [dBm]	Tag Threshold Power [mW]	Read Range [m]
915.00	0.33	0.50	26.99	1.64	1.64	0.40	0.00	–10.00	0.10	2.7731
915.00	0.33	0.50	26.99	1.64	1.64	0.50	0.00	–10.00	0.10	2.6203
915.00	0.33	0.50	26.99	1.64	1.64	0.60	0.00	–10.00	0.10	2.4205
915.00	0.33	2.44	33.87	1.64	1.64	0.40	0.00	–10.00	0.10	6.1259
915.00	0.33	2.44	33.87	1.64	1.64	0.50	0.00	–10.00	0.10	5.7884
915.00	0.33	2.44	33.87	1.64	1.64	0.60	0.00	–10.00	0.10	5.3471

Unfortunately, the human body is made up of mostly water; thus, if the RFID tag is placed close to the human body, performance will suffer.

As far as metals are concerned, they reflect or scatter these higher frequency signals, depending on the size of the metal object in relation to the wavelength of the incident signal. Such effects can impair the range that can be achieved and, in some cases, can screen the reader from the tag and prevent it from being read. Any metal near the tag, such as keys or coins, can also cause the tag to be undetectable.

The proximity of tags may also exhibit a similar effect. Reflections and diffraction effects can often allow pathways around metal objects within an interrogation zone. Because it is difficult to generalize on the effects of clutter within the interrogation zone, it is expedient where possible to avoid clutter and choose a carrier frequency that is appropriate to the conditions to be expected.

Passive RF tags in the UHF and microwave bands have drawn considerable attention because of their great potential for use in many RFID applications [10]. However, more basic research is needed to increase the range and reliability of a passive RF tag's radio link, particularly when the RF tag is placed onto any lossy dielectric or metallic surface. This radio link budget is dependent on the *gain penalty losses* (L_{GP}), a term that quantifies the reduction in RF tag antenna gain due to material attachment.

After combining (5.16) and (5.21), we get the following expression:

$$P_{REC} = \frac{P_R G_R^2 \lambda^2 \sigma}{(4\pi)^3 r^4} = \frac{P_R G_R^2 G_T^2 \lambda^4 (\Delta\rho)^2}{(4\pi)^4 r^4} \tag{5.44}$$

The assumption in this case is that the gains of the reader's transmitting and receiving antennas are the same, which may not always be the case; the reason is that the single-antenna readers are inexpensive and compact but need excellent matching circuits, a high-isolation coupler with extremely high isolation between ports, and electronic circuitry with a wide dynamic range. In the logarithmic form, the same expression for the backscattered power received at the reader looks like this:

$$P_{REC} = P_R + 2G_R + 2G_T + 20\log(\Delta\rho) + 40\log\left(\frac{\lambda}{2\pi}\right) - 40\log r \tag{5.45}$$

where $\Delta\rho$ is a reflection change between switched loads.

Now, we can include in (5.44) additional losses due to the antenna being attached to different types of materials in the form of an adjustment for on-object degradation. In doing so, we get:

$$\begin{aligned} P_{REC} &= P_R + 2G_R + 2G_T + 20\log(\Delta\rho) \\ &\quad + 40\log\left(\frac{\lambda}{2\pi}\right) - 40\log r - 2L_{GP} \end{aligned} \tag{5.46}$$

A series of measurements was used to measure the far-field gain pattern and gain penalty of several flexible 915-MHz antennas when attached to cardboard, pine plywood, acrylic, deionized water, ethylene glycol, ground beef, and an aluminum slab. It has been shown that the gain penalty due to material attachment can result in more than 20 dB of excess loss in the backscatter communication link.

From the reader's perspective, handheld and portable antennas are very likely to operate in proximity to people's hands and arms, as well as other obstacles. The amount of power reflected from the antenna, measured by its reflection coefficient or return loss, should ideally be unaffected by such obstacles unless they are actually within the antenna beam. The best return loss performance in the presence of near-field objects is usually obtained from balanced antennas, in which the two halves of an antenna are driven by precisely opposed currents and there is no large ground plane. However, such antennas are relatively large compared to single-ended (nonbalanced) antennas and require a balanced–unbalanced transformer (balun) to connect them to ground-referenced antenna cables or circuit board connectors. With a balun, the antenna is less sensitive to the presence of near-field objects.

5.4.5 UHF Reader Electronic Circuitry

To shrink the size of the RF portion of an RFID reader, it is necessary to increase the functions in each element. Figure 5.19 shows a typical block diagram for an RFID reader and shows one possible way of integrating elements into a chipset. Each module is briefly described in the following sections.

5.4.5.1 UHF Reader Source Module

The purpose of the *source module* is to provide a synthesized *local oscillator* (LO) for transmitting (Tx) and receiving (Rx) paths in an RFID reader. The updated FCC standard requires frequencies to be within 10 ppm over the operating temperature ranges. It is necessary to amplify the signal after the synthesizer, in order to provide adequate LO input to the Tx and Rx signal paths due to typical synthesizer output powers and the loss of the power divider. For a source module, it is critical that the part be adaptable so that a single PC-board footprint can be used to handle all of the different bands. Using an integrated synthesizer/voltage-controlled oscillator (VCO) IC, it is possible to center the VCO bands by using different inductor values. The Japanese band requires a faster

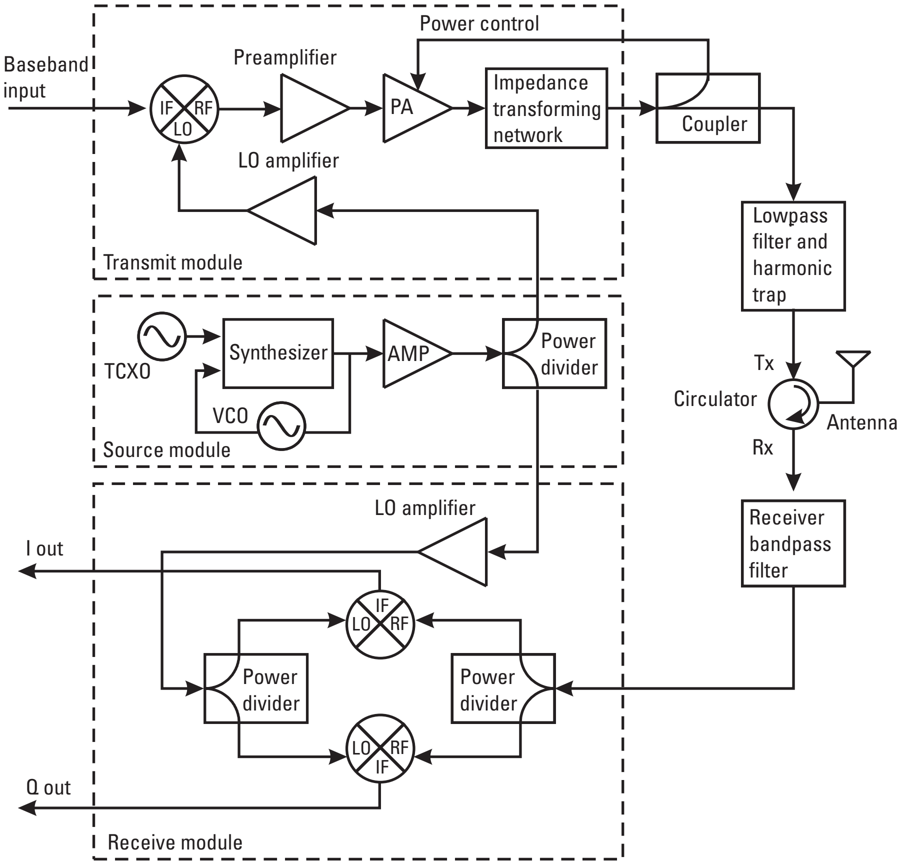


Figure 5.19 UHF RFID chipset block diagram.

switching speed than the U.S. and European bands, which can still be realized with a 5-kHz bandwidth loop filter, but with different component values. It is desirable to have isolation on the order of 20 dB in the power divider. For cost reasons, monolithic narrowband power dividers are generally used and are not optimal for covering 850 to 960 MHz. To optimize the isolation for each, tuning inductors and/or capacitors are used to recenter the power divider isolation. To shrink the size and reduce the overall component count, it is necessary to combine somewhat diverse parts to create a source module. An additional requirement that is typical of synthesizer/source modules is that shielding is required for loop stability and minimization of phase noise.

5.4.5.2 UHF Reader Transmitting Module

As depicted in Figure 5.19, a typical transmitting module would include a double balanced modulator (DBM), LO amplifier, preamplifier, power amplifier, and impedance transforming network (ITN). The high level of integration, with over 50 dB of available small-signal gain, requires careful module layout. To maintain stability, it is necessary to keep the preamplifier located as far as possible from the power amplifier. The DBM provides a means to modulate the carrier signal. An LO amplifier is included to raise the signal available from the source module to a level sufficient to drive the mixers. Additionally, having the LO amplifier provide a 50Ω interface allows for simple interconnection to the source module. The modulated RF output from the mixer goes to a preamplifier and then to a power amplifier. The preamplifier has a gain of 17 dB and the power amplifier, implemented as a three-stage device, provides a small signal gain of 35 dB.

Also included in the transmit module is an impedance transforming network (ITN). The purpose of this network is to transform the 50Ω load impedance to a level that the power amplifier needs to drive in order to produce the desired output power at the available supply voltage. For a typical supply of 3.6V, this impedance is only a few ohms, creating large circulating currents. These low impedances necessitate proper handling of circuit parasitics. This circuit requires careful design and implementation from performance and reliability perspectives. To be able to provide the desired 1W RF level at the antenna terminals typical for UHF readers, the power amplifier needs to be capable of providing sufficient power output capability to overcome the signal losses introduced between the transmitting module output and the antenna. These losses would include any coupler, filter, circulator, connector, and cabling used in the path to the antenna. It is desirable to control the power in order both to set the output level to various requirements and to implement a commonly used form of carrier amplitude modulation called *pulse-interval modulation*, which is used to interrogate tags. The modulation bandwidth must be sufficient for the intended data rates without significant distortion, but as much circuitry as possible should be broadband.

The transmitter transmits encoding data with ASK modulation, including DSB-ASK, and SSB-ASK for forward link, and sends an unmodulated carrier for the return link. The maximum output power from the PA is restricted to 30 dBm (1W).

5.4.5.3 UHF Reader Receiving Module

Most modern wireless communication systems use digital modulation/demodulation techniques, and there is a good reason for this. They provide increased channel capacity and greater accuracy in the transmitted and received messages in the presence of noise and distortion. In digital communication systems, a finite number of electrical waveforms or symbols are transmitted, where each symbol can represent 1 or more bits. It is the job of the receiver to identify which symbol was sent by the transmitter even after the addition of noise and distortion. Distortion in wireless communication can be caused by several things such as passing a signal through filters having insufficient bandwidth or inefficient switching of nonlinear elements. Ultimately, the effects of such events within communication systems are termed *intersymbol interference* (ISI). In addition to ISI, there are other types of distortion more notably termed *delay spread* and noise. Delay spread occurs when multiple versions of the same signal are received at different times. This occurs when the transmitted signal reflects off multiple objects on its way to the receiver (multipath). System designers are focusing their attention on their transceivers in search of a method or components that might help them achieve a superior signal-to-noise ratio, resulting in a lower bit error rate. It is widely projected that one of the reasons for the delay in wide-scale adoption of RFID systems has been the unacceptable bit error rate of RFID tag reading.

In addition, RFID systems operating in the UHF band have unique attributes; during operation, the reader antenna emits electromagnetic energy in the form of radio waves that are directed toward an RFID tag. The tag absorbs energy, and through its built-in microchip/diode, uses it to change the load on the antenna, which in turn reflects an altered signal to the reader. This method is known as backscatter and is the basis by which a passive RFID tag identifies its presence. These backscattered signals are essentially at the same frequency as that of the transmitted signal. The backscattered signal antenna received is sent to the receiver through a directional coupler. The receiver front end must be designed to withstand high-interference signal levels without introducing significant distortion spurs. The receiver noise needs to be low enough that the system has sufficient dynamic range to allow error-free detection of low-level responding tag signals.

Homodyne detection, whereby a sample of the transmitted signal prior to modulation is used as the LO source for the receiving I/Q demodulator, is utilized. Having both the transmitted and received signals at the same frequency exacerbates the difficulty of recovering the weak reflected signal, because it has to be identified in the presence of the higher powered carrier frequency. Consequently, it is an advantageous to choose transceiver components that help improve the overall signal-to-noise ratio as well as minimize LO carrier leakage. The I/Q demodulator is a key element that can be used to maximize the signal-to-noise ratio and to minimize LO carrier leakage. Direct conversion to baseband frequency with the lowest bit error rate and the highest sensitivity possible is crucial, not only for reader accuracy, but also to its range of usage.

5.5 RFID Power Sources

RFID tags need power to sense, compute, and communicate, which is further classified into three categories: storage (batteries, capacitors), energy harvesting mechanisms (vibrations/movement, photovoltaic, thermal gradient, and so on), and energy transfer (inductive coupling, capacitive coupling, backscatter). Because many of these devices are expected to operate with a minimum of human intervention, optimizing power consumption is a very important research area. RFID tags may derive the energy to operate either from an on-tag battery or by scavenging power from the electromagnetic radiation emitted by tag readers. *Storage* refers to the way devices store power for their operation, done by means of batteries or capacitors. Batteries are used when a longer life is required, and capacitors are used in applications that require energy bursts for very short durations [11].

5.5.1 Power Harvesting Systems

Power harvesting (sometimes termed *energy scavenging*) is the process of acquiring energy from the surrounding environment (ambient energy) and converting it into usable electrical energy; the self-winding watch is a historical example of a power-harvesting device. The watches were wound by cleverly extracting mechanical energy from the wearer's arm movements. In medical devices, for example, a patient's normal daily activities could power an implantable pump that delivers insulin to a diabetic. The use of piezoelectric materials to harvest power has already become popular. Piezoelectric materials have the ability to transform mechanical strain energy into electrical charge. Piezo elements are being embedded in walkways to recover the "people energy" of footsteps. They can also be embedded in shoes to recover walking energy.

Energy transfer is the way by which passive RF devices are powered. The energy transfer mechanisms are inductive coupling, capacitive coupling, and passive backscattering. Inductive coupling is the transfer of energy between two electronic circuits due to the mutual inductance between them. Similarly, capacitive coupling is the transfer of energy between two circuits due to the mutual capacitance between them. Passive backscattering is a way of reflecting back the energy from one circuit to another.

Passive RFID tags obtain their operating power by harvesting energy from the electromagnetic field of the reader's communication signal. The limited resources of a passive tag require it to both harvest its energy and communicate with a reader within a narrow frequency band as permitted by regulatory agencies. A passive tag's power comes from the communication signal either through inductive coupling or far-field energy harvesting. Inductive coupling uses the magnetic field generated by the communication signal to induce a current in its coupling element (usually a coiled antenna and a capacitor). The current induced in the coupling element charges the on-tag capacitor that provides the operating voltage, and power, for the tag. In this way, inductively coupled systems behave like loosely coupled transformers. Consequently, inductive coupling works only in the near field of the communication signal.

Far-field energy harvesting uses the energy from the interrogation signal's far-field signal to power the tag. The signal incident on the tag antenna induces a voltage at the input terminals of the tag. This voltage is detected by the RF front-end circuitry of the tag and is used to charge a capacitor that provides the operating voltage for the tag. In the far field, tag-to-reader communication is achieved by modulating the RCS of the tag antenna (backscatter modulation.)

There is a fundamental limitation on the power detected a distance away from a reader antenna. In a lossless medium, the power transmitted by the reader decreases as a function of the inverse square of the distance from the reader antenna in the far field. A reader communicates with and powers a passive tag using the same signal. The fact that the same signal is used to transmit power and communicate data creates some challenging trade-offs. First, any modulation of the signal causes a reduction in power to the tag. Second, modulating information onto an otherwise spectrally pure sinusoid spreads the signal in the frequency domain. This spread, referred to as a *sideband,* along with the maximum power transmitted at any frequency, is regulated by local government bodies in most parts of the world. These regulations limit the rate of information that can be sent from the reader to the tag. RFID systems usually operate in the free ISM bands, where the emitted power levels and the sideband limits tend to be especially stringent.

The signaling from the tag to the reader in passive RFID systems is not achieved by active transmission. Because passive tags do not actively transmit a signal, they do not have a regulated limit on the rate of information that can be sent from the passive tag to the reader. Passive tags obtain impinging energy during reader interrogation periods, and this energy is used to power tag ICs. In the near field, tag-to-reader communication is achieved by modulating the impedance (load modulation) of the tag as seen by the reader [12]. For the maximum reading range, one has to ensure maximum power transfer efficiency from the reader to the tag. What makes the problem challenging is that in the case of an inductively coupled reader tag, the reader must deal with a changing effective load due to the location-dependent mutual coupling effect between the reader and tag as well as the unpredictable number of tags in the read zone of the reader.

The powering of and communication with passive tags with the same communication signal places restrictions on the functionality and transactions the tags are capable of. First, very little power is available to the digital portion of the integrated circuit on the tag, thus limiting the functionality of the tag. Second, the length of transactions with the tag is limited to the time for which the tag is expected to be powered and within communication range. Governmental regulations can further limit communication timings. In the United States'

915-MHz ISM band, regulations require that, under certain operating conditions, the communication frequency change every 400 ms. Because every change in frequency may cause loss of communication with a tag, transponders must not be assumed to communicate effectively for longer than 400 ms. Finally, it is important to minimize state information required in passive tags. In many practical situations, power supplied to the tag may be erratic, and any long-term reliance on state in the tag may lead to errors in the operation of a communications protocol.

5.5.2 Active Power Sources

5.5.2.1 Batteries

Battery-assisted backscatter tags have their own power source to preenergize the silicon chip. The data is otherwise sent and received from the reader in the same way as a passive tag. This is of benefit when many tags are present in an interrogation zone; if they are all passive, they all need a lot of energy initially to reach sufficient voltage to turn on. With metals and fluids near tags, this is even harder due to interference and blind spots in the field. An on-board power source on each tag helps to overcome this.

Primary lithium has been a favorite option in this market, because the chemistry offers several positive factors including high-energy density, long life (approximately 10 years), and long storage life. Additionally, this chemistry is ideal for RFID tag applications because it is lightweight. For RFID tag systems, primary lithium/manganese dioxide (Li-MnO_2) and lithium-thionyl chloride (Li-$SOCL_2$) are the two types of batteries that are most common. These lithium batteries offer a set of performance and safety characteristics that is optimal for RFID tag applications. Li-MnO_2 is relatively safe, compared to volatile lithium batteries, such as lithium-sulfur dioxide (Li-SO_2) and lithium-thionyl chloride (Li-$SOCL_2$), and does not develop any gas or pressure during battery operation.

However, one main disadvantage is that a single Li-MnO_2 cell cannot operate at voltages greater than 3.0V. These are typical in high-pulse applications, which Li-SO_2 and Li-$SOCL_2$ can satisfy. Li-MnO_2 cells are best suited for applications that have relatively high continuous or pulse current requirements. However, because most electronic components used in RFID tags require a minimum operating voltage of 3V, at least two Li-MnO_2 cells must be connected in series to ensure a proper margin of safety for system reliability. This requirement adds weight and cost while potentially decreasing reliability due to increased part count.

Overall, the Li-MnO_2 chemistry has a high energy density and has the ability to maintain a high rate of discharge for long periods of time. It can be stored for a long time (typically between 5 and 10 years) due to its low self-discharge rates. It also has the capability to supply both pulse loads and maintain a constant discharge voltage. Li-MnO_2 cells can operate in temperatures ranging from −20°C to +70°C, although storage in temperatures exceeding +55°C is not highly recommended, and operation will be below full energy capacity at low temperatures. Their nominal voltage is typically 3.0V, which is 2 times the amount of that found in alkaline manganese batteries.

Li-$SOCL_2$ is a low-pressure system that is considered superior to lithium-sulfur dioxide systems in terms of high-temperature and/or unusual form-factor applications. Due to its low self-discharge rate, Li-$SOCL_2$ has a maximum shelf life of 10 to 15 years. This service life is the same for all construction, whether cylindrical, coin, or wafer. This chemistry also has the highest open circuit voltage of 3.6V.

For most applications, only one cell of Li-$SOCL_2$ is required to maintain sufficient operating voltage. This is true as long as one cell can provide enough current to uphold the operating lifetime. RFID tag applications require very low continuous current and moderate pulse current, which Li-$SOCL_2$ batteries have no problem providing.

5.5.2.2 Other Power Sources

In the design of mobile electronics, power is one of the most difficult restrictions to overcome, and current trends indicate that this will continue to be an issue in the future. Designers must weigh wireless connectivity, CPU speed, and other functionality versus battery life in the creation of any mobile device. Power generation from the user may alleviate such design restrictions and may enable new products, such as batteryless on-body sensors. Power may be recovered passively from body heat, arm motion, typing, or walking or actively through user actions, such as winding or pedaling. In cases where the devices are not actively driven, only limited power can generally be scavenged (with the possible exception of tapping into heel-strike energy) without inconveniencing or annoying the user. That said, clever power management techniques combined with new fabrication and device technologies are steadily decreasing the energy needed for electronics to perform useful functions, providing an increasingly relevant niche for power harvesting. Current and historical devices have shown that such mechanisms can be practical and desirable, yet much work remains in the creation and exploitation of these microgenerators.

RFID technology was originally thought to be a passive technology because the tags had no batteries; they just collected energy from the reader and sent back their information (limiting in this way the distance between the reader and the tags). New advancements in the technology, however, have allowed the development of enhanced tags (active RFID) whose function fills the gap between the RFID traditional field and wireless sensor networks field. Recent research has revealed nuclear power as a possible source of power for wireless sensor and RFID networks [13]. Although certainly a little bit frightening at first thought, note that the isotopes used in the actual prototypes penetrate no more than 25 μm in most solids and liquids, so in a battery they could be safely contained by means of a simple plastic package. (Most smoke detectors and some emergency exit signs already contain radioactive material.) The huge amount of energy these devices can produce is illustrated by these figures: The energy density measured in mWh/mg is 0.3 for a lithium-ion battery, 3 for a methanol-based fuel cell, 850 for a tritium-based nuclear battery, and 57,000 for a polonium-210 nuclear battery. The current efficiency of a nuclear battery is around 4%, and current research projects (e.g., as part of the new DARPA program called Radio-Isotope Micropower Sources) aim at 20%. To make a little more sense out of these figures, for example, with 10 mg of polonium-210 (contained in about 1 mm^3) a nuclear battery could produce 50 mW of electric power for more than 4 months.

5.6 Review Questions and Problems

1. The reader produces a magnetic field that triggers the tag as shown in Figure 5.20. When the reader receives the transmitted data, it interprets the data and takes appropriate action. When the transponder enters the field produced by the reader, the coil produces a voltage inside the tag. In a passive transponder, this voltage can be used to power the tag. In an active transponder, the voltage is used to wake the tag and use its internal battery. Active transponders generally have longer read distances, have a shorter operational life, and are larger and more costly to manufacture. Passive transponders are generally smaller, have a longer life, and are less expensive to manufacture. For optimum performance, the transponder coil is used in a parallel LC circuit designed to resonate at the operating frequency of the reader.

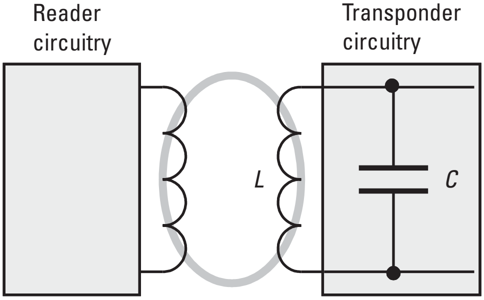


Figure 5.20 RFID system and a resonant-frequency calculation.

a. Calculate the capacitor value for a 4.9-mH transponder coil operating at 125 kHz. (*Answer:* $C = 331$ pF.)
b. What would be the resonant frequency f_1 if the overlapped tags have a new total inductance of 5.5 mH? (*Answer:* $f_1 = 117.96$ kHz.)

2. What do you think about the idea of passive RFID devices for locating small children?
3. You want an RFID tag that supports longer distance communications and does not rely on the reader to provide power to the tag. What kind of tag do you need?
4. Are there any health risks associated with RFID and its radio waves? Discuss.
5. Formula for EIRP in dBm:

$$\text{EIRP} = \frac{E^2 \cdot r^2}{30\Omega}$$

where EIRP is in watts, E is in volts per meter, and r is in meters.

a. Show the EIRP in dBm, using E in dBμV/m and r in meters.
(*Answer:* $\text{EIRP}_{[\text{dBm}]} = E_{[\text{dB}\mu\text{V/m}]} + 20 \log r_{[\text{meters}]} - \left(10 \log 30 + 90\right)_{[\text{dB}]}$.)

b. In standard test setups, the electrical field strength is often measured at a distance of 3m. Show that in this case we can use the simplified formula:
$\text{EIRP} = E_{[\text{dBm}]} = E_{[\text{dB}\mu\text{V/m}]} - 95.23_{[\text{dB}]}$

6. The chip device turns on when the antenna coil develops 4 V_{PP} across it. This voltage is rectified and the device starts to operate when it reaches 2.4 V_{DC}.

a. Calculate the B-field to induce a 4-V_{PP} coil voltage with an ISO Standard 7810 card size (85.6 × 54 × 0.76 mm), using the coil voltage equation. Frequency = 13.56 MHz, number of turns is 4, the Q of the tag antenna coil is 40, and $\cos \alpha = 1$ (normal direction, $\alpha = 0°$).
b. Calculate the induced voltage, assuming that the frequency of the reader was 1,000 Hz off from the resonant frequency of the tag. What conclusion can you make from this calculation?

$$V_{Tag} = 2\pi f N S Q B \cos \alpha$$

From here we have:

$$B = \frac{V_{tag}}{2\pi fNSQ\cos\alpha}$$

$$\text{Tag coil size} = (85.6 \times 54)\ \text{mm}^2\ (\text{ISO card size}) = 0.0046224\ \text{m}^2$$

$$B = \frac{4/\sqrt{2}}{2\pi \cdot 13.56 \cdot 10^6 \cdot 4 \cdot 4.6 \cdot 10^{-3} \cdot 40 \cdot 1}$$

$$B = 0.045[\mu T]\ ^*$$

For the reader frequency offset, instead of frequency f, we use the following expression to calculate f_1:

$$\begin{aligned} f_1 &= \frac{f_0}{1+\Delta f} = \frac{13.56\ \text{MHz}}{1+10^{-3}} = 13.546\ \text{MHz} \\ V_{tag} &= 2\pi fNSQB\cos\alpha = 2.83\ [V] \end{aligned} \tag{5.47}$$

**Note:* The tesla (symbol T) is the SI-derived unit of magnetic flux density (or magnetic induction). It is used to define the intensity (density) of a magnetic field. It is named in honor of world-renowned inventor, scientist, and electrical engineer Nikola Tesla. The tesla, equal to 1 weber per square meter, was defined in 1960.

7. The use of the elecromagnetic field for energy scavenging has been considered [14]. Research and calculate how far you have to be from a cellular base station in order to achieve successful energy scavenging. Are there any other urban areas offering a similar level of electromagnetic field sufficient for energy scavenging?

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