Int J Adv Manuf Technol (2003) 21:769–774
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The International Journal of
Advanced Manufacturing Technology

Radio Frequency Technology for Automated Manufacturing and Logistics Control. Part 1: Passive RFID Systems and the Effects of Antenna Parameters on Operational Distance

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Identification plays an important role in automation. In the near future radio frequency identification (RFID) will be an option for mass production automation projects. RFID represents a contactless method for data transfer in object identification. Generally, RFID systems consists of three components:

1. *A small electronic data carrying device called a transponder, or a tag that is attached to the item to be identified.*
2. *A reader or a scanner that communicates with the tag by using radio frequency signals.*
3. *A host data processing system that contains information on the identified item and distributes information to other remote data processing systems.*

An RFID system can be considered as a wireless communication system because the scanner communicates with the tag by using electromagnetic waves at radio frequencies. The performance of this communication link can be studied by determining the read range for backscatter RFID systems. The read range, or the distance at which the reader unit notices the tag, depends on many factors. Several parameters, e.g. the frequency used for identification, the gain, the orientation and the polarisation of the reader antenna and the transponder antenna, and the placement of the tag on the object to be identified, will all have an impact on the RFID system read range.

In this paper, Part 1, we focus on presenting an overview of different passive RFID systems and the read range of the backscatter RFID system. The function of frequency, antenna gain and polarisation mismatch are analysed and discussed. In Part 2, several manufacturing automation cases of different natures will be presented. These cases contain a selection of requirements for an RFID system and they are analysed using the information presented in this paper.

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Received 20 February 2002
Accepted 15 April 2002

Keywords: Antennas; Identification; Logistics control; Manufacturing; Production planning; RFID

1. Introduction

A typical manufacturing process contains several phases in which items are handled and are to be identified. Automated identification has benefits, such as the reduction of both labour costs and errors in identification. The usability of radio frequency identification (RFID) is based on costs and reliability [1–3]. From the cost point of view, the use of RFID is limited, and if we are using low-cost bulk material, e.g. powder, it is not essential to identify small parts of this product. However, the identification of larger quantities, i.e. transportation units such as bags or containers is necessary. Perhaps the main initial market for RFID technology comes from the manufacturing of products with a high unit price because it is essential to apply lean philosophy and reduce product flow as much as possible to compete in the market. This emphasises the importance of tracking and identification.

On the basis of the power supply principles, RFID systems can be divided into two categories: active and passive systems.

1.1 Active RFID System

In an active system the transponder has its own power source. Typically, this is a battery, which is enclosed in the transponder housing. This type of RFID transponder can be considered as a normal mobile radio device, and the operational range is easy to increase. However, it has a limited operational life cycle and modern batteries are typically classified as environmental hazardous waste. A cold environment also greatly reduces battery lifetime. One of the main benefits of an active transponder is that it can carry out more complex operations. It can have several sensors and they can be microprocessor controlled. Typical implementations are the logging of temperature, humidity or other environmental parameters. These transponders can be reused within the limits of battery lifetime, and the ID code can also be changed. However, multipurpose active RFID transponders are not widely adopted because they are expensive.

1.2 Passive RFID System

A passive RFID transponder does not have any energy source. It takes all the required power from the electromagnetic radiation of the reader system. Thus, the life cycle of the transponder is not limited and the transponder can be used over a long time period. A passive RFID system can be produced at a favourable price, but the read range is strongly limited by the overall efficiency of the system. A passive RFID system is planned for use in high volume products, and an electronic product code (EPC) for it has been designed by the MIT Auto-ID Center [4].

There are some smaller applications, which can recycle transponders and operate in a controlled warm environment, and some of these applications can also accept higher costs. Nevertheless, most of the volume applications are extremely cost-sensitive, and so we will focus on low-cost passive RFID solutions.

2. Overview of Passive RFID System

In passive RFID systems, the energy needed for the communication is supplied entirely from the reader device. In these systems care must be take to ensure that antennae and transponders are correctly assembled for proper link connections. In passive RFID systems, the reader read range is relatively short, i.e. only a couple of metres, and the items to be identified should be located within the reader read range. Basic methods for data transmission between the passive transponder and the reader device are piezoelectric and backscatter or load modulation methods and frequency dividers.

2.1 Frequency Divider

The operation of a divide by two frequency divider transponder is simple. It delivers response at half the frequency transmitted by the reader, and the reader, is capable of receiving this divided frequency. Frequency divider systems are used mainly for electronic article surveillance (EAS), i.e. security applications. Thus, they only deliver information on transponder presence within the reader range without any character identification. The lack of proper ID limits their use in manufacturing technology.

2.2 Surface Acoustic Wave Transponders

In surface acoustic wave (SAW) transponders, the request signal from the reader device is captured by the tag antenna and converted into surface waves on a piezoelectric crystal, which have a slower speed than radio waves in the air. The crystal contains structures that reflect surface waves. These reflected surface waves are then guided through the converter and transmitted back to the reader device by using the tag antenna. The identification number of the item is coded into these reflected signals, which can be detected as peaks in the time domain.

The ID code of a SAW transponder is defined by the position of the reflective structures along the transponder crystal body. These reflectors are assembled during the production process of transponders, i.e. a SAW transponder has a fixed ID code, which complicates its use with common product codes, such as EPC or European article number (EAN).

2.3 Backscatter Transponder

Passive transponders that are based on backscatter technology use load modulation for communication with the reader. A modulated RF signal is emitted from the reader antenna; a proportion of the signal reaches the transponder antenna. Owing to the RF field from the reader antenna, voltage is induced at the input terminals of the transponder. This d.c. voltage is used to charge a capacitor to provide the bias for the processing circuitry (Fig. 1) [5].

In the return link from the transponder to the reader, the proportion of incoming RF signal is backscattered from the transponder antenna back to the reader antenna. The processing circuit of the transponder changes the RF impedance of the transponder antenna and controls the amount of this scattered field. In this case the modulation of the scattered field contains the identification information [6]. The transponder is identified when the backscattered field is received and decoded by the reader unit. The role of the antennae is crucial in this kind of communication system.

The characteristics for transponder antennae used in RFID systems are outlined as follows [7]:

They must have dimensions small enough to be attached to the required object.

They must have omnidirectional or hemispherical coverage.

They must provide a maximum possible signal to the ASIC.

They must have a polarisation which matches the enquiry signal regardless of the physical orientation of the protected object.

They must be robust.

They must be extremely inexpensive.

Similarly, we can define characteristics for antennae used in RFID reader devices:

They must have high directivity.

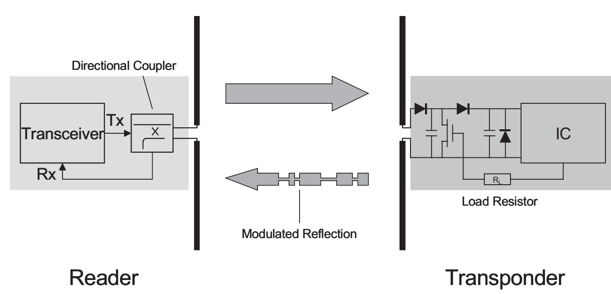

Fig. 1. Backscatter RFID system.

They must have high radiation efficiency.

They must have low side-lobe level to reduce interference.

The radiation pattern must be optimised to the reading zone.

They must be robust.

They must be inexpensive.

In the microwave range there are several types of antenna that can be used for RFID. Common antenna types for this frequency range are dipoles (wire, printed, folded), patches, PIFAs (planar inverted-F antenna) and helix antennae. The electrical size of these antenna types is comparable to the wavelength of the given frequency. Depending on the design used, the gain and the radiation pattern vary. The radiation pattern can be omnidirectional with a peak gain of 0–2 dBi, or directional, in which the radiation pattern has a definite lobe and the peak gain might be several dB [7]. The antenna characteristics have a radical effect on the read range of RFID systems. In the following paragraphs, we study the effect of antenna properties on the read range of passive backscatter RFID systems.

3. Antenna Parameters

In passive systems, the operational power required by the transponder is transmitted from the reader. This calls attention to the total performance of the radio link between the reader device and the transponder. For example, if we double the distance, we have to improve, by at least 12 dB, the reader properties, such as transmitter power, antenna gain, and receiver sensitivity.

3.1 Effect of Antenna Gain on Read Range

Antenna gain affects the read/write range of the RFID system. The effect of antenna gain on the read range is next studied in backscatter RFID systems in which the reflection of electromagnetic waves from the object is used for data transmission from the transponder to the reader [5].

The RF power is propagated in all directions by the reader antenna. The power density S at the location of the transponder is

$$S = \frac{P\ G_t}{4\pi R^2} \tag{1}$$

where P is the transmission power of the reader, G_t is the gain of the transmitter antenna and R is the distance between the reader and the transponder. The transponder reflects a power P_2, which is proportional to the power density S

$$P_2 = \sigma S \tag{2}$$

The radar cross-section σ is a measure of an object's ability to reflect electromagnetic waves. Depending on the matching of the transponder antenna, σ can vary from 0 to σ_{max}. The lower value appears if the transponder antenna is matched; then it will absorb completely all the radiated energy and there will be no reflections. The maximum value appears if the transponder antenna terminals are either short-circuited or left open; then it reflects all the energy arriving and acts as a reflecting surface.

$$\sigma_{max} = \frac{\lambda_0^2}{4\pi} G_r \tag{3}$$

The following equation describes the power density S_{BACK} , which finally returns to the reader antenna.

$$S_{BACK} = \frac{PG_t\sigma}{(4\pi)^2R^4} = \frac{PG_t\lambda_0^2G_r}{(4\pi)^3R^4} \tag{4}$$

The maximum received power, which can be drawn from the antenna, given optimal alignment and correct polarisation, is proportional to the power density of the incoming wave. The proportionality factor denoted as the effective area A_e of the antenna is proportional to its gain and equals σ_{max} and is defined as

$$A_e = \frac{\lambda_0^2}{4\pi} G_t \tag{5}$$

The reception power P_{BACK} of the reader antenna is then

$$P_{BACK} = S_{BACK}A_e = \frac{PG_t^2\lambda_0^4G_r}{(4\pi)^4R^4} \tag{6}$$

The equation demonstrates that the read range of such a backscatter RFID system is proportional to the fourth root of the transmission power of the reader. If all other things are equal, we must multiply the transmission power by 16 to double the range.

To show the effect of the antenna gain, the read range R is solved from the Eq. (6).

$$R = \frac{\lambda_0}{4\pi} \sqrt[4]{\frac{P \cdot G_t^2 \cdot G_r}{P_{BACK}}} \tag{7}$$

The antenna gain affects the read/write range of the RFID system. The read range for three different transponder antenna types is illustrated in Fig. 2 as a function of reader antenna gain. The read range is calculated from Eq. (7) for the system in which the sensitivity of the reader P_{BACK} is −70 dBm and the transmitted power P is 20 dBm at the frequency 2.45 GHz (λ_0 = 0.122 m). Values used are typical for backscatter RFID systems operating at 2.45 GHz ISM band.

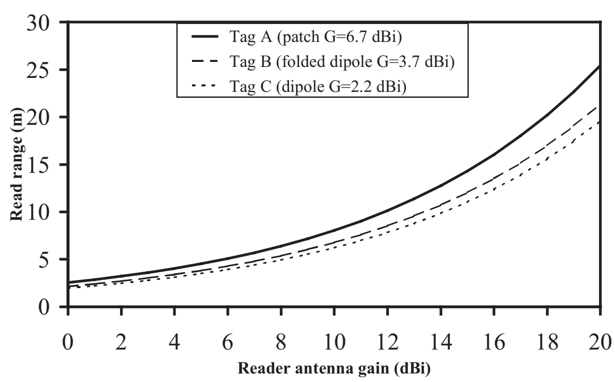

Fig. 2. Effect of antenna gain on read range (f = 2.45 GHz).

Table 1. The effect of reader antenna gain on the read range.

Reader antenna type	Read range (m)
Dipole (G = 2.2 dBi)	2.76
Patch (G = 6.7 dBi)	4.64
Patch array (G = 13.2 dBi)	9.80

In Table 1, the effect of the reader antenna gain on the read range is presented for three different reader antenna types in the case of a folded dipole tag antenna (G = 3.7 dBi). In Table 1, the three different reader antennae are dipole (G = 2.2 dBi), patch (G = 6.7 dBi) and 5-element patch array (G = 13.2 dBi).

These calculated values in Fig. 2, and in Table 1, are theoretically maximum read ranges in which the reader unit can detect the reflection from the transponder antenna under ideal conditions. Reflections from conductive surfaces, background noise, and antenna alignment cut down the read range to at least half of the theoretical maximum when the RFID system is operating in a real environment.

As we can see from Fig. 2, the read range is highly dependent on the RFID reader antenna gain. Using multiple antennae connected to the reader unit or antenna arrays can increase the gain. Adding even a few elements to form an antenna array can increase the gain of the antenna system significantly.

3.2 Effect of Frequency

The operation frequency ranges of operation for common backscatter RFID systems are 915 MHz, 2.45 GHz, and 5.8 GHz. Correspondingly, wavelengths for these frequencies are 0.328 m, 0.122 m, and 0.051 m. In Eq. (7) the read range is directly proportional to the wavelength used. By using a lower frequency, in other words a longer wavelength, the read range can be increased. The read range is presented in Fig. 3 as a function of reader antenna gain for 915 MHz, 2.45 GHz, and 5.8 GHz RFID systems. The transponder antenna that is used for read range calculations is a folded dipole antenna (G = 3.7 dBi).

In some cases the RF signal from the reader to the transponder has to propagate through an absorbing material. The frequency used has an effect on the propagation losses in the material. The effect of frequency on radio wave attenuation in a paper reel is presented in Fig. 4 [8]. The attenuation between two triple-band antennae was first measured in air, and after that through a paper reel with the transmitting antenna inside the reel core. The characteristic frequencies of the triple-band antenna used were 450, 900, and 1900 MHz. As we can see from Fig. 4, the attenuation in the paper reel increases as the frequency rises. The attenuation in the measured paper reel is 8 dB at 450 MHz, 10 dB at 900 MHz, and 16 dB at 1900 MHz.

Since antenna dimensions are proportional to the wavelength used, a lower frequency and a longer wavelength inevitably mean a larger transponder size. In most cases, the antenna size is a limiting factor in the miniaturising of RFID system transponders. The length of a folded dipole antenna, which is commonly used as a transponder antenna, is $\lambda_0/2$. This means that the size of the transponder in the 915 MHz system is approximately 164 mm, whereas the same type of transponder antenna in the 2.45 GHz system fits into 61 mm.

3.3 Effect of Antenna Polarisation Mismatch

The polarisation inequality between the receiving antenna and the transmitting antenna or the incoming wave can be termed the polarisation mismatch. The amount of power extracted by the antenna from the incoming signal will not be a maximum because of the polarisation loss [9].

Assuming that the electric field of the incoming wave can be expressed as

$$\mathbf{E}_i = \hat{\boldsymbol{\rho}}_w E_i \tag{8}$$

where $\boldsymbol{\rho}_w$ is the unit vector of the wave, and the polarisation of the electric field polarisation of the receiving antenna can be written as

$$E_a = \hat{\boldsymbol{\rho}}_a \tag{9}$$

where $\hat{\boldsymbol{\rho}}_a$ is its polarisation vector; the polarisation loss can then be taken into account by introducing a polarisation loss factor. The polarisation factor (PLF) is defined as

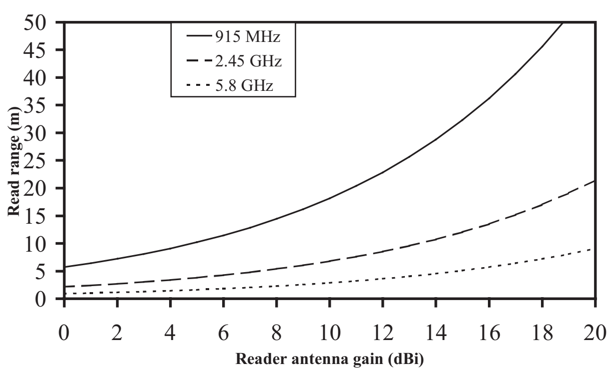

Fig. 3. Effect of frequency on read range.

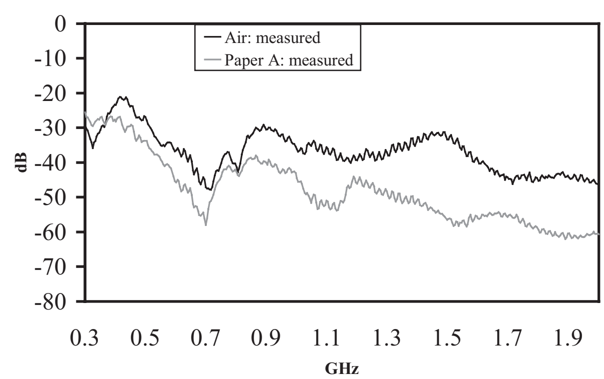

Fig. 4. Effect of frequency on radio wave attenuation in paper reel.

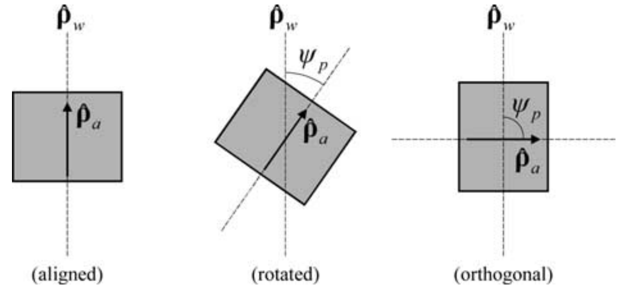

Fig. 5. Polarisation of antenna and incident wave.

$$\mathrm{PLF} = |\hat{\boldsymbol{\rho}}_w \cdot \hat{\boldsymbol{\rho}}_a|^2 = |\cos\varphi_p|^2 \tag{10}$$

where φ_p is the angle between the unit vector of the incident wave and the antenna polarisation vector (Fig. 5).

The polarisation loss factor PLF expressed in decibels

$$\mathrm{PLF(dB)} = 10 \log_{10} \mathrm{PLF} \tag{11}$$

is illustrated in Fig. 6, for polarisation mismatch from 0° to 90°. For antenna misalignments under 45°, the power loss is less than 3 dB. If the angle of polarisation mismatch increases, the power loss starts to increase significantly.

3.4 Using Circular Polarisation

Circular polarisation can be obtained in the antenna by feeding it with two orthogonal, linear field components having the same magnitude and time phase difference of odd multiples of 90° [9].

$$E_{x0} = E_{y0} \tag{12}$$

$$\Delta\phi = \phi_y - \phi_x = \begin{cases} +\left(\frac{1}{2} + 2n\right)\pi, & n = 0, 1, 2, \dots \\ -\left(\frac{1}{2} + 2n\right)\pi, & n = 0, 1, 2, \dots \end{cases} \tag{13}$$

In some cases, the use of circularly polarised antennae on the RFID reader improves the system performance. In those cases the effect of polarisation mismatch can be neglected and the angle between the reader antenna and the transponder antenna has no effect on the read range. However, if the transponder antenna is linearly polarised, but the reader antenna is circularly polarised, there is a 3 dB power loss, irrespective of the angle between the antennae, compared to the case in which the polarisation-matched, linearly polarised antennae are used on both the reader and the tag. This is because the circularly polarised field consists of two linear fields having a 90° phase shift and the linearly polarised antenna in the transponder detects the part of the field which matches its polarisation.

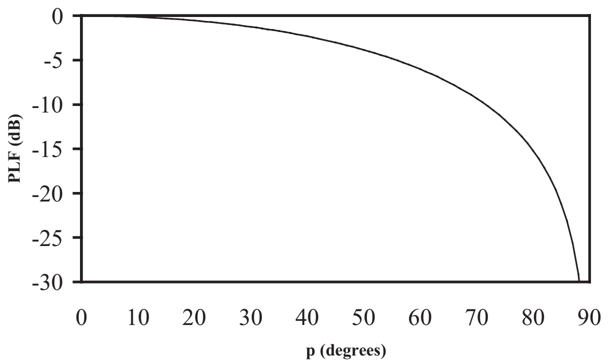

Fig. 6. PLF (dB) as a function of polarisation mismatch angle.

4. Conclusion

In this paper, the basic principle of a passive RFID system using backscattered waves was presented. In passive RFID systems, the energy needed for communication is entirely from the reader device. Passive RFID systems are easy to apply to manufacturing and logistics control systems because transponders are inexpensive, and are small and easy to fix to the object to be identified.

The effect of antenna properties on the read range and the performance of the passive backscatter RFID system were analysed. The read range in backscatter RFID systems depends on the transmitted power, the frequency used, the gain of the reader and the tag antennae and the sensitivity of the receiver. The authorities regulate the transmitted power for used frequency range, and the maximum allowed power level must not be exceeded. To improve the performance of the RFID system, we can concentrate on antennae. By using high-gain antennae, antenna arrays, or multiple antennae connected to the reader unit, the read range can be increased. In most cases, the size of the transponder is a limiting factor for a technically feasible antenna structure. The size of the transponder also limits the frequency used because the size of the antenna is proportional to the wavelength.

In many manufacturing control applications, the position of the object to be identified on a conveyor is known. In these cases, polarisation-matched, linearly polarised antennae can be used to maximise the read range and the RFID system performance. If the position and the angle between the antennae during the identification event are not known, there may be losses due to the polarisation mismatch. The effect of polarisation mismatch can be neglected in these cases by using circularly polarised antennae in the RFID reader. However, if the transponder antenna is linearly polarised and the reader antenna is circularly polarised, the maximum read range is in any case less than the read range for polarisation-matched, linearly polarised antennae.

The performance of an RFID system is highly dependent on the antennae. Choosing the right antenna for the RFID system can increase the reliability of the identification event and improve the efficiency of the manufacturing and logistics control system. Therefore, our future work will be concentrated on different reader antenna systems and transponder antenna geometries and the different implementation possibilities that they can offer for manufacturing and logistics control applications.

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