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RFID HANDBOOK

Fundamentals and Applications in Contactless Smart Cards and Identification

Second Edition

KLAUS FINKENZELLER

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Table 3.5 Typical operating parameters of acoustomagnetic systems (VDI 4471)

Parameter	Typical value
Resonant frequency f_0	58 kHz
Frequency tolerance	±0.52%
Quality factor Q	>150
Minimum field strength H_A for activation	>16 000 A/m
ON duration of the field	2 ms
Field pause (OFF duration)	20 ms
Decay process of the security element	5 ms

metal strip so it can no longer be excited by the operating frequency of the security system. The hard magnetic metal strip can only be demagnetised by a strong magnetic alternating field with a slowly decaying field strength. It is thus absolutely impossible for the security element to be manipulated by permanent magnets brought into the store by customers.

3.2 Full and Half Duplex Procedure

In contrast to 1-bit transponders, which normally exploit simple physical effects (oscillation stimulation procedures, stimulation of harmonics by diodes or the nonlinear hysteresis curve of metals), the transponders described in this and subsequent sections use an electronic microchip as the data-carrying device. This has a data storage capacity of up to a few kilobytes. To read from or write to the data-carrying device it must be possible to transfer data between the transponder and a reader. This transfer takes place according to one of two main procedures: full and half duplex procedures, which are described in this section, and sequential systems, which are described in the following section.

In the *half duplex procedure* (HDX) the data transfer from the transponder to the reader alternates with data transfer from the reader to the transponder. At frequencies below 30 MHz this is most often used with the load modulation procedure, either with or without a subcarrier, which involves very simple circuitry. Closely related to this is the modulated reflected cross-section procedure that is familiar from radar technology and is used at frequencies above 100 MHz. Load modulation and modulated reflected cross-section procedures directly influence the magnetic or electromagnetic field generated by the reader and are therefore known as *harmonic* procedures.

In the *full duplex procedure* (FDX) the data transfer from the transponder to the reader takes place at the same time as the data transfer from the reader to the transponder. This includes procedures in which data is transmitted from the transponder at a fraction of the frequency of the reader, i.e. a *subharmonic*, or at a completely independent, i.e. an *anharmonic*, frequency.

However, both procedures have in common the fact that the transfer of energy from the reader to the transponder is continuous, i.e. it is independent of the direction of data flow. In sequential systems (SEQ), on the other hand, the transfer of energy from the transponder to the reader takes place for a limited period of time only (pulse

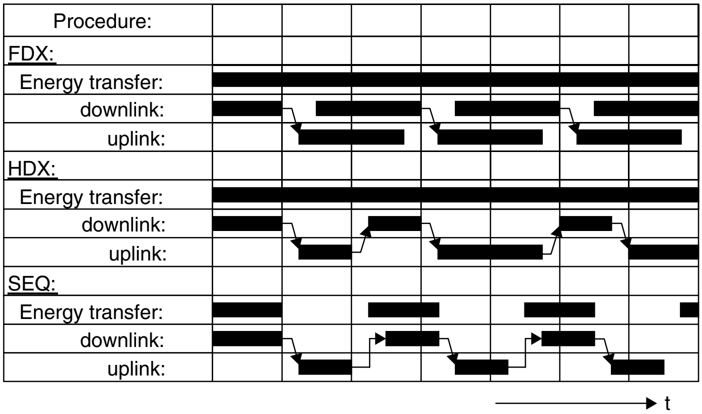

Figure 3.12 Representation of full duplex, half duplex and sequential systems over time. Data transfer from the reader to the transponder is termed downlink, while data transfer from the transponder to the reader is termed uplink

operation → *pulsed system*). Data transfer from the transponder to the reader occurs in the pauses between the power supply to the transponder. See Figure 3.12 for a representation of full duplex, half duplex and sequential systems.

Unfortunately, the literature relating to RFID has not yet been able to agree a consistent nomenclature for these system variants. Rather, there has been a confusing and inconsistent classification of individual systems into full and half duplex procedures. Thus pulsed systems are often termed half duplex systems — this is correct from the point of view of data transfer — and all unpulsed systems are falsely classified as full duplex systems. For this reason, in this book pulsed systems — for differentiation from other procedures, and unlike most RFID literature(!) — are termed sequential systems (SEQ).

3.2.1 Inductive coupling

3.2.1.1 Power supply to passive transponders

An inductively coupled transponder comprises an electronic data-carrying device, usually a single microchip, and a large area coil that functions as an antenna.

Inductively coupled transponders are almost always operated passively. This means that all the energy needed for the operation of the microchip has to be provided by the reader (Figure 3.13). For this purpose, the reader's antenna coil generates a strong, high frequency electromagnetic field, which penetrates the cross-section of the coil area and the area around the coil. Because the wavelength of the frequency range used (<135 kHz: 2400 m, 13.56 MHz: 22.1 m) is several times greater than the distance between the reader's antenna and the transponder, the electromagnetic field may be treated as a simple magnetic alternating field with regard to the distance between transponder and antenna (see Section 4.2.1.1 for further details).

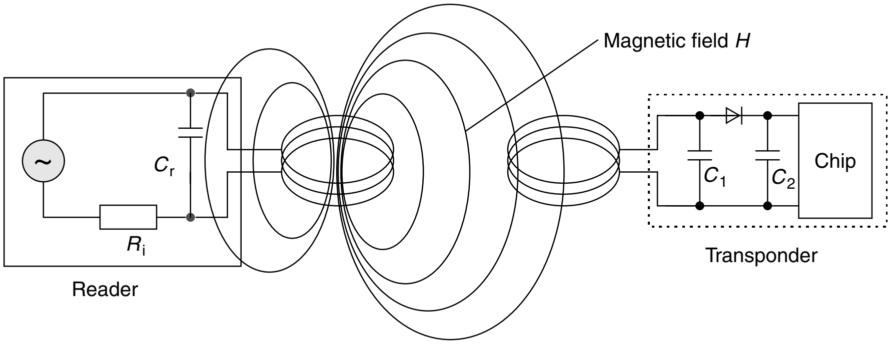

Figure 3.13 Power supply to an inductively coupled transponder from the energy of the magnetic alternating field generated by the reader

A small part of the emitted field penetrates the antenna coil of the transponder, which is some distance away from the coil of the reader. A voltage U_i is generated in the transponder's antenna coil by inductance. This voltage is rectified and serves as the power supply for the data-carrying device (microchip). A capacitor C_r is connected in parallel with the reader's antenna coil, the capacitance of this capacitor being selected such that it works with the coil inductance of the antenna coil to form a parallel resonant circuit with a resonant frequency that corresponds with the transmission frequency of the reader. Very high currents are generated in the antenna coil of the reader by resonance step-up in the parallel resonant circuit, which can be used to generate the required field strengths for the operation of the remote transponder.

The antenna coil of the transponder and the capacitor C_1 form a resonant circuit tuned to the transmission frequency of the reader. The voltage U at the transponder coil reaches a maximum due to resonance step-up in the parallel resonant circuit.

The layout of the two coils can also be interpreted as a transformer (*transformer coupling*), in which case there is only a very weak coupling between the two windings (Figure 3.14). The efficiency of power transfer between the antenna coil of the reader and the transponder is proportional to the operating frequency f, the number of windings n, the area A enclosed by the transponder coil, the angle of the two coils relative to each other and the distance between the two coils.

As frequency f increases, the required coil inductance of the transponder coil, and thus the number of windings n decreases (135 kHz: typical 100–1000 windings, 13.56 MHz: typical 3–10 windings). Because the voltage induced in the transponder is still proportional to frequency f (see Chapter 4), the reduced number of windings barely affects the efficiency of power transfer at higher frequencies. Figure 3.15 shows a reader for an inductively coupled transponder.

3.2.1.2 Data transfer transponder → reader

Load modulation As described above, inductively coupled systems are based upon a *transformer-type coupling* between the primary coil in the reader and the secondary coil in the transponder. This is true when the distance between the coils does not exceed

4

Physical Principles of RFID Systems

The vast majority of RFID systems operate according to the principle of *inductive coupling*. Therefore, understanding of the procedures of power and data transfer requires a thorough grounding in the physical principles of magnetic phenomena. This chapter therefore contains a particularly intensive study of the theory of magnetic fields from the point of view of RFID.

Electromagnetic fields — radio waves in the classic sense — are used in RFID systems that operate at above 30 MHz. To aid understanding of these systems we will investigate the propagation of waves in the far field and the principles of radar technology.

Electric fields play a secondary role and are only exploited for capacitive data transmission in close coupling systems. Therefore, this type of field will not be discussed further.

4.1 Magnetic Field

4.1.1 Magnetic field strength *H*

Every moving charge (electrons in wires or in a vacuum), i.e. flow of current, is associated with a *magnetic field* (Figure 4.1). The intensity of the magnetic field can be demonstrated experimentally by the forces acting on a magnetic needle (compass) or a second electric current. The magnitude of the magnetic field is described by the *magnetic field strength* H regardless of the material properties of the space.

In the general form we can say that: 'the contour integral of magnetic field strength along a closed curve is equal to the sum of the current strengths of the currents within it' (Kuchling, 1985).

$$\sum I = \oint \vec{H} \cdot \vec{ds} \tag{4.1}$$

We can use this formula to calculate the field strength H for different types of conductor. See Figure 4.2.

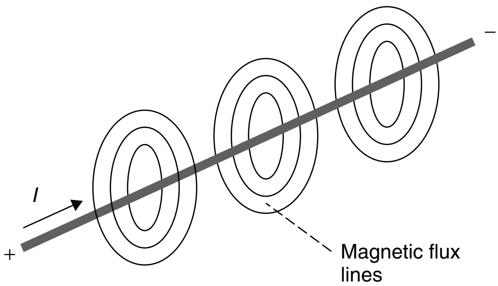

Figure 4.1 Lines of magnetic flux are generated around every current-carrying conductor

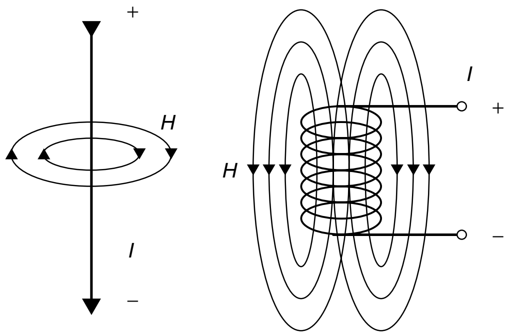

Figure 4.2 Lines of magnetic flux around a current-carrying conductor and a current-carrying cylindrical coil

Table 4.1 Constants used

Constant	Symbol	Value and unit
Electric field constant	ε_0	8.85×10^{-12} As/Vm
Magnetic field constant	μ_0	1.257×10^{-6} Vs/Am
Speed of light	c	299 792 km/s
Boltzmann constant	k	$1.380\,662 \times 10^{-23}$ J/K

In a straight conductor the field strength H along a circular *flux line* at a distance r is constant. The following is true (Kuchling, 1985):

$$H = \frac{1}{2\pi r} \tag{4.2}$$

4.1.1.1 Path of field strength H(x) in conductor loops

So-called 'short cylindrical coils' or conductor loops are used as magnetic antennas to generate the *magnetic alternating field* in the write/read devices of inductively coupled RFID systems (Figure 4.3).

Table 4.2 Units and abbreviations used

Variable	Symbol	Unit	Abbreviation
Magnetic field strength	H	Ampere per meter	A/m
Magnetic flux (n = number of windings)	Φ	Volt seconds	Vs
	$\Psi = n\Phi$		
Magnetic inductance	B	Volt seconds per meter squared	Vs/m^2
Inductance	L	Henry	H
Mutual inductance	M	Henry	H
Electric field strength	E	Volts per metre	V/m
Electric current	I	Ampere	A
Electric voltage	U	Volt	V
Capacitance	C	Farad	F
Frequency	f	Hertz	Hz
Angular frequency	$\omega = 2\pi \mathrm{f}$	1/seconds	1/s
Length	l	Metre	m
Area	A	Metre squared	m^2
Speed	v	Metres per second	m/s
Impedance	Z	Ohm	Ω
Wavelength	λ	Metre	m
Power	P	Watt	W
Power density	S	Watts per metre squared	W/m^2

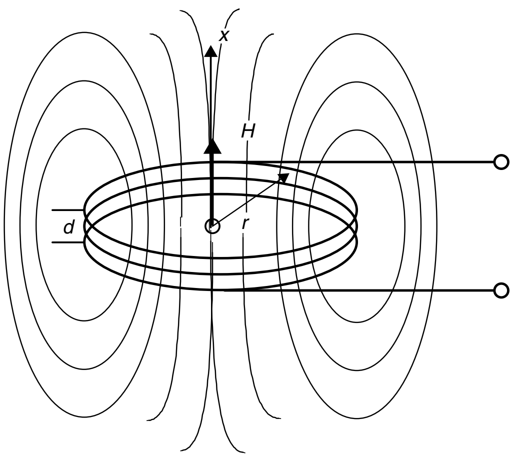

Figure 4.3 The path of the lines of magnetic flux around a short cylindrical coil, or conductor loop, similar to those employed in the transmitter antennas of inductively coupled RFID systems

If the measuring point is moved away from the centre of the coil along the coil axis (x axis), then the strength of the field H will decrease as the distance x is increased. A more in-depth investigation shows that the field strength in relation to the radius (or area) of the coil remains constant up to a certain distance and then falls rapidly (see Figure 4.4). In free space, the decay of field strength is approximately 60 dB per

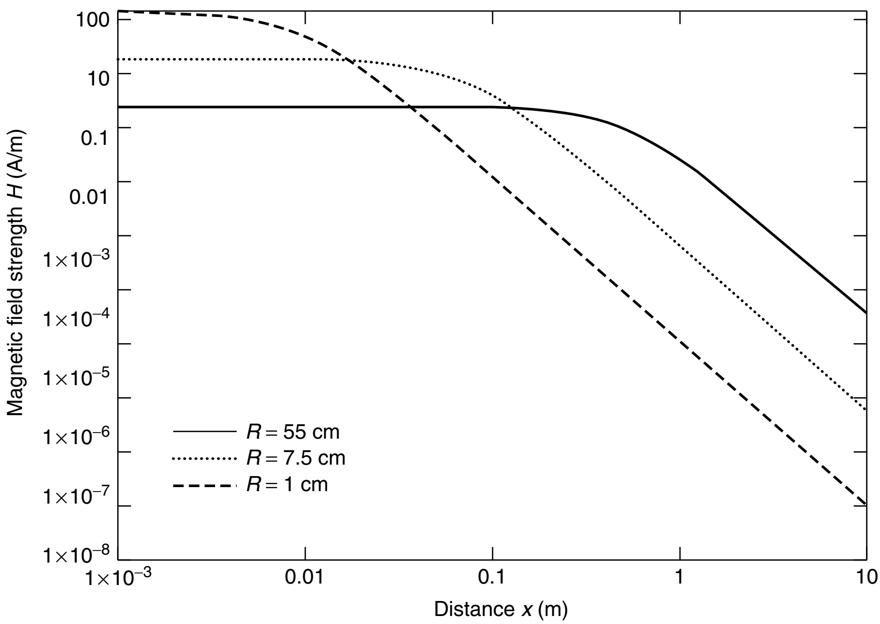

Figure 4.4 Path of magnetic field strength H in the near field of short cylinder coils, or conductor coils, as the distance in the x direction is increased

decade in the near field of the coil, and flattens out to 20 dB per decade in the far field of the electromagnetic wave that is generated (a more precise explanation of these effects can be found in Section 4.2.1).

The following equation can be used to calculate the path of field strength along the x axis of a round coil (= conductor loop) similar to those employed in the transmitter antennas of inductively coupled RFID systems (Paul, 1993):

$$H = \frac{I \cdot N \cdot R^2}{2\sqrt{(R^2 + x^2)^3}} \tag{4.3}$$

where N is the number of windings, R is the circle radius r and x is the distance from the centre of the coil in the x direction. The following boundary condition applies to this equation: $d \ll R$ and $x < \lambda/2\pi$ (the transition into the electromagnetic far field begins at a distance $>2\pi$; see Section 4.2.1).

At distance 0 or, in other words, at the centre of the antenna, the formula can be simplified to (Kuchling, 1985):

$$H = \frac{I \cdot N}{2R} \tag{4.4}$$

We can calculate the *field strength path* of a rectangular conductor loop with edge length $a \times b$ at a distance of x using the following equation. This format is often used as a transmitter antenna.

$$H = \frac{N \cdot I \cdot ab}{4\pi\sqrt{\left(\frac{a}{2}\right)^2 + \left(\frac{b}{2}\right)^2 + x^2}} \cdot \left(\frac{1}{\left(\frac{a}{2}\right)^2 + x^2} + \frac{1}{\left(\frac{b}{2}\right)^2 + x^2} \right) \tag{4.5}$$

Figure 4.4 shows the calculated field strength path $H(x)$ for three different antennas at a distance 0–20 m. The number of windings and the antenna current are constant in each case; the antennas differ only in radius R. The calculation is based upon the following values: $H1$: $R = 55$ cm, $H2$: $R = 7.5$ cm, $H3$: $R = 1$ cm.

The calculation results confirm that the increase in field strength flattens out at short distances ($x < R$) from the antenna coil. Interestingly, the smallest antenna exhibits a significantly higher field strength at the centre of the antenna (distance = 0), but at greater distances ($x > R$) the largest antenna generates a significantly higher field strength. It is vital that this effect is taken into account in the design of antennas for inductively coupled RFID systems.

4.1.1.2 Optimal antenna diameter

If the radius R of the transmitter antenna is varied at a constant distance x from the transmitter antenna under the simplifying assumption of constant coil current I in the transmitter antenna, then field strength H is found to be at its highest at a certain ratio of distance x to antenna radius R. This means that for every *read range* of an RFID system there is an optimal antenna radius R. This is quickly illustrated by a glance at Figure 4.4: if the selected antenna radius is too great, the field strength is too low even at a distance $x = 0$ from the transmission antenna. If, on the other hand, the selected antenna radius is too small, then we find ourselves within the range in which the field strength falls in proportion to x^3.

Figure 4.5 shows the graph of field strength H as the coil radius R is varied. The optimal coil radius for different read ranges is always the maximum point of the graph $H(R)$. To find the mathematical relationship between the maximum field strength H and the coil radius R we must first find the inflection point of the function $H(R)$ (see equation 4.3) (Lee, 1999). To do this we find the first derivative $H'(R)$ by differentiating $H(R)$ with respect to R:

$$H'(R) = \frac{\mathrm{d}}{\mathrm{d}R}H(R) = \frac{2 \cdot I \cdot N \cdot R}{\sqrt{(R^2 + x^2)^3}} - \frac{3 \cdot I \cdot N \cdot R^3}{(R^2 + x^2) \cdot \sqrt{(R^2 + x^2)^3}} \tag{4.6}$$

The inflection point, and thus the maximum value of the function $H(R)$, is found from the following zero points of the derivative $H'(R)$:

$$R_1 = x \cdot \sqrt{2}; \qquad R_2 = -x \cdot \sqrt{2} \tag{4.7}$$

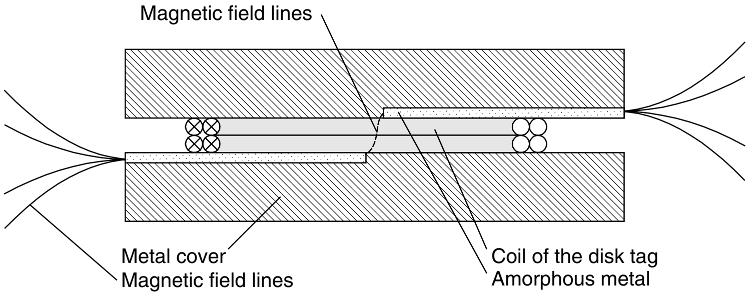

Figure 4.55 Cross-section through a sandwich made of disk transponder and metal plates. Foils made of amorphous metal cause the magnetic field lines to be directed outwards

space (rotational field). It surrounds the electric field and itself varies over time, thus generating another electric field. Due to the mutual dependence of the time varying fields there is a chain effect of electric and magnetic fields in space (Fricke *et al.*, 1979).

Radiation can only occur given a finite propagation speed ($c \approx 300\,000$ km/s; *speed of light*) for the electromagnetic field, which prevents a change in the voltage at the antenna from being followed immediately by the field in the vicinity of the change. Figure 4.56 shows the creation of an *electromagnetic wave* at a *dipole antenna*. Even at the alternating voltage's zero crossover (Figure 4.56c), the field lines remaining in space from the previous half wave cannot end at the antenna, but close into themselves, forming eddies. The eddies in the opposite direction that occur in the next half wave propel the existing eddies, and thus the energy stored in this field, away from the emitter at the speed of light c. The magnetic field is interlinked with the varying electrical field that propagates at the same time. When a certain distance is reached, the fields are released from the emitter, and this point represents the beginning of electromagnetic radiation (→ far field). At high frequencies, that is small wavelengths, the radiation generated is particularly effective, because in this case the separation takes place in the direct vicinity of the emitter, where high field strengths still exist (Fricke *et al.*, 1979).

The distance between two field eddies rotating in the same direction is called the *wavelength* λ of the electromagnetic wave, and is calculated from the quotient of the speed of light c and the frequency of the radiation:

$$\lambda = \frac{c}{f} \tag{4.60}$$

4.2.1.1 Transition from near field to far field in conductor loops

The primary magnetic field generated by a *conductor loop* begins at the antenna (see also Section 4.1.1.1). As the magnetic field propagates an electric field increasingly also develops by induction (compare Figure 4.11). The field, which was originally purely magnetic, is thus continuously transformed into an electromagnetic field. Moreover,

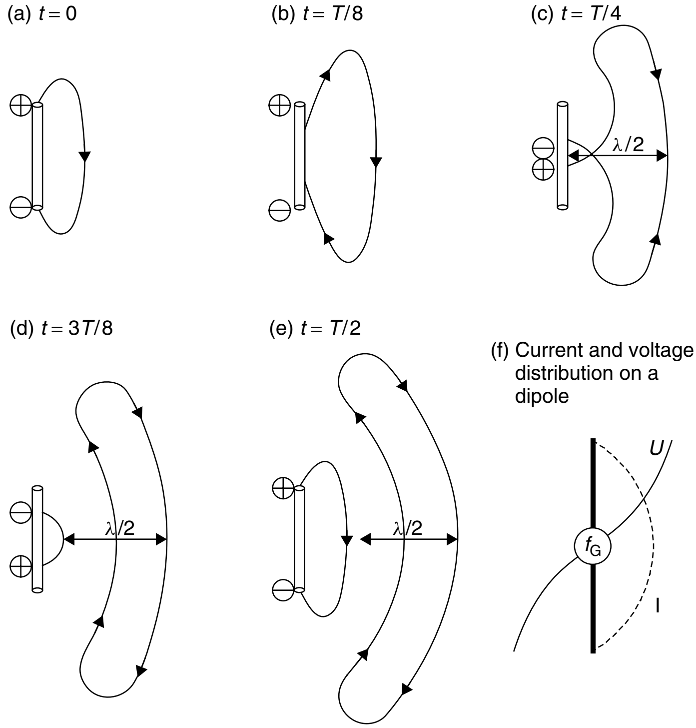

Figure 4.56 The creation of an electromagnetic wave at a dipole antenna. The electric field E is shown. The magnetic field H forms as a ring around the antenna and thus lies at right angles to the electric field

at a distance of $\lambda/2\pi$ the electromagnetic field begins to separate from the antenna and wanders into space in the form of an electromagnetic wave. The area from the antenna to the point where the electromagnetic field forms is called the *near field* of the antenna. The area after the point at which the electromagnetic wave has fully formed and separated from the antenna is called the *far field*.

A separated electromagnetic wave can no longer retroact upon the antenna that generated it by inductive or capacitive coupling. For inductively coupled RFID systems this means that once the far field has begun a *transformer (inductive) coupling* is no

Table 4.5 Frequency and wavelengths of different VHF–UHF frequencies

Frequency	Wavelength (cm)
433 MHz	69 (70 cm band)
868 MHz	34
915 MHz	33
2.45 GHz	12
5.8 GHz	5.2

Table 4.6 r_F and λ for different frequency ranges

Frequency	Wavelength λ (m)	$\lambda/2\pi$ (m)
<135 kHz	>2222	>353
6.78 MHz	44.7	7.1
13.56 MHz	22.1	3.5
27.125 MHz	11.0	1.7

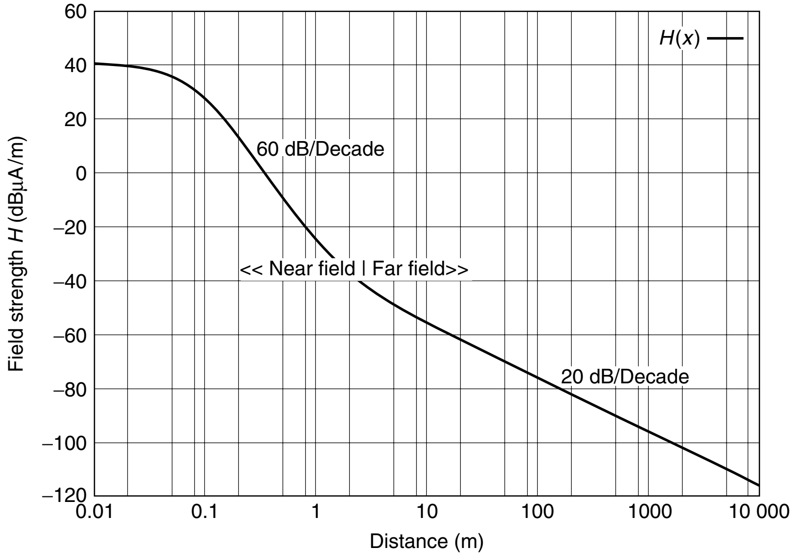

Figure 4.57 Graph of the magnetic field strength H in the transition from near to far field at a frequency of 13.56 MHz

longer possible. The beginning of the far field (the radius $r_F = \lambda/2\pi$ can be used as a rule of thumb) around the antenna thus represents an insurmountable *range limit* for inductively coupled systems.

The field strength path of a magnetic antenna along the coil x axis follows the relationship $1/d^3$ in the near field, as demonstrated above. This corresponds with a damping of 60 dB per decade (of distance). Upon the transition to the far field, on the other hand, the damping path flattens out, because after the separation of the field from the antenna only the *free space attenuation* of the electromagnetic waves is relevant to the field strength path (Figure 4.57). The field strength then decreases only according to the relationship $1/d$ as distance increases (see equation (4.65)). This corresponds with a damping of just 20 dB per decade (of distance).

4.2.2 Radiation density *S*

An *electromagnetic wave* propagates into space spherically from the point of its creation. At the same time, the electromagnetic wave transports energy in the surrounding

Table 9.5 Position 1 (state A, unmodulated; state A′, modulated)

A	A′
ΦF	1Φ′F1 = ΦF1 − 90°
ΦF3 = ΦF1 + 90°	Φ′F3 = ΦF3 + 90°

Table 9.6 Position 2 (state A, unmodulated; state A′, modulated)

A	A′
F1	Φ′F1 = Φ′F1 + 90°
ΦF3 = ΦF1 − 90°	Φ′F3 = Φ′F3 − 90°

9.2.2 ISO 14443 – Proximity coupling smart cards

ISO standard 14443 entitled 'Identification cards — Proximity integrated circuit(s) cards' describes the operating method and operating parameters of contactless proximity coupling smart cards. This means contactless smart cards with an approximate range of 7–15 cm, like those used predominantly in the field of ticketing. The data carrier of these smart cards is normally a microprocessor and they often have additional contacts (see also Section 10.2.1).

The standard comprises the following parts:

- Part 1: Physical characteristics.
- Part 2: Radio frequency power and signal interface.
- Part 3: Initialisation and anticollision (still in preparation).
- Part 4: Transmission protocols (in preparation).

9.2.2.1 Part 1 – Physical characteristics

Part 1 of the standard defines the mechanical properties of the smart cards. The dimensions correspond with the values specified in ISO 7810, i.e. 85.72 mm × 54.03 mm × 0.76 mm ± tolerances.

Furthermore, this part of the standard also includes notes on the testing of the dynamic bending stress and dynamic torsion stress, plus irradiation with UV, x-ray and electromagnetic radiation.

9.2.2.2 Part 2 – Radio frequency interference

The power supply of inductively coupled *proximity cards* (*PICC*) is provided by the magnetic alternating field of a reader (PCD) at a transmission frequency of 13.56 MHz.

To this end the card incorporates a large area antenna coil typically with 3–6 windings of wire (see Figures 2.11 and 2.12).

The magnetic field generated by the reader must be within the range 1.5 A/m $\leq H \leq$ 7.5 A/m. Thus the *interrogation field strength* H_{min} of a proximity coupling smart card is automatically $H_{min} \leq$ 1.5 A/m. This is the only way to ensure that a smart card with an interrogation field strength $H_{min} =$ 1.5 A/m can be read by a reader that generates a field strength of just 1.5 A/m (e.g. a portable, battery operated reader with a correspondingly lower transmission power), at least at distance $x = 0$ from the transmission antenna (smart card in contact) (Berger, 1998).

If the field strength curve of a reader and the interrogation field strength of a proximity coupling smart card are known, then the range of the system can be calculated. The field strength curve of a typical reader in accordance with ISO 14443 is shown in Figure 9.11 (see Section 4.1.1.1). In this case, a smart card interrogation field strength of 1.5 A/m results in a range of 10 cm.

Unfortunately it was not possible to agree to a common communication interface in the development of this standard. For this reason, two completely different procedures for the data transfer between reader and proximity coupling smart card have found a place in ISO 14443 — Type A and Type B. A smart card only has to support one of the two communication procedures. A reader conforming to the standard, on the other hand, must be able to communicate equally well by both procedures, and thus support all smart cards. This means that the reader must switch between the two communication procedures (polling) periodically during 'idle' mode ('wait for smart card').

However, the reader may not switch between the two procedures during an existing communication relationship between reader and card.

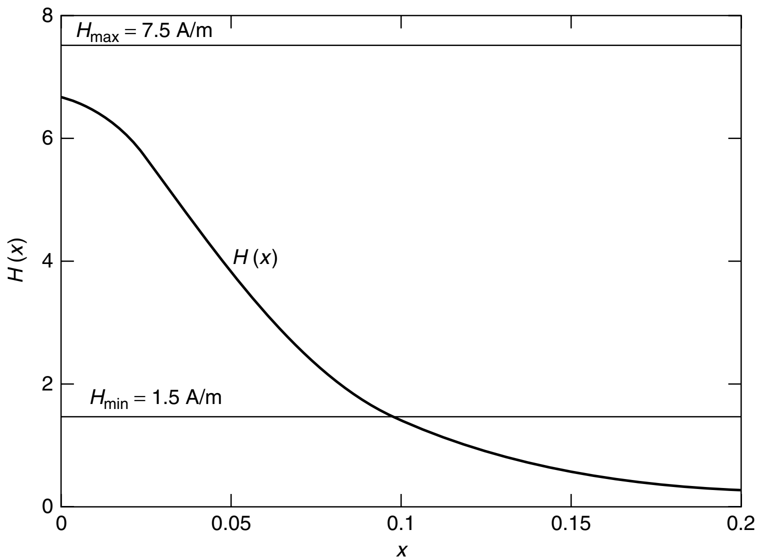

Figure 9.11 Typical field strength curve of a reader for proximity coupling smart cards (antenna current i_1 = 1A, antenna diameter D = 15 cm, number of windings N = 1)