3

Fundamental Operating Principles

This chapter describes the basic interaction between transponder and reader, in particular the power supply to the transponder and the data transfer between transponder and reader (Figure 3.1). For a more in-depth description of the physical interactions and mathematical models relating to inductive coupling or backscatter systems please refer to Chapter 4.

3.1 1-Bit Transponder

A bit is the smallest unit of information that can be represented and has only two states: 1 and 0. This means that only two states can be represented by systems based upon a *1-bit transponder*: 'transponder in interrogation zone' and 'no transponder in interrogation zone'. Despite this limitation, 1-bit transponders are very widespread — their main field of application is in electronic *anti-theft devices* in shops (*EAS*, electronic article surveillance).

An EAS system is made up of the following components: the antenna of a 'reader' or interrogator, the *security element* or *tag*, and an optional *deactivation device* for deactivating the tag after payment. In modern systems deactivation takes place when the price code is registered at the till. Some systems also incorporate an *activator*, which is used to reactivate the security element after deactivation (Gillert, 1997). The main performance characteristic for all systems is the recognition or *detection rate* in relation to the gate width (maximum distance between transponder and interrogator antenna).

The procedure for the inspection and testing of installed article surveillance systems is specified in the guideline *VDI 4470* entitled 'Anti-theft systems for goods — detection gates. Inspection guidelines for customers'. This guideline contains definitions and testing procedures for the calculation of the detection rate and false alarm ratio. It can be used by the retail trade as the basis for sales contracts or for monitoring the performance of installed systems on an ongoing basis. For the product manufacturer, the Inspection Guidelines for Customers represents an effective benchmark in the development and optimisation of integrated solutions for security projects (in accordance with VDI 4470).

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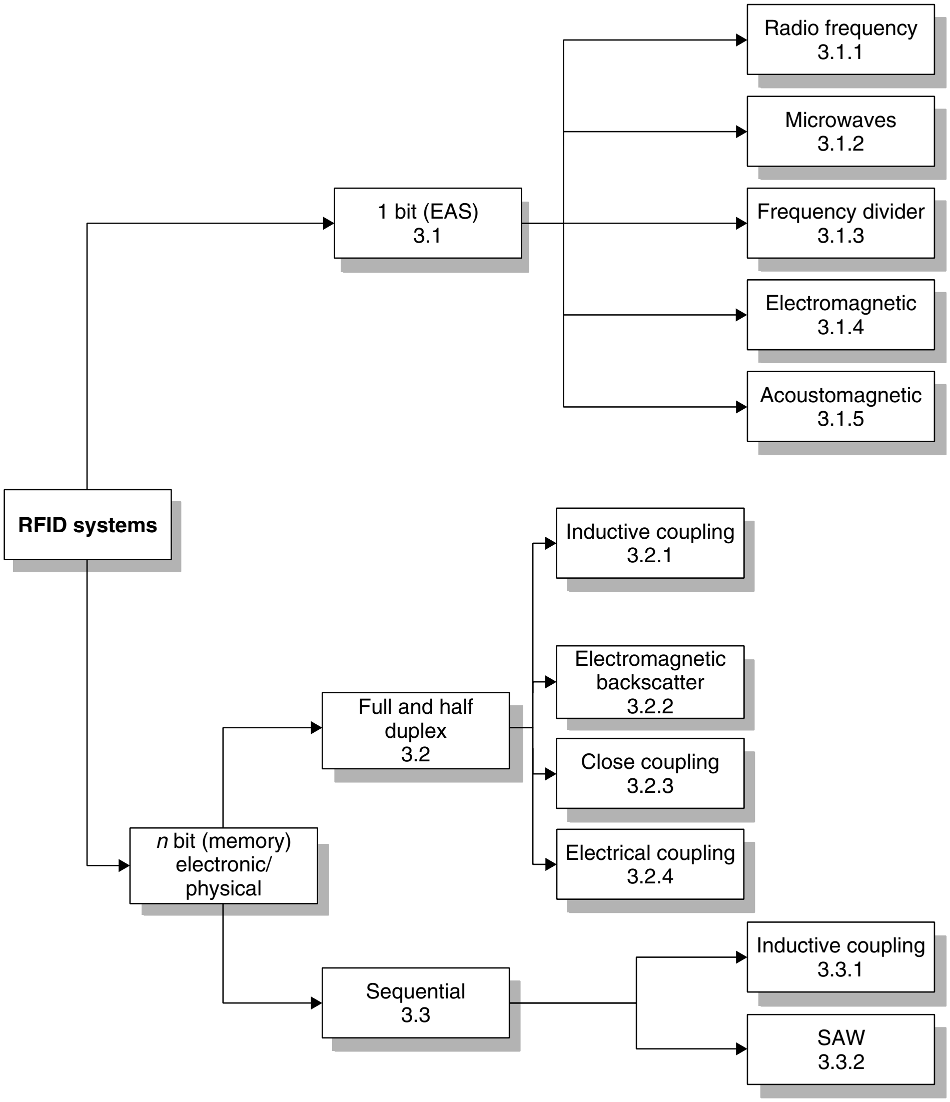

Figure 3.1 The allocation of the different operating principles of RFID systems into the sections of the chapter

3.1.1 Radio frequency

The *radio frequency (RF) procedure* is based upon LC resonant circuits adjusted to a defined resonant frequency f_R. Early versions employed inductive resistors made of wound enamelled copper wire with a soldered on capacitor in a plastic housing (*hard tag*). Modern systems employ coils etched between foils in the form of stick-on labels. To ensure that the damping resistance does not become too high and reduce the quality of the resonant circuit to an unacceptable level, the thickness of the aluminium conduction tracks on the 25 μm thick *polyethylene foil* must be at least 50 μm (Jörn, 1994). Intermediate foils of 10 μm thickness are used to manufacture the capacitor plates.

The reader (detector) generates a magnetic alternating field in the radio frequency range (Figure 3.2). If the LC resonant circuit is moved into the vicinity of the magnetic alternating field, energy from the alternating field can be induced in the resonant circuit via its coils (Faraday's law). If the frequency f_G of the alternating field corresponds with the resonant frequency f_R of the LC resonant circuit the resonant circuit produces a *sympathetic oscillation*. The current that flows in the resonant circuit as a result of this acts against its cause, i.e. it acts against the external magnetic alternating field (see Section 4.1.10.1). This effect is noticeable as a result of a small change in the voltage drop across the transmitter's generator coil and ultimately leads to a weakening of the measurable magnetic field strength. A change to the induced voltage can also be detected in an optional sensor coil as soon as a resonant oscillating circuit is brought into the magnetic field of the generator coil.

The relative magnitude of this dip is dependent upon the gap between the two coils (generator coil — security element, security element — sensor coil) and the quality Q of the induced resonant circuit (in the security element).

The relative magnitude of the changes in voltage at the generator and sensor coils is generally very low and thus difficult to detect. However, the signal should be as clear as possible so that the security element can be reliably detected. This is achieved using a bit of a trick: the frequency of the magnetic field generated is not constant, it is 'swept'. This means that the generator frequency continuously crosses the range between minimum and maximum. The frequency range available to the swept systems is 8.2 MHz ±10% (Jörn, 1994).

Whenever the swept generator frequency exactly corresponds with the resonant frequency of the resonant circuit (in the transponder), the transponder begins to oscillate, producing a clear dip in the voltages at the generator and sensor coils (Figure 3.3). Frequency tolerances of the security element, which depend upon manufacturing tolerances

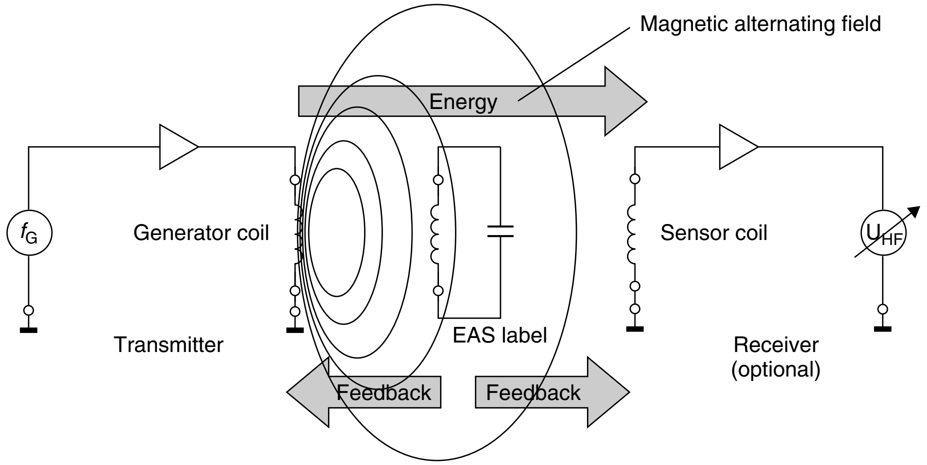

Figure 3.2 Operating principle of the EAS radio frequency procedure

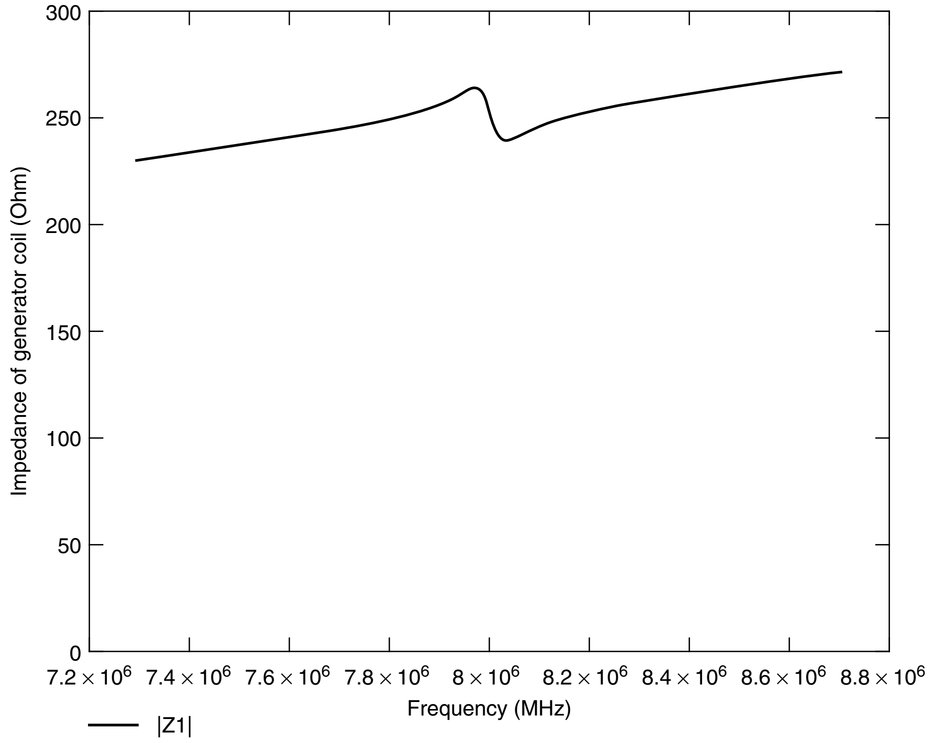

Figure 3.3 The occurrence of an impedance 'dip' at the generator coil at the resonant frequency of the security element ($Q = 90$, $k = 1\%$). The generator frequency f_G is continuously swept between two cut-off frequencies. An RF tag in the generator field generates a clear dip at its resonant frequency f_R

and vary in the presence of a metallic environment, no longer play a role as a result of the 'scanning' of the entire frequency range.

Because the tags are not removed at the till, they must be altered so that they do not activate the anti-theft system. To achieve this, the cashier places the protected product into a device — the deactivator — that generates a sufficiently high magnetic field that the induced voltage destroys the foil capacitor of the transponder. The capacitors are designed with intentional short-circuit points, so-called *dimples*. The breakdown of the capacitors is irreversible and detunes the resonant circuit to such a degree that this can no longer be excited by the *sweep signal*.

Large area *frame antennas* are used to generate the required magnetic alternating field in the detection area. The frame antennas are integrated into columns and combined to form gates. The classic design that can be seen in every large department store is illustrated in Figure 3.4. Gate widths of up to 2 m can be achieved using the RF procedure. The relatively low detection rate of 70% (Gillert, 1997) is disproportionately influenced by certain product materials. Metals in particular (e.g. food tins) affect the resonant frequency of the tags and the coupling to the detector coil and thus have a negative effect on the detection rate. Tags of 50 mm × 50 mm must be used to achieve the gate width and detection rate mentioned above.

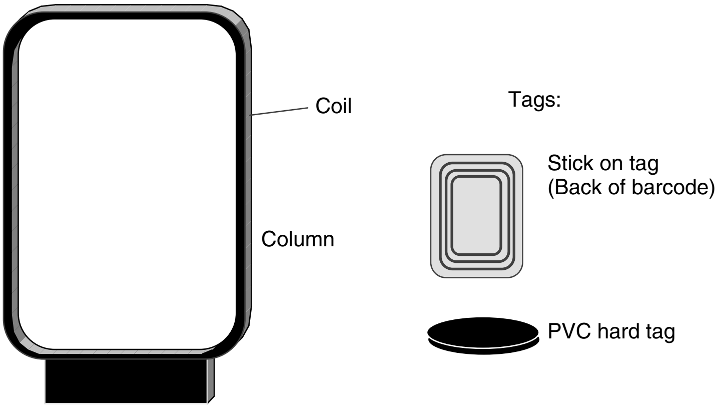

Figure 3.4 Left, typical frame antenna of an RF system (height 1.20–1.60 m); right, tag designs

Table 3.1 Typical system parameters for RF systems (VDI 4471)

Quality factor Q of the security element	>60–80
Minimum deactivation field strength H_D	1.5 A/m
Maximum field strength in the deactivation range	0.9 A/m

Table 3.2 Frequency range of different RF security systems (Plotzke *et al.*, 1994)

	System 1	**System 2**	**System 3**	**System 4**
Frequency (MHz)	1.86–2.18	7.44–8.73	7.30–8.70	7.40–8.60
Sweep frequency (Hz)	141	141	85	85

The range of products that have their own resonant frequencies (e.g. cable drums) presents a great challenge for system manufacturers. If these resonant frequencies lie within the sweep frequency 8.2 MHz ± 10% they will always trigger false alarms.

3.1.2 Microwaves

EAS systems in the *microwave range* exploit the generation of harmonics at components with nonlinear characteristic lines (e.g. diodes). The *harmonic* of a sinusoidal voltage A with a defined frequency f_A is a sinusoidal voltage B, whose frequency f_B is an integer multiple of the frequency f_A. The subharmonics of the frequency f_A are thus the frequencies $2f_A$, $3f_A$, $4f_A$ etc. The Nth multiple of the output frequency is termed the Nth harmonic (Nth harmonic wave) in radio-engineering; the output frequency itself is termed the carrier wave or first harmonic.

In principle, every two-terminal network with a nonlinear characteristic generates harmonics at the first harmonic. In the case of *nonlinear resistances*, however, energy is consumed, so that only a small part of the first harmonic power is converted into the harmonic oscillation. Under favourable conditions, the multiplication of f to $n \times f$

occurs with an efficiency of $\eta = 1/n^2$. However, if nonlinear energy storage is used for multiplication, then in the ideal case there are no losses (Fleckner, 1987).

Capacitance diodes are particularly suitable nonlinear energy stores for frequency multiplication. The number and intensity of the harmonics that are generated depend upon the capacitance diode's *dopant profile* and characteristic line gradient. The exponent n (also γ) is a measure for the gradient (=capacitance-voltage characteristic). For simple diffused diodes, this is 0.33 (e.g. BA110), for alloyed diodes it is 0.5 and for tuner diodes with a hyper-abrupt P-N junction it is around 0.75 (e.g. BB 141) (Intermetal Semiconductors ITT, 1996).

The capacitance-voltage characteristic of alloyed capacitance diodes has a quadratic path and is therefore best suited for the doubling of frequencies. Simple diffused diodes can be used to produce higher harmonics (Fleckner, 1987).

The layout of a 1-bit transponder for the generation of harmonics is extremely simple: a capacitance diode is connected to the base of a *dipole* adjusted to the carrier wave (Figure 3.5). Given a carrier wave frequency of 2.45 GHz the dipole has a total length of 6 cm. The carrier wave frequencies used are 915 MHz (outside Europe), 2.45 GHz or 5.6 GHz. If the transponder is located within the transmitter's range, then the flow of current within the diode generates and re-emits harmonics of the carrier wave. Particularly distinctive signals are obtained at two or three times the carrier wave, depending upon the type of diode used.

Transponders of this type cast in plastic (hard tags) are used mainly to protect textiles. The tags are removed at the till when the goods are paid for and they are subsequently reused.

Figure 3.6 shows a transponder being placed within the range of a microwave transmitter operating at 2.45 GHz. The second harmonic of 4.90 GHz generated in the diode characteristic of the transponder is re-transmitted and detected by a receiver, which is adjusted to this precise frequency. The reception of a signal at the frequency of the second harmonic can then trigger an alarm system.

If the amplitude or frequency of the carrier wave is modulated (ASK, FSK), then all harmonics incorporate the same modulation. This can be used to distinguish between 'interference' and 'useful' signals, preventing false alarms caused by external signals.

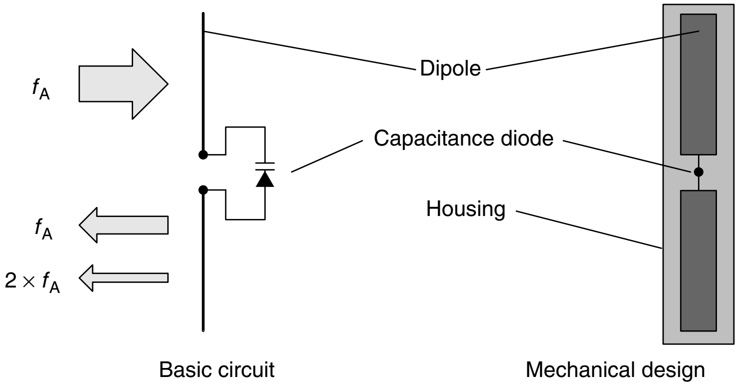

Figure 3.5 Basic circuit and typical construction format of a microwave tag

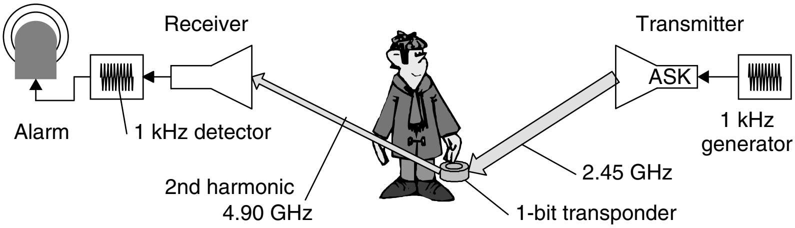

Figure 3.6 Microwave tag in the interrogation zone of a detector

In the example above, the amplitude of the carrier wave is modulated with a signal of 1 kHz (100% ASK). The second harmonic generated at the transponder is also modulated at 1 kHz ASK. The signal received at the receiver is demodulated and forwarded to a 1 kHz detector. Interference signals that happen to be at the reception frequency of 4.90 GHz cannot trigger false alarms because these are not normally modulated and, if they are, they will have a different modulation.

3.1.3 Frequency divider

This procedure operates in the long wave range at 100–135.5 kHz. The security tags contain a semiconductor circuit (microchip) and a resonant circuit coil made of wound enamelled copper. The resonant circuit is made to resonate at the operating frequency of the EAS system using a soldered capacitor. These transponders can be obtained in the form of hard tags (plastic) and are removed when goods are purchased.

The microchip in the transponder receives its power supply from the magnetic field of the security device (see Section 3.2.1.1). The frequency at the self-inductive coil is divided by two by the microchip and sent back to the security device. The signal at half the original frequency is fed by a tap into the resonant circuit coil (Figure 3.7).

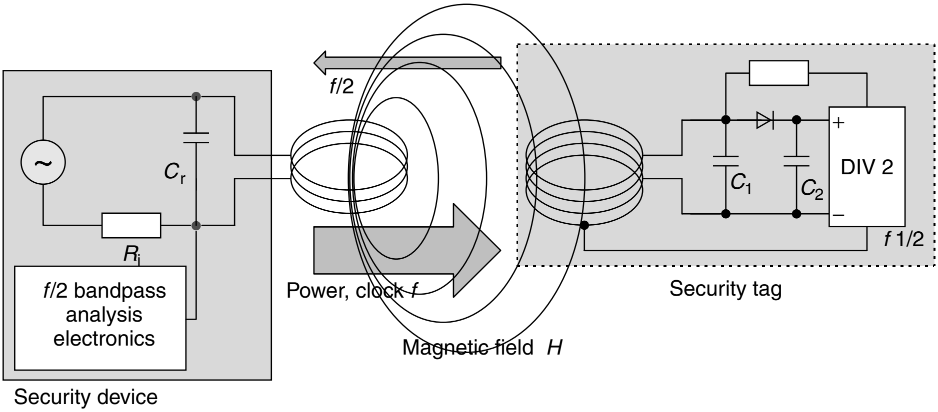

Figure 3.7 Basic circuit diagram of the EAS frequency division procedure: security tag (transponder) and detector (evaluation device)

Table 3.3 Typical system parameters (Plotzke *et al.*, 1994)

Frequency	130 kHz
Modulation type:	100% ASK
Modulation frequency/modulation signal:	12.5 Hz or 25 Hz, rectangle 50%

The magnetic field of the security device is pulsed at a lower frequency (ASK modulated) to improve the detection rate. Similarly to the procedure for the generation of harmonics, the modulation of the carrier wave (ASK or FSK) is maintained at half the frequency (*subharmonic*). This is used to differentiate between 'interference' and 'useful' signals. This system almost entirely rules out false alarms.

Frame antennas, described in Section 3.1.1, are used as sensor antennas.

3.1.4 Electromagnetic types

Electromagnetic types operate using strong magnetic fields in the *NF range* from 10 Hz to around 20 kHz. The security elements contain a soft magnetic *amorphous metal* strip with a steep flanked hysteresis curve (see also Section 4.1.12). The magnetisation of these strips is periodically reversed and the strips taken to magnetic saturation by a strong magnetic alternating field. The markedly nonlinear relationship between the applied field strength H and the magnetic flux density B near saturation (see also Figure 4.50), plus the sudden change of flux density B in the vicinity of the zero crossover of the applied field strength H, generates harmonics at the basic frequency of the security device, and these harmonics can be received and evaluated by the security device.

The electromagnetic type is optimised by superimposing additional signal sections with higher frequencies over the main signal. The marked nonlinearity of the strip's hysteresis curve generates not only harmonics but also signal sections with summation and differential frequencies of the supplied signals. Given a main signal of frequency $f_S = 20\,\text{Hz}$ and the additional signals $f_1 = 3.5$ and $f_2 = 5.3\,\text{kHz}$, the following signals are generated (first order):

$$f_1 + f_2 = f_{1+2} = 8.80\,\text{kHz}$$

$$f_1 - f_2 = f_{1-2} = 1.80\,\text{kHz}$$

$$f_S + f_1 = f_{S+1} = 3.52\,\text{kHz and so on}$$

The security device does not react to the harmonic of the basic frequency in this case, but rather to the summation or differential frequency of the extra signals.

The tags are available in the form of self-adhesive strips with lengths ranging from a few centimetres to 20 cm. Due to the extremely low operating frequency, electromagnetic systems are the only systems suitable for products containing metal. However, these systems have the disadvantage that the function of the tags is dependent upon position: for reliable detection the magnetic field lines of the security device must run vertically through the amorphous metal strip. Figure 3.8 shows a typical design for a security system.

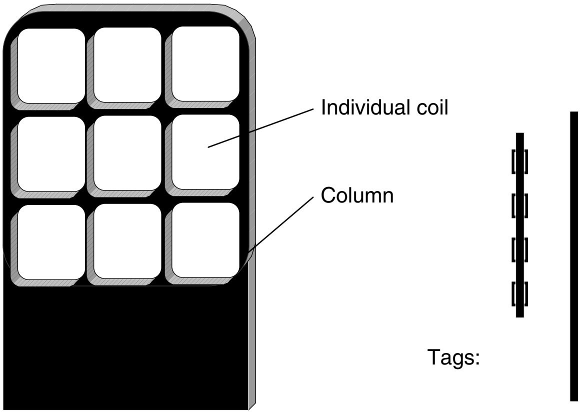

Figure 3.8 Left, typical antenna design for a security system (height approximately 1.40 m); right, possible tag designs

For deactivation, the tags are coated with a layer of hard magnetic metal or partially covered by hard magnetic plates. At the till the cashier runs a strong *permanent magnet* along the metal strip to deactivate the security elements (Plotzke *et al.*, 1994). This magnetises the hard magnetic metal plates. The metal strips are designed such that the remanence field strength (see Section 4.1.12) of the plate is sufficient to keep the amorphous metal strips at saturation point so that the magnetic alternating field of the security system can no longer be activated.

The tags can be reactivated at any time by demagnetisation. The process of deactivation and reactivation can be performed any number of times. For this reason, electromagnetic goods protection systems were originally used mainly in lending libraries. Because the tags are small (min. 32 mm short strips) and cheap, these systems are now being used increasingly in the grocery industry. See Figure 3.9.

In order to achieve the field strength necessary for demagnetisation of the permalloy strips, the field is generated by two coil systems in the columns at either side of a narrow passage. Several individual coils, typically 9 to 12, are located in the two pillars, and these generate weak magnetic fields in the centre and stronger magnetic fields on the outside (Plotzke *et al.*, 1994). Gate widths of up to 1.50 m can now be realised using this method, while still achieving detection rates of 70% (Gillert, 1997) (Figure 3.10).

3.1.5 Acoustomagnetic

Acoustomagnetic systems for security elements consist of extremely small plastic boxes around 40 mm long, 8 to 14 mm wide depending upon design, and just a millimetre

Table 3.4 Typical system parameters (Plotzke *et al.*, 1997)

Frequency	70 Hz
Optional combination frequencies of different systems	12 Hz, 215 Hz, 3.3 kHz, 5 kHz
Field strength H_{eff} in the detection zone	25–120 A/m
Minimum field strength for deactivation	16 000 A/m

Figure 3.9 Electromagnetic labels in use (reproduced by permission of Schreiner Codedruck, Munich)

Figure 3.10 Practical design of an antenna for an article surveillance system (reproduced by permission of METO EAS System 2200, Esselte Meto, Hirschborn)

high. The boxes contain two metal strips, a *hard magnetic metal strip* permanently connected to the plastic box, plus a strip made of *amorphous metal*, positioned such that it is free to vibrate mechanically (Zechbauer, 1999).

Ferromagnetic metals (nickel, iron etc.) change slightly in length in a magnetic field under the influence of the field strength H. This effect is called *magnetostriction* and results from a small change in the interatomic distance as a result of magnetisation. In a magnetic alternating field a magnetostrictive metal strip vibrates in the longitudinal direction at the frequency of the field. The amplitude of the vibration is especially high if the frequency of the magnetic alternating field corresponds with that of the (acoustic) resonant frequency of the metal strip. This effect is particularly marked in amorphous materials.

The decisive factor is that the magnetostrictive effect is also reversible. This means that an oscillating magnetostrictive metal strip emits a magnetic alternating field. *Acoustomagnetic security systems* are designed such that the frequency of the magnetic alternating field generated precisely coincides with the resonant frequencies of the metal strips in the security element. The amorphous metal strip begins to oscillate under the influence of the magnetic field. If the magnetic alternating field is switched off after some time, the excited magnetic strip continues to oscillate for a while like a tuning fork and thereby itself generates a magnetic alternating field that can easily be detected by the security system (Figure 3.11).

The great advantage of this procedure is that the security system is not itself transmitting while the security element is responding and the detection receiver can thus be designed with a corresponding degree of sensitivity.

In their activated state, acoustomagnetic security elements are magnetised, i.e. the above-mentioned hard magnetic metal strip has a high remanence field strength and thus forms a permanent magnet. To deactivate the security element the hard magnetic metal strip must be demagnetised. This detunes the resonant frequency of the amorphous

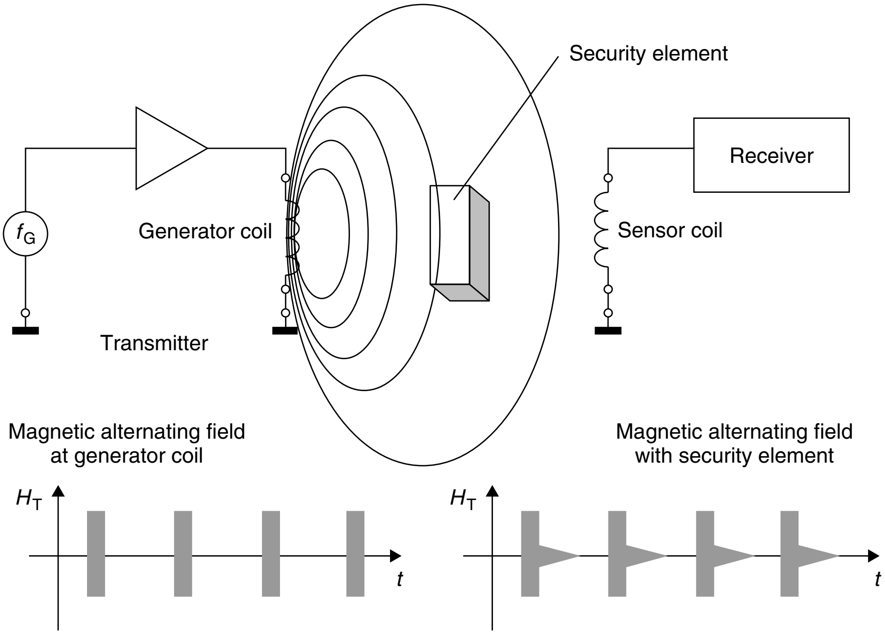

Figure 3.11 Acoustomagnetic system comprising transmitter and detection device (receiver). If a security element is within the field of the generator coil this oscillates like a tuning fork in time with the pulses of the generator coil. The transient characteristics can be detected by an analysing unit

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

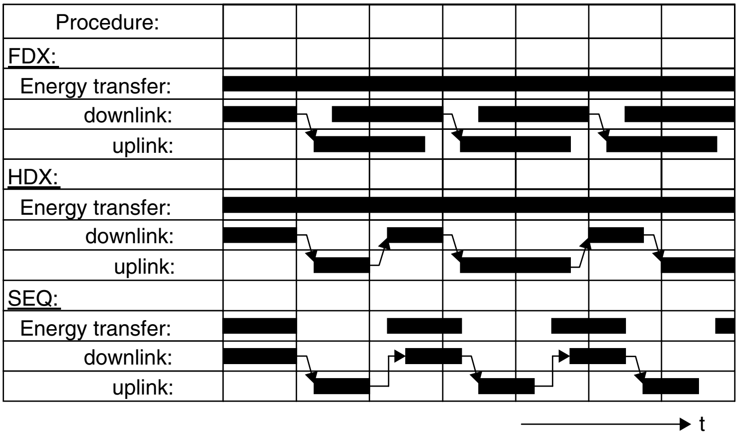

Figure 3.12 Representation of full duplex, half duplex and sequential systems over time. Data transfer from the reader to the transponder is termed downlink, while data transfer from the transponder to the reader is termed uplink

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).

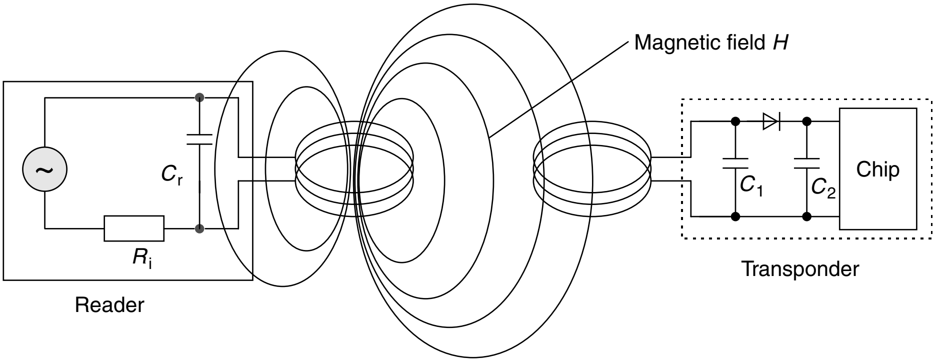

Figure 3.13 Power supply to an inductively coupled transponder from the energy of the magnetic alternating field generated by the reader

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

Figure 3.14 Different designs of inductively coupled transponders. The photo shows half finished transponders, i.e. transponders before injection into a plastic housing (reproduced by permission of AmaTech GmbH & Co. KG, D-Pfronten)

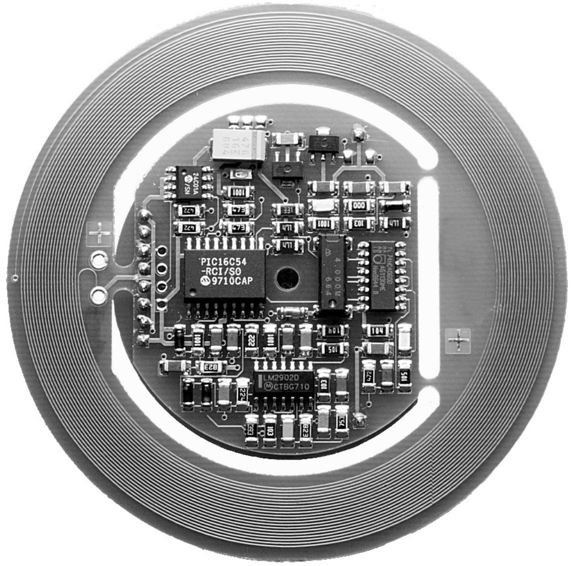

Figure 3.15 Reader for inductively coupled transponder in the frequency range <135 kHz with integral antenna (reproduced by permission of easy-key System, micron, Halbergmoos)

0.16 λ, so that the transponder is located in the *near field* of the transmitter antenna (for a more detailed definition of the near and far fields, please refer to Chapter 4).

If a resonant transponder (i.e. a transponder with a self-resonant frequency corresponding with the transmission frequency of the reader) is placed within the magnetic alternating field of the reader's antenna, the transponder draws energy from the magnetic field. The resulting feedback of the transponder on the reader's antenna can be

Table 3.6 Overview of the power consumption of various RFID-ASIC building blocks (Atmel, 1994). The minimum supply voltage required for the operation of the microchip is 1.8 V, the maximum permissible voltage is 10 V

	Memory (Bytes)	Write/read distance	Power consumption	Frequency	Application
ASIC#1	6	15 cm	10 μA	120 kHz	Animal ID
ASIC#2	32	13 cm	600 μA	120 kHz	Goods flow, access check
ASIC#3	256	2 cm	6 μA	128 kHz	Public transport
ASIC#4	256	0.5 cm	<1 mA	4 MHz*	Goods flow, public transport
ASIC#5	256	<2 cm	~1 mA	4/13.56 MHz	Goods flow
ASIC#6	256	100 cm	500 μA	125 kHz	Access check
ASIC#7	2048	0.3 cm	<10 mA	4.91 MHz*	Contactless chip cards
ASIC#8	1024	10 cm	~1 mA	13.56 MHz	Public transport
ASIC#9	8	100 cm	<1 mA	125 kHz	Goods flow
ASIC#10	128	100 cm	<1 mA	125 kHz	Access check

*Close coupling system.

represented as *transformed impedance* Z_T in the antenna coil of the reader. Switching a *load resistor* on and off at the transponder's antenna therefore brings about a change in the impedance Z_T, and thus voltage changes at the reader's antenna (see Section 4.1.10.3). This has the effect of an amplitude modulation of the voltage U_L at the reader's antenna coil by the remote transponder. If the timing with which the load resistor is switched on and off is controlled by data, this data can be transferred from the transponder to the reader. This type of data transfer is called *load modulation*.

To reclaim the data at the reader, the voltage tapped at the reader's antenna is rectified. This represents the demodulation of an amplitude modulated signal. An example circuit is shown in Section 11.3.

Load modulation with subcarrier Due to the weak coupling between the reader antenna and the transponder antenna, the voltage fluctuations at the antenna of the reader that represent the useful signal are smaller by orders of magnitude than the output voltage of the reader.

In practice, for a 13.56 MHz system, given an antenna voltage of approximately 100 V (voltage step-up by resonance) a useful signal of around 10 mV can be expected (=80 dB signal/noise ratio). Because detecting this slight voltage change requires highly complicated circuitry, the modulation sidebands created by the amplitude modulation of the antenna voltage are utilised (Figure 3.16).

If the additional load resistor in the transponder is switched on and off at a very high elementary frequency f_S, then two spectral lines are created at a distance of $\pm f_S$ around the transmission frequency of the reader f_{READER}, and these can be easily detected (however f_S must be less than f_{READER}). In the terminology of radio technology the new elementary frequency is called a *subcarrier*). Data transfer is by ASK, FSK or PSK modulation of the subcarrier in time with the data flow. This represents an amplitude modulation of the subcarrier.

Load modulation with a subcarrier creates two modulation sidebands at the reader's antenna at the distance of the subcarrier frequency around the operating frequency f_{READER} (Figure 3.17). These modulation sidebands can be separated from

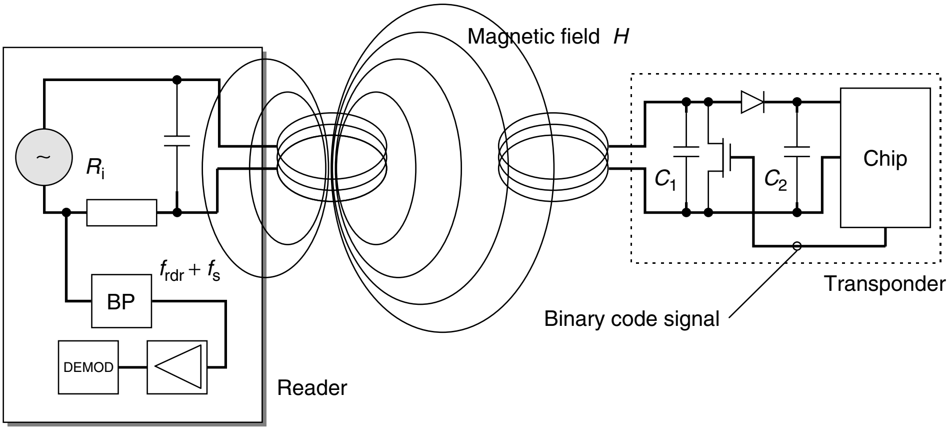

Figure 3.16 Generation of load modulation in the transponder by switching the drain-source resistance of an FET on the chip. The reader illustrated is designed for the detection of a subcarrier

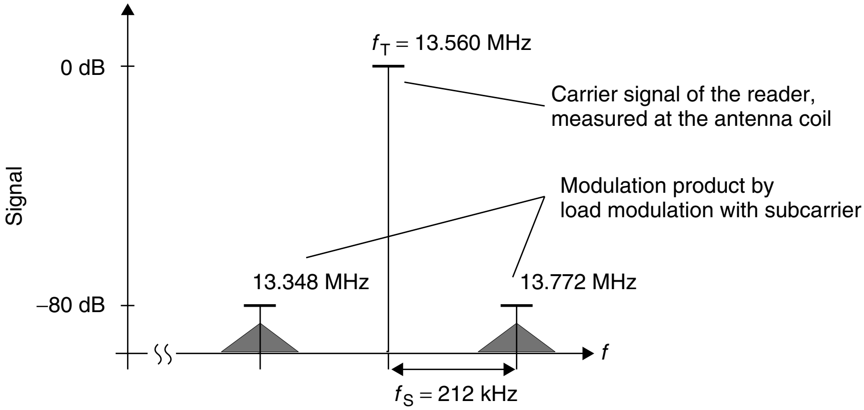

Figure 3.17 Load modulation creates two sidebands at a distance of the subcarrier frequency f_S around the transmission frequency of the reader. The actual information is carried in the sidebands of the two subcarrier sidebands, which are themselves created by the modulation of the subcarrier

the significantly stronger signal of the reader by bandpass (BP) filtering on one of the two frequencies $f_{\text{READER}} \pm f_S$. Once it has been amplified, the subcarrier signal is now very simple to demodulate.

Because of the large bandwidth required for the transmission of a subcarrier, this procedure can only be used in the ISM frequency ranges for which this is permitted, 6.78 MHz, 13.56 MHz and 27.125 MHz (see also Chapter 5).

Example circuit–load modulation with subcarrier Figure 3.18 shows an example circuit for a transponder using load modulation with a subcarrier. The circuit is designed for an operating frequency of 13.56 MHz and generates a subcarrier of 212 kHz.

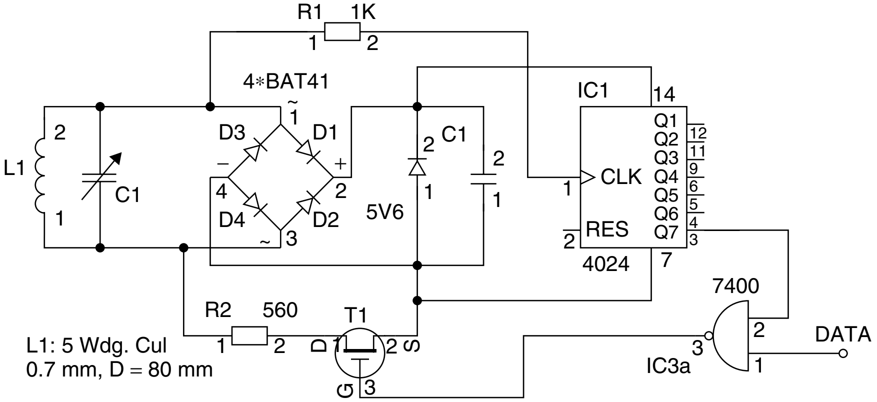

Figure 3.18 Example circuit for the generation of load modulation with subcarrier in an inductively coupled transponder

The voltage induced at the antenna coil L1 by the magnetic alternating field of the reader is rectified using the bridge rectifier (D1–D4) and after additional smoothing (C1) is available to the circuit as supply voltage. The parallel regulator (ZD 5V6) prevents the supply voltage from being subject to an uncontrolled increase when the transponder approaches the reader antenna.

Part of the high frequency antenna voltage (13.56 MHz) travels to the frequency divider's timing input (CLK) via the protective resistor (R1) and provides the transponder with the basis for the generation of an internal clocking signal. After division by $2^6 (= 64)$ a subcarrier clocking signal of 212 kHz is available at output Q7. The subcarrier clocking signal, controlled by a serial data flow at the data input (DATA), is passed to the switch (T1). If there is a logical HIGH signal at the data input (DATA), then the subcarrier clocking signal is passed to the switch (T1). The load resistor (R2) is then switched on and off in time with the subcarrier frequency.

Optionally in the depicted circuit the transponder resonant circuit can be brought into resonance with the capacitor C1 at 13.56 MHz. The range of this 'minimal transponder' can be significantly increased in this manner.

Subharmonic procedure The subharmonic of a sinusoidal voltage A with a defined frequency f_A is a sinusoidal voltage B, whose frequency f_B is derived from an integer division of the frequency f_A. The subharmonics of the frequency f_A are therefore the frequencies $f_A/2, f_A/3, f_A/4 \ldots$.

In the subharmonic transfer procedure, a second frequency f_B, which is usually lower by a factor of two, is derived by digital division by two of the reader's transmission frequency f_A. The output signal f_B of a binary divider can now be modulated with the data stream from the transponder. The modulated signal is then fed back into the transponder's antenna via an output driver.

One popular operating frequency for subharmonic systems is 128 kHz. This gives rise to a transponder response frequency of 64 kHz.

The transponder's antenna consists of a coil with a central tap, whereby the power supply is taken from one end. The transponder's return signal is fed into the coil's second connection (Figure 3.19).

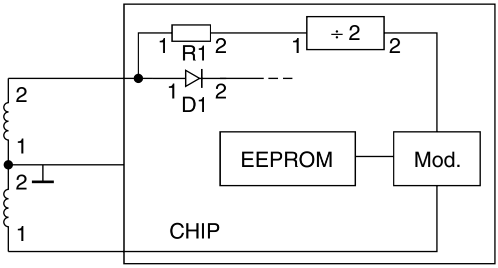

Figure 3.19 Basic circuit of a transponder with subharmonic back frequency. The received clocking signal is split into two, the data is modulated and fed into the transponder coil via a tap

3.2.2 Electromagnetic backscatter coupling

3.2.2.1 Power supply to the transponder

RFID systems in which the gap between reader and transponder is greater than 1 m are called *long-range systems*. These systems are operated at the *UHF frequencies* of 868 MHz (Europe) and 915 MHz (USA), and at the *microwave frequencies* 2.5 GHz and 5.8 GHz. The short wavelengths of these frequency ranges facilitate the construction of antennas with far smaller dimensions and greater efficiency than would be possible using frequency ranges below 30 MHz.

In order to be able to assess the energy available for the operation of a transponder we first calculate the *free space path loss* a_F in relation to the distance r between the transponder and the reader's antenna, the gain G_T and G_R of the transponder's and reader's antenna, plus the transmission frequency f of the reader:

$$a_F = -147.6 + 20\log(r) + 20\log(f) - 10\log(G_T) - 10\log(G_R) \qquad (3.1)$$

The free space path loss is a measure of the relationship between the HF power emitted by a reader into 'free space' and the HF power received by the transponder.

Using current low power semiconductor technology, transponder chips can be produced with a power consumption of no more than 5 μW (Friedrich and Annala, 2001). The efficiency of an integrated rectifier can be assumed to be 5–25% in the UHF and microwave range (Tanneberger, 1995). Given an efficiency of 10%, we thus require received power of $P_e = 50\,\mu W$ at the terminal of the transponder antenna for the operation of the transponder chip. This means that where the reader's transmission power is $P_s = 0.5$ W EIRP (effective isotropic radiated power) the free space path loss may not exceed 40 dB ($P_s/P_e = 10\,000/1$) if sufficiently high power is to be obtained at the transponder antenna for the operation of the transponder. A glance at Table 3.7 shows that at a transmission frequency of 868 MHz a *range* of a little over 3 m would be realisable; at 2.45 GHz a little over 1 m could be achieved. If the transponder's chip had a greater power consumption the achievable range would fall accordingly.

In order to achieve long ranges of up to 15 m or to be able to operate transponder chips with a greater power consumption at an acceptable range, backscatter transponders often have a backup battery to supply power to the transponder chip (Figure 3.20). To prevent this battery from being loaded unnecessarily, the microchips generally have

Table 3.7 Free space path loss a_F at different frequencies and distances. The gain of the transponder's antenna was assumed to be 1.64 (dipole), the gain of the reader's antenna was assumed to be 1 (isotropic emitter)

Distance *r*	**868 MHz**	**915 MHz**	**2.45 GHz**
0.3 m	18.6 dB	19.0 dB	27.6 dB
1 m	29.0 dB	29.5 dB	38.0 dB
3 m	38.6 dB	39.0 dB	47.6 dB
10 m	49.0 dB	49.5 dB	58.0 dB

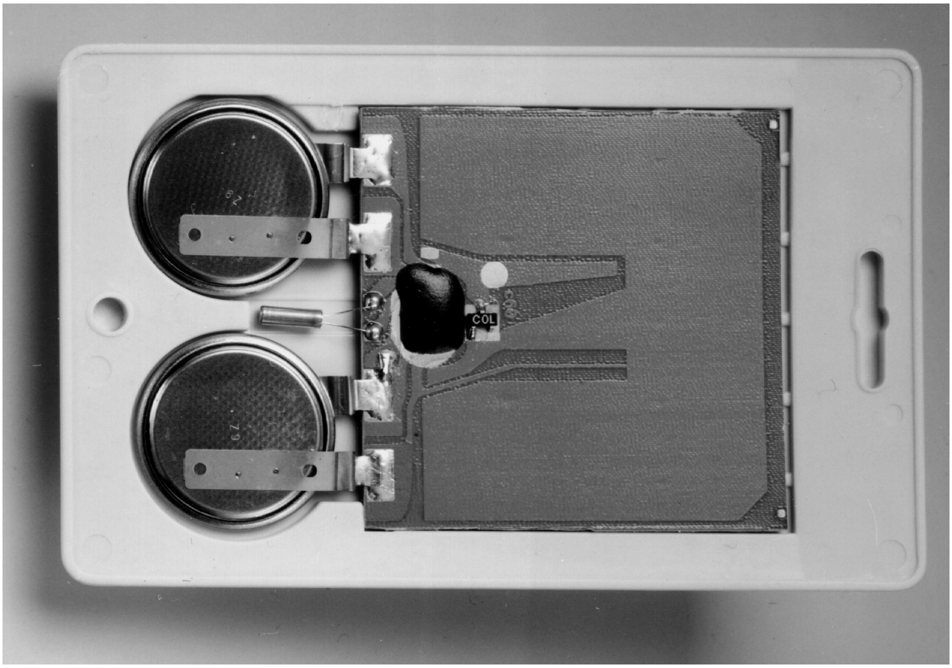

Figure 3.20 Active transponder for the frequency range 2.45 GHz. The data carrier is supplied with power by two *lithium batteries*. The transponder's microwave antenna is visible on the printed circuit board in the form of a u-shaped area (reproduced by permission of Pepperl & Fuchs, Mannheim)

a power saving 'power down' or 'stand-by' mode. If the transponder moves out of range of a reader, then the chip automatically switches over to the power saving 'power down' mode. In this state the power consumption is a few μA at most. The chip is not reactivated until a sufficiently strong signal is received in the read range of a reader, whereupon it switches back to normal operation. However, the battery of an active transponder never provides power for the transmission of data between transponder and reader, but serves exclusively for the supply of the microchip. Data transmission between transponder and reader relies exclusively upon the power of the electromagnetic field emitted by the reader.

3.2.2.2 Data transmission → reader

Modulated reflection cross-section We know from the field of *radar technology* that electromagnetic waves are reflected by objects with dimensions greater than around half the wavelength of the wave. The efficiency with which an object reflects electromagnetic waves is described by its *reflection cross-section*. Objects that are in resonance with the wave front that hits them, as is the case for antennas at the appropriate frequency, for example, have a particularly large reflection cross-section.

Power P_1 is emitted from the reader's antenna, a small proportion of which (free space attenuation) reaches the transponder's antenna (Figure 3.21). The power P_1' is supplied to the antenna connections as HF voltage and after rectification by the diodes D_1 and D_2 this can be used as turn-on voltage for the deactivation or activation of the power saving 'power down' mode. The diodes used here are *low barrier Schottky diodes*, which have a particularly low threshold voltage. The voltage obtained may also be sufficient to serve as a power supply for short ranges.

A proportion of the incoming power P_1' is reflected by the antenna and returned as power P_2. The *reflection characteristics* (=reflection cross-section) of the antenna can be influenced by altering the load connected to the antenna. In order to transmit data from the transponder to the reader, a load resistor R_L connected in parallel with the antenna is switched on and off in time with the data stream to be transmitted. The amplitude of the power P_2 reflected from the transponder can thus be modulated (→ modulated backscatter).

The power P_2 reflected from the transponder is radiated into free space. A small proportion of this (free space attenuation) is picked up by the reader's antenna. The reflected signal therefore travels into the antenna connection of the reader in the backwards direction and can be decoupled using a *directional coupler* and transferred to the receiver input of a reader. The forward signal of the transmitter, which is stronger by powers of ten, is to a large degree suppressed by the directional coupler.

The ratio of power transmitted by the reader and power returning from the transponder (P_1/P_2) can be estimated using the radar equation (for an explanation, refer to Chapter 4).

3.2.3 Close coupling

3.2.3.1 Power supply to the transponder

Close coupling systems are designed for ranges between 0.1 cm and a maximum of 1 cm. The transponder is therefore inserted into the reader or placed onto a marked surface ('*touch & go*') for operation.

Inserting the transponder into the reader, or placing it on the reader, allows the transponder coil to be precisely positioned in the *air gap* of a ring-shaped or U-shaped core. The functional layout of the transponder coil and reader coil corresponds with that of a transformer (Figure 3.22). The reader represents the primary winding and the transponder coil represents the secondary winding of a transformer. A high frequency alternating current in the primary winding generates a high frequency magnetic field in the core and air gap of the arrangement, which also flows through the transponder coil. This power is rectified to provide a power supply to the chip.

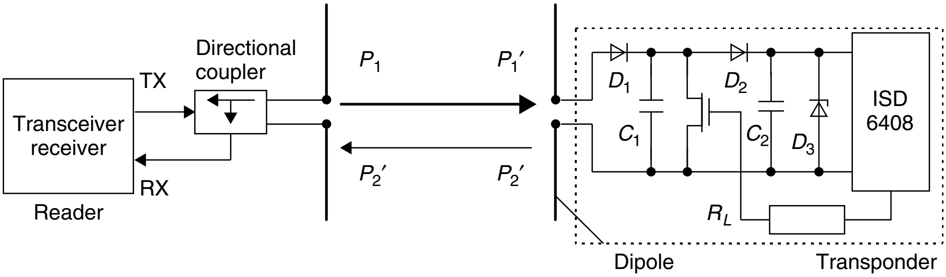

Figure 3.21 Operating principle of a backscatter transponder. The impedance of the chip is 'modulated' by switching the chip's FET (Integrated Silicon Design, 1996)

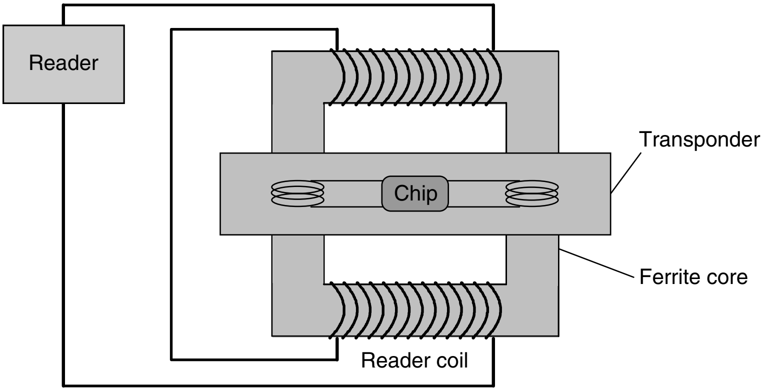

Figure 3.22 Close coupling transponder in an insertion reader with magnetic coupling coils

Because the voltage U induced in the transponder coil is proportional to the frequency f of the exciting current, the frequency selected for power transfer should be as high as possible. In practice, frequencies in the range 1–10 MHz are used. In order to keep the losses in the transformer core low, a ferrite material that is suitable for this frequency must be selected as the core material.

Because, in contrast to inductively coupled or microwave systems, the efficiency of power transfer from reader to transponder is very good, close coupling systems are excellently suited for the operation of chips with a high power consumption. This includes microprocessors, which still require some 10 mW power for operation (Sickert, 1994). For this reason, the close coupling chip card systems on the market all contain microprocessors.

The mechanical and electrical parameters of contactless close coupling chip cards are defined in their own standard, ISO 10536. For other designs the operating parameters can be freely defined.

3.2.3.2 Data transfer transponder → reader

Magnetic coupling Load modulation with subcarrier is also used for magnetically coupled data transfer from the transponder to the reader in close coupling systems.

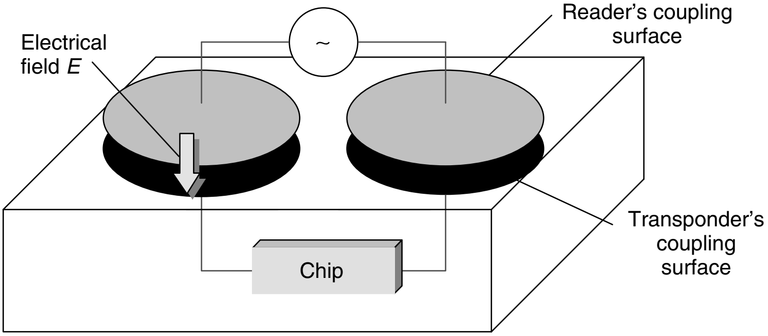

Figure 3.23 Capacitive coupling in close coupling systems occurs between two parallel metal surfaces positioned a short distance apart from each other

Subcarrier frequency and modulation is specified in ISO 10536 for close coupling chip cards.

Capacitive coupling Due to the short distance between the reader and transponder, close coupling systems may also employ *capacitive coupling* for data transmission. Plate capacitors are constructed from coupling surfaces isolated from one another, and these are arranged in the transponder and reader such that when a transponder is inserted they are exactly parallel to one another (Figure 3.23).

This procedure is also used in close coupling smart cards. The mechanical and electrical characteristics of these cards are defined in ISO 10536.

3.2.4 Electrical coupling

3.2.4.1 Power supply of passive transponders

In *electrically* (i.e. *capacitively*) coupled systems the reader generates a strong, high-frequency *electrical field*. The reader's antenna consists of a large, electrically conductive area (*electrode*), generally a metal foil or a metal plate. If a high-frequency voltage is applied to the electrode a high-frequency electric field forms between the electrode and the earth potential (ground). The voltages required for this, ranging between a few hundred volts and a few thousand volts, are generated in the reader by voltage rise in a resonant circuit made up of a coil L_1 in the reader, plus the parallel connection of an internal capacitor C_1 and the capacitance active between the electrode and the earth potential $C_{\text{R-GND}}$. The resonant frequency of the resonant circuit corresponds with the transmission frequency of the reader.

The antenna of the transponder is made up of two conductive surfaces lying in a plane (electrodes). If the transponder is placed within the electrical field of the reader, then an electric voltage arises between the two transponder electrodes, which is used to supply power to the transponder chips (Figure 3.24).

Since a capacitor is active both between the transponder and the transmission antenna ($C_{\text{R-T}}$) and between the transponder antenna and the earth potential ($C_{\text{T-GND}}$) the equivalent circuit diagram for an electrical coupling can be considered in a simplified form

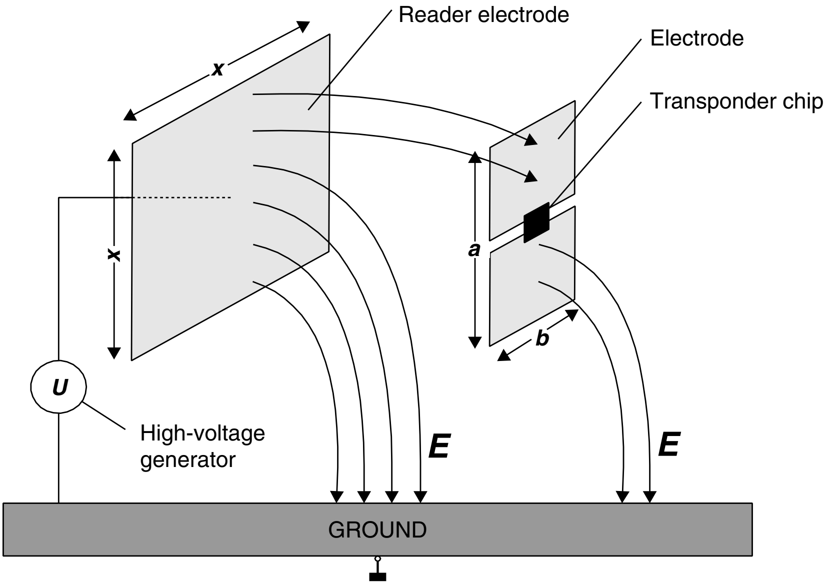

Figure 3.24 An electrically coupled system uses electrical (electrostatic) fields for the transmission of energy and data

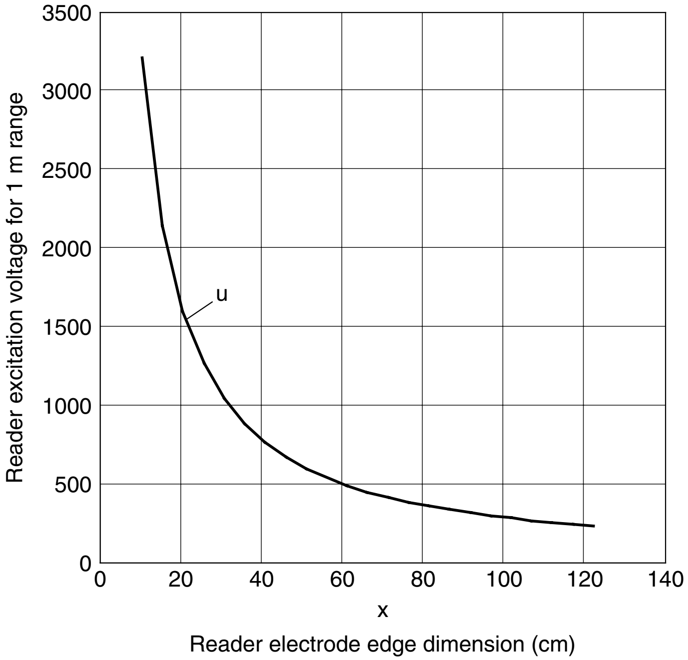

Figure 3.25 Necessary electrode voltage for the reading of a transponder with the electrode size a × b = 4.5 cm × 7 cm (format corresponds with a smart card), at a distance of 1 m ($f = 125\,\text{kHz}$)

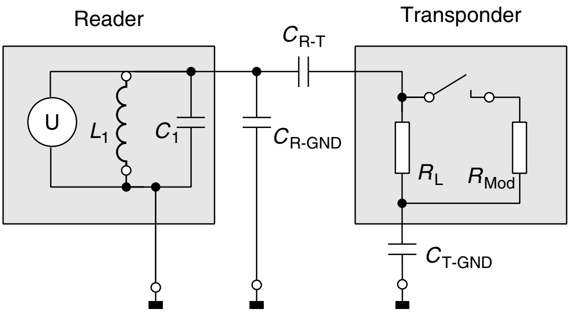

Figure 3.26 Equivalent circuit diagram of an electrically coupled RFID system

as a *voltage divider* with the elements C_{R-T}, R_L (input resistance of the transponder) and C_{T-GND} (see Figure 3.26). Touching one of the transponder's electrodes results in the capacitance C_{T-GND}, and thus also the *read range*, becoming significantly greater.

The currents that flow in the electrode surfaces of the transponder are very small. Therefore, no particular requirements are imposed upon the conductivity of the electrode material. In addition to the normal metal surfaces (metal foil) the electrodes can thus also be made of conductive colours (e.g. a *silver conductive paste*) or a *graphite coating* (Motorola, Inc., 1999).

3.2.4.2 Data transfer transponder → reader

If an electrically coupled transponder is placed within the interrogation zone of a reader, the input resistance R_L of the transponder acts upon the resonant circuit of the reader via the coupling capacitance C_{R-T} active between the reader and transponder electrodes, damping the resonant circuit slightly. This damping can be switched between two values by switching a modulation resistor R_{mod} in the transponder on and off. Switching the modulation resistor R_{mod} on and off thereby generates an amplitude modulation of the voltage present at L_1 and C_1 by the remote transponder. By switching the modulation resistor R_{mod} on and off in time with data, this data can be transmitted to the reader. This procedure is called *load modulation*.

3.2.5 Data transfer reader → transponder

All known digital modulation procedures are used in data transfer from the reader to the transponder in full and half duplex systems, irrespective of the operating frequency or the coupling procedure. There are three basic procedures:

- ASK: amplitude shift keying
- FSK: frequency shift keying
- PSK: phase shift keying

Because of the simplicity of demodulation, the majority of systems use ASK modulation.

3.3 Sequential Procedures

If the transmission of data and power from the reader to the data carrier alternates with data transfer from the transponder to the reader, then we speak of a *sequential procedure* (SEQ).

The characteristics used to differentiate between SEQ and other systems have already been described in Section 3.2.

3.3.1 Inductive coupling

3.3.1.1 Power supply to the transponder

Sequential systems using inductive coupling are operated exclusively at frequencies below 135 kHz. A transformer type coupling is created between the reader's coil and the transponder's coil. The induced voltage generated in the transponder coil by the effect of an alternating field from the reader is rectified and can be used as a power supply.

In order to achieve higher efficiency of data transfer, the transponder frequency must be precisely matched to that of the reader, and the quality of the transponder coil must be carefully specified. For this reason the transponder contains an *on-chip trimming capacitor* to compensate for resonant frequency manufacturing tolerances.

However, unlike full and half duplex systems, in sequential systems the reader's transmitter does not operate on a continuous basis. The energy transferred to the transmitter during the transmission operation charges up a *charging capacitor* to provide an energy store. The transponder chip is switched over to stand-by or power saving mode during the charging operation, so that almost all of the energy received is used to charge up the charging capacitor. After a fixed charging period the reader's transmitter is switched off again.

The energy stored in the transponder is used to send a reply to the reader. The minimum capacitance of the charging capacitor can be calculated from the necessary operating voltage and the chip's power consumption:

$$C = \frac{Q}{U} = \frac{It}{[V_{\max} - V_{\min}]} \tag{3.2}$$

where $V_{\max}$, $V_{\min}$ are limit values for operating voltage that may not be exceeded, I is the power consumption of the chip during operation and t is the time required for the transmission of data from transponder to reader.

For example, the parameters $I = 5\,\mu\text{A}$, $t = 20\,\text{ms}$, $V_{\max} = 4.5\,\text{V}$ and $V_{\min} = 3.5\,\text{V}$ yield a charging capacitor of $C = 100\,\text{nF}$ (Schürmann, 1993).

3.3.1.2 A comparison between FDX/HDX and SEQ systems

Figure 3.27 illustrates the different conditions arising from full/half duplex (FDX/HDX) and sequential (SEQ) systems.

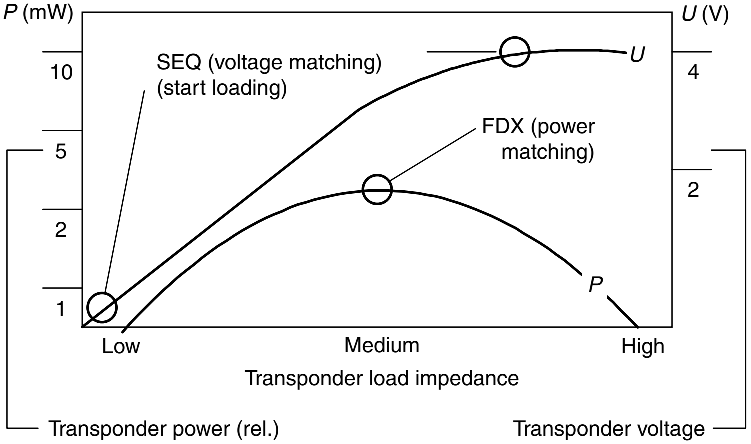

Figure 3.27 Comparison of induced transponder voltage in FDX/HDX and SEQ systems (Schürmann, 1993)

Because the power supply from the reader to the transponder in full duplex systems occurs at the same time as data transfer in both directions, the chip is permanently in operating mode. *Power matching* between the transponder antenna (current source) and the chip (current consumer) is desirable to utilise the transmitted energy optimally. However, if precise power matching is used only half of the source voltage (=open circuit voltage of the coil) is available. The only option for increasing the available operating voltage is to increase the impedance (=load resistance) of the chip. However, this is the same as decreasing the power consumption.

Therefore the design of full duplex systems is always a compromise between power matching (maximum power consumption P_{chip} at $U_{\text{chip}} = 1/2U_{\text{O}}$) and voltage matching (minimum power consumption P_{chip} at maximum voltage $U_{\text{chip}} = U_{\text{O}}$).

The situation is completely different in sequential systems: during the charging process the chip is in stand-by or power saving mode, which means that almost no power is drawn through the chip.

The charging capacitor is fully discharged at the beginning of the charging process and therefore represents a very low ohmic load for the voltage source (Figure 3.27: start loading). In this state, the maximum amount of current flows into the charging capacitor, whereas the voltage approaches zero (=*current matching*). As the charging capacitor is charged, the charging current starts to decrease according to an exponential function, and reaches zero when the capacitor is fully charged. The state of the charged capacitor corresponds with *voltage matching* at the transponder coil.

This achieves the following advantages for the chip power supply compared to a full/half duplex system:

- The full source voltage of the transponder coil is available for the operation of the chip. Thus the available operating voltage is up to twice that of a comparable full/half duplex system.
- The energy available to the chip is determined only by the capacitance of the charging capacitor and the charging period. Both values can in theory (!) be given any

required magnitude. In full/half duplex systems the maximum power consumption of the chip is fixed by the power matching point (i.e. by the coil geometry and field strength H).

3.3.1.3 Data transmission transponder → reader

In sequential systems (Figure 3.28) a full read cycle consists of two phases, the charging phase and the reading phase (Figure 3.29).

The end of the charging phase is detected by an *end of burst detector*, which monitors the path of voltage at the transponder coil and thus recognises the moment when the reader field is switched off. At the end of the charging phase an on-chip oscillator, which uses the resonant circuit formed by the transponder coil as a frequency determining component, is activated. A weak magnetic alternating field is generated by the transponder coil, and this can be received by the reader. This gives an improved signal-interference distance of typically 20 dB compared to full/half duplex systems, which has a positive effect upon the ranges that can be achieved using sequential systems.

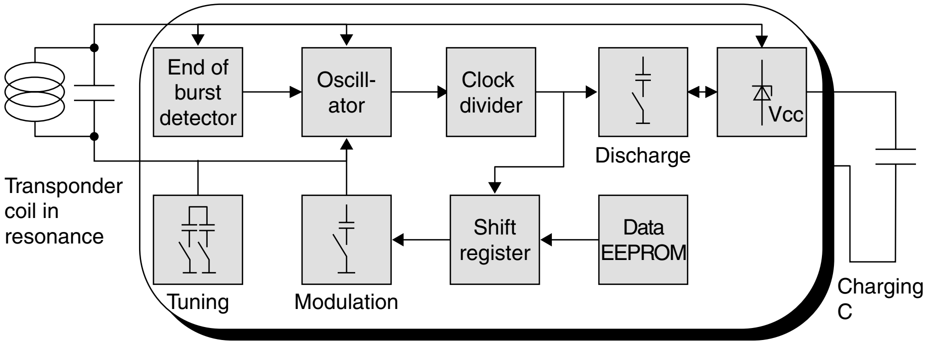

Figure 3.28 Block diagram of a sequential transponder by Texas Instruments TIRIS® Systems, using inductive coupling

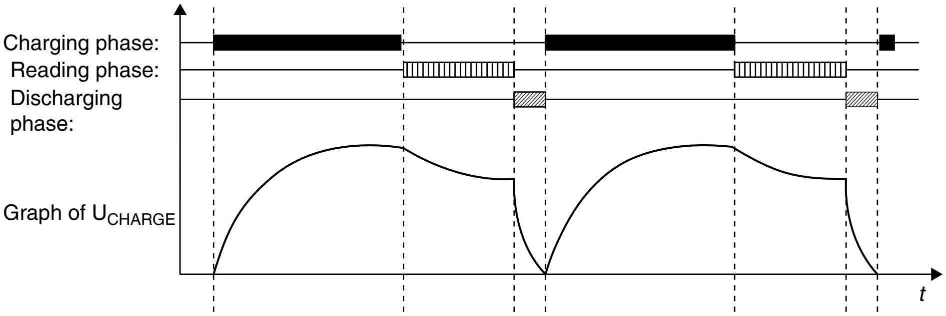

Figure 3.29 Voltage path of the charging capacitor of an inductively coupled SEQ transponder during operation

The transmission frequency of the transponder corresponds with the resonant frequency of the transponder coil, which was adjusted to the transmission frequency of the reader when it was generated.

In order to be able to modulate the HF signal generated in the absence of a power supply, an additional modulation capacitor is connected in parallel with the resonant circuit in time with the data flow. The resulting frequency shift keying provides a *2 FSK modulation*.

After all the data has been transmitted, the discharge mode is activated to fully discharge the charging capacitor. This guarantees a safe Power-On-Reset at the start of the next charging cycle.

3.3.2 Surface acoustic wave transponder

Surface acoustic wave (SAW) devices are based upon the piezoelectric effect and on the surface-related dispersion of elastic (=acoustic) waves at low speed. If an (ionic) crystal is elastically deformed in a certain direction, surface charges occur, giving rise to electric voltages in the crystal (application: piezo lighter). Conversely, the application of a surface charge to a crystal leads to an elastic deformation in the crystal grid (application: piezo buzzer). Surface acoustic wave devices are operated at microwave frequencies, normally in the ISM range 2.45 GHz.

Electroacoustic transducers (interdigital transducers) and *reflectors* can be created using planar electrode structures on piezoelectric substrates. The normal substrate used for this application is *lithium niobate* or *lithium tantalate*. The electrode structure is created by a photolithographic procedure, similar to the procedure used in microelectronics for the manufacture of integrated circuits.

Figure 3.30 illustrates the basic layout of a surface wave transponder. A finger-shaped electrode structure — the *interdigital transducer* — is positioned at the end of a long piezoelectrical substrate, and a suitable *dipole antenna* for the operating frequency is attached to its busbar. The interdigital transducer is used to convert between electrical signals and acoustic surface waves.

An electrical impulse applied to the busbar causes a mechanical deformation to the surface of the substrate due to the piezoelectrical effect between the electrodes (fingers), which disperses in both directions in the form of a surface wave (rayleigh wave). For a normal substrate the dispersion speed lies between 3000 and 4000 m/s. Similarly, a *surface wave* entering the converter creates an electrical impulse at the busbar of the interdigital transducer due to the piezoelectric effect.

Individual electrodes are positioned along the remaining length of the surface wave transponder. The edges of the electrodes form a reflective strip and reflect a small proportion of the incoming surface waves. Reflector strips are normally made of aluminium; however some reflector strips are also in the form of etched grooves (Meinke, 1992).

A high frequency *scanning pulse* generated by a reader is supplied from the dipole antenna of the transponder into the interdigital transducer and is thus converted into an acoustic surface wave, which flows through the substrate in the longitudinal direction. The frequency of the surface wave corresponds with the carrier frequency of the sampling pulse (e.g. 2.45 GHz) (Figure 3.31). The carrier frequency of the reflected

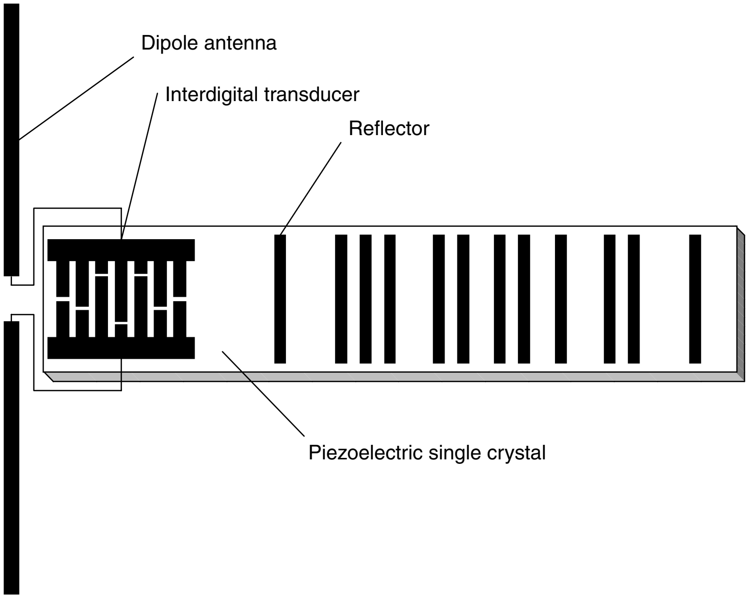

Figure 3.30 Basic layout of an SAW transponder. Interdigital transducers and reflectors are positioned on the piezoelectric crystal

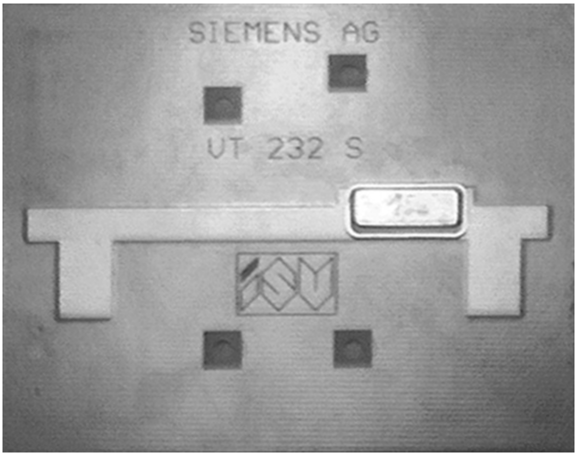

Figure 3.31 Surface acoustic wave transponder for the frequency range 2.45 GHz with antenna in the form of microstrip line. The piezocrystal itself is located in an additional metal housing to protect it against environmental influences (reproduced by permission of Siemens AG, ZT KM, Munich)

and returned pulse sequence thus corresponds with the transmission frequency of the sampling pulse.

Part of the surface wave is reflected off each of the reflective strips that are distributed across the substrate, while the remaining part of the surface wave continues to travel to the end of the substrate and is absorbed there.

The reflected parts of the wave travel back to the interdigital transducer, where they are converted into a high frequency pulse sequence and are emitted by the dipole antenna. This pulse sequence can be received by the reader. The number of pulses received corresponds with the number of reflective strips on the substrate. Likewise, the delay between the individual pulses is proportional to the spatial distance between the reflector strips on the substrate, and so the spatial layout of the reflector strips can represent a binary sequence of digits.

Due to the slow dispersion speed of the surface waves on the substrate the first response pulse is only received by the reader after a dead time of around 1.5 ms after the transmission of the scanning pulse. This gives decisive advantages for the reception of the pulse.

Reflections of the scanning pulse on the metal surfaces of the environment travel back to the antenna of the reader at the speed of light. A reflection over a distance of 100 m to the reader would arrive at the reader 0.6 ms after emission from the reader's antenna (travel time there and back, the signal is damped by >160 dB). Therefore, when the transponder signal returns after 1.5 ms all reflections from the environment of the reader have long since died away, so they cannot lead to errors in the pulse sequence (Dziggel, 1997).

The data storage capacity and data transfer speed of a surface wave transponder depend upon the size of the substrate and the realisable minimum distance between the reflector strips on the substrate. In practice, around 16–32 bits are transferred at a data transfer rate of 500 kbit/s (Siemens, n.d.).

The range of a surface wave system depends mainly upon the transmission power of the scanning pulse and can be estimated using the radar equation (Chapter 4). At the permissible transmission power in the 2.45 GHz ISM frequency range a range of 1–2 m can be expected.