1
Ultra-Wideband Sensing – An Overview

1.1
Introduction

For the human beings (and most of the animals), the scattering of electromagnetic waves, for example the scattering of sunlight at trees, buildings or the face of a friend or an enemy, is the most important source to gain information on the surroundings. As known from everybody's experience, the images gained from light scattering (i.e. photos) provide a detailed geometrical structure of the surroundings since the wavelengths are very small compared to the size of the objects of interest. Furthermore, the time history of that 'scattering behaviour' gives us a deep view inside the nature of an object or process. However, there are many cases where light scattering fails and we are not able to receive the wanted information by our native sense. Therefore, technical apparatuses were created which use different parts of the electromagnetic spectrum as X-rays, infrared and Terahertz radiation or microwaves exploiting each with specific properties of wave propagation.

Ultra-wideband (UWB) sensors are dealing with microwaves occupying a very large spectral band typically located within the lower GHz range. On the one hand, such waves can penetrate most (non-metallic) materials so that hidden objects may be detected, and on the other hand, they provide object resolution in the decimetre, centimetre or even millimetre range due to their large bandwidth. Moreover, polar molecules, for example water, are showing relaxation effects within these frequency bands which give the opportunity of substance characterization and validation. In general, it can be stated that a large bandwidth of a sounding signal provides more information on the object of interest.

With the availability of network analysers and the time domain reflectometry (TDR) since the 60th of the last century, very wideband measurements have been established but they were banned to laboratory environments. New and cheaper solutions for the RF-electronics, improved numerical capabilities to extract the wanted information from the gathered data and the effected ongoing adaptation of radio regulation rules by national and international regulation authorities allow this

Handbook of Ultra-Wideband Short-Range Sensing: Theory, Sensors, Applications, First Edition. Jürgen Sachs.

sensor approach to move stepwise in practice now. Ultra-wideband sensing is an upcoming technique to gather data from complex scenarios such as nature, industrial facilities, public or private environments, for medical applications, non-destructive testing, security and surveillance, for rescue operations and many more. Currently, it is hard to estimate the full spread of future applications.

The objective of this book is to introduce the reader to some aspects of ultra-wideband sensing. Such sensors use very weak and harmless electromagnetic sounding waves to 'explore' their surroundings. Sensor principles using electromagnetic waves are not new and are in use for many years. But they are typically based on narrowband signals. In contrast, the specific of UWB sensors is to be seen in the fact that they apply sounding signals of a very large bandwidth whereas bandwidth and centre frequency[1)] are of the same order.

Concerning their application there are four major consequences:

- As a generic rule of thumb one can state that increasing frequency diversity leads to more information about the scenario under test. This observation is well respected by UWB sensors due to their large bandwidth. Hence they will have better resolution, lower cross-ambiguities or better recognition capabilities than their narrowband 'brothers'.
- The spectral band occupied by UWB sensors is placed at comparatively low frequencies. Typical values are 100 MHz–10 GHz. This involves a good (reasonable) penetration of the sounding wave in many materials (except metal) which makes such sensors useful to investigate opaque objects and detect hidden targets.
- In the past, UWB techniques were largely banned to the laboratory due to the need of bulky and expensive electronic devices. But recent developments in RF-system and antenna design, RF-circuit integration and digital signal processing promote the step from the laboratory into the real world. Costs, robustness and power consumption of the sensor devices as well as reliability of the sensing method will be important aspects for the future application of UWB sensing.
- The large bandwidth of UWB devices causes inevitably interferences with other electronic devices, that is mainly with classical narrowband radio services and with other UWB devices. Simply spoken, UWB sensors increase the background noise. In order to limit this noise, the maximum power emission of UWB devices is typically restricted to an interference level which is generally accepted for unintentional radiations of all electric devices. Exceptions are high-power devices for research or military purposes [1].

In this book, we will discuss various UWB sensing approaches exclusively based on low-power emission. The most applied and considered one is probably the radar principle which is meanwhile more than 100 years old. But so far most radar devices are working with a sounding signal of comparatively narrow bandwidth. Here, we will address specific features of very wideband systems because 'Future Radar development must increase the quantity and quality of information for the user. The long-term objective is to provide radar sensing to aid human activities

1) Please note that we do not speak about carrier frequency.

with new and unique capabilities. Use of UWB radar signals appears to be the most promising future approach to building radar systems with new and better capabilities and direct applications to civil uses and environmental monitoring [2]'.

A further principle is the impedance or dielectric spectroscopy which is aimed to determine the electric material parameters $(\varepsilon, \mu, \sigma)$ as function of the frequency. These parameters allow interfering with the state or quality of various substances by a non-destructive and continuously working method. Narrowband measurements suffer from cross-ambiguities since the electric material parameters depend on many things. Observations over a larger bandwidth may possibly reduce these indeterminacies if, for example, superimposed material effects show different frequency behaviour. So far, wideband measurements of this kind were mainly band to the laboratory due to the need of expensive and bulky devices, for example network analysers requiring specifically skilled persons to operate them. New UWB device conceptions adapted to a specific task will promote the dissemination of such sensing methods for industrial purposes or in our daily life.

The previous remarks gave a guideline of possible applications for UWB sensors. As long as the sensors should be accessible for a larger community, they must be restricted to low-power emissions which entitles them to short-range sensing, that is up to about 100 m. A large bandwidth combined with high jitter immunity provides high-range resolution and accuracy down to the μm range, permitting high-resolution radar images and recording of weak movements or other target variations. Furthermore, the interaction of electromagnetic waves with matter provides the opportunity of remote material characterization via permittivity measurements. As examples, we can find applications in following arbitrarily ordered areas:

- Geology, archaeology
- Non-destructive testing
- Metrology
- Microwave imaging
- Quality control
- Inspection of buildings
- Medical engineering
- Search and rescue
- Localization and positioning
- Ranging, collision avoidance
- Law enforcement, intrusion detection, forensic science
- Assistance of handicapped people
- Labour protection[2)] and others.

Due to the low emissions, ultra-wideband short-range sensing will become an interesting extension of the radar approach to daily life applications. For large-scale applications, the step from the laboratory into the real world will require further system integration as well as reduction of costs and power consumption. The

2) For example, against severe injuries of hands and arms by rotating tools or squeezing machines; admission control for hazard zones.

processing of the captured data may become a challenging issue, since the measurement principles are often indirect approaches which involve the solution of ill-conditioned inverse problems.

The book is addressed to all who are interested in sensing technology specifically in microwave sensing. Particularly it is addressed to students of electrical engineering, sensor developers, appliers and researches. Reading the book supposes only some very basic knowledge in mathematics, electromagnetic field theory as well as system and signal theory. In order to concentrate on the main aspects and features of UWB sensing, the discussions of many issues will be based on an 'engineering approach' than on rigorous solutions of mathematical or electric field problems. Some considerations within the book may possibly appear somewhat unusual since it was tried to follow a way which is a bit different than usually applied. The classical signal and system theory and the theory of electromagnetic fields too are more or less 'narrowband'. That is, the majority of publications and text books in that area deal with sinusoidal signals or waves. There are two simple reasons why: First, it was forbidden to transmit wideband signals since the second decade of the twentieth century, and narrowband devices were more efficient in the early days of radio development and they cause less interference.

The second reason is of theoretical nature. Let us consider, for example the propagation of waves and their interaction with objects. As long as this interaction is based on linear dynamic effects (Section 2.4 explains what this means), the actual type of the sounding signals does not matter. Hence, one can look for a signal which largely simplifies the solution of equations that model the test scenarios. The sine wave (the decaying sine wave[3]) is such a signal since it always maintains its shape and frequency. As a consequence of a linear interaction, a sinusoid can only sustain a variation of its amplitude and a time delay usually expressed as phase shift. This simple signal enables to find a rigorous solution of the equations for many cases since linear differential equations can be reduced to algebraic ones. However, the resulting equations are often quite complex and less comprehensible or illustrative. They represent the steady state of superimposed components of wave fields at a single frequency which often leads to not apprehensible interference pattern.

The developer and the applier of UWB sensors need a more pristine view on the wave phenomena, which allows him to understand and interpret measurement data even from complex test scenarios. The human brain is trained since childhood to observe and analyse processes by their temporal evolution and causality. Hence it is much easier to understand propagation, reflection, diffraction and so on of short and pulse-like waves than the superposition of infinitely expanded sine waves of different frequencies. Mathematically both considerations will lead to the same result since they may be mutually transformed by the Fourier transform (the Laplace transform). But the solution of system equations with respect to pulse

3) In the literature of electrical engineering, a sine or a damped sine are usually expressed by exponential functions $\sin 2\pi f t = \Im\left\{e^{j2\pi f t}\right\}$ and $e^{\sigma t} \sin 2\pi f t = \Im\{e^{st}\}$; $s = \sigma + j2\pi f$; $\sigma \leq 0$. s is also assigned as complex frequency.

excitation (or generally signals of arbitrary shape) is much more complicated and requires bigger computational effort than for sine waves. The reason is that non-sinusoidal waves typically cannot maintain their shape by interacting with an object. As we will see later, such kind of signal deformations will be expressed by a so-called convolution.

If interaction phenomena between sounding signal and test object[4] are discussed on the base of sine wave signals, one usually talks from frequency (spectral) domain consideration. If one deals with pulse-shaped signals, then it is assigned as time domain consideration which our preferential approach will be. It should be noted that the expression ‘time domain consideration’ is usually not limited to the exclusive use of pulse-shaped signals. In this book, however, we will restrict ourselves to pulse signals in connection with this term since they best illustrate wave propagation phenomena. But it doesn’t mean at all that we will only deal with pulses here. Quite the contrary, we will also respect wideband signals which are expanded in time as a sine wave. They are often referred to as continuous wave (CW) UWB signals. But then, we run in the same or even more critical incomprehensibility of wave propagation phenomena as for sine waves. Fortunately, we can resolve this by applying the correlation approach which transforms a wideband signal of any kind into a short pulse so that ‘impulse thinking’ is applicable as before.

In this book, we will follow both approaches – time and frequency domain consideration – for three reasons. Recently, most parameters or characteristic functions of electronic devices or sensors and test objects are given by frequency domain quantities. Consequently, we need some tools to translate them in time domain equivalences and to assess their usefulness for our ‘time domain’ purposes. A further point is that wave propagation is indeed quite comprehensible in time domain but some interaction phenomena between the electromagnetic field and matter as well as some measurement approaches are easier to understand in the frequency domain, that is with sine wave excitation. Finally, many algorithms of signal processing are running much faster in the spectral domain than in time domain.

The book is organized in six chapters. Here, in this chapter, we will introduce the UWB term, give a short historical overview about the UWB technique and consider some aspects of information gathering by UWB sensors from a general point of view.

The second chapter reviews basic aspects of signal and system theory focused on topics of wideband systems. This involves the definition of common signal and system parameters and characteristic functions in time and frequency domains, overview of important wideband signals as well as a discussion of deterministic and random errors.

4) Depending on the actual application of UWB sensors, the items of interest may be quite different. It may be an individual body, a number of bodies, a certain arrangement or a whole scenario including its temporal evolution. For these items, we will use several synonyms – object under test, object of interest, observed object and correspondingly for scenario, system, process or target.

The working principles of the various UWB sensor approaches are discussed in Chapter 3. It covers the basics on generating and gathering very wideband signals as well as the fundamental measurement circuitry. The different UWB approaches are usually designated by the type of sounding signal which is applied. Here, we will distinguish between pulse, pseudo-random code, sine wave and random noise-based sensor conceptions.

Chapter 4 discusses specific aspects of UWB radar and remote sensing. In generalized terms, it means the investigation of distributed systems and scenarios which extends the considerations in Chapter 2 on systems with a finite number of lumped ports to scenarios with a theoretically infinite number of measurement positions. Some important differences between narrowband and UWB radar are analysed. Obtaining an intuitive idea on how UWB radar works, we deal with a very elementary and simplified understanding of wave propagation. Furthermore, we discuss some issues of resolution limits and sensitivity, try to systematize the various approaches of UWB imaging and introduce characteristic values and functions in the time domain in order to quantify UWB antennas.

The fifth chapter summarizes basics on electromagnetic wave propagation. Up to this point, the vector nature of the electromagnetic field, dispersion, interaction with matter and so on were omitted. We will catch up on this in this chapter so that the reader can assess the validity of the simplified approaches considered in Chapter 4 in case of a specific application.

The final chapter describes several applications. For brevity, we only refer to a few examples but they originate from quite different sensing topics in order to give the reader an idea about possible applications of UWB sensing in the future.

The book is closed with a list of applied symbols and notations. Additionally, some appendices, colored pictures and movies are available online, which may be downloaded from the Wiley Homepage www.wiley.com by searching the book title or the ISBN number. The appendices summarize useful mathematical basics, some fundamentals of signal and system theory and selected aspects of electromagnetic field theory. A couple of gray scaled pictures of the book are reproduced there in a colored fashion and further we have inserted some movies with the aim to better illustrate time dependent processes. The availability of related online topics will be indicated at corresponding passages in the text.

About 30 years ago, H. Harmuth, one of the pioneers of the UWB technique, stated [3]: 'The relative bandwidth[5] $\eta = (f_H - f_L)/(f_H + f_L)$ can have any value in the range $1 \geq \eta \geq 0$. Our current technology is based on a theory for the limit $\eta \to 0$. Both theory and technology that apply to the whole range $1 \geq \eta \geq 0$ will have to be more general and more sophisticated than a theory and technology that apply to the limit $\eta \to 0$ only. Skolnik, M. I. Radar Handbook, McGraw-Hill, Inc. 1970.

Meanwhile we have seen some remarkable progress in theory and sensor technology. Nevertheless, 'the insufficiency of the theoretical basis for the development of UWB technique and technology as a system and as a tool for the design of individual

5) Currently, a slightly modified definition with different symbols is in use. We will introduce it in the next section (see (1.1)–(1.3)).

devices, especially antenna systems' and scattering, 'remains an obstacle to further progress' [4]. Therefore, we can only hope that electrical engineers and appliers are furthermore attracted by the potentials of UWB sensing in order to improve the theoretical basis and the sensor technique and to make them accessible to a wide audience.

In this context, we have to focus on remarkable differences in the development of classical narrowband radar and UWB sensing. Narrowband and UWB long-range radar were, and will be, mainly pushed by military needs, and are reserved to a comparatively small community of specialists. In the case of UWB high-resolution short-range sensing the situation is different. There exists an industrial and civil interest besides the military one. On one hand this will widen the field of applications with all its impacts on sensor and theory development. On the other hand, the audience involved in such developments and applications will be less homogenous than the (classical) radar community. Hence, one has to find out a reasonable way to communicate this sensing technique effectively.

1.2
Ultra-Wideband – Definition and Consequences of a Large Bandwidth

The UWB term actually implies two aspects – a large fractional bandwidth and a huge absolute bandwidth. The operational band typically occupies a certain part of the spectrum within the range of 100 MHz to 10 GHz. If UWB devices are used on a large scale, they have to be bound to low emission levels in order to avoid interference with other communication systems [5]. Therefore, high-power medium- and long-range radar systems will always be reserved for special (usually military) use. This book considers high-resolution short-range devices which deal with low radiation power (typical power < 1 mW) and may be of interest for a wider audience than military only.

Let us now take a closer look at the definition and role of a large fractional bandwidth. The term ultra-wideband relates to a normalized width of a spectral band which is occupied by a signal and in which a device is able to operate. For example, we consider Figure 1.1a. It illustrates either the power spectrum of a signal or the

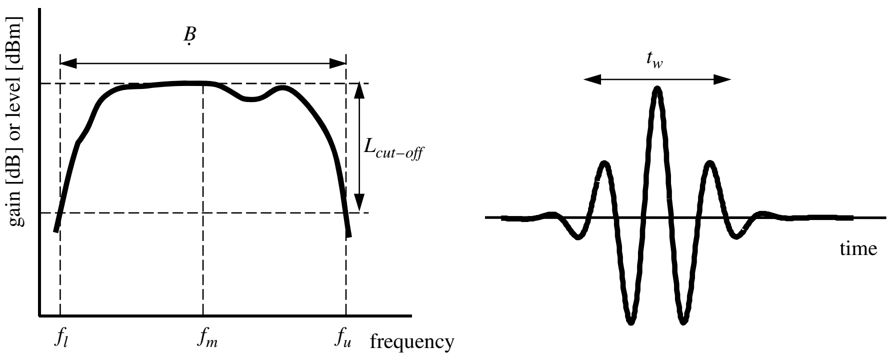

Figure 1.1 Example of power spectrum or transfer function (a) and corresponding time shape or pulse response (b) of a signal or transmission system.

gain of a transmission system. Herein, f_l,f_u are the lower and upper cut-off frequencies referring to an (more or less) arbitrary fixed threshold level $L_{\text{cut-off}}$. The arithmetic mean between both cut-off frequencies is $f_m = (f_u - f_l)/2$. It represents the centre frequency. The absolute bandwidth of the signal and device is given by $\underset{\cdot}{B} = f_u - f_l$ supposing that the spectral power or gain exceeds the threshold level $L_{\text{cut-off}}$ within the whole range. We have several possibilities to normalize the involved frequency quantities. Three of them are shown here:

$$\text{Frequency ratio:} \quad b_{\text{fr}} = \frac{f_u}{f_l} \quad b_{\text{fr}} \in [1, \infty) \tag{1.1}$$

$$\text{Relative bandwidth:} \quad b_{\text{rb}} = \frac{f_u - f_l}{f_u + f_l} \quad b_{\text{rb}} \in [0, 1] \tag{1.2}$$

$$\text{Fractional bandwidth:} \quad b_{\text{f}} = \frac{\underset{\cdot}{B}}{f_m} = 2\frac{f_u - f_l}{f_u + f_l} \quad b_{\text{f}} \in [0, 2] \tag{1.3}$$

We will only deal with the last definition (1.3) by which a signal or device is called ultra-wideband if its fractional bandwidth exceeds a lower bound $b_{\text{f}} \geq b_{\text{f0}}$. This lower bound is typically fixed at $b_{\text{f0}} = 0.2$ in connection with a cut-off level of $L_{\text{cut-off}} = -10\,\text{dB}$. In order to avoid ambiguities with acoustic systems (audio devices, ultrasound or sonar sensors), one additionally requires an absolute bandwidth larger than a given value $\underset{\cdot}{B} \geq B_0$ for UWB signals and devices: $B_0 = 50 - 500\,\text{MHz}$ depending on the country.

Nevertheless, a comparison with acoustic sensing approaches reveals interesting similarities. Namely, the human ear and UWB sensors are working at comparable wavelengths (see Table 1.1). Furthermore, the human eye operates on visible light with wavelength ranging from 390 to 780 nm. Using (1.3) leads to a fractional bandwidth of $b_{\text{f}} \approx 0,63$ for the visual sense. Hence, the human beings (and many animals too) have a set[6] of highly sensitive 'ultra-wideband sensors' in order to capture information about their environment. With these sensors, they capture most of the information about their environment and control their lives. It is amazing which information a human being can infer from a physical phenomenon such as reflection and diffraction captured with their 'visual sensors'. But, beside these sensors, an efficient and powerful instrument such as the brain is required to interpret the incoming sensor stimuli. The brain – as synonym for data processing, feature extraction, data mining and so on –plays an even more important role as the bandwidth of the sensors increases since more information must be decrypted from an ever-growing amount of data.

These examples underline the need and the potential of ultra-wideband sensors for future technical and industrial developments, whereas the term 'ultra-wideband' should be seen under a generic aspect[7] for any type of sensing principle and not only restricted to the frequency band of sounding waves. It also shows that signal processing and data mining will become a key point in future development of

6) Including'ultra-wideband' chemical sensors for various substances.
7) The usually applied term in this connection is 'diversity'.

Table 1.1 Wavelength versus frequency for electromagnetic and acoustic waves for propagation in air and water.

Wavelength	Electromagnetic wave		Acoustic wave	
	Air $c \approx 30$ cm/ns	Water $c \approx 3.3$ cm/ns	Air $c \approx 330$ m/s	Water $c \approx 1.5$ m/ms
3 m	100 MHz	11 MHz	110 Hz	500 Hz
30 cm	1 GHz	110 MHz	1.1 kHz	5 kHz
3 cm	10 GHz	1.1 GHz	11 kHz	50 kHz

UWB sensing in order to be able to explore and exploit the wanted information hidden in the captured data. Data processing will gain much more importance than it has in narrowband sensing.

Let us come back to our initial discussion of UWB signals and systems. What is the impact of a large bandwidth on the time evolution of the involved signals? In order to be illustrative, we restrict ourselves to short pulses first (refer to Figure 1.1b). Its duration is t_w (FDHM[8]) – full duration at half maximum) and it is composed of N oscillations. Thus, a (centre) frequency f_m can be roughly assigned to our pulse which is calculated from $N \approx f_m t_w = (f_u + f_l) t_w/2$. Since for a band-pass pulse $t_w B = (f_u - f_l) t_w \approx 1$ (see Section 2.2.5, Eq. (2.77)), relation (1.3) can also be expressed as

$$b_f N \approx 1 \tag{1.4}$$

Hence, pulse-like wideband signals are composed of only few oscillations because b_f takes values from 0.2 to 2 in the UWB case while narrowband signals ($b_f \to 0$) have many of them. We can extend this condition to any type of wideband signal by referring to the auto-correlation function instead of the actual time shape (see Section 2.2.4).

The behaviour of an UWB system/device also underlies the condition, (1.4) that is, if they are stimulated by a short impact, they will react typically with only a few oscillations that strongly decay.

1.2.1
Basic Potentials of Ultra-Wideband Remote Sensing

In anticipation of later discussions (mainly in Chapters 4 and 6), we will shortly summarize the main consequences of a large absolute and fractional bandwidth on remote sensing applications. As long as the targets do not move too fast, all objects included in the radar channel (antennas and scatterers) may be considered as LTI (linear time invariant) systems. Hence, the electrodynamics of transmission, receiving and scattering, can be formally described by impulse response functions. The target responses can be interpreted either as the reaction of different bodies to an incident field or the reaction of distinct scattering centres of a composed target.

8) One can also find the notation: FWHM – full width at half maximum.

The scatterer response contains all information about the target accessible by radar measurement. Some sensing features are summarized below that are promoted by a large bandwidth:

Target identification [6–8]: We consider a single body of complex structure. Its total scattering response typically comprises a number of peaks (caused, e.g., by specular reflections) and damped oscillations (representing the eigenmodes of the target). In order to resolve these properties, the temporal width t_p of the sounding wave must be shorter than the time distances between adjacent peaks in the response function and the sounding bandwidth should cover at least a few eigenfrequencies of the target. The temporal structure of the specular reflections and the eigenfrequencies are distinctive parameters since they relate to characteristic body dimensions. Hence, to achieve both – separation of specular reflections and a mix of natural frequencies – a large fractional bandwidth is needed. The demands on absolute bandwidth result from the smallest dimensions to be resolved.

Detection of hidden targets and investigation of opaque structures [9]: On one hand, microwave penetration in most of the substances or randomly distributed bodies (e.g. foliage, soil) is restricted to low frequencies, but on the other hand, reasonable range resolution requires bandwidth. To bring both aspects together, the fractional bandwidth must be large. The absolute bandwidth is typically limited by the properties of the propagation medium.

Separation of stationary targets [10]: Scattered waves of two targets located nearby will overlap. They may be separated as long as the signals do not constitute too many oscillations, that is if their fractional bandwidth is large enough. Otherwise a periodic ambiguity of the separated signals will arise. SAGE and MATCHING PURSUIT are numerical techniques using such approaches.

Small target detection and localization: Backscattering from thin layers or cracks is proportional to the first temporal derivative of the sounding wave; small volume scatterers (Rayleigh scattering) cause a second derivation. That is, high frequencies promote the detection of small defects and a large bandwidth leads to their localization. If the small targets of interest are embedded in any substance, a frequency and bandwidth compromise between penetration, detection and localization precision must be found.

Moving target detection: Moving targets covered by strong stationary clutter can be detected by weak variations in the backscattered signals caused, for example, even by small motions. Again, large fractional and absolute bandwidths are beneficial for penetration of opaque objects, the registration of movements and target separation.

1.2.2 Radiation Regulation

UWB devices radiate electromagnetic energy over a large spectral band. Hence, they will increase the level of the noise background. In order to avoid any impact on existing communications systems, the maximum radiation level and the frequency bands of a licence-free operation of UWB devices are restricted by law.

Operational modes requiring deviations from the corresponding radiation rules need consultation with the local authorities for radio communication.

By definition, a UWB device must occupy instantaneously a spectral band which has either a fractional bandwidth $b_f \geq 0.2$ or an absolute bandwidth $B \geq 500\,\mathrm{MHz}$ in the United States and $B \geq 50\,\mathrm{MHz}$ in Europe. Hence, UWB sensors using swept or stepped sine waves do not belong to UWB devices in the strong sense of the definition. Nevertheless, we will also consider sine wave approaches here since there is no physical reason which prohibits their use for wideband measurements.

The international rules for licence-free operation of UWB devices largely orientate at the maximum allowed perturbation level for unintentional radiation which is often simply termed as 'part 15 limits'. The 'part 15' (exactly 47 CFR §§15) is a section of US Federal Communications Commission (FCC) rules and regulations. It mainly regards unlicensed transmissions. It is a part of Title 47 of the Code of Federal Regulations (CFR). The part 15 limit refers to an effective isotropically radiated power (for definition see Section 4.8.2) of $\mathrm{EIRP} = -41.3\,\mathrm{dBm/MHz} \mathrel{\hat{=}} 74\,\mathrm{nW/MHz}$ which corresponds to an effective strength of the electric field of about $E_{\mathrm{rms}} \approx 500\,\mu\mathrm{V}/\left(\mathrm{m}\sqrt{\mathrm{MHz}}\right)$ at a distance of 3 m from the radiator. Hence, the spectral power density of a licence-free UWB radiation is worldwide limited to a maximum value of $-41.3\,\mathrm{dBm/MHz}$. It represents an average value. The peak power level may be typically 40 dB higher than the average spectral power density level. It is determined over a frequency band of 50 MHz width. Its absolute maximum is 0 dBm. Depending on the region and the intended device application, the approved frequency bands for UWB operation are different. The following figure summarizes some of these rules (Figures 1.2–1.4).

The very first obligatory rules for UWB radiation were introduced by the FCC in the United States in 2002. As can be seen from Figure 1.2, the FCC rules provide a large frequency band from 3.1 to 10.6 GHz for UWB radiation with maximum power limitations as for 'part 15 limits'. These frequencies are very well suited for communication purposes but less useful for many sensing applications due to the bad wave penetration into substances.

Other countries modified these rules according to their situation. The main promoter of UWB regulation was the communication industry since it expected a huge market for high-data-rate short-range communication. But the initial effort to develop such communication devices has been largely reduced following a typical hype cycle.

For many people working in this field, UWB technique is linked with the frequency band 3.1–10.6 GHz (FCC–UWB band) and the use of pulse signals. But these simplifications and reductions are not true. They may have historical roots:

- The large influence of the communication industry mainly moulded the public image of UWB technology.
- The first UWB regulation was performed in the United States, resulting in the well-known FFC–UWB band.
- The early and most of the current UWB systems – radio devices, high-resolution radars, ground-penetrating radars (GPRs) and so on – used pulses.

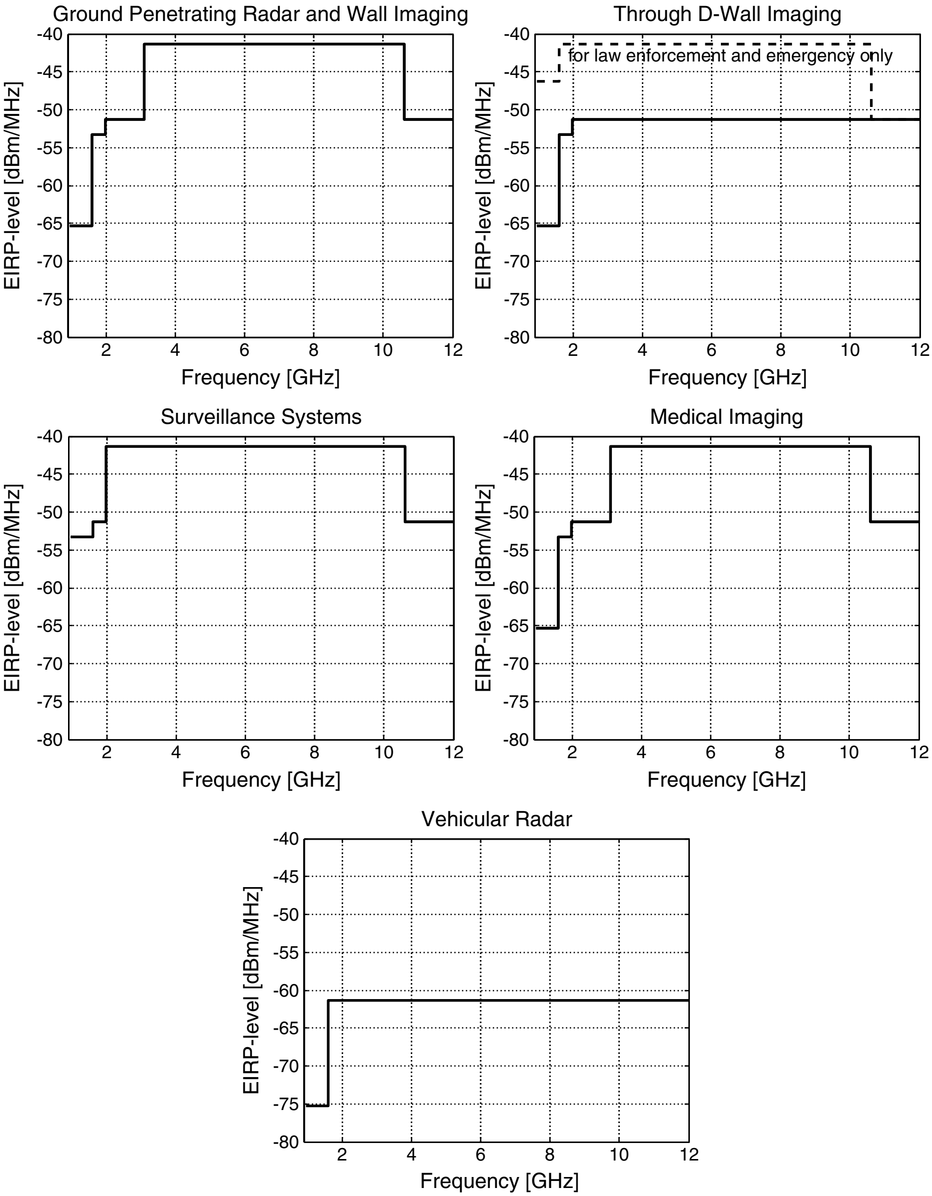

Figure 1.2 FCC-radiation limits for the United States [12]. The spectral power of the radiated signals is measured at 1 MHz resolution bandwidth.

We will not impose such restrictions ourselves here. First, not all countries allow such wide UWB band as the FCC. Second, UWB sensing needs, in certain circumstances, the whole frequency spectrum without gaps, for example, for sounding of hidden objects. Hence, we need exceptional rules for specific applications (e.g. in

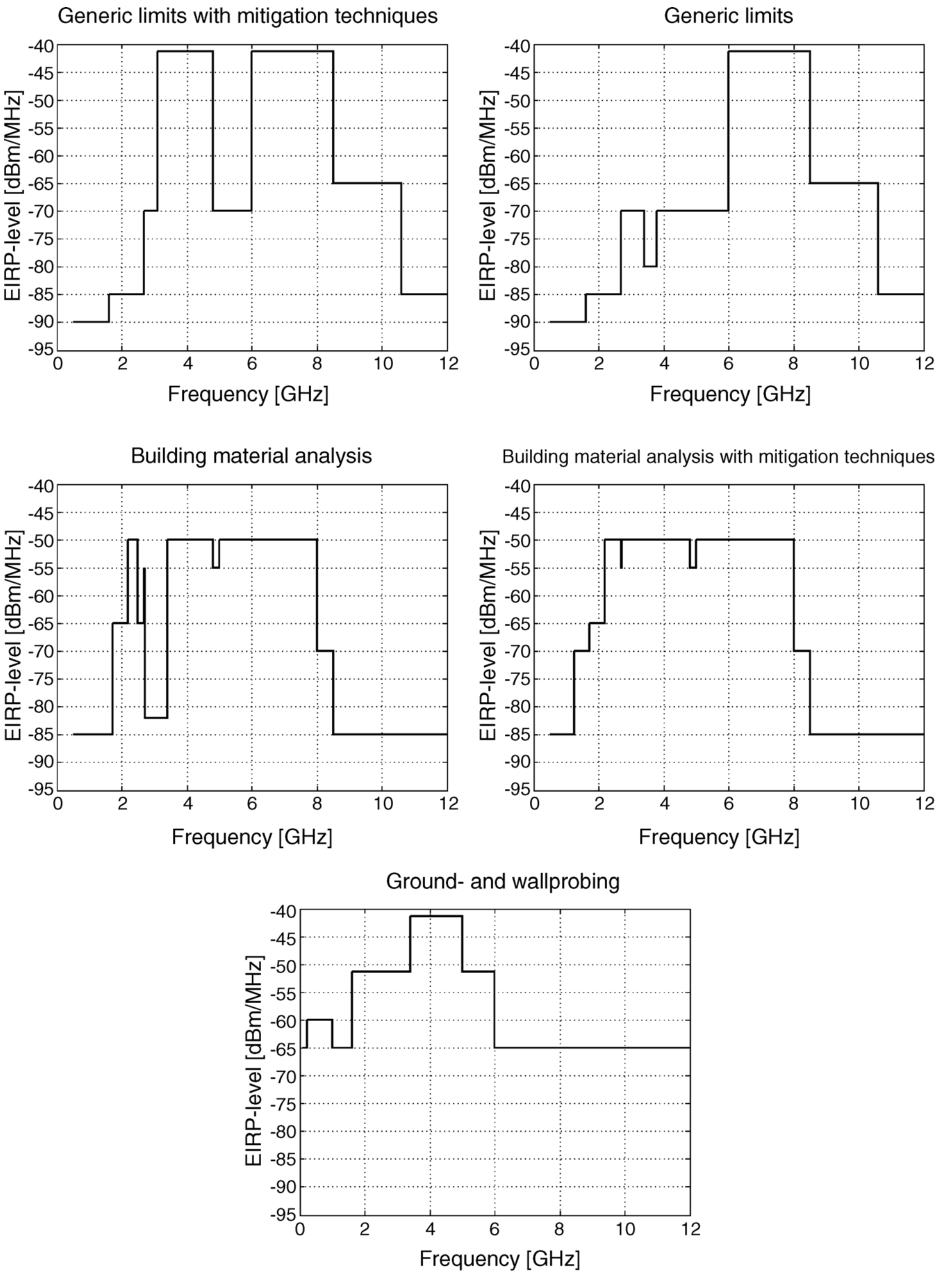

Figure 1.3 ECC-radiation limits in Europe for selected UWB devices [23, 24, 26, 29].

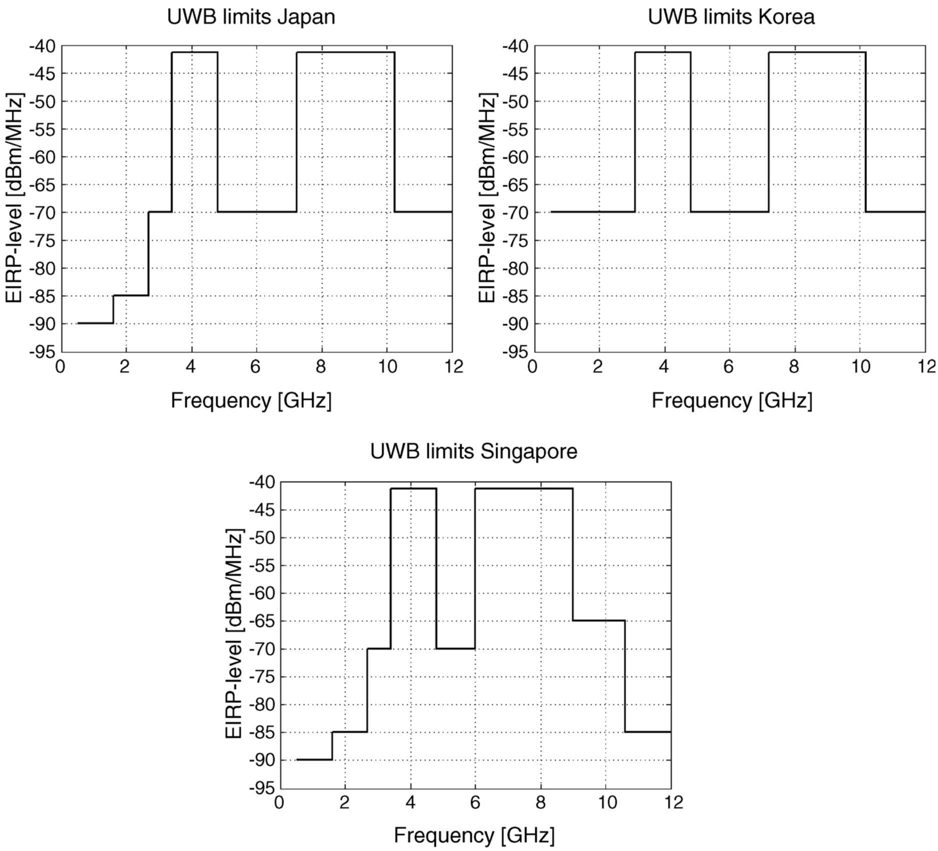

Figure 1.4 Selected radiation limits for some Asian countries: MIC-radiation limits in Japan for indoor device [30], for South Korea [31] and Singapore [32].

public interest – search and rescue) or the measurement environment has to be shielded appropriately to avoid interference with other devices (e.g. medical or industrial applications). Third, modern technology of electronic devices promotes the generation of a larger family of UWB signals than only pulses. Hence, one will have more flexibility in selecting adequate sensing principles for his application.

For detailed discussions on regulation and definition issues or UWB interference with other communication devices the interested reader may refer to Refs [11–30].

1.2.2.1 **Implication of UWB Radiation on Biological Tissue**

The spectrum of electromagnetic waves, which is in technical use, extends from several kHz to about 10^{20} Hz corresponding to wavelengths of kilometres to nanometres or picometres. The spectral range used by UWB sensors (about 100 MHz – 10 GHz) seems to be comparatively small, which largely reduces the impact of the radiation on biological tissues.

The physical impact of electromagnetic radiation on substances can roughly be classified into heating, ionization and cracking of molecules. Classically, the interaction of electromagnetic field and matter is described by two fundamental approaches – one deals with waves and the other with a kind of 'particles', that is the photons.

Heating can be explained by a wave model; that is, an electric wave (field) penetrates the body and moves charged particles (ions, molecules with dipole moment etc.). This can lead to relaxation phenomena (see, e.g., water relaxation, Section 5.3) which results in heating as it is exploited in microwave ovens. The specific heating power P_V caused from a homogenous electric field E due to dielectric losses is given by (ε'' is the imaginary part of permittivity, f is the frequency):

$$P_V = 2\pi \int_{f_l}^{f_u} f \varepsilon''(f) E_{rms}^2(f) df \quad [W/m^3] \tag{1.5}$$

Using exemplarily water as the main substance of tissue, we get an induced heating power of about 8 mW/m^3 and 8 μW/kg if we expose the tissue to an UWB field corresponding to the FCC limits (i.e. 7 GHz bandwidth and −41.3 dBm/MHz power spectral density). This power is extremely low and absolutely harmless. It should be noted that the radiated power of a cell phone is more than thousand times higher than that permitted for an UWB device according to the comparatively relaxed FCC rules. The power entry in case of the medically used diathermy (commonly used for muscle relaxation) covers several watts per kilogram tissue.

Ionization and molecule destruction may be caused by electric sparks or highly energetic photons. An electric spark creates a 'conductive tunnel' of high current density which leads to local overheating and consequently to material destruction. The creation of electric sparks in isolators needs electrical fields of several kV/mm. Such high fields occur inside high-power short pulse devices [1] but are far from any reality in UWB short-range applications. The exposition of various organisms and biological tissue by pulse-shaped electric fields did not indicate any harmful impact [33–37].

Photon energy becomes harmful for biological tissue if the radiation frequency exceeds that of the visible light, that is ultra-violet, X-ray and gamma rays. The photon energy W is calculated as follows ($h = 6.62 \times 10^{-34}$ J s $= 4.13 \times 10^{-15}$ eV s – Planck constant):

$$W = hf \tag{1.6}$$

Hence, the photon energy of the still harmless blue light (380 nm) is about $W \approx$ 3 eV (eV – electron volt) while that of a 10 GHz microwave is $W \approx 40\,\mu$eV, that is 100 000 times less. Consequently, short-range UWB sensing is an absolutely harmless sensing technique which can be applied preferentially for medical purposes and also in private homes.

1.3
A Brief History of UWB Technique

Some people date the beginning of ultra-wideband techniques to the famous experiments of Heinrich Hertz to prove the existence of electromagnetic waves [38]. But this is quite vague and was not proposed by him. Even if he used a transmitter principle – the spark gap – as it can be found also in modern high-power pulse systems, the actual and intentional UWB research started in the 1950s and the 1960s. This activity was essentially driven by three communities:

- **Radar:** Ground and foliage penetration as well as high-resolution imaging and target classification.
- **Communications:** High data rate, multi-path immunity, licence-free operation.
- **High power:** EMP simulations and non-lethal weapons.

At that time the theoretical basis and the technical conditions to operate a very wideband system started to develop. First, wideband devices (sampling oscilloscopes, network analysers, time domain reflectometers) were launched on the market. The key points of this development were the understanding and the development of antennas for non-sinusoidal signals, pulse sources and wideband receivers. Later, the handling and processing of digitized data gained more and more importance, permitting to manage the large data and to extract the wanted information from the measurements more efficiently.

In the early phase of development, terms such as baseband, carrier-free, impulse, time domain, non-sinusoidal and so on were commonly used to describe wideband techniques. The currently used notation 'ultra-wideband' was introduced by the DARPA (US Defence Advanced Research Projects Agency) around 1990; not everybody is satisfied with this definition (see, e.g., [16]). According to DARPA rules, devices or signals are called ultra-wideband if they cover a fractional bandwidth $b = 2(f_u - f_l)/(f_u + f_l) \geq b_0$ larger than a given threshold b_0. f_u,f_l are the upper and lower cut-off frequencies of the spectral band occupied by the sounding signal. Initially, the threshold was fixed to $b_0 = 0.25$ at -20 dB cut-off level. Later in 2002, it was reduced to $b_0 = 0.2$ at -10 dB cut-off level by the FCC and other regulation authorities (e.g. ECC for Europe, MIC for Japan) made further modifications.

The early UWB radar activities were directed, on one hand, to develop high-resolution military radars with improved target recognition capabilities. On the other hand, the good penetration of UWB signals into opaque objects was exploited by establishing ground-penetrating radar (around 1974). Finally, in the last decade of twentieth century, the first low-power, low-cost and lightweight UWB devices were constructed, opening the field of numerous civil applications. We will neither delve deeper into UWB history here nor discuss the pros and cons of the various aspects of the whole UWB technique. We will mainly consider issues on low-power sensing application. The interested reader can find more information on the mentioned topics in Refs [1, 4, 39–52].

The books published so far on UWB technique are aimed at radars and localization [8, 6, 30, 53–56], ground penetration [9] and through wall radar [57], medical sensing [58] and communications [59–74]. Some pioneered works can be found in Refs [3, 75, 76]. A summary on UWB antennas is given in Refs [77–79], and Refs [80–83] report about integrated UWB devices.

The growing interest in UWB techniques and adjacent topics is also expressed in a number of international conferences and workshops such as the annual conference ICUWB (IEEE International Conference on Ultra-Wideband, former UWBST) and the bi-annual conferences GPR (International Conference on Ground Penetrating Radar) and AMEREM/EUROEM (American Electromagnetics/European Electromagnetics) which publishes the book series 'Ultra-Wideband Short-Pulse Electromagnetics' [84–92].

1.4 Information Gathering by UWB Sensors

The sensing technique should never be considered uncoupled from its final destination as part of a control loop depicted in Figure 1.5. Such loops can be components of an engine control or the regulation of industrial processes. But sophisticated sensors may also control or monitor social and medical procedures (e.g. vital data capturing for law enforcement, patient supervision, assistance of handicapped people etc.). The task of the sensor is to provide reasonable information which allows to initiate purposeful actions. Sophisticated concepts of control loops consist of several layers providing sufficient flexibility to react to different situations. Such flexibility mainly results from two aspects:

- The sensor which observes the object/process of interest is not restricted to a simple transformation of a physical value to another one as it is done by classical sensor devices. Rather, the sensor may be divided in two parts. One part is the sensor head which initially only provides a neutral observation signal. The

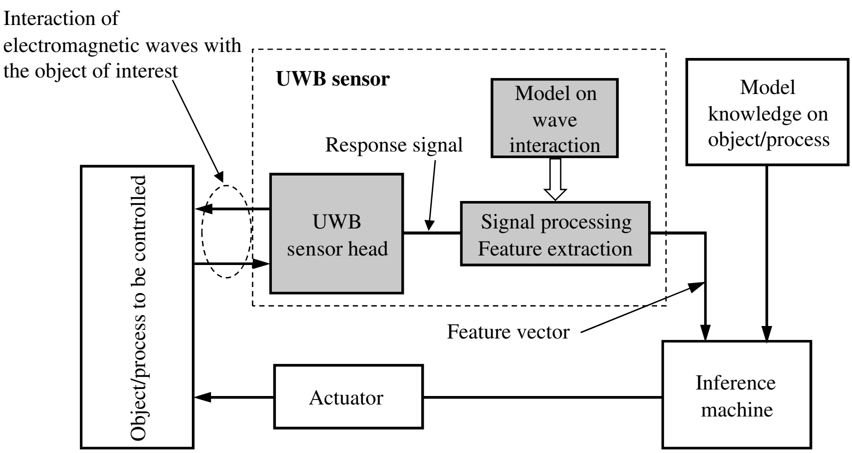

Figure 1.5 Generic control loop using UWB sensors for the observation of an object/process of interest.

second part concerns the data processing which extracts the wanted information from the observations depending on the object/process of interest and depending on the target of the intended actions. In case of UWB sensors, one is often able to extract several characteristic values from the captured data, not only one quantity as in case of many classical sensors. Such information is often supplied as the so-called features vector, that is a set of numbers summarizing some characteristic properties of the object/process of interest.

- The simple determination of the difference between observation and reference as used in primal control loops is replaced by a more complex inference system which includes knowledge about the nature of the object/process of interest and the objective of the actions to be controlled. The inference system may also work on the observations from a number of spatially distributed sensors of the same type (sensor array) and/or it may fuse the information gained from sensors of different kind collecting various physical quantities of the object/process of interest. Additionally, one may insert a 'man in the loop' which either supervises the whole system or contributes to feature extraction and inference.

There is no rigid and clear separation between sensor and inference system. This mainly concerns the level of the models and a priori knowledge, which are required to extract reasonable features and deduce the correct actions. Nevertheless, here in this book, we want to restrict to the working principle of the sensor elements and to the extraction of appropriate features. But we should always have in mind that the selection of appropriate sensors and data processing strategies depends on the structure and objective of the whole control loop.

UWB sensors exploit electromagnetic waves of extremely low power for sensing the scenario under test as illustrated in Figure 1.6. It is well known that the wave

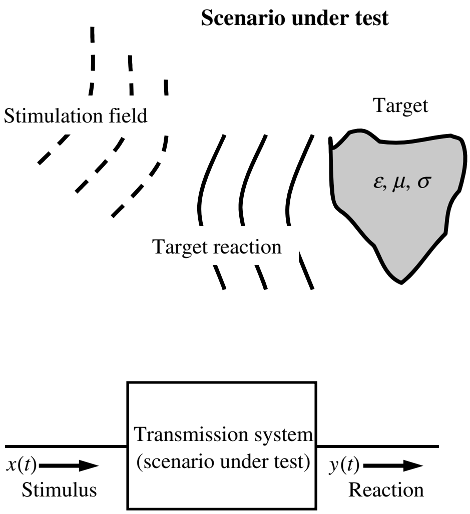

Figure 1.6 Symbolized interaction of an electromagnetic wave with an arbitrary object and formalization of the interaction by a transmission system.

propagation is influenced by objects located within the propagation path. The wave interaction is described by Maxwell's laws and the corresponding boundary conditions. Consequently, the deformation of the stimulation field depends on the geometry of the object as well as the substances from which it is built (expressed by the material parameters permittivity ε, permeability μ and conductivity σ). Therefore, there is some hope to infer the cause (e.g. the geometric structure of the scenario) of such deformations from the captured field. The way of deduction is directed opposite to the chain of reaction; thus, a so-called inverse problem has to be solved in order to gain information about the scenario under test.

Since we will restrict ourselves to the macroscopic world and test objects with linear behaviour against electromagnetic fields, the chain of reaction implies that a certain action on an object or scenario leads to a specific reaction. Hence we can predict the dynamic reaction of a system if we know both its structure and the stimulation signal. Such a prediction is also referred as a solution of a forward problem for which there always exists a solution and this solution will be unique.

The inversion of this problem, that is either to conclude the stimulus of the system from the knowledge of the system behaviour and the system reaction (type 1), or to determine the system behaviour from the known stimulus and the system reaction (type 2), is usually not unique. From a mathematical point of view, inverse problems are often ill-posed problems. According to Jacques Hadamard, well-posed problems should have the following properties:

- A solution exists.
- The solution must be unique.
- The solution depends continuously on the data.

Ill-posed problems violate at least one of these conditions.

We will only deal with the type 2 of inverse problem, that is to look for the system behaviour in order to get some indications about the type and state of the investigated scenario and we mainly have to combat against the last two implications of an ill-posed problem. That is, we may need some regularization techniques in order to avoid data disruption and we have to accept that our endeavour to characterize or to identify an unknown scenario/object under test may lead to the right result only with a certain probability.

The probability of a correct solution improves with increasing prior knowledge about the test scenario and the number of disjoint features gained from the sensors. The better one can confine the variability of a test scenario, the less disjoint features are required for a reliable characterization and identification of the tested system. The uniqueness of information collected from the test objects depends strongly on the diversity of the observations (measurements). Such diversity of information capturing basically reflects in the following points:

- **Capturing of quantities of different nature:** Exploitation of different interaction phenomena (electrical, sound, vibration, chemical, gas and so on; active and passive sensors) reduces cross-ambiguities since different objects show very rarely identical behaviour with respect to all interaction phenomena.

- **Diversity in space–time:** All interaction phenomena take place in space and time. Hence, stimulation of test objects and capturing of their reaction should be performed at several locations and we need dedicated stimulation procedures, that is sounding signals of an appropriate time evolution. As we will see later, we can generalize the term 'signal of appropriate time evolution' by the term 'frequency diversity', that is signal bandwidth which is a point of major concern in ultra-wideband sensing.
- **Diversity in observation time:** The properties and the behaviour of a test scenario may change over time. Often the time variations of these properties (i.e. the 'history' of the property variations) are also characteristic for a specific scenario or test object. Thus, the observation of a scenario over a long duration may bring additional information and reliability.

A discussion on diversity in sensor principles will not play any role in what follows since we will restrict ourselves to UWB sensing which is based on purely electromagnetic interactions. But diversity in space–time and observation time will be essential for many UWB sensing applications. UWB array, UWB-MiMo[9] array, UWB scanning and others are the practical counterparts of the abstract term 'space–time diversity'.

The term 'time' needs still some clarification since it is used in different contexts. Basically, we have three procedures running in parallel if we are dealing with UWB sensing.

1) The interaction of the sounding signal or wave with the test objects.
2) The capturing of measurement data created from the stimulated objects.
3) The temporal variation of the test scenario.

Usually all these procedures are overlapped and mixed together. But fortunately, in UWB sensing, we can consider them separately. We apply sounding waves which travel with the speed of light ($c \approx 30\,\text{cm/ns}$) and we are restricted to short-range sensing. Hence, the interaction of sounding signals with the scenario under test extends only over the nanosecond range. The time frame within which such interactions take place is called interaction time t (sometimes also called 'fast time').

Compared to that, the observed objects and scenario change their behaviour quite smoothly so that they can be considered stationary over the interaction time. A temporal change in properties of the scenarios and objects usually includes a mass transport of any kind (movement of a body, mechanical oscillations, variation of substance composition etc.). These phenomena proceed slower, by many orders, than the propagation of electromagnetic waves so that repetition rates in the range of 1–1000 measurements per second or even less are sufficient in most cases to observe the ('historical') evolution of the test scenario. The time frame within

9) MiMo – multiple input and multiple output; the term MiMo array assigns an antenna array/ arrangement which includes radiators that may act as transmitter (multiple output) or receiver (multiple input). Typically, the individual radiators may be operated independently from each other.

which the scenarios under test change (remarkably and hence observably) their behaviour is called observation time T (sometimes also called 'slow time').

As the examples show, there is still a big gap between the duration of wave interaction and the actual required measurement interval. This gap can be used to extend the duration of data recording in order to increase the statistical confidence in the measurement (e.g. by repeating the measurement several times) or/and to simplify the receiver circuits by applying stroboscopic sampling. The time we finally need to capture a whole data set is called recording timeT_R. Its duration must be equal to or larger than the interaction time of the sounding signal and it must be equal to or shorter than the time interval between two succeeding measurements. Hence, its maximum value will be fixed either by the Nyquist theorem concerning the time variability (bandwidth) of the scenario to be observed or by the Doppler effect[10)] which is linked to the speed of a body moving through the observed scenario.

After having the data captured from the test scenario, the measurements have to be processed appropriately. Figure 1.7 depicts a possible way to extract information about the scenario under test. For that purpose, we illustrate the interaction of the stimulus signal with the scenario by a transmission system (black-box model) which describes the dynamics of interaction (see Figure 1.6). Starting from the measurement of the stimulus and the reaction of the observed scenario, one can first determine a characteristic function which is either the impulse response function $g(t)$ or frequency response function $\underline{G}(f)$ (they are introduced in Section 2.4). This step is also called system identification. It provides a so-called non-parametric system description.

One can extract meaningful parameters from the determined functions $g(t)$ or $\underline{G}(f)$ (note that some methods of parameter extraction may also work directly on the captured data). This step supposes a model about the interactions of the test objects with the sounding field since otherwise the determined functions cannot be interpreted in a meaningful way. Model structure and the resulting parameter set are summarized by the term parametric system description. The parameter estimation leads to a drastic reduction in data amount since the number of parameters are usually orders less than the number of data samples in $g(t)$ or $\underline{G}(f)$. Parametric and non-parametric system identifications are counted among the ill-conditioned problems which require appropriate regularization.

Finally, depending on the actual application, some of these parameters or even a combination of them will shape up as the most descriptive quantities. They represent the features. These characteristic numbers will find access to an inference or classification process running at higher layers of signal processing which we will exclude from our further considerations due to its strong dependence on the actual application.

10) The limitation of the recording time due to the Doppler effect has only to be respected as long as the measurement scenario should be considered as stationary during the recording time. If one abandons this requirement, the recording time may be extended at the expense of more complex receivers or data processing (see Sections 3.3.6 and 3.4.4).

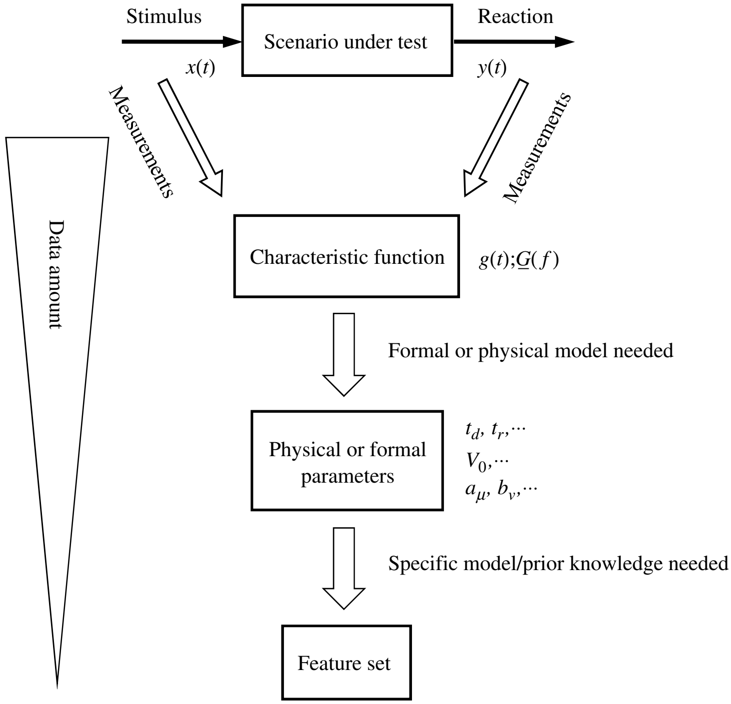

Figure 1.7 Typical approach to extract information about a scenario under test. The mentioned functions and parameters are introduced in Chapter 2.

The capturing of the test system behaviour may be based on different measurement arrangements (see Figure 1.8). One of them involves a small (ideally point shaped) measurement volume (Figure 1.8a) in which only the stray field components at the end of the probe contribute to the measurement result. This method will be applied if only the material parameters (ε, μ, σ) at a certain location are of interest. Scanning the probe across a surface may lead to high-resolution images due to the small interaction volume of the probing field. Such measurements are usually referred to as impedance spectroscopy or dielectric[11)] spectroscopy since the measurement results are usually given in dependence of the frequency. The interaction of the sounding field and the material under test is based on near field effects. These fields rapidly decay with the distance from the probe which leads to the small interaction volumes.

A second method provides a line-shaped measurement volume (Figure 1.8b). Here, a non-shielded transmission line, for example a two- or three-wire line, is surrounded by the material of interest. The inserted sounding wave is guided through the line whereas its propagation is largely influenced by the embedding material. Therefore, the injected wave will be partially reflected, some parts are absorbed and others are transmitted so that conclusions concerning the

11) This notation supposes a relative permeability $\mu_r = 1$ which is valid for most substances.

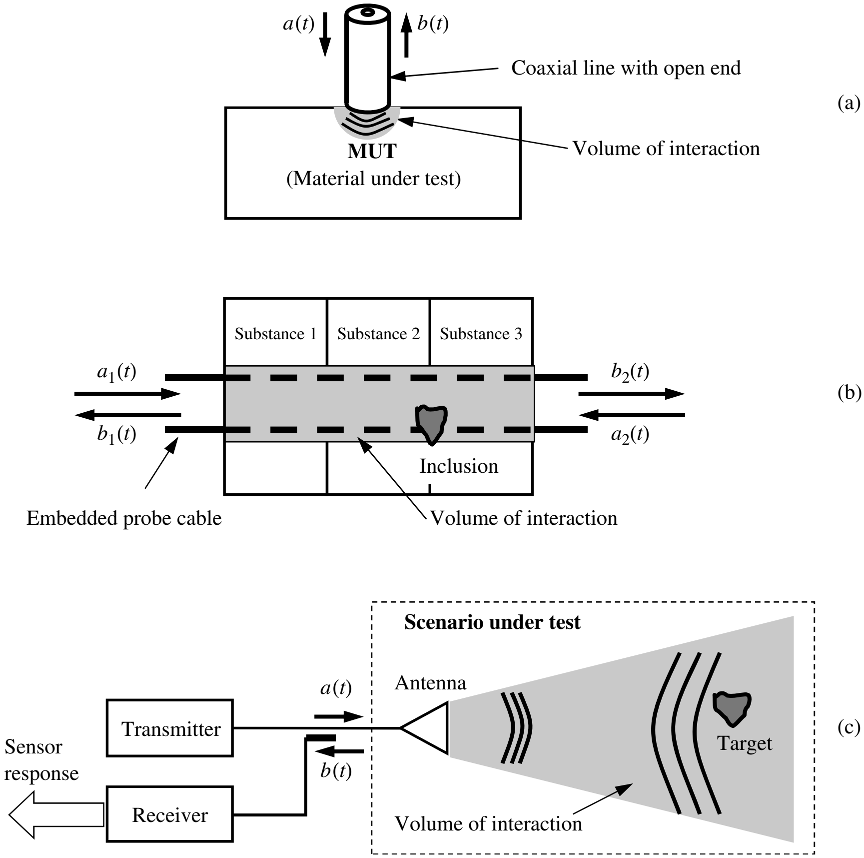

Figure 1.8 Basic measurement arrangements. *a* and *b* represent guided waves which are incident on and emanate from the scenario under test.

embedding material can be drawn by evaluating the deformations which the inserted signal has sustained by travelling through the cable. These techniques are called TDR and TDT (time domain transmission).

A further approach is depicted in Figure 1.8c. It is based on sounding with free waves which are generated and received by antennas. Depending on the antenna characteristics, the observation volume is either cone shaped or omnidirectional. This method permits a contactless sounding over a certain distance. It is usually referred as a radar technique. If the waves are penetrating soil, walls or other construction elements and so on to check hidden targets, it is also called GPR, SPR (surface-penetrating radar) or TWR (through wall radar).

In order to give a vision on the future potential of UWB sensing, let us compare this technical sensing approach with two comparable methods which were 'engineered' by the nature itself – the human eye and the sonar of a bat. All these methods apply scattering of electromagnetic or acoustic waves as source of information. Hence, the 'philosophy' behind the UWB radar sensors is very close to that of the human eyes or the bats' echolocation. So we can learn a lot from the nature for a better understanding of problems and challenges of UWB sounding.

Our eyes (in connection with our brain) which exploit electromagnetic waves as UWB sensors are our major tool to capture information about the environment. If the UWB sensing technique and its further development are seen under such a light, a great deal of new applications and sensing approaches will be expected within the next years. Its field of use will span from simplest tasks as distance measurements to sophisticated target recognition problems applied under relaxed as well as harsh conditions.

However, there are some important differences between both concepts:

- **The different wavelength of the sounding waves:** The human eyes exploit light scattering which involves electromagnetic waves having a wavelength between 380 nm (blue light) and 780 nm (red light). UWB radar sensors use microwaves having a wavelength ranging from centimetres to decimetres. Therefore, light waves can better map the (outer) geometry of items of daily life. These objects are typically thousands of times larger than the wavelength of light. In contrast to that, microwaves can better penetrate materials (except metal), so they are able to look 'behind things'.
- **Illumination of the scene:** The human eye needs an external source for the sounding waves that is the light of the sun or of a lamp. The eye is not synchronized to that source. The UWB radar sensors provide its own sounding signal on which it is synchronized.
- **Data capturing:** In the case of the eye, the data capturing is non-coherent due to the lack of synchronization with the light source. The receptors in the eye only gather light power. It is roughly divided into three spectral ranges –red, green and blue. The receptors are arranged in a dense array (the retina), which finally provides a projection of the waves that are backscattered from the objects within the considered scene. The image creation is done by a lens having a diameter of few millimetres. It is large compared to the wavelength resulting in a very fine angular resolution of about 0.02[12)] degrees. The colour impression comes from frequency-dependent material parameters or subtle structured surfaces. The lack of synchronization with the sounding waves avoids direct range information. Therefore, the object distance has to be estimated by auxiliary methods (estimation of apparent object size or angle estimation by two eyes) which are less precise than range estimation by round-trip time.

In contrast, the UWB radar sensor works in a synchronous way. It captures the actual time shape of the scattered electromagnetic field. Therefore, it provides immediately precise range information via the travelling time of the waves. The modification of the time shape of the backscattered signal is caused due to the geometric structure, the surface texture and the material composition of the observed objects. Depending on the application, UWB sensors appear as single sensor or multi-sensor (sensor array) system. UWB imaging always requires a sensor array

12) This corresponds to a 1-cent coin seen from 50 m distance.

approach. The image creation is usually done by signal processing avoiding any lenses. The resolution of an UWB radar image is orders below that of an optical image due to the longer sounding signals. An UWB array which would have an angular resolution (in the far field) comparable to that of an eye would cover a field of about 900 m of diameter, which is far from any realistic arrangement. However, a UWB radar system is able to provide real 3D-images of an investigated volume, it can image optically hidden objects, and it is robust against dust, smoke and fog. Since the size of the imaged objects is often in the same order as the spatial extension of the sounding wave, diffraction and resonance phenomena complicate the UWB imaging. Consequently, one should not try to see UWB radar images with the 'human eye' (i.e. in a purely geometric way); rather, we should better understand the pretended image artefacts.

- **Information extraction:** The data capturing by the eyes or by any other sensor is meaningless if no appropriate conclusions can be extracted. Here, the human eye has advantage over technical sensors since its 'data' are processed by the brain, the most excellent tool to extract information.

In the second example mentioned above – the echolocation of a bat – the similarities to UWB sensing are to be seen in a comparable[13] wavelength of both types of sounding waves and the comparatively simple sensor arrangement – one transmitter (mouth) and two receivers (ears) – creating an interferometric radar/sonar. In the case of the bat (and other mammals, for example, whales apply the same principle), we can recognize the performance of this principle of autonomous orientation, localization and target classification. Here, the data capturing and 'image' formation is strongly dependent on the movement of the 'sensor platform' in order to gain the spatial diversity to reconstruct an 'image' of the environment [93, 94]. Certainly the brain will again play a particular role within the whole sensor system, which underlines the increasing importance and challenges of signal processing of ultra-wideband data. The bat has learned during its evolution to interpret backscattered signals correctly even if they are affected by resonance effects and diffraction phenomena. So we can hope to improve considerably the UWB sensing technique in the future by adopting their 'thinking' as our own.

The above-mentioned comparison of UWB sensing with the human eye (with some analogies also to optical imaging and image processing) should not lead to the conclusion that UWB sensing will compete with optical or infrared sensors. It is, in contrast, far from that. First of all, image creation is only one option of UWB sensors. As mentioned, in the case where images were created, they are usually not comparable with optical images and difficult to interpret. The only reason we referred to the human eye and the sonar of the bat is to allude to achievable performance of sensors which are based on similar physics – that is electromagnetic

13) The wavelengths of the sounding waves generated by a bat are about 5–20 time shorter than in the case of an ordinary UWB sensor. If an UWB sensor would operate within the frequency band from 20 to 100 GHz, it would provide sounding wave of identical wavelength than some bat species. In contrast, the wavelength ratio between light and UWB signals is about 10^5.

or acoustic wave scattering – in order to motivate further research and encourage future developments of UWB sensing. The largest development potentials will be found in the field of scenario adaptive sensor electronics and application-specific data processing and information extraction.

Summarising the previous discussion the applications of UWB sensors are mainly to be seen under the following aspects:

- **Investigation of material parameters or mixture of substances within the microwave range:** Within the considered frequency range (i.e. about 100 MHz–10 GHz), mainly dipole relaxations of less heavy molecules occur. Here, water is a very important candidate for microwave measurements. It is found in food staff, building material and so on and it is one of the most important substances of biological tissue. Therefore, quality control, non-destructive testing in civil engineering (NDTCE) and medical engineering will be corresponding fields of application.
- **High-resolution distance measurements:** This is the classical field of radar applications. But in contrast to the conventional radar and due to the high bandwidth as well as the low-power emission, these sensors are small and lightweight and therefore well suited for industrial, automotive or other civil sensing tasks including home and office applications. UWB sensors are able to separate objects within the centimetre range and they can register target movements down to the micrometre range.
- **Detection and imaging of obscured objects or structures:** Most materials (except metal) provide a reasonable penetration of dm- and cm-waves. Clothes and some plastic foils or layers may be penetrated even by mm-waves. Applications are to be seen in archaeology, geology, non-destructive testing in civil engineering, homeland security, rescue operations, medical engineering, foreign body detection and so forth.
- ***Target recognition and tracking*:** The large bandwidth of the sounding signal leads to a wave interaction which is specific for every target. Therefore, a target leaves a 'fingerprint' in the scattered signal which can be used for recognition if corresponding mapping rules are known. By distributing several UWB sensors over an observation area and combining their data appropriately, the movement of targets (and possibly their behaviour) may be tracked. Ambient assisted living (AAL, i.e. assistance of handicapped people), homeland security, labour protection and localization are some catchwords of possible operational areas.
- ***Autonomous orientation*:** A relatively simple[14)] sensor arrangement is able to provide excellent performance in orientation and classification based on sophisticated sensing strategies and exploiting sounding waves whose wavelengths are spread over nearly one decade. Approaching such performances by technical radar sensors would lead to a much wider variety of applications areas such as remote sensing, robotics, transportation and stock-keeping, sensor networks, homeland security and counter-terrorism.

14) The word 'simple' should be seen here in the sense of the number of involved sensor components – one transmitter and two receivers – but it does not refer to adaptivity and flexibility of the sensing strategy.

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