Jürgen Sachs

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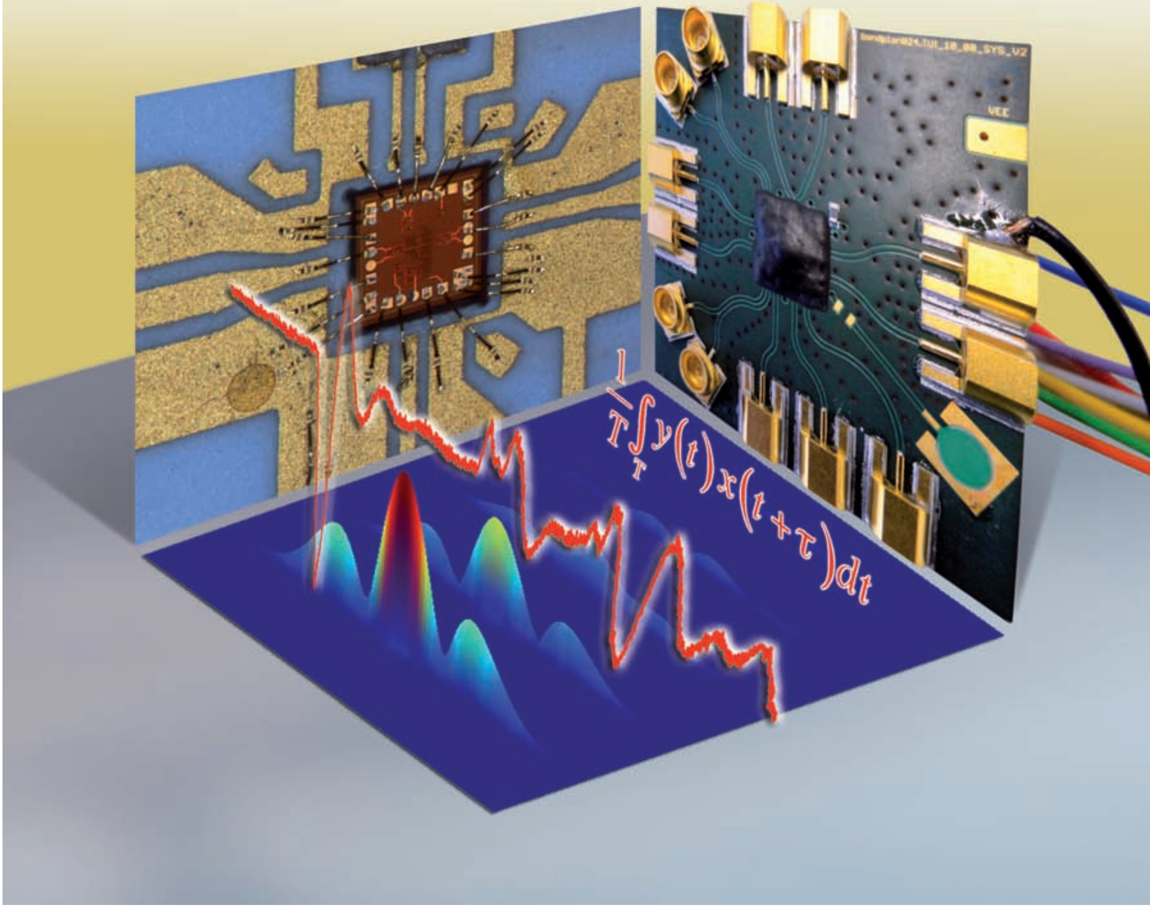
Handbook of Ultra-Wideband Short-Range Sensing

Theory, Sensors, Applications



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Contents

Preface

Ultra-wideband (UWB) sensors exploit the manifold interactions between electromagnetic fields and matter. They aim at gaining information about a target, the environment, a technical process, or a substance by remote, non-destructive, continuous and fast measurement procedures. The applied sounding waves are of low power (typically thousand times less than the radiation of a mobile phone) and their frequencies range within the lower gigahertz domain. This enables acceptable wave penetration into optically opaque objects. Furthermore, the electromagnetic waves are harmless due to their low power and they are non-ionizing. This makes ultra-wideband sensors attractive for many short-range sensing tasks covering industrial, medical, security and rescue issues of detection, recognition, tracking, surveillance, quality control and so on.

Electromagnetic sounding is an inverse and indirect approach to gather information about the objects of interest. Inverse and indirect methods – independent of the underlying physical principles – are always prone to ambiguities with unwanted objects or events. The reduction of such cross-sensitivity needs diversity in data capturing in order to comprise preferably orthogonal interaction phenomena into data interpretation, data fusion and decision. Restricting to the determination of purely electrical properties, some ways to increase the diversity of data capturing consist of (a) measuring over a large frequency band, (b) measuring at many points in space, (c) observing the evolution of the scenario over a long time and (d) respecting the vector nature of the electromagnetic field by including polarimetric data. In addition, the measurement of non-electric properties may further reduce the ambiguities. However, we will exclude non-electric measurements from our discussions here. As is clear from the title of the book itself, it is point (a) that will be in the foreground of our interest, giving an outline of this book without losing however our other important viewpoints.

With a few exceptions, the classical electrical engineering is ‘narrowband’. This has not only historical but also theoretical roots. One, essentially by theory-motivated reason, to deal with narrowband (i.e. ‘gently’ modulated sine wave) signals is the property of a sine wave to keep its time evolution by interacting with a (linear) object. This reduces and simplifies theoretical evaluations to (not necessarily facile) magnitude and phase calculations and accelerates numerical computations. But corresponding considerations presume steady-state conditions which often obscure the intuitive understanding of the occurring processes.

Short pulses count to the class of wideband signals that are of major interest here. They are traditionally used in ultra-wideband technique. Pulse propagation is easy to comprehend. However, such signals are subjected to a modification of their time shape if interacting with an object or propagating in a lossy medium. These time shape variations are our major source of information about the objects of interest, but they are also more demanding with respect to modelling and mathematical treatment.

The propagation of time-extended wideband signals (e.g. random or pseudo-random signals) is intuitively less comprehensive, though the technical implementation of related sensor electronics provides some advantages in favour of pulse systems. In order to retrieve the illustrative understanding of wave propagation, we will trace back such signals to impulse-like time functions which can be handled like real pulses for our scope of application.

The purpose of this book is to give an overview of theoretical, implementation and application aspects of low-power – and hence short-range – ultra-wideband sensing. Intended readers are students, engineers and researches with a background in undergraduate level of mathematics, signal and system theory, electric circuit theory and electromagnetic wave propagation. The introductory part of the book introduces the definition of the UWB term and it gives a short overview of UWB history, the radiation regulations, possible fields of application and the basic approach of information gathering by UWB sensors.

Chapter 2 defines characteristic functions and parameters and summarizes basic concepts of signal and system theory which are important for the understanding of functioning of UWB sensors and their applications. It is mainly targeted at the less experienced reader in this field. Numerous figures are inserted to illustrate the basic relations and, in addition, an annex available at Wiley homepage (http://www.wiley-vch.de, search for ISBN 978-3-527-40853-5) provides a collection of useful mathematical rules, properties of signal transformations, and some basic considerations on signals and elementary signal operations. Furthermore, the reader can also find also some colored figures here and a couple of movies which complement several figures to better illustrate three-dimensional data sets.

Chapter 3 deals with the different concepts of UWB sensing electronics and their key properties. Developments within the last decade educe new and improved sensor principles allowing manufacturing inexpensive, monolithically integrated, lightweight and small microwave devices. They are prerequisites to pave the way for UWB sensing from laboratory to the field.

Chapter 4 discusses some peculiarities of UWB radar whose physical principle is indeed the same as for the 'traditional' radar, but the large fractional bandwidth requires some extensions and specifications of the classical radar theory. They are mainly required by the fact that achievable UWB resolutions may be far better than the geometric size of involved bodies as antennas and targets. The considerations are focused on wideband aspects of wave propagation but they are restricted to a simplified model of scalar waves.

In Chapter 5, the actual vector character of the electromagnetic wave and some of its implications are briefly treated, introducing some basic time domain models of wave propagation.

In the final chapter, some selected aspects of sensor implementation and application are discussed. These topics are contributed by several co-authors who were cooperating with me in numerous UWB projects during the last years.

I take this opportunity to thank all these co-authors and ancient project collaborators, institutions and companies for their fruitful work and pleasant collaboration. These projects and consequently this book could not have been possible without the chance to work on interesting tasks of the ultra-wideband technique at Ilmenau University of Technology and without the encouragement and support of many of the colleagues from research and technical staff as well as the administration. In particular, I would like to thank my colleagues at Electronic Measurement Research Lab for their support, engagement and productive interaction. I also owe a great deal to Stephen Crabbe who promoted and managed our first projects which bred the ultra-wideband M-sequence approach. The support of our research from the German Science Foundation (DFG) through the UKoLoS Program and also from various national and European projects is gratefully acknowledged. I am indebted to Valerie Molière of Wiley-VCH Verlag GmbH for inviting me to write this book and to Nina Stadthaus for her help and patience with any delays and project modifications. Thanks are due to Vibhu Dubey from Thomson Digital for manuscript corrections and typesetting. Last but not least, I am deeply grateful to my wife and my family, who displayed such appreciation, patience, support and love while I was occupied with this book.

Even if the extent of the book largely exceeds the initial intention, the text is by no means complete and all-embracing. In order to limit the number of pages and to complete the work in a reasonable amount of time, some decisions had to make what topics could be appropriate and what subjects could be omitted or reduced in the depth of their consideration. I may only hope that the reader can identify with my decision and that the work of the many researchers in the field of ultra-wideband technique is adequately appreciated. Clearly, the blame for any errors and omissions lies with the author. Let me know if you encounter any.

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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

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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 (ε, μ, σ) 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

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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

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3) In the literature of electrical engineering, a sine or a damped sine are usually expressed by exponential functions $\sin 2\pi f t = \Im\{\mathrm{e}^{j2\pi f t}\}$ and $\mathrm{e}^{\sigma t} \sin 2\pi f t = \Im\{\mathrm{e}^{st}\}$; $s = \sigma + j2\pi f$; $\sigma \le 0$. 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.

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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

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[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 $< 1\,\text{mW}$) 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

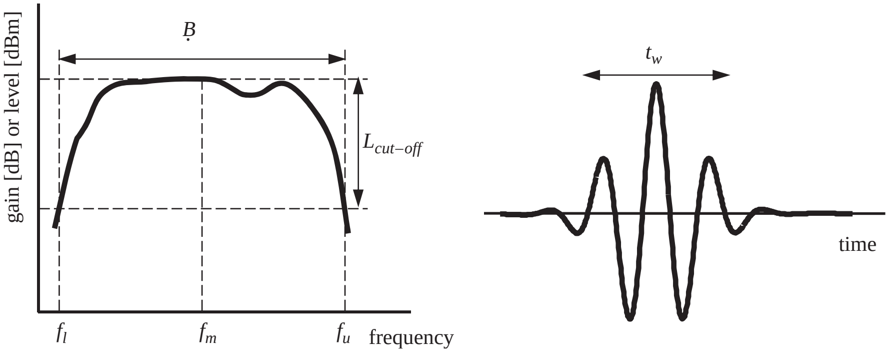

Figure 1.1 Example of power spectrum or transfer function (a) and corresponding time shape or pulse response (b) of a signal or transmission system.

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 $f_\text{m} = \left(f_\text{u} - f_\text{l}\right)/2$. It represents the centre frequency. The absolute bandwidth of the signal and device is given by $\underset{\cdot}{B} = f_\text{u} - f_\text{l}$ 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:

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

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

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

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

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[6] Including‘ultra-wideband’ chemical sensors for various substances.

[7] The usually applied term in this connection is ‘diversity’.