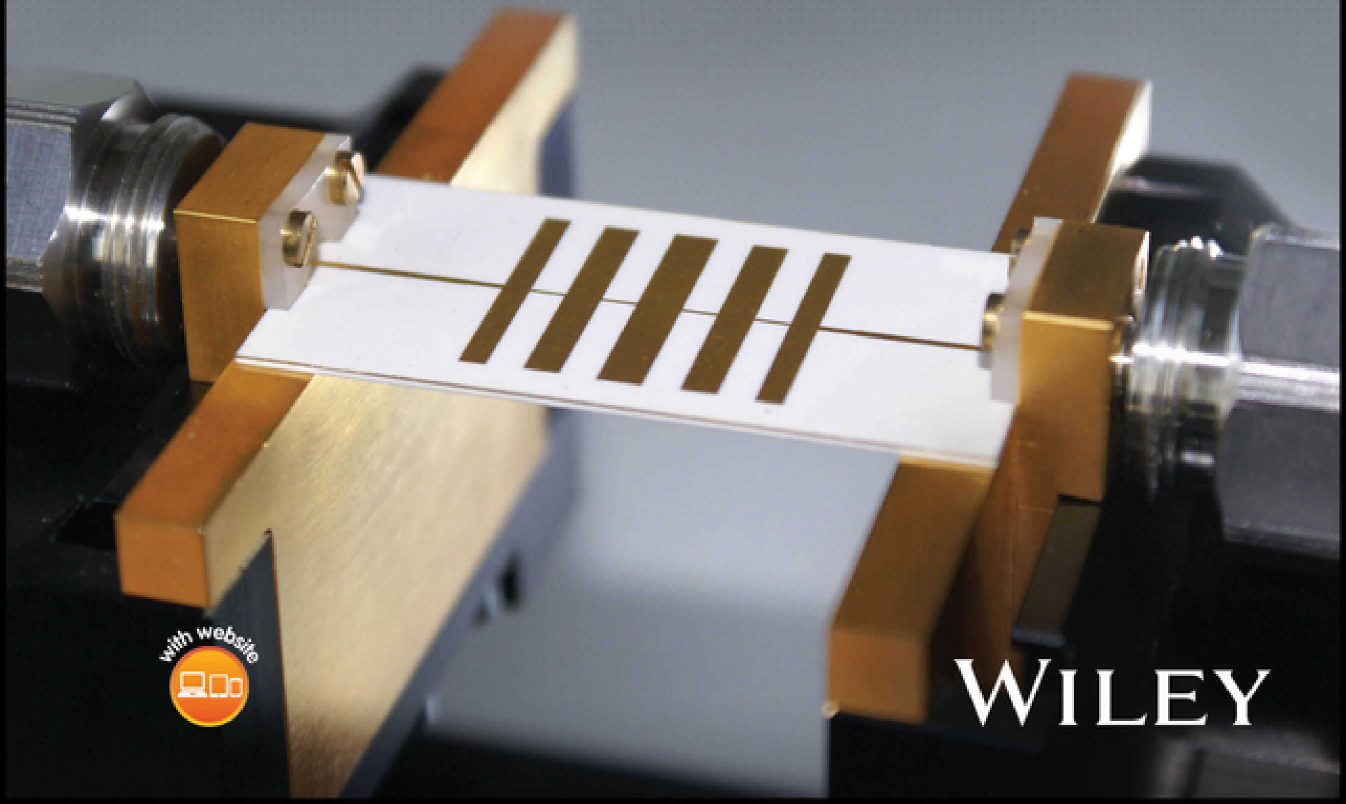
Frank Gustrau

Fourth Edition

RF and Microwave Engineering

Fundamentals of Wireless Communications



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RF AND MICROWAVE ENGINEERING

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FUNDAMENTALS OF WIRELESS COMMUNICATIONS

Fourth Edition

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(Translated from the original German language edition by Frank Gustrau)

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Contents

Preface

This textbook offers students a practical introduction to the field of high-frequency technology and the physical aspects of radio communication. Wireless technologies in the fields of communication (data networks, and mobile telephony), identification (RFID), navigation (GPS), and positioning (radar) are ubiquitous today. In the field of radio applications, comparatively high carrier frequencies have always been used, as this enables good utilization of the electromagnetic spectrum and the construction of efficient antennas. Cost-effective manufacturing processes and the use of computer-aided 3D design tools are constantly opening up new areas of application for radio technology with increasing bandwidths.

In the field of circuit technology, the use of higher data rates in circuits and the associated high-frequency signal components lead to new requirements in circuit design. Transmission lines suddenly require detailed consideration, couplings between neighboring components become more apparent, and there is unwanted radiation of electromagnetic waves. In design, distributed structures have increasing advantages over classic concentrated components. Digital engineers therefore also come into contact with terms like *characteristic line impedance* and *antenna*.

Today, a wide range of radio applications and high data rate communication can also be found in technical products that used to be part of mechanical engineering, such as the automobile. High-frequency technology is therefore – in its fundamentals – no longer a specialized discipline but a basic discipline for all engineers in the fields of electrical engineering, information and communication technology, and the related fields of mechatronics, automotive electronics, and biomedical engineering.

Considering the breadth of the subject of high-frequency technology, a sensible limitation of the material must of course be made for the presentation in this book. The first thing that distinguishes high-frequency technology from classical electrical engineering is the fact that the dimensions of the structures are no longer small in relation to the wavelength. The associated wave propagation processes lead to the typical high-frequency phenomena. The book therefore focuses on wave propagation processes, their description, their consequences, and their utilization in passive circuits and antenna structures.

Active electronic circuits and the entire field of high-frequency electronics, such as the design of amplifiers, mixers, and oscillators, are largely omitted from this book. In order to deal with this subject area in detail, an approach via the basics of electronics and semiconductor components would have to be chosen.

Numerical field simulations have become an integral part of the development process for high-frequency components and antennas. For this reason, numerous examples in this book were calculated with the support of modern high-frequency circuit and field simulators. In detail, the following program packages were used:

- ADS (Advanced Design System) from Keysight Technologies
- CST Studio Suite from CST
- Empire XPU from IMST
- Pathwave electromagnetic (EM) Design (EMPro) from Keysight Technologies

The market for these software products is developing rapidly, so readers are advised to do their own research when choosing a suitable simulator. There are exercises at the end of each chapter. The solutions to the end-of-chapter problems are available on the Wiley Book Companion Site:

www.wiley.com/go/gustrauRF

The warm reception of this textbook by the readership has now made possible a fourth edition with technical extensions. In this edition, for example, the topics of radar backscatter cross-section, slot antenna, horn antenna, and substrate-integrated waveguide have been added and illustrated with additional examples.

The book's concept of combining physical-technical principles with numerical electromagnetic field simulations has proven its worth in courses and enables students to put their learning into practice and reflect critically on it at the same time.

I would like to take this opportunity to thank all my colleagues and students who have contributed to this book with their suggestions, either by asking questions in lectures or by reading individual chapters.

December 10, 2024

Frank Gustrau
Dortmund, Germany

Symbols and Abbreviations

Latin Letters

A	Area (m^2)
A_{dB}	Attenuation (dB)
$\vec{A}$	Magnetic vector potential (Tm)
A_{eff}	Effective antenna area (m^2)
$\mathbf{A}$	ABCD matrix (matrix elements have different units)
$\vec{B}$	Magnetic flux density (magnetic induction) (T; Tesla)
B	Bandwidth (Hz; Hertz)
BW	Bandwidth (angular frequency) (1/s)
c	Velocity of electromagnetic waves (m/s)
c_0	Velocity of electromagnetic waves in free space (m/s)
C	Capacitance (F; Farad)
$C(\varphi, \vartheta)$	Radiation pattern function (dimensionless)
C'	Capacitance per unit length (F/m)
D	Directivity (dimensionless)
$\vec{D}$	Electric flux density ($\mathrm{C/m}^2$)
$\vec{E}$	Electric field strength (V/m)
f	Frequency (Hz)
f_{c}	Cut-off frequency (Hz)
$\vec{F}$	Force (N; Newton)
$\vec{F}_{\mathrm{C}}$	Coulomb force (N)
$\vec{F}_{\mathrm{L}}$	Lorentz force (N)
G	Conductance ($1/\Omega = S$; Siemens)
G	Gain (dimensionless)
G	Green’s function (1/m)
G'	Conductance per unit length (S/m)
$\vec{H}$	Magnetic field strength (A/m)
$\mathbf{H}$	Hybrid matrix (matrix elements have different units)
I	Current (A; Ampere)
$\mathbf{I}$	Identity matrix (dimensionless)
j	Imaginary unit (dimensionless)
$\vec{J}$	Electric current density ($\mathrm{A/m}^2$)
$\vec{J}_S$	Surface current density (A/m)
k	Coupling coefficient (dimensionless)
k	Wave number (1/m)
k_{c}	Cut-off wave number (1/m)

$\vec{k}$	Wave vector (1/m)
ℓ, L	Length (m)
L	Inductance (H; Henry)
L	Path loss (dimensionless)
L'	Inductance per unit length (H/m)
p	Power density $(\mathrm{W/m^3})$
P	Power (W; Watt)
P_{antenna}	Accepted power (W)
P_{inc}	Incoming power (W)
P_{rad}	Radiated power (W)
Q	Charge (C; Coulomb)
Q	Quality factor (dimensionless)
r	Radial coordinate in spherical coordinates (m)
R	Radial coordinate in cylindrical coordinates (m)
R	Resistance (Ω)
R_{DC}	Resistance for steady currents (Ω)
R_{ESR}	Equivalent series resistance (Ω)
R_{RF}	Resistance for radio frequencies (Ω)
R_{rad}	Radiation resistance (Ω)
R'	Resistance per unit length (Ω/m)
s_{kl}	Scattering parameter (dimensionless)
$\mathbf{S}$	Scattering matrix (dimensionless)
$\vec{S}$	Poynting vector $(\mathrm{W/m^2})$
$\vec{S}_{\mathrm{av}}$	Average value of Poynting vector $(\mathrm{W/m^2})$
t	Time (s; Second)
T	Period (s)
$\tan\delta$	Loss tangent (dimensionless)
U	Voltage (V; Volt)
$\vec{v}$	Velocity (m/s)
v_{ph}	Phase velocity (m/s)
v_{gr}	Group velocity (m/s)
V	Volume $(\mathrm{m^3})$
w_{e}	Electric energy density $(\mathrm{J/m^3})$
W_{e}	Electric energy (J; Joule)
w_{m}	Magnetic energy density $(\mathrm{J/m^3})$
W_{m}	Magnetic energy (J)
x, y, z	Cartesian coordinates (m)
Y	Admittance (S; Siemens)
$\mathbf{Y}$	Admittance matrix (S)
Z_{A}	Load impedance (Ω)
Z_{in}	Input impedance (Ω)
Z_{F}	Characteristic wave impedance (intrinsic impedance) (Ω)
Z_{F0}	Characteristic wave impedance of free space (Ω)
Z_0	Characteristic line impedance (Ω) Port reference impedance (Ω)
$Z_{0,\mathrm{cm}}$	Common mode line impedance (Ω)
$Z_{0,\mathrm{diff}}$	Differential mode line impedance (Ω)
$Z_{0\mathrm{e}}$	Even mode line impedance (Ω)
$Z_{0\mathrm{o}}$	Odd mode line impedance (Ω)
$\mathbf{Z}$	Impedance matrix (Ω)

Greek Letters

α	Attenuation coefficient (1/m)
β	Phase constant (1/m)
γ	Propagation constant (1/m)
δ	Skin depth (m)
δ	Decay constant (1/s)
Δ	Laplace operator (1/m^2)
$\varepsilon = \varepsilon_0\varepsilon_\mathrm{r}$	Permittivity (As/(Vm))
ε_0	Permittivity of free space (As/(Vm))
ε_r	Relative permittivity (dimensionless)
$\varepsilon_\mathrm{r,eff}$	Effective relative permittivity (dimensionless)
η	Radiation efficiency (dimensionless)
η_total	Total radiation efficiency (dimensionless)
ϑ	Elevation angle (rad)
ϑ_iB	Brewster angle (rad)
ϑ_ic	Critical angle (rad)
λ	Wavelength (m)
λ_W	Wavelength inside waveguide (m)
$\mu = \mu_0\mu_\mathrm{r}$	Permeability (Vs/(Am))
μ_0	Permeability of free space (Vs/(Am))
μ_r	Relative permeability (dimensionless)
ϱ	Volume charge density (C/m^3)
ϱ_S	Surface charge density (C/m^2)
σ	Electric conductivity (S/m; Siemens/m)
σ	Radar cross-section (m^2)
φ	Phase angle (rad)
φ	Azimuth angle (rad)
φ_0	Initial phase (rad)
ϕ	Scalar electric potential (V)
Ψ_e	Electric flux (As)
Ψ_m	Magnetic flux (Wb, Weber) (Vs)
ω	Angular frequency (1/s)
∇	Nabla operator (1/m)

Abbreviations

5G	Fifth Generation Mobile Communication Standard
ADS	Advanced Design System
Balun	Balanced-to-Unbalanced
BEM	Boundary Element Method
CAD	Computer Aided Design
CW	Continuos Wave (Monofrequent signal)
dB	Decibel
dBi	Decibel (Reference: isotropic radiator)
dBsm	Decibel (Reference: 1 m^2, square meter)
DC	Direct Current
DFT	Discrete Fourier Transform
DIN	Deutsche Industrienorm (German institute for standardization)
DUT	Device Under Test
EIRP	Equivalent Isotropically Radiated Power

EM	ElectroMagnetic
EMC	ElectroMagnetic Compatibility
FDTD	Finite-Difference Time-Domain
FEM	Finite Element Method
FR4	Glass reinforced epoxy laminate
GPS	Global Positioning System
GSM	Global System for Mobile communication
GTD	Geometrical Theory of Diffraction
GUI	Graphical User Interface
HPBW	Half Power Beam Width
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IFA	Inverted-F Antenna
IoT	Internet of Things
ISM	Industrial, Scientific, Medical
ISO	International Organization for Standardization
ITU	International Telecommunication Union
LNA	Low-Noise Amplifier
LOS	Line of Sight
LTCC	Low-Temperature Cofired Ceramics
LTE	Long Term Evolution (Fourth Generation Mobile Communication Standard)
MIMO	Multiple-Input Multiple-Output
MMIC	Monolithic Microwave Integrated Circuits
MoM	Method of Moments
NLOS	Non Line of Sight
PEC	Perfect Electric Conductor
PML	Perfectly Matched Layer
RADAR	Radio Detection and Ranging
RCS	Radar Cross-Section
RF	Radio Frequency
RFID	Radio Frequency Identification
RMS	Root Mean Square
SIW	Substrate-Integrated Waveguide
SMD	Surface Mounted Device
SNR	Signal-to-Noise Ratio
TEM	Transversal Electromagnetic
UMTS	Universal Mobile Telecommunication System
UTD	Uniform Theory of Diffraction
UWB	Ultra-WideBand
VNA	Vector Network Analyzer
VSWR	Voltage Standing Wave Ratio
WLAN	Wireless Local Area Network

Physical Constants

μ_0	$4\pi \cdot 10^{-7}$ Vs/(Am)	Permeability of free space
ε_0	$8.854 \cdot 10^{-12}$ As/(Vm)	Permittivity of free space
c_0	$2.99792458 \cdot 10^{8}$ m/s	Speed of light in vacuum
e	$1.602 \cdot 10^{-19}$ C	Elementary charge
Z_{F0}	$376.730 \ldots \Omega \approx 120\,\pi\,\Omega$	Wave impedance of free space

About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/gustrauRF

The website includes solution manuals.

1

Introduction

1.1 Radiofrequency and Microwave Applications

Today at home or on the move, every one of us uses devices that employ wireless technology to an increasing extent. Figure 1.1a shows a selection of wireless communication, navigation, identification and detection applications.

In the future we will see a growing progression of the trend to apply components and systems of high-frequency technology in new areas of application. Development and maintenance of such systems requires an extensive knowledge of high-frequency behavior of basic elements (e.g. resistors, capacitors, inductors, transmission lines, transistors), components (e.g. antennas), circuits (e.g. filters, amplifiers, mixers) including physical issues such as electromagnetic wave propagation (Figure 1.1b).

Table 1.1 shows a number of standard RF and microwave applications and their associated frequency bands [1–3]. The applications include terrestrial voice and data communication, which means cellular networks and wireless communication networks, as well as terrestrial and satellite-based broadcasting systems. Wireless identification systems (RFID) within *industrial, scientific, and medical* (ISM) bands enjoy increasing popularity among cargo traffic and logistics businesses. As for the field of navigation, GPS should be pointed out, which today is already installed in numerous vehicles and mobile devices. Looking at the automotive sector, radar systems are being used to monitor the surrounding area or serve as sensors for driver assistance systems.

The various application areas are developing rapidly. Let’s take a look at the development of mobile telephony as an example. In the early days of mobile telephony, the focus was on voice communication. Analog terminals were bulky and expensive. With the second generation (2G/GSM), digital technology was introduced to mobile telephony in the 1990s. Terminals became more compact and affordable for the masses. In addition to voice communication, a text service or short message service (SMS) was established. At the turn of the millennium, the third generation (3G/UMTS) saw the development of mobile broadband applications with the possibility of using multimedia content (photo, video, music) and the Internet on the move. Under the influence of the new technical possibilities, the operating concepts of the end devices changed (touchscreen instead of the keyboard) and the equipment of the devices became more complex (e.g. built-in cameras).

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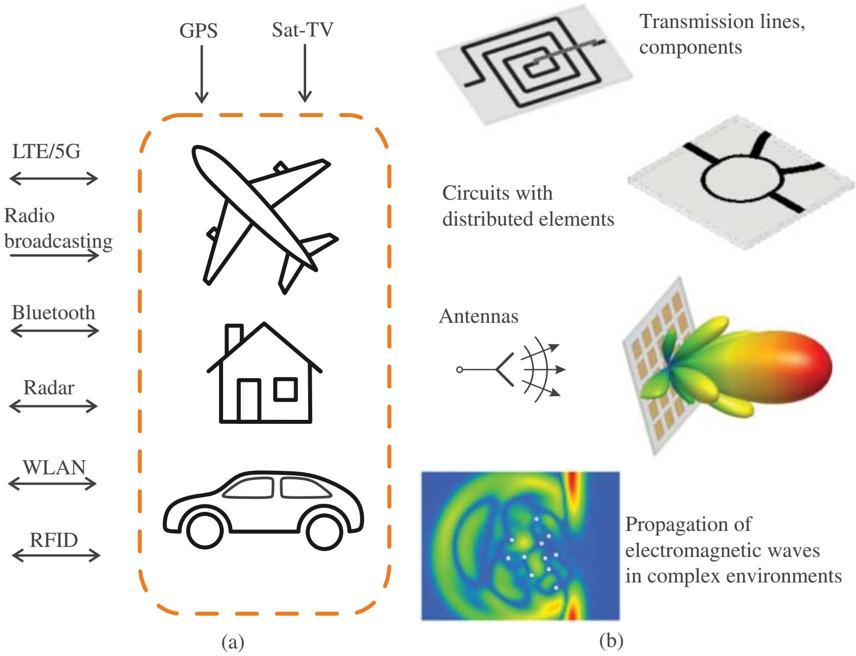

Figure 1.1 (a) Examples of wireless applications and (b) RF components and propagation of electromagnetic waves.

With the fourth-generation mobile communications standard (4G/LTE-Advanced[1]) from around 2010, mobile broadband access was further developed, data rates were increased and capacity (number of simultaneously active subscribers in the network) was increased. Inexpensive devices and tariffs led to mobile broadband access for everyone. In addition to fast mobile broadband access, an expansion of the LTE standard (NB-IoT[2]) also included applications in the area of Industry 4.0 and the Internet of Things. The data rates in this field of application are comparatively low, but the requirements for energy efficiency and reliability are very high.

A fifth-generation mobile communications standard (5G) is currently being established in order to meet increasing requirements and open up further fields of application for mobile communications [4, 5]. A total of three application scenarios are being addressed:

- Improvements in mobile broadband applications (eMBB = enhanced Mobile Broadband): Higher data rates and reduced delay rates for VR[3] and AR[4] applications, among others.
- Communication between a large number of low-cost and energy-efficient devices for industrial applications (mMTC = massive Machine Type Communications).
- Applications with low latency and high reliability for autonomous driving, for example (URLLC = Ultra Reliable Low Latency Communications).

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[1] LTE-Advanced is often simply abbreviated as LTE for reasons of language economy. In any case, this refers to fourth-generation mobile communications or further developments within this generation.

[2] Narrow Band Internet of Things.

[3] Virtual Reality.

[4] Augmented Reality.

Table 1.1 Wireless applications and frequency ranges

Cellular mobile telephony		
GSM	Global System for Mobile Communication (2nd generation mobile communication standard)	900 MHz, 1800 MHz
UMTS	Universal Mobile Telecommunications System (3rd generation mobile communication standard)	2100 MHz
LTE	Long Term Evolution (4th generation mobile communication standard)	800 MHz, 1800 MHz, 2600 MHz
5G	5th generation mobile communication standard ((*) Other frequency ranges planned)	700 MHz, 3400 … 3800 MHz, 28 GHz (*)
Tetra	Trunked radio	450 MHz
Wireless networks		
WLAN	Wireless local area network	2.45 GHz, 5 GHz
Bluetooth	Short range radio	2.45 GHz
Navigation		
GPS	Global Positioning System	1.2 GHz, 1.575 GHz
Identification		
RFID	Radio-Frequency Identification	13.56 MHz, 868 MHz, 2.45 GHz, 5 GHz
Radio broadcasting		
FM	Analog broadcast transmitter network	87.5 … 108 MHz
DAB	Digital Audio Broadcasting	200 MHz
DVB-T2	Digital Video Broadcasting – Terrestrial	470 … 690 MHz
DVB-S	Digital Video Broadcasting – Satellite	10.7 … 12.75 GHz
Radar applications		
SRR	Automotive short range radar	24 GHz
ACC	Adaptive cruise control radar	77 GHz

Significant changes have been made to the radio interface, among other things, in order to meet the requirements of the various application scenarios. All previous standards operated in the frequency range below 3 GHz (Table 1.1). The radio interface of the fifth generation of mobile communications (5G NR = 5G New Radio) distinguishes between the frequency range FR1 (Frequency Range 1) below 6 GHz and the frequency range FR2 (Frequency Range 2) above 24.25 GHz. The low frequencies (e.g. 700 MHz) are suitable for good network coverage in the area and for coverage in critical building areas (e.g. basements). In the 3–4 GHz range, propagation conditions are similar to those of the previous standards. The newly added millimeter wave range (e.g. 28 GHz) allows very high data rates and a very high capacity in small spatial areas. Multi-antenna concepts with beamforming can be realized at high frequencies with the help of very compact antenna systems. Overall, the development in the field of mobile radio is not foreseeable. In this book, we will lay the *physical-technical* foundations for understanding the *high-frequency technical aspects* of the various radio technologies and, for example, discuss antenna technology and wave propagation on lines, in circuits and in complex spatial environments.

However, high-frequency technology does not only play a decisive role in radio technology. Due to the increasing processing speed of digital circuits, high-frequency signal components are emerging, which means that high-frequency engineering design methods are also used for fast digital circuits.

Due to its proximity to electromagnetic field theory, high-frequency technology also extends into the field of electromagnetic compatibility.[5] On the one hand, the measurement setups used here with cables and antennas are based directly on high-frequency principles. On the other hand, non-compliance with specified EMC limits generally requires a detailed analysis of the situation in order to achieve improvements. The inclusion of high-frequency aspects often leads to significant progress.

1.2 Frequency Bands

For better orientation, the electromagnetic spectrum is divided into a number of frequency bands. Various naming conventions have been established in different parts of the world, which often are used in parallel. Table 1.2 shows a customary classification of the frequency range from 3 kHz to 300 GHz into eight frequency decades according to a recommendation of the *International Telecommunications Union* (ITU) [6].

Figure 1.2a shows commonly used designation of different frequency bands according to IEEE standards [7]. The unsystematic use of characters and band ranges, which has developed over the years though can be regarded as a clear disadvantage. A more recent naming convention according

Table 1.2 Frequency denomination according to ITU

Frequency range	Denomination
3 … 30 kHz	VLF – Very Low Frequency
30 … 300 kHz	LF – Low Frequency
300 kHz … 3 MHz	MF – Medium Frequency
3 … 30 MHz	HF – High Frequency
30 … 300 MHz	VHF – Very High Frequency
300 MHz … 3 GHz	UHF – Ultra High Frequency
3 … 30 GHz	SHF – Super High Frequency
30 … 300 GHz	EHF – Extremely High Frequency

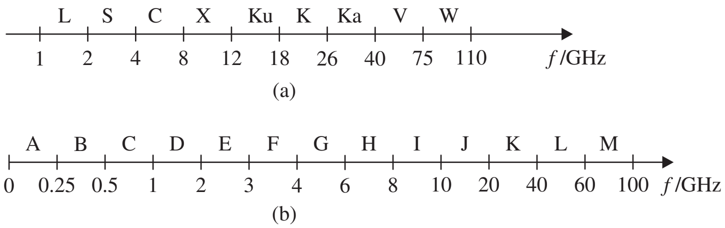

Figure 1.2 Denomination of frequency bands according to different standards: (a) denomination according to IEEE Std. 521-2002 and (b) according to NATO.

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[5] Electromagnetic compatibility (EMC) deals with the avoidance of interfering interactions between technical devices. Devices are tested for compliance with technical limits in standardized measurement setups.