ANTENNAS FOR PORTABLE DEVICES

Zhi Ning Chen
Institute for Infocomm Research
Singapore
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Foreword

The tremendous success enjoyed by the cellular phone industry and advances in radio frequency integrated circuits have in recent years fostered the development of various wireless technologies, including RFID, mobile internet, body-centric communications, and UWB, which are operated at microwave frequencies. For aesthetic reasons, all these systems require small antennas that can be embedded into the mobile units. Furthermore, for minimally invasive microwave thermal therapies, small and thin antennas are much preferred.

Ten years ago, Dr Zhi Ning Chen the editor of this book was a research fellow at the City University of Hong Kong, working on the design of dielectric resonator antennas. Back then, we were already impressed by the creativity he showed in antenna research and by his leadership skills. His achievements in designing many innovative antennas for wireless applications have been outstanding. This edited book represents another significant achievement, bringing together contributions from key players in the topical areas of antenna designs for RFID tags, laptop computers, wearable devices, UWB systems, and microwave thermal therapies. Major issues and design considerations are discussed and explained in the various chapters.

I am sure that this book will be proven to be of considerable value to practising engineers, graduate students, and professors engaging in modern antenna research. I am delighted to extend my hearty congratulations to Dr Chen and all the authors of the chapters of the book.

Kwai-Man Luk
Head and Chair Professor
Department of Electronic Engineering
City University of Hong Kong
Hong Kong SAR, PR China
Acknowledgements

It is, as always, a pleasure to express my appreciation to those people who have helped and encouraged me in some way in the completion of this project. As the editor of this book, I would first of all like to express my heartfelt gratitude to my generous co-authors, my close friends. Without their excellent and professional contributions and collaboration, this book would not have been published on time. They have given generously their time and energy to share their experiences with us.

I would like to thank Sarah Hinton and Olivia Underhill from Wiley for encouraging me to propose this book right after finishing my first book, Broadband Planar Antennas: Design and Applications, published by Wiley in February 2006. Sarah was in charge of that work. I am grateful to Mark Hammond, also from Wiley, for his continuous support while the present work was under way. My grateful thanks are also due to our reviewers, content editor, copy-editor, typesetter as well as cover designers for their helpful and professional comments and work on this book.

As a researcher for the Institute for Infocomm Research, I would like to thank the senior management and my colleagues for their continuous and kind support and understanding. The Institute has provided me with generous facilities for research and development work since I joined in 1999. Most of our work on Chapters 3 and 7 was finished at the Institute.

As a supervisor, I would like to express my gratitude to my ex-students for their contribution to research on ultra-wideband and radio-frequency identification antennas. They are Ning Yang, Xuan Hui Wu, Dong Mei Shan, Terence See, Ailian Cai, Tao Wang, Yan Zhang, and Hui Feng Li.

Finally, I am immensely grateful to my wife, Lin Liu and our twin sons, Shi Feng and Shi Ya, for their understanding and support during the period when I was devoting all my weekends and holidays to preparing, writing, and editing this book. I hope its success, and my promise to spend more time with them in future, will compensate them for all they have lost.

Brian Collins would like to thank his colleagues at Antenova Ltd for their support and helpful suggestions as well as for access to their experimental results. He would also like to thank CST GmbH for providing the simulation results in Chapter 2 illustrating the interaction of fields with the human body.

Duixian Liu and Brian Gaucher would like to thank the IBM Yamato ThinkPad design team for their contributions of range and performance testing as well as the production level models used in testing. Peter Lee, Thomas Studwell and Thomas Hildner of IBM Raleigh had both the foresight and tenacity to understand how important wireless would be before
it happened, and stuck by their convictions, providing the support to further this work. They also thank Frances O’Sullivan, Peter Hortensius, and Jeffrey Clark of IBM Raleigh, Arimasa Naitoh and Sohichi Yokota of IBM Yamato, Japan, and Ellen Yoffa, Modest Oprysko, and Mehmet Soyuer of the IBM Watson Research Center in Yorktown Heights for their leadership and vision on the ThinkPad antenna integration project. Much material was provided by Hitachi Cables of Japan, particularly Mr. Hisashi Tate. Without his patient and prompt support, the chapter would be incomplete. Mr. Shohei Fujio of the IBM Yamato lab in Japan was also kind enough to provide his plots and drawings. Mr. Hideyuki Usui and Mr. Kazuo Masuda of Lenovo Japan (formerly of the IBM Yamato lab) gave generously of their time for laptop wireless discussions as well as providing related information.

Xianming Qing wishes to thank his wife, Xiaoqing Yang, and sons (Qing Ke and Qing Yi) for their understanding and support during the preparation of this book. He would also like to thank Mr Terence See for his helpful comments, which resulted in welcome improvements to Chapter 3.

Koichi Ito and Kazuyuki Saito would like to thank Prof. Yutaka Aoyagi and Mr. Hirotoshi Horita, Tokyo Dental College, Japan, for their contributions to the use of antennas in clinical trials. They would also like to thank Dr Toshio Tsuyuguchi, School of Medicine, Chiba University, Japan, and Prof. Hideaki Takahashi, Brain Research Institute, Niigata University, Japan, for their valuable comments from the clinical side.
List of Contributors

Akram Alomainy  Queen Mary, University of London, United Kingdom
Zhi Ning Chen  Institute for Infocomm Research, Singapore
Brian Collins  Antenova Limited, United Kingdom
Brian P. Gaucher  International Business Machines Corporation, United States of America
Yang Hao  Queen Mary, University of London, United Kingdom
Koichi Ito  Chiba University, Japan
Duixian Liu  International Business Machines Corporation, United States of America
Frank Pasveer  Philips Research, Netherlands
Xianming Qing  Institute for Infocomm Research, Singapore
Kazuyuki Saito  Chiba University, Japan
Terence S.P. See  Institute for Infocomm Research, Singapore
Introduction

Zhi Ning Chen
Institute for Infocom Research, Singapore

Electronic devices are a part of modern life. We are constantly surrounded by the electromagnetic waves emitted from a variety of fixed and mobile wireless devices, such as fixed base stations for audio/video broadcasting, fixed wireless access points, fixed radio frequency identification (RFID) readers, as well as mobile terminals such as mobile phones, wireless access terminals on laptops, sensors worn on the body, RFID tags, and radio frequency/microwave thermal therapy probes in hospitals. Besides the fixed base stations, many wireless devices are expected to be portable for mobile applications. Mobile phones, laptops with wireless connection, wearable sensors, RFID tags, wireless universal serial bus (USB) dongles, and handheld microwave thermal therapy probes have been extensively used for communications, security, healthcare, medical treatment, and entertainment. Users of portable wireless devices always desire such devices to be of small volume, light weight, and low cost.

With the huge progress in very large scale integration (VLSI) technology, this dream has become a reality in the past two decades. For example, the mobile phone has seen a significant volume reduction from 6700 cm$^3$ to 200 cm$^3$ since 1979 [1]. However, with this dramatic reduction in overall size, the antennas used in such portable devices have become one of their biggest components. Therefore, much effort has been devoted to miniaturizing the size of antennas to meet the demand for devices with smaller volume and lighter weight.

In the past two decades, antenna researchers and engineers have achieved considerable reductions in the size of antennas installed in portable devices, although physical constraints have essentially limited such reductions. Today, almost all antennas for portable devices can be embedded in the devices. This creates a transparent usage model for the user, that is, the user never needs to be ware of the presence of the antenna. The appearance of the device is enhanced, and the possibility of accidental breakage is reduced.
Antennas for portable devices may be small in terms of [2]:

1. _electrical size_. The antenna can be physically bounded by a sphere having a radius equal to \( \frac{\lambda_{\text{freespace}}}{2\pi} \). Planar inverted-F antennas with shorting pins or/and slots are typical examples of this category.

2. _physical size_. An antenna which is not electrically small may feature a substantial size reduction in one dimension or plane. Microstrip patch antennas with ultra low profiles belong to this category.

3. _function_. An antenna which is not electrically or physically small in size may possess additional functions without any increase in size. Dielectric resonator antennas operating in multiple modes fit this definition.

Therefore, the miniaturization of antennas for portable devices can be carried out in various ways because basically, the research and development of antenna technology are application-oriented.

With the rapid increase in the number of mobile portable devices, many technologies have been developed to miniaturize the antennas. The technologies can be broadly classified as follows:

1. _The design and optimization of antenna geometric/mechanical structures, in particular, the shape and orientation of the radiators, loading, as well as the feeding network_. This is a conventional approach and most often employed in antenna design. Inverted-F antennas, top-loaded dipole antennas, and slotted planar antennas all fall into this category.

2. _The use of non-conducting material_. Antennas loaded with ferrite or high-permittivity dielectric materials (for instance, ceramics) are examples of this type of technology, as is the dielectric resonant antenna.

3. _The application of special fabrication processes_. The fabrication of printed circuit boards and low-temperature co-fired ceramics have made co-planar and multiple-layer microstrip patch antennas popular. Such technologies are conducive to the mass production of miniaturized antennas at low cost.

This book aims to introduce the advanced progress in miniaturizing antennas for portable mobile devices. The portable mobile devices will include: mobile phone handsets; RFID tags; laptops with embedded wireless local area network (WLAN) access points; medical devices for microwave thermal therapy; sensors installed on or above the human body; and ultra-wideband (UWB) based high-data-rate wireless connectors such as the wireless USB dongle. All of these portable mobile devices are widely used. The antennas used in them have become a bottleneck in the miniaturization of portable devices in terms of performance, size, and cost. The increasing design challenges have made the antenna design for portable devices much more critical than before.

In this book, various challenging design issues will be addressed from a technology and application point of view. Authors from both academia and industry will present the latest concepts, procedures, and solutions for practical antenna designs for portable devices. Several case studies will be provided, together with detailed descriptions of the technologies and systems.
Chapter 2 presents the antennas for the most popular wireless communication devices and handsets, delving into practical issues covering the radio frequency (RF) link budget, small antenna basis, measurement and simulation methods, and specific absorption rate (SAR). Handsets with embedded and external antennas are shown in Figure 1.1.

The term handset here covers almost all mobile devices such as mobile phones, camera phones, personal digital assistants, and any other handheld devices which are able to communicate through wireless networks or from device to device. The large number of antenna designs has been detailed in many references and published books. This chapter is mainly focused on the discussion of antennas operating in the environment of the handset and the influence of handset design on the potential RF performance. Much of the discussion will be of relevance to the industrial designer, the layout engineer, as well as the antenna engineer.

This chapter will treat the topics in the general order of the process by which the antenna designer will evaluate the target specifications from customers, the dimensions and configuration of the handset, and the local environment of the antenna relative to other components. After examining these factors, the antenna engineer will begin the design procedure by choosing potential electrical designs for the antenna by simulation and experiment, testing all the parameters of interest, optimizing the antenna performance before finalizing the design to be embedded into the handset devices.

In Chapter 3 a systematic description of antenna design issues related to the RFID system and tags is provided. The RFID is a technology which transmits data by using a mobile tag. The data will be read by an RFID reader and processed according to the needs of the particular application. The data transmitted by the tag may provide identification, location information, or specifics about the product tagged, such as price, colour, and date of purchase. RFID systems have been widely applied in tracking and access applications since the 1980s. Recently, RFID applications have increasingly captured the attention of academia and industry because of the growth in demand from sectors such as warehousing, libraries, retail, and car parks due to the great reduction in the cost of RFID systems, especially for tags with an antenna and microchip. Figure 1.2 shows RFID tag antennas operating at 13.56, 433, 869, and 915 MHz, developed in the Institute for Infocomm Research, Singapore.

This chapter will briefly introduce RFID systems in order to give readers a basic understanding of RFID operation and the requirements for RFID antennas, particularly tag antennas. Next, the RFID tag antenna design will be addressed. As the frequency used for RFID varies from very low (below 135kHz) to millimetre wave (27.125 GHz), so will the antenna design. For near-field (inductively coupled) RFID systems, the antenna is made
up of a coil with a specified inductance for circuit resonance with an adequate quality factor. For far-field (wave radiation) RFID systems, various types of antennas, such as the dipole antenna, meander line antenna, and patch antenna, can be used. Generally, a tag antenna must have the following characteristics: small size, omnidirectional or hemispherical radiation coverage, good impedance match, typically linear polarization or dual polarization, robustness, and low cost.

This chapter also investigates the environment effect on RFID tag antennas. Tag antennas are always attached to specified objects, such as books, bottles, boxes, or containers. These objects may affect the performance of the tag antenna. The effects on the tag antennas will be severe when it is attached to metal objects or lossy materials. Some results are presented in the last part of this chapter.

Chapter 4 will discuss the integrated antenna design, test, and integration methodology for laptop computers as shown in Figure 1.3. A laptop has a much larger potential surface area for the antenna than a mobile phone. However, unlike the handsets of mobile phones, the laptop enclosure is intentionally designed to prevent electromagnetic emissions and, as a consequence, RF emissions. In addition, laptop users do not expect antenna protrusions as normally found on mobile phones. Two key parameters are proposed and discussed for laptop antenna design and evaluation: standing wave ratio (SWR) and average antenna gain. Though seemingly obvious, a novel averaging technique is developed and applied to yield a measurable, repeatable, and generalized metric.

The chapter covers three major topics. First, it discusses the antenna locations on laptops, particularly on the laptop display. Actual measurements are performed at different locations using an inverted-F antenna. The measurements indicate that the antenna location effects on the radiation patterns and SWR bandwidth. The second topic discusses link budget calculations. These calculations relate the antenna average gain value to wireless communication performance such as data rate or coverage distance. The third topic covers some practical antenna designs used in laptops for Bluetooth™ and WLAN. A PC card version of the wireless system is
also discussed and compared with the integrated version. An integrated wireless system always outperforms the PC card version. This chapter emphasizes practicality by extensive measurements and using actual laptop antennas.

Chapter 5 introduces the antenna design for portable medical devices. This is the only chapter in the book which does not involve wireless communications but microwave-based applications. It exhibits the wide coverage of antenna technology for antenna researchers working on wireless communications as shown in Figure 1.4.

Recently, a variety of microwave-based medical applications have been widely investigated and reported. In particular, minimally invasive microwave thermal therapies using thin antennas are of great interest, among them the interstitial microwave hyperthermia and microwave coagulation therapy for medical treatment of cancer, cardiac catheter ablation for ventricular arrhythmia treatment, and thermal treatment of benign prostatic hypertrophy. The principle of the hyperthermic treatment for cancer is described, and some heating schemes using microwave techniques are explained. Next, a coaxial-slot antenna, which is a type of thin coaxial antenna, and array applicators comprised of several coaxial-slot antennas are also introduced. Moreover, some fundamental characteristics of the coaxial-slot antenna and the array applicators, such as the specific absorption rate, temperature distributions

**Figure 1.3** An antenna embedded into the cover of a laptop computer.

**Figure 1.4** Microwave thermal therapy with coaxial slot antennas.
Introduction

around the antennas inside the human body, and the current distributions on the antenna, are described by employing the finite-difference time domain (FDTD) calculations and the temperature computations inside the biological tissues by solving the bioheat transfer equation. Finally, some results of actual clinical trials using the proposed coaxial-slot antennas are explained from a technical point of view. In addition, other therapeutic applications of the coaxial-slot antennas such as the coagulation therapy for hepatocellular carcinoma, the hyperthermic treatment for brain tumours, and the intracavitary hyperthermia for bile duct carcinoma are introduced.

Chapter 6 briefly introduces the wireless personal area networks (WPAN) and the progression to body area networks (BAN), highlighting the properties and applications of such networks. Figure 1.5 shows the scenario where the antenna is installed on the human body (phantom) in simulation. The main characteristics of body-worn antennas, their design requirements, and theoretical considerations are discussed. The effects of antenna types on radio channels in body-centric networks are demonstrated. In order to give a clearer picture of the practical considerations required in antenna design for body-worn devices deployed in commercial applications, a case study is presented with a detailed analysis of the design and performance enhancement procedures to obtain the optimum antenna system for healthcare sensors.

Communication technologies are heading towards a future with user-specified information easily accessible whenever and wherever required. In order to ensure the smooth transition of information from surrounding networks and shared devices, there is a need for computing and communication equipment to be body-centric. The antenna is an essential part of the wireless body-centric network. Its complexity not only depends on the radio transceiver requirements but also on the propagation characteristics of the surrounding environment. For the long to short wave radio communications, conventional antennas have proven to be more than sufficient to provide the desired performance, minimizing the constraints on the cost and time spent on producing such antennas. On the other hand, for the communication devices today and in the future, the antenna is required to perform more than one task,
or in other words, the antenna will be needed to operate at different frequencies so as to account for the increasing introduction of new technologies and services available to the user. Therefore, careful consideration is required for antennas applied in body-worn devices, which are often hidden, small in size, and light in weight.

In Chapter 7, the final chapter of this book, the UWB, an emerging technology for short-range high-data-rate wireless connections, high-accuracy image radar, and localization systems is introduced. Due to the extremely broad bandwidth and carrier-free features, antenna design is facing many challenges. The conventional design considerations are insufficient to evaluate and guide the design. Therefore, this chapter will begin with a discussion of the special design considerations for UWB antennas. The design considerations reflect the uniqueness of the UWB system requirements for the antennas. In accordance with these considerations, the antennas suitable for portable mobile UWB devices are presented. In particular, this chapter elaborates the design and state of the art of the planar UWB antennas. The latest developed UWB antennas will be reviewed with illustrations as well as simulated and measured data. Finally, a new concept for the design of small UWB antennas with reduced ground plane effect is introduced and applied to practical scenarios. Two versions of the small printed UWB antennas designed for wireless USB dongles installed on laptop computers are investigated in the case studies. Figure 1.6 shows an antenna embedded into a UWB-based wireless USB dongle.

As the design of antennas for portable devices is an area of rapidly growing research and development, this book is expected to provide readers with the fundamental issues and solutions to existing as well as forthcoming applications.

References


Handset Antennas

Brian S. Collins
Antenova Ltd, United Kingdom

2.1 Introduction

The user’s experience of a mobile communications system entirely depends on the performance of the bidirectional radio link between the base station and the handset. Each mobile network operator creates a system of linked base stations located to provide coverage of as large a physical area as possible, providing as much coverage and capacity as is appropriate for the expected traffic demand – or as much as technical considerations will permit. While the base station will typically be equipped with a high-gain antenna and a transmitter capable of delivering some tens of watts of radio frequency (RF) power, the handset relies on an antenna whose dimensions are severely constrained by those of the handset in which it is fitted, with a typical maximum effective radiated power of 1 watt. While the base station antenna is generally mounted in a clear location 10 m or more above ground level, the handset will be in the user’s hand, perhaps held against the head, within 1.5 m of the ground.

Practical considerations of radio link performance result in the need to allow a substantial margin on the link budget, and the shortcomings of the handset form the single largest intrinsically reducible loss in the system. These shortcomings are not very noticeable when the handset is used in a well-served urban environment, but they become critical when the user is in an area of marginal network coverage or inside a building.

The design challenge posed by handset antennas is becoming more critical as networks evolve to offer a wider range of services. We now expect a pocket-sized mobile terminal to be able to deliver telephony (potentially video telephony), high-speed data services, location and navigation services, entertainment . . . and more to come in the future. Not only do some of the new services require higher data rates, but the increasing number of different facilities in the terminal puts great pressure on the available space for antennas. Handset designers expect that multiple antennas can be operated successfully in close proximity to components such as cameras, flash units, loudspeakers, batteries and the other hardware needed to support the growing capabilities of the terminal.
In this chapter the term handset will be used to cover mobile phones, camera phones, personal digital assistants (PDAs), entertainment terminals and any other pocket-size devices which must communicate with the network. To avoid repeated lists of frequencies the band terminology listed in Table 2.1 will be used in this chapter. The complexity of this list itself – which omits some major national assignments – emphasizes the varied demands made on the functionality of handsets.

This chapter deals only in outline with the large numbers of different designs for the antenna itself – these are described in detail in the accompanying references. The main emphasis is on the operation of the antenna in the environment of the handset and the influence of handset design on the potential RF performance that can be obtained. Much of the discussion is of importance to the industrial designer and the engineer laying out the electronic components of the handset, as well as to the antenna engineer.

The order of treatment of the topics follows the general order of the process by which the antenna designer will assess the design task – reviewing the target specification, the dimensions and configuration of the handset and the local environment of the antenna relative to other components. The antenna engineer will choose potential electrical designs for the antenna after first examining these factors.

### Table 2.1 Frequency bands, nomenclatures and uses.

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<td>Radio broadcast</td>
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<tr>
<td>2–30 MHz</td>
<td>HF radio</td>
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<td>Radio broadcast</td>
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<td>174–240 MHz</td>
<td>Band III</td>
<td>T-DMB TV</td>
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<td>450–470 MHz</td>
<td>450 MHz</td>
<td>Phone + data</td>
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<tr>
<td>470–750 MHz</td>
<td>Band IV/V</td>
<td>DVB-H TV</td>
</tr>
<tr>
<td>824–890 MHz</td>
<td>850 MHz</td>
<td>Phone + data</td>
</tr>
<tr>
<td>870 (880)–960 MHz</td>
<td>900 MHz</td>
<td>Phone + data</td>
</tr>
<tr>
<td>824–960 MHz (850 and 900 MHz)</td>
<td>Low bands</td>
<td>Phone + data</td>
</tr>
<tr>
<td>1575 MHz</td>
<td>GPS</td>
<td>Geolocation</td>
</tr>
<tr>
<td>1710–1880 MHz</td>
<td>1800 MHz</td>
<td>Phone + data</td>
</tr>
<tr>
<td>1850–1990 MHz</td>
<td>1900 MHz</td>
<td>Phone + data</td>
</tr>
<tr>
<td>1900–2170 MHz</td>
<td>2100 MHz</td>
<td>Phone + data</td>
</tr>
<tr>
<td>1710–2170 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1800, 1900 and 2100 MHz)</td>
<td>High bands</td>
<td>Phone + data</td>
</tr>
<tr>
<td>2.4–2.485 MHz</td>
<td>2.4 GHz</td>
<td>WLAN</td>
</tr>
<tr>
<td>2.5–2.69 GHz</td>
<td>2.5 GHz</td>
<td>WiMAX™</td>
</tr>
<tr>
<td>3.4–3.6 GHz</td>
<td>3.6 GHz</td>
<td>WiMAX™</td>
</tr>
<tr>
<td>4.9–5.9 GHz</td>
<td>5 GHz</td>
<td>WLAN, WiMAX™</td>
</tr>
</tbody>
</table>

The list above includes most major world-wide assignments, but some other frequency bands are allocated in certain countries. Future bands for UMTS are not included. Following the transfer of broadcast TV services to digital formats, it is expected that a significant amount of the present analog TV bands will be assigned for mobile services.
2.2 Performance Requirements

Before examining antenna design we should define handset performance parameters and examine the way in which these interact with network operation. A subset of these parameters is usually specified in connection with a target handset design.

Gain. The use of the simple term gain when applied to a handset antenna is not explicit and should generally be avoided – see efficiency and mean effective gain below.

Efficiency. The efficiency of a handset antenna is the ratio of the total power radiated by the antenna to the forward power available at its terminals (or those of its associated matching network). Some workers separately define terminal efficiency as indicating the ratio of radiated power to the net power delivered to the antenna (forward power — reflected power), and total efficiency as meaning the definition here adopted, but these terms will not be used in this chapter.

Efficiency may be measured either with the antenna driven from an external signal source (its passive efficiency) or with the antenna driven by the RF output of the phone (its active efficiency). In active measurements it is difficult to determine the forward power, so the better active parameter is a measurement of the total radiated power (TRP) – which is what matters in network performance.

Bandwidth. The bandwidth of an antenna is the frequency range over which some specified set of parameters is maintained. The objective of handset antenna design is that the bandwidth is sufficient to cover the frequency bands over which the handset is intended to operate.

Radiation patterns. It is relatively uncommon for the specification for a handset antenna to include any reference to its radiation patterns, although these are commonly measured during the development of the antenna. The reason for this lack of specification is partly that the designer has only limited ability to control the patterns, but also that the handset will be operated in contact with the hand (and sometimes the head) of the user, so any measurement of the patterns is of limited significance. Radiation patterns are usually measured in the three principal planes of the physical handset.

Polarization. The radiation from a handset is regarded as having randomly-oriented elliptical polarization. Measurements of radiated power are usually made separately for linear orthogonally polarized signal components. This means that the full 3D radiation characteristics of the handset are characterized by six separate patterns (three cuts and two polarization components). For most purposes the energy contained in orthogonal linear polarizations is added vectorially – as, for example, in efficiency or TRP measurements.

Mean effective gain (MEG). This is calculated by averaging the measured gain at sufficient points on a (typically spherical) surface around the handset. If the antenna were lossless, then the mean gain would be 0 dBi, so the MEG is effectively the same as \(10 \log_{10} \eta\), where \(\eta\) is the efficiency.

Total radiated power. This is the total power flowing from the handset when it is transmitting. To measure this the handset is controlled by a base station simulator and the outgoing power (summed in orthogonal polarizations) sampled at points over a closed surface surrounding the handset.

Total isotropic sensitivity (TIS). The sensitivity is defined as being the input signal power which gives rise to a specific frame error rate or residual bit error rate. The sensitivity
is sampled in orthogonal polarizations at points spread over a surface surrounding the handset.

The TIS and TRP together determine the effectiveness of the handset as a piece of radio equipment, in particular the maximum range at which the handset can operate from a base station with some given level of performance. It is essential that the TIS and TRP are properly related to one another. The link budgets for the up- and down-links (to and from the base station) are based on specific assumptions about handset performance assuming that efficiency is maintained across the whole of both the transmit and receive frequency bands.

**Input return loss and voltage standing wave ratio (VSWR).** Input matching can be described either by return loss or VSWR, the two terms being easily converted:

- \[ VSWR = \frac{1 + \rho_v}{1 + \rho_v}, \] where \( \rho_v \) is the modulus of the voltage reflection coefficient – the ratio of the reflected wave to the forward wave expressed in volts.
- \[ \text{Return loss} = 20 \log_{10} \rho_v. \] (The \( - \) sign should be omitted, as it is unnecessary and leads to confusion in such phrases as ‘a return loss greater than \(-8\) dB’.)

In this chapter the less specific terms match/matching can be taken as referring to either.

- The **power reflection coefficient** = \( \rho_p^2 \) so the power delivered to the load is \( (1-\rho_p^2) \) and the corresponding **reflection loss** = \( 10 \log_{10}(1-\rho_p^2) \).

The input match of a handset antenna is one of its most important parameters. As we shall see, the small size of the handset and its antenna create fundamental problems in obtaining a low-input VSWR over the required frequency bands. The main effect of high VSWR is to cause input reflection loss which reduces the efficiency of the handset; in general, the efficiency target takes precedence over VSWR which is not regarded as the primary parameter. It is of essential interest to the antenna designer, but it is efficiency which determines network operation.

**Passive test.** In a passive test a small coaxial cable or microstrip line is connected between the antenna and an input connector, allowing the designer to measure the VSWR, radiation patterns and efficiency of the antenna mounted in place on the handset (or perhaps for initial evaluation on a representative dummy of the handset). Passive testing is used during initial design while the antenna configuration is optimized and an input matching circuit is devised.

**Active test.** In an active test, no external connection is made to the handset. A base station simulator is used to set up a call to a complete operating handset in an anechoic chamber and measurements are made to establish the TRP and TIS. These parameters determine the performance that will be experienced by a user in network service. If users experience poor call quality they will usually complain about poor network coverage; to avoid this, many network operators establish standards of TRP/TIS performance which must be met by handsets before they are permitted to be used on their network. Standard test methods are described in [1].

Sometimes a handset that appears to perform well in passive tests is shown to be substandard in active tests. There are several factors which contribute to the differences between active and passive measurements:
• In a TRP measurement the output of the power amplifier (PA) is fed through internal connecting transmission lines and a switch or diplexer. These may be mismatched or may be more lossy than expected.
• In a passive measurement the antenna is fed from a well-matched 50-ohm source. In an active TRP measurement the power delivered by the PA will depend on the complex impedance presented to it by the transmission line connecting it to the switch/diplexer and antenna. The load-line characteristic of the PA will determine how much power it will deliver into this impedance, which is likely to change very significantly over each operating band.
• In a TIS measurement the sensitivity of the receiver is reduced by any noise sources within the handset because the noise may mask low-level signals. Displays and cameras, and their associated feed circuits, often generate noise, especially in the low bands.

Active measurements are important because they represent the behavior of the handset in use; passive measurements are simpler to understand. The difference between them is a very important diagnostic tool for rectifying unexpected problems.

Free-space, in-hand and head-position measurements. During the antenna development process the measurements described above are typically made with the handset in an isolated test fixture made from low-density polystyrene foam. In operation the handset may be held away from the head (for example, when texting or accessing Web-based services) or against the head as in normal phone operation. To simulate these scenarios a handset is tested in conjunction with physical models of lossy hands and heads – known as phantoms. There are often major differences between performance in the presence of the phantom and in a free-space environment.

The effects of head and hand are sometimes referred to as detuning, but this term is not really very helpful; whether the resonant frequency of the antenna changes or not, power is deposited in the phantom. The input match may actually improve when the handset is placed against it, but this simply confirms that less power is being reflected from the antenna. Specifying detuning by reference to the change of the frequency of optimum antenna match is not helpful; it neither indicates the fall in efficiency in the presence of the phantom, nor the frequency of optimum efficiency. It is more helpful to refer to the change in efficiency when the handset is held, averaged across the relevant frequency bands.

Specific absorption rate (SAR). A handset placed alongside the user’s body will deposit energy in the tissue penetrated by electromagnetic fields. To study possible effects on body tissues we must examine the rate at which energy is deposited in a given volume of tissue. This is the specific absorption rate, whose units are watts per kilogram of tissue. To control the possibility of high local peaks, the maximum permitted SAR is specified as applying to any 1 g or 10 g of tissue.

It is important to distinguish between limits for exposure to electromagnetic fields and maximum permitted SAR levels. Limits for exposure to fields are quoted in terms of the power (in watts per square metre) carried by a plane wave (or by specifying maximum electric or magnetic fields). SAR limits are more complex and relate to the power absorbed by the user’s body.

There is no single world-wide standard limit for SAR, and some current standards are shown in Table 2.2 [2–11].

In use, the handset is positioned so that its near field penetrates the user’s body. The body is not electrically homogeneous – bone, brain, skin, and other tissues have different
densities, dielectric constants, dielectric loss factors and complex shapes. This is a situation which has to be simplified to provide handset designers with engineering guidelines with which they can work, so for regulatory purposes a standard physical phantom head is used in which the internal organs are represented by a homogeneous fluid with defined electrical properties. With a handset positioned beside the phantom and with its transmitter switched on, the fields are probed inside the phantom. They are translated into SAR values and the pattern of energy deposition is mapped to determine the regions with the highest SAR averaged over 1 g and 10 g samples. Simulations are often carried out using this ‘standard head’, but more realistic information is obtained using high-resolution computer models based on anatomical data.

Extensive investigation of possible health effects of RF energy absorbed from mobile phones has been carried out in many countries. Current results suggest that any effects are very small, at least over the time period for which mobile handsets have been in widespread use. Those interested should consult the websites of the major national occupational health administrations and medical journals. The responsibility of the antenna designer is to ensure that the user is exposed to the lowest values of SAR consistent with the transmission of a radio signal with the power demanded by the network.

**Hearing aid compatibility.** Handsets operating with time-division multiplex protocols such as GSM emit short pulses of radio energy. A hearing aid contains a small-signal audio amplifier and if this is presented with a high-level pulsed radio signal the result of any non-linearity in the amplifier will be the generation of an unpleasant buzzing sound. Some administrations place networks under a responsibility to provide some proportion of their handsets which are designed to minimize these interactions.

### 2.3 Electrically Small Antennas

The dimensions of handset antennas are very small compared with the operating wavelength, particularly in the low bands. Not only is the antenna small, but the length of the handset to which it is attached – typically between 80 and 100 mm – is also only a fraction of a wavelength long. A typical handset antenna is less than 4 ml in volume (about one thousandth of a cubic wavelength) and a 90 mm chassis is only 0.27λ long at 915 MHz.

The operation of electrically small antennas is dictated by fundamental relationships which relate their minimum $Q$-factor to the volume of the smallest sphere in which they can be enclosed, often referred to as the Chu-Harrington limit [12, 13]. The $Q$ relates stored energy...