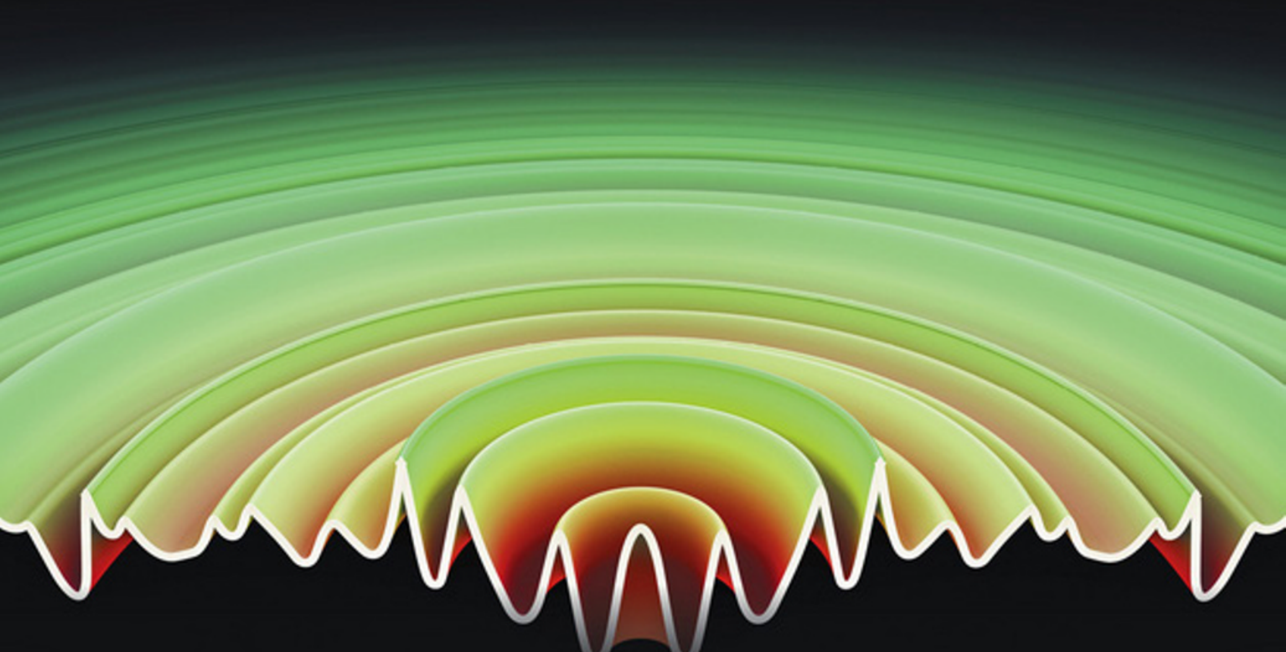
ANTENNA DESIGN FOR MOBILE DEVICES

SECOND EDITION



ZHIJUN ZHANG

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Second Edition

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To my wife Sheng Li

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About the Author

Dr. Zhijun Zhang is currently a professor at the State Key Lab of Microwave and Communications, the Department of Electronic Engineering at Tsinghua University, China. He received his BS and MS from the University of Electronic Science and Technology of China, in 1992 and 1995, respectively, and his PhD from Tsinghua University, China, in 1999. From 1999, he was a Post-doctoral Fellow with the Department of Electrical Engineering, University of Utah, where he was appointed as a Research Assistant Professor in 2001. In May 2002, he became an Assistant Researcher with the University of Hawaii at Manoa, Honolulu. In November 2002, he joined Amphenol T&M Antennas, Vernon Hills, IL, as a Senior Staff Antenna Development Engineer and was then promoted to the position of Antenna Engineer Manager. In 2004, he joined Nokia Inc., San Diego, CA, as a Senior Antenna Design Engineer. In 2006, he joined Apple Inc., Cupertino, CA, as a Senior Antenna Design Engineer and was then promoted to the position of Principal Antenna Engineer. Since August 2007, Dr. Zhang has been with Tsinghua University. He has published over 100 peer-reviewed journal papers, and has also been awarded 9 US patents and 40+ Chinese patents.

Dr. Zhang is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE). He has served as the Associate Editor of the *IEEE Transactions on Antennas and Propagation* (2010–2014) and *IEEE Antennas and Wireless Propagation Letters* (2009–2015).

Preface

I started my career as an antenna engineer in the mobile phone industry during the early 2000s. Despite over 10 years of researching electromagnetic topics, I felt that I lacked a lot of important aspects of a good antenna engineer, and there was no book available to provide all the necessary information. It took me several years to collect bits and pieces by learning from different sources. Since then, I have worked on both sides of the antenna business, as a vendor when I was with Amphenol Inc.; and then as a client when I was with Nokia Inc. and Apple Inc. My job also changed back and forth between antenna engineer and engineering manager. The experience gave me an opportunity to view antenna design from various angles.

This book presents most of the issues that directly concern mobile antenna design, what I have learned and many ideas I accumulated during the years. I hope the book can help students who want to pursue a career as an antenna engineer in the wireless communication industry. Another goal of the book is to provide a shortcut for electronic engineers who do not know a lot about antennas but want to design some simple antennas without the hassle of learning from various sources. For antenna engineers already working in the field, the challenge facing them is how to squeeze an antenna into a smaller enclosure and still meet all the bandwidth, multiband, and efficiency specifications. The book provides various advanced antenna design techniques, which should be useful to most intermediate antenna engineers.

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Acknowledgments

It is a great pleasure to have a chance to thank the three most important people in my academic life. I would like to thank Professor Zhengde Wu, who was my supervisor when I studied at the University of Electronic Science and Technology of China as a master's student. Professor Wu equipped me with the most essential engineering skills which have benefited me ever since. I would also like to thank Professor Zhenghe Feng and Professor Magdy F. Iskander. Professor Feng was my advisor when I studied for my PhD degree at Tsinghua University. Professor Iskander was my supervisor when I worked as a postdoctoral graduate at the University of Utah. Both of them are my lifetime mentors. With their care and encouragement, I successfully made a mid-life career change, from an engineer to a professor. Since I joined Tsinghua University, I have cooperated successfully with Professor Feng and Professor Iskander, and I cannot thank them enough for all their help and guidance during this period, and hope to enjoy a continuous fruitful collaboration with them.

To the companies and individuals who provided illustrations and the copyright permissions for the illustrations, I am most appreciative. I am especially grateful to Yaobin (Richard) Gu and Xiaodong (Amanda) Jiang from Shanghai *Amphenol* Airwave Inc., who provided most of the photos and drawings of the production antennas in the book. I would also like to express my gratitude to the staff at John Wiley & Sons, especially James Murphy, Renee Lee, and Shelley Chow.

In the second edition of the book, some practical designs of real phones are included. I would like to thank Xiaohui Pi and Dr. Wendong Liu from Xiaomi Inc. for providing phone samples. I would also like to thank Lizhong Li from Shanghai *Amphenol* Airwave Inc. for providing semifinished antenna parts specially prepared for the book.

Abbreviations

3GPP	Third-Generation Partnership Project
AMPS	Advanced Mobile Phone Service
BT	Bluetooth
CDMA	Code division multiple access
CTIA	Cellular Telephone Industries Association
DCS	Digital Cellular Service
DS-MID	Double-shot molded interconnect device
EIRP	Effective isotropic radiated power
EIS	Effective isotropic sensitivity
EMC	Electromagnetic compatibility
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FER	Frame error rate
GPS	Global Positioning System
GSM	Global System for Mobile communication
HAC	Hearing aid compatibility
ICs	Integrated circuits
ID	Industrial design
IFA	Inverted-F antenna
LDS	Laser direct structuring
LTCC	Low-temperature co-fired ceramic
MIMO	Multiple input and multiple output
NHPIS	Near-horizon partial isotropic sensitivity
NHPRP	Near-horizon partial radiated power
OTA	Over the air
PCB	Printed circuit board
PCS	Personal Communications Service
PIFA	Planar inverted-F antenna
PTT	Push to talk

RAM	Radiation absorbent material
RL	Return loss
SAR	Specific absorption rate
SNA	Scalar network analyzer
SRF	Self-resonance frequency
TEM	Transverse electromagnetic
TIS	Total isotropic sensitivity
TRP	Total radiate power
UMTS	Universal Mobile Telecommunications System
UWB	Ultrawide band
VNA	Vector network analyzer
VSWR	Voltage standing wave ratio
Wi-Fi	Wireless fidelity
WLAN	Wireless local area network

1

Introduction

The twenty-first century is the wireless century. In the near future, it is very likely that most electronic devices will include some wireless functionality. If we look at the job market, known brands which seem to have nothing to do with antennas, such as Microsoft, Google, Amazon, and so on, are all recruiting engineers with antenna knowledge. On the other hand, there are not that many antenna engineers out there. The root cause of the shortage of antenna engineers can be traced all the way back to the university. The cornerstone of antenna engineering is *electromagnetics* (EMs), which is a quite abstract class and involves a lot of mathematics. The world unveiled by EMs is a four-dimensional one, which includes three spatial dimensions and one temporal dimension. To most students, the many new concepts introduced in the class are counterintuitive and confusing. As a logical consequence of natural selection, the EM major is removed by most students from their list of favorites.

People like to think of antennas as a black box of magic. The explanations given by antenna engineers are always so vague that it seems they never give people a definitive answer. It is easy to come to the conclusion that even designing a simple antenna requires years of experience. The truth is that if there was an appropriate book which presented all the required information, most electronic engineers who have studied some EM theory in university could design antennas. You do not need any mathematics to design an antenna. What you need is an understanding of how an antenna works. Of course, if you want to be an exceptional antenna engineer and design antennas with extreme constraints, a solid knowledge of EM theory and years of experience are still necessary.

This book provides a comprehensive discussion of the state-of-the-art technologies of antenna design for mobile communications. The book covers all the important aspects an engineer might need when designing an antenna, which includes how to make a fixture, how to design various antennas, how to optimize match circuits, and carry out different measurements.

Antenna Design for Mobile Devices, Second Edition. Zhijun Zhang.

It is recommended that the book is read in its entirety. However, for engineers who only want to design a single-band antenna in the shortest time possible, Section 1.6 will provide enough knowledge to kick-start a simple antenna project.

The book has six chapters, and the chapters are arranged as follows:

Chapter 1 provides an overview of most antenna design technologies used in mobile devices. Before anyone starts to design an antenna, it is very helpful for him or her to understand the following: (1) What can be done? (2) What kind of freedom do we have? Both topics will be briefly discussed here. Based on readers' feedback from the book's first edition, a practical example is added in Section 1.6. The section can also serve as a gamebook which can divert readers to different sections if they want to explore more.

Chapter 2 describes different matching techniques used in antenna design. In real-world engineering, antenna matching circuits are widely used, probably in at least half of all devices. The popularity of the matching network is due to two reasons: (1) it gives the engineer more freedom, one more parameter to play with when making design trade-offs; and (2) the value change of a matching component is quite a quick process, which can be a last-minute change. On the other hand, an antenna modification needs at least several days of lead time. The chapter discusses single-band matching, multiband matching, and advanced matching techniques. Complementary software written by the author will be provided to provide practice matching techniques (see the web address on the back cover).

Chapter 3 introduces different external antennas, including both stubby and whip–stubby antennas. The external antenna dominated the cell phone antenna design. The market share of external antennas has been consistently decreasing in the past decade, but it is still a very important antenna configuration. Many basic techniques used in external antennas, such as multimode single-radiator multiband antennas and multi-radiator multiband antennas, are also used in internal antennas.

Chapter 4 introduces different internal antennas. The internal antenna is the current fashion. Under the internal antenna category, there are several different concepts, such as folded monopole, inverted-F antenna/planar inverted-F antenna (IFA/PIFA), loop, and ceramic antenna. All of these will be discussed in the chapter.

Chapter 5 introduces important issues related to engineering antenna measurement. Besides the passive antenna measurement, which is familiar to most electronic engineers, active measurement will also be discussed. Some details, which are key to accurate measurement, such as how to make fixtures and use a choke, will all be covered in the chapter. Various antenna measurements in the production line are also covered in the chapter.

Chapter 6 is about the various regulations which are important to antenna engineers. These can be split into three topics: (1) specific absorption rate (SAR), which is about the radiation to the head and body; (2) hearing aid compatibility (HAC), which is about electromagnetic compatibility (EMC) with hearing aids; and (3) EMC, which is about the EMC with other devices.

1.1 The Evolution of Mobile Antennas

There is some argument about who invented the first mobile communication system, because for some people mobile communication also means vehicle communication. However, when referring to the first commercial handheld cellular phone, the answer is Motorola DynaTAC 8000X [1], without any doubt, which was introduced in 1983, as shown in Figure 1.1.

Figure 1.1 Sleeve dipole antenna on a Motorola DynaTAC 8000X (1983). (*Source*: Reproduced with permission of Motorola.)

The antenna installed on a DynaTAC 8000X is a sleeve dipole antenna [2], which now is an obsolete design in the mobile phone industry but still widely adopted by various wireless LAN access points, such as the one shown in Figure 1.2. Sleeve dipole antenna is the best performing antenna ever installed on any cellular phone; however, this is also the largest cellular phone antenna. The length of a sleeve dipole is about half the wavelength at its working frequency. At 850 MHz, the antenna itself needs a length of 176 mm. At the dawn of the personal mobile communication era, those dimensions look quite reasonable when compared to a vintage cellular phone. For instance, the dimensions of a DynaTAC 8000X are 330 mm × 44 mm × 89 mm, without the antenna.

With the significant improvement in cellular technology and the aggressive shrinkage of the size of phones, soon the size of a sleeve dipole was no longer proportional to the phone. Unlike dipole antennas, a monopole antenna [3] on a ground plane has only a length of a quarter of a wavelength, which is 88 mm at 850 MHz. Shown in Figure 1.3 is a Motorola MicroTAC 9800X sitting on a charger. The phone is a flip phone and has a microphone located inside the flip. The thin wire on the top of the phone is a monopole whip antenna.

A sleeve dipole, such as the one shown in Figure 1.1, has an integrated choke which retains most radiation current within the antenna; thus, the antenna is insulated from the phone and also from a user's hand on the phone. However, a monopole antenna must use the metal inside a phone as part of the antenna's radiating structure. Some portion of radiating current must

Figure 1.2 Sleeve dipole antennas on a wireless LAN access point. Linksys WAP55AG. (*Source*: Cisco, Inc.)

Figure 1.3 Whip antenna on a Motorola MicroTAC 9800X (1989). (*Source*: Reproduced with permission of Motorola.)

flow over the phone. Putting one's hand on the phone absorbs some energy, and thus decreases the overall antenna performance. Although the performance of a whip monopole antenna is inferior to a sleeve dipole, it is still better than all other members of the family of cellular phone antennas. The whip antenna is the second largest one in the family.

In fact, the antenna used on the MicroTAC 9800X is a retractable antenna. A retractable antenna is a combination of a whip antenna and a helix stubby antenna. When the antenna is extended, it functions as a whip monopole and provides good performance. When the antenna is retracted, it functions as a stubby antenna and still has acceptable performance. The retractable antenna has the best of both worlds, as it is a low-profile solution and is still capable of providing good performance when needed.

Obviously, the mechanical structure of a retractable antenna is quite complex, as it involves moving parts and multiple radiators. A stubby antenna, as shown in Figure 1.4, eliminates the whip in a retractable antenna. From the performance point of view, a stubby antenna is not as good as a retractable one. However, stubby antennas dominated the cellular phone market at the end of the past century. The reason for the wide adoption of stubby antennas is the significant improvement in cellular networks. As the number of mobile phone users exploded, the density of base stations also increased dramatically. That means the distance from any user to the nearest base station is much shorter than previously. As the path loss between a cellular phone and a base station tower is directly proportional to the distance between them, a shorter distance means less strain on the antenna's performance. Inside a stubby antenna, the metal radiator can be a helix made of a metal wire, a meander line made of flexible printed circuit board (PCB), or a sheet metal stamping part.

Figure 1.4 Nokia, Inc. Stubby antenna on a Nokia 5110 (1998). (*Source*: Reproduced with permission of Nokia.)

Figure 1.5 Nokia, Inc. Internal antenna on a Nokia 3210 (1999). (*Source*: Reproduced with permission of Nokia.)

The next antenna to enter the market was the internal antenna. The phone shown in Figure 1.5 is not the first phone to adopt an internal antenna; however, it is one of the most successful phones with an internal antenna. Nokia sold approximately 160 million Nokia 3210 during the phone's whole life span. When tested in free space or next to a phantom head, an internal antenna can achieve performance similar to a stubby antenna. In everyday use, internal antennas are more vulnerable to hand blockage by the user. It is quite a natural gesture for a user to put his or her fingers on top of the antenna and bring the speaker closer to his or her ear.

From the mechanical point of view, the internal antenna is better than the external antenna, as it eliminates the through hole and mating features necessary to accommodate an external antenna. A phone with an internal antenna normally has better performance in drop tests, wearing tests, and various other mechanical tests. Because an internal antenna is totally concealed in the phone, the phone user has little chance to abuse it. Some people have the habit of playing with the item in their hand when they are sitting in meetings or are idle in front of their desks. I have seen some colleagues unconsciously extend and retract their antenna's whip hundred of times in a single meeting.

All traditional internal antennas are located on the upper part of a phone. In a normal talking position, the distance between the top internal antenna and the user's head is quite small. To eliminate the influence of a user's head on the antenna's performance and also decrease the harmful radiation emitted toward the head, a ground layer must be placed beneath the antenna to increase isolation between the user's head and the antenna. However, the ground layer decreases an antenna's bandwidth. To compensate, the antenna size must be increased. The Motorola Razr V3 was the first phone to adopt a bottom internal antenna. It was a brave act. According to the conventional wisdom of that time, an antenna in the bottom would be held in the center of a user's palm; a bottom antenna might have good performance in the lab but could not provide acceptable performance in real use. That conventional wisdom was proved wrong by the Motorola V3. The Motorola V3 has become another legend in cellular phone history. It sold more than 110 million. By relocating the antenna to the bottom, the antenna is away from the head. The ground layer, which is required by top internal antennas, can be eliminated. Furthermore, the antenna's thickness and volume can both be significantly decreased, as shown in Figure 1.6. The Motorola V3 was the slimmest phone when it was released. Since then, many slim phones have adopted bottom internal antennas, and most big players in the cellular phone market have their own versions of bottom antenna phones. The new wisdom is that whenever you need to design a slim phone, it is better to put the antenna on the bottom.

Shown in Figure 1.7 is the first-generation iPhone, which was released in 2007 by Apple Inc. iPhone is the first phone equipped with a capacitive touch screen. Unlike its predecessor's resistive touch screen, capacitive touch screen does not require a stylus and can be controlled directly by fingers. The detecting layer of capacitive touch screen, which is usually made of a transparent conductor such as indium tin oxide, is embedded under a piece of glass. This configuration gives capacitive touch screen a sleek feeling and almost infinite life span. Companies with the iOS software, iPhone became a disruptive force in the phone market.

Figure 1.6 Bottom internal monopole antenna on a Motorola Razr V3 (2004). (*Source*: Reproduced with permission of Motorola.)

Figure 1.7 First-generation iPhone (2007). (*Source*: Apple, Inc.)

Since the appearance of the first-generation iPhone, the whole phone industry starts to converge. All companies which insist on including a keypad on their phones didn't end well. In 2015, front portraits of most phones look like they are taken from identical twins. If only looking from the front, one might find it is quite difficult to separate a sub-100 US dollar functional phone from a 600+ US dollar flagship phone. Shown in Figure 1.8 is an iPhone 6s plus. A big screen takes out most of the area of the front surface. Two slices of blank areas, one on the top and one on the bottom, occupy the rest of the area.

The current trends of mobile phone designs are making the screen larger and pushing the device thinner. When the original iPhone came out, it was considered a large-screen phone and also the thinnest. It has a 3.5-inch screen and measured 11.6 mm thick. After 8 years, a 4.5-inch screen is considered small. The iPhone 6 plus has a 5.5-inch screen and its thickness is only 7.1 mm. Some companies, such as Huawei, have even released 6- and 7-inch models. The boundary between phone and tablet device has been blurred.

All these trends have considerable impacts on the antenna designing and manufacturing techniques. As the big screen is actually a liquid crystal display (LCD), which is one of the main noise sources, a piece of metal shielding is always applied on LCD's back. This shielding and the phone's slim form factor make it almost impossible to design antennas in the middle portion of a phone. Thus, pretty much every phone puts its battery and main circuit board in the middle and squeezes all antennas into blank areas on top and bottom of a phone, as illustrated in Figure 1.8.

Figure 1.8 Top and bottom antenna arrangement on an iPhone 6s plus (2015). (*Source*: Apple, Inc.)

Due to the concern of radiation to human brain, most companies put their main antenna, which is responsible for transmitting second-generation (2G), third-generation (3G), or fourth-generation (4G) signals, on the bottom of the phone. The only exception the author is aware of is iPhone. Before iPhone 4s, similar to others, iPhone only had one bottom main antenna. Then there was the infamous "Antennagate." The performance of an iPhone 4 antenna could be significantly degraded by tightly holding the phone's bottom portion, which is nicknamed as "death grip." The solution Apple came out with is dual main antennas, one on the top and one on the bottom. Since iPhone 4s, all iPhones have two main antennas. It can dynamically switch between these two antennas based on usage. If it detects a head next to phone, it switches to the bottom antenna. If someone is holding the phone at the bottom and the signal strength is too weak, it will switch to the top antenna. As Apple is holding several patents [4, 5] on this switching scheme, it will be difficult for other companies to follow suit.

Thousands of models of cell phones have hit the streets since 1983. It is almost impossible to list them all. To get more comprehensive information, the Internet is a good resource. Some posts [6] show chronicles of cellular phones. Some websites [7] are dedicated to the phones' news. For more detailed information about certain phones, which are sold in the United States, go to the Federal Communications Commission (FCC) website [8].

1.2 How to Quantitatively Evaluate an Antenna

After designing an antenna, we cannot say whether it is good or bad by simply looking at it. We must find a way to quantitatively evaluate it. In cellular antenna's designs, the frequently used parameters are the reflection coefficient, the voltage standing wave ratio (VSWR), efficiency, gain, and bandwidth. The contents of this section are only a brief review of the frequently used parameters. More comprehensive materials and detailed deductions can be found in some classical textbooks [3, 9–12].

From the circuit point of view, an antenna is a single-port device. A transmission line can be used to feed the antenna, as shown in Figure 1.9. An input signal takes the form of an incident wave traveling along the transmission line. It flows from the signal source toward the antenna, assuming that the amplitude of the incident wave is V_{incident}. At the antenna port, some of the energy carried by the incident wave is radiated by the antenna. In the meantime, the residual energy is reflected at the port and travels back along the transmission line. The amplitude of the reflected wave is $V_{\text{reflected}}$.

The reflection coefficient is given by

$$\Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}} \tag{1.1}$$

Clearly, all the reflected energy will be wasted. When designing an antenna, our goal is to minimize the reflection at the antenna port. A perfectly matched antenna can radiate all energy, thus its reflection coefficient is 0. When a device reflects all the energy back, its reflection coefficient is 1.

In microwave theory, the *S*-parameter matrix is used to quantitatively describe a multiport network. The *S* stands for scattering. A one-port network is a special type of multiport networks; its S-matrix degenerates to a single element, S_{11}. For an antenna, the definition of S_{11} is identical to the reflection coefficient.

$$S_{11} = \Gamma \tag{1.2}$$

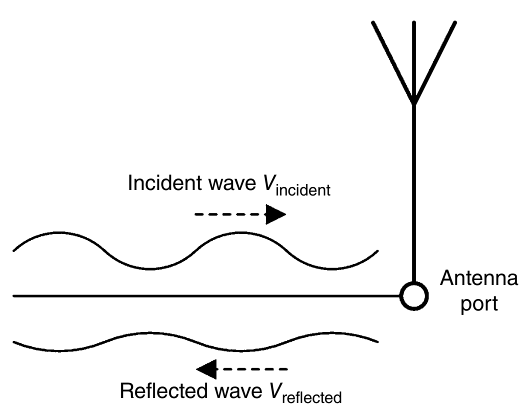

Figure 1.9 Reflection coefficient.

In engineering, the S_{11} is often used in the decibel (dB) scale.

$$S_{11}(\text{dB}) = 20\log_{10}\left(\left|S_{11}\right|\right) \tag{1.3}$$

The S_{11} is defined by the ratio of the voltages of incident and reflected wave, while the S_{11} (dB) is defined by the incident and reflected power. That is the reason why the coefficient in Equation 1.3 is 20. As the $|S_{11}|$ of any antenna is a value less than 1, the S_{11} (dB) is always a negative value. The absolute value of S_{11} (dB) is called the "return loss" (RL):

$$\text{RL} = \left|S_{11}(\text{dB})\right| \tag{1.4}$$

Although the definitions of Γ, S_{11}, S_{11} (dB), and the RL are somehow different, they are all deduced from the incident wave and the reflected wave. The other commonly used parameter, VSWR, is directly defined by the standing wave formed by the superposition of the incident and reflected waves.

$$\text{VSWR} = \frac{\left|V_{\text{max}}\right|}{\left|V_{\text{min}}\right|} \tag{1.5}$$

The VSWR is the ratio of the amplitude of a partial standing wave at an antinode (maximum voltage) to the amplitude at an adjacent node (minimum voltage) in an electrical transmission line. Although the VSWR's physical meaning might seem less straightforward than Γ, the VSWR is the only parameter that could be easily measured when the microwave and antenna technology was still in its infancy. Today, the VSWR is still widely used, especially in the antenna business. The correct format of VSWR is X : 1, such as 2 : 1, 3 : 1, and so on. A VSWR 2 : 1 means the maximum voltage is twice as much as the minimum voltage.

As the V_{max} and V_{min} are formed when the incident and reflected waves are constructively and destructively superimposed, respectively, Equation 1.5 can be rewritten as follows:

$$\text{VSWR} = \frac{\left|V_{\text{incident}}\right| + \left|V_{\text{reflected}}\right|}{\left|V_{\text{incident}}\right| - \left|V_{\text{reflected}}\right|} = \left(1 + \frac{\left|V_{\text{reflected}}\right|}{\left|V_{\text{incident}}\right|}\right) \Big/ \left(1 - \frac{\left|V_{\text{reflected}}\right|}{\left|V_{\text{incident}}\right|}\right) = \frac{1+\left|\Gamma\right|}{1-\left|\Gamma\right|} \tag{1.6}$$

The relation between VSWR and Γ, or the RL, is a one-to-one correspondence. The RL of 10 dB is a commonly used specification for antennas. The corresponding VSWR is approximately 2 : 1.

Bandwidth is another important parameter used to describe antennas. Whenever we give an antenna's bandwidth, we must give the criteria that define the bandwidth. As shown in Figure 1.10, the antenna has a −10 dB bandwidth of 70 MHz. However, you can also claim that the antenna's bandwidth is 132 MHz, if one uses −6 dB as the criteria. Different companies might use different criteria to measure their antennas; it is our responsibility to pay a little more attention to the details.

A well-matched antenna does not necessarily mean it is a good antenna. Efficiency is the parameter which tells us how well an antenna can radiate. The efficiency is given by

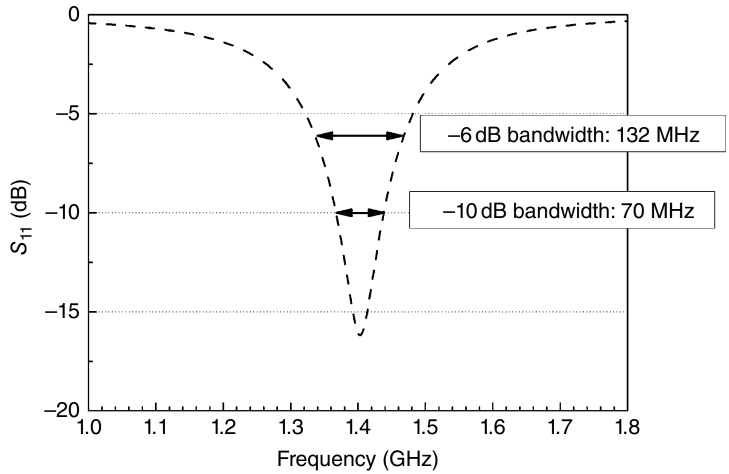

Figure 1.10 Defining an antenna's bandwidth.

$$\text{Efficiency} = \frac{P_{\text{radiated}}}{P_{\text{total available}}} \tag{1.7}$$

where the P_{radiated} is all the power radiated and the $P_{\text{total available}}$ is the total available power from the signal source. Efficiency is a value between 0 and 1. In the antenna business, the efficiency in dB is also commonly used.

$$\text{Efficiency}(\text{dB}) = 10\log_{10}(\text{efficiency}) \tag{1.8}$$

A dB efficiency of −3 dB means 0.5 or 50% efficiency in the linear scale, which is still a pretty good value for real antennas.

In the cellular antenna's world, the gain is not an important parameter, because it is mostly decided by the position in which an antenna is installed and the size of the grounding structure. The antenna element itself does not have too much to do with deciding the gain. The commonly used units for gain measurements are dBi, dBd, and dBic. These are normalized to isotropic linear polarized antenna, dipole antenna, and isotropic circular polarized antenna, respectively. More information about gain can be found in Chapter 5.

1.3 The Limits of Antenna Designs

As antenna engineers, we are under consistent pressure to shrink the size of the antennas and still provide better performance. There is an elegant art to communicating with team members and managers from other disciplines when explaining that a limit in antenna design does exist. For each kind of antenna, there is a boundary, which regulates an antenna's size and its performance. As a new engineer, the easiest way to get a feeling for that boundary is by measuring various phones designed by different companies. Also a much quicker way to learn new design techniques is by reverse engineering using existing antennas on the market.

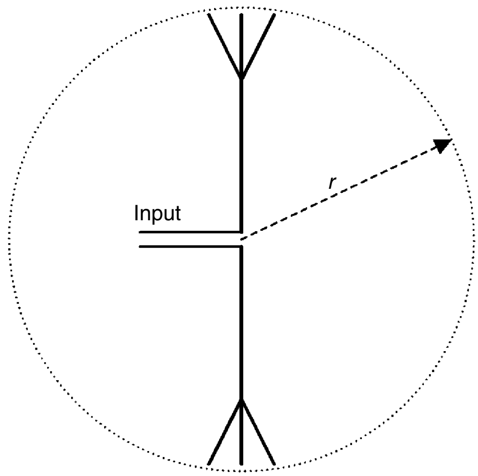

Figure 1.11 The minimal sphere encloses an antenna.

In 1948, L. J. Chu published a paper [13] which quantified the relationship between the lower boundary for the radiation quality Q of an electrically small antenna and its physical size relative to the wavelength. This lower boundary is now known as the "Chu" limit. Shown in Figure 1.11 is a schematic diagram of a vertically polarized omnidirectional antenna. The sphere with radius r is the minimum one which can enclose the antenna. The lower boundary for the radiation Q is decided by r/λ. The boundary given by Chu is based on a simplified model and is considered as the strictest one. Several boundaries based on more realistic scenarios [14–18] have been proposed since then. However, Chu's limit is still the one that is most referred to.

Bandwidth can be derived from Q by assuming that the antenna is a resonant circuit with fixed values. The normalized bandwidth between the half-power frequencies is [14]

$$\text{Bandwidth} = \frac{f_{\text{upper}} - f_{\text{lower}}}{f_{\text{center}}} = \frac{1}{Q} \tag{1.9}$$

Equation 1.9 is a good approximation when $Q \gg 1$. Otherwise, the representation is no longer accurate. Shown in Figure 1.12 is a figure presented in reference [14]. The x-axis is $\text{kr} = 2\pi\left(r/\lambda\right)$. The y-axis represents the quality. Different curves are single mode Q for various antenna efficiencies.

With a fixed efficiency value, say, 100%, when the sphere's radius increases, the radiation Q decreases, which also means that the maximum achievable bandwidth increases. Of course, the bandwidth predicted by the curve can never be achieved in an actual implementation. Various studies [19–22] have been done to approach the limit.

Another thing that can be observed in Figure 1.12 is that a lossy antenna, which has lower efficiency, always has a wider bandwidth. In the real world when the bandwidth of an antenna is abnormally wide, this is not good news, because most of the time it is due to unwanted loss.

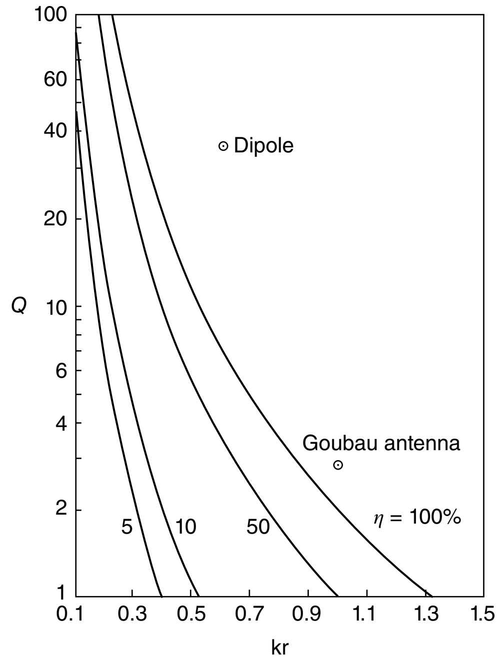

Figure 1.12 Chu–Harrington fundamental limitations for single-mode antenna versus efficiency. (*Source*: Hansen [14]. Reproduced with permission of IEEE.)

As antenna engineers, we do not really evaluate the achievable bandwidth based on figures and formulas given in references. It is very difficult to define the minimum sphere to enclose the antenna in a cellular phone. It will be demonstrated later that all metal structures, including the ground, in a phone can give off radiation. If we define a sphere that encloses the whole phone, the bandwidth calculated by the Chu limit can be so wide that it is meaningless. From time to time, there are claims that the Chu limit has been surpassed. In most cases, the sphere used in calculations only encloses the antenna element itself. As the ground is also part of the radiator, by excluding the ground from the sphere, the achievable bandwidth is artificially narrowed, and that is why those antennas have wider bandwidth than the theoretical limit.

When designing a cellular antenna, many factors, such as the nearby battery, the speaker under the antenna, the metal bezel on the phone, and so on, all play a role in determining the achievable bandwidth. With the accumulation of experience, eventually one can estimate the achievable bandwidth more accurately.

1.4 The Trade-Offs in Antenna Designs

To be a good antenna engineer not only means designing an antenna with the best performance, but it also means having a profound understanding of the possible trade-offs in antenna designs. Among them, some trade-offs are the same ones which are applicable in all engineering disciplines, such as the trade-offs between the design time and performance. Designing