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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.

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 \times 44 mm \times 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 11.6mm 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

$$\Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}} \quad (1.1)$$

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.

$$S_{11} = \Gamma \quad (1.2)$$

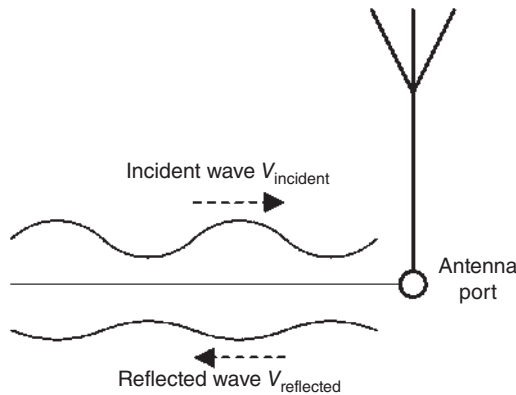


Figure 1.9 Reflection coefficient.

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

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

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):

$$\text{RL} = |S_{11} \text{ (dB)}| \quad (1.4)$$

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.

$$\text{VSWR} = \frac{|V_{\max}|}{|V_{\min}|} \quad (1.5)$$

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:

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

The relation between VSWR and Γ , or the RL, is a one-to-one correspondence. The RL of 10dB 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

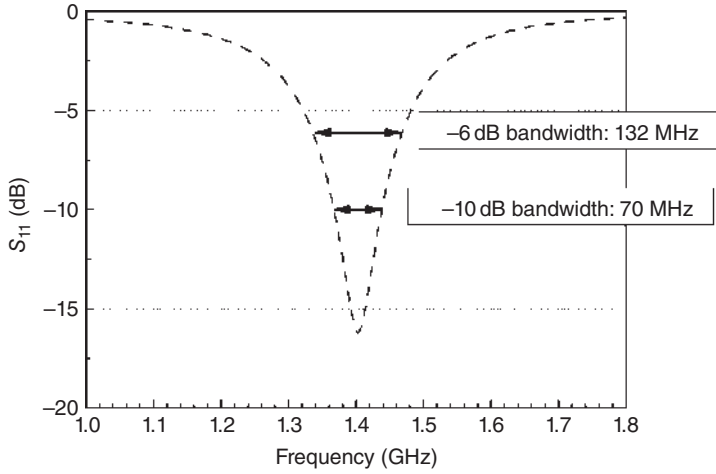


Figure 1.10 Defining an antenna's bandwidth.

$$\text{Efficiency} = \frac{P_{\text{radiated}}}{P_{\text{total available}}} \quad (1.7)$$

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.

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

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.

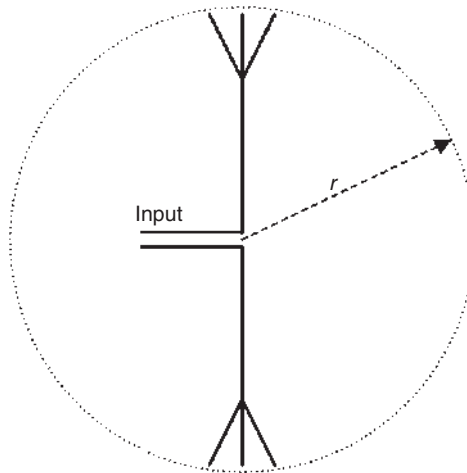


Figure 1.11 The minimal sphere encloses an antenna.

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]

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

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 $kr = 2\pi(r/\lambda)$. 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.

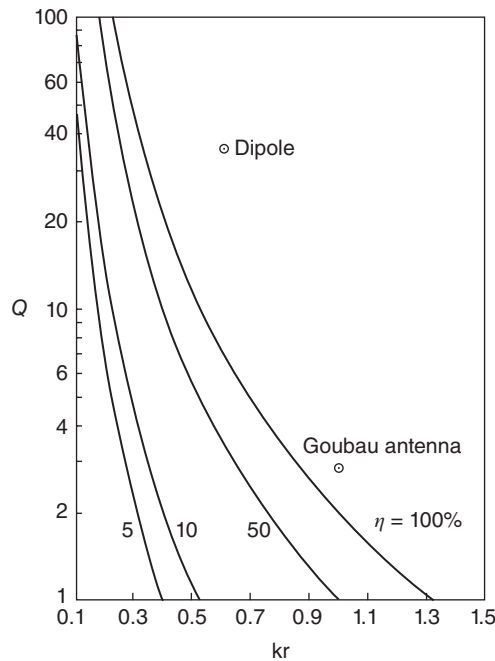


Figure 1.12 Chu–Harrington fundamental limitations for single-mode antenna versus efficiency. (Source: Hansen [14]. Reproduced with permission of IEEE.)

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

an antenna is a project with a time constraint instead of an open-ended art creation. The thought of designing a perfect antenna might do more harm than good. In addition to those commonsense trade-offs, there are some that are particular to antennas:

- **Bandwidth trade-off.** In Section 1.3, the bandwidth limit of a single-band antenna was discussed. Most phone antennas used today are multiband antennas. A similar limit also applies to their combined bandwidth. If an antenna is well designed, whenever the bandwidth of one band increases, the bandwidth of the other bands must shrink. To fully understand the design technique of one kind of antenna, we need to find out how to trade-off bandwidth between different bands. For example, if the specification for an antenna is 50% efficiency across all bands, and the efficiency of the antenna designed is 60% at the lower band and 40% at the high band, your work hasn't finished yet. The unbalanced performance tells everybody that you have not really mastered the design skills of this antenna.
- **Trade-off between complexity and performance.** By introducing more freedom into an antenna's design, it is possible to achieve better performance. However, the marginal improvement of each incremental variable is regressive. As a new antenna engineer, try to avoid using complex designs in the beginning. It is quite easy to be drowned by a large amount of variables. One should start from simple designs and assess the impact of each design variable. For many applications, an antenna with a handful of variables is good enough.
- **Trade-off between manufacture consistency, tooling time, and cost.** Better manufacturing consistency means less antenna variation and better antenna performance. However, better consistency also means longer tooling time and higher cost. There is no manufacturing solution that can provide all the benefits; otherwise, it would already have been part of the antenna's manufacturing process. Many different manufacturing processes are available; one should understand the advantages and the disadvantages of each of them. Taking the processing of internal antenna as an example, there is metal-stamping, flex circuit, double-shot molded interconnect device (DS-MID), laser direct structuring (LDS), and so on. The metal-stamping technology is the cheapest and can be adjusted quite quickly if the parameter that needs to be adjusted is known and already included in the tooling design. The flex circuit technologies have better consistency than the metal-stamping; however, it is a little more expensive and it takes a longer time to implement a design change. Both DS-MID and LDS technology have the best consistency, because antennas are part of the plastic structure instead of separate parts. Both of them are based on a technique called "selective metallization." The DS-MID process begins with the application of a shot of plateable thermoplastic resin in an injection mold cavity. Next, the cavity is changed and a second shot of nonplateable thermoplastic resin is molded around the first shot to create a circuit pattern from the plateable material. Depending on the antenna shape, the two resins can be reversed in shot order. After two shots, a part has its intended geometry with select plateable surfaces exposed. These surfaces are then plated with a layer of copper. The DS-MID takes the longest lead time, because any modification to the antenna pattern requires tooling changes. The LDS is a relatively new process. The thermoplastic resin used in LDS process is nonplateable after the molding process and can be transformed to plateable by using a laser beam to activate it. The LDS process literally draws the antenna pattern onto the plastic. The pattern can be adjusted quite easily by uploading a new pattern file to the laser. Similar to the DS-MID, a plating process is required to deposit copper onto the part's surface.

- Trade-off between total radiated power and radiation exposure. Higher total radiated power and lower radiation to the human body are a pair of contradictory requirements. Ideally, we should first design an antenna to have an on-phantom efficiency as high as possible, then choose an appropriate conductive power level to meet the human exposure specification. In reality, there are three constraints: the conductive power, the total radiated power, and the human exposure. An antenna with very good efficiency might give you trouble later on. In the whole design process, one should always keep these three specifications in mind and check their status constantly.

1.5 Mobile Communication and Band Allocations

The radio frequency (RF) EM spectrum is an aspect of the physical world which, like land, water, and air, is subject to usage limitations. The use of RF bands in the EM spectrum is regulated by governments in most countries, in a spectrum management process known as frequency allocation or spectrum allocation [23]. Although countries are working on a universal frequency allocation plan, the existing frequency allocations are still country dependent. In the United States, the spectrum from 0Hz to 1000GHz was allocated by the Federal Communications Commission (FCC) [24]. The US Department of Commerce has a color chart of frequency allocation, which covers 3 kHz to 300GHz [25]. In most countries, the spectrum allocation plan is not a static one and is being continuously revised.

Most bands used in the design of mobile phones are given in Figure 1.13. However, this is not a complete list.

There are some ambiguities when referring to bands and their respective technology. Only the band names are given in Figure 1.13. Depending on the different countries, the exact frequency range of each band might vary slightly.

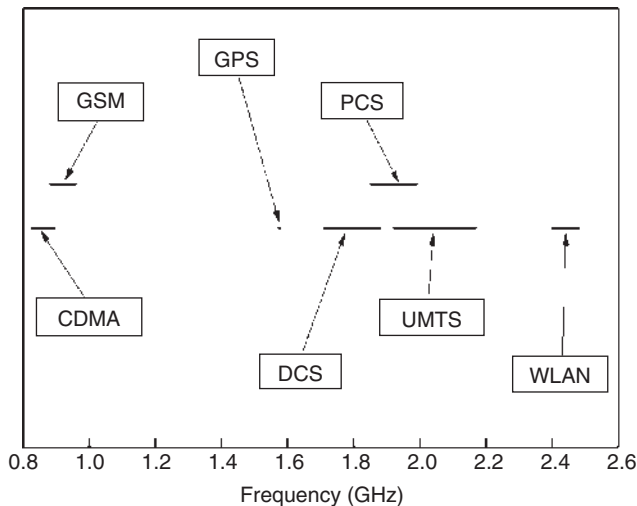


Figure 1.13 Band allocation.

- CDMA band: also known as AMPS band or 850MHz band, 824–894MHz
- GSM band: also known as 900MHz band, 880–960MHz
- GPS band: 1575MHz
- DCS band: also known as 1800MHz band, 1710–1880MHz
- PCS band: also known as 1900MHz band, 1850–1990MHz
- UMTS band: also known as 3G band or 2100MHz band, 1920–2170MHz
- LTE band: also known as 4G band, 700–800MHz and 1710–2700MHz
- WLAN band: also known as Bluetooth band or 2.4GHz band, 2400–2480MHz

Strictly speaking, using those abbreviations to name bands is not appropriate. Some of them are based on specific technologies. The following are brief introductions; more comprehensive information can be found on their respective websites and in other books [26].

- AMPS is the abbreviation for Advanced Mobile Phone Service. It is an analog standard used by the first cellular communication network. Motorola DynaTAC 8000X is based on AMPS technology. It is obsolete in most countries. The United States was one of the last to shut down AMPS services. The final date of use was February 18, 2008.
- CDMA is the abbreviation for code division multiple access [27]. In the cellular business, this means the IS-95 standard or the cdmaOne standard. The technology itself is band independent. In the United States, CDMA systems are deployed in both 850 and 1900MHz bands.
- GSM is the abbreviation for Global System for Mobile Communications [28]. Both GSM and CDMA are 2G cellular communication standards. In the global market, GSM is the most influential standard. About 80% of the global mobile market used this standard in 2009 [28]. The GSM technology itself is also band independent. GSM systems are deployed in different bands, such as 850, 900, 1800, and 1900MHz.
- GPS is the abbreviation for Global Positioning System [29]. GPS is a receiver-only technology. It can extract positioning and timing information from signals transmitted by GPS satellites. It is not a mandatory feature for a phone. However, it gradually has become a standard functionality for most middle- to high-tier phones.
- DCS is the abbreviation for Digital Cellular Service. It is the name of the 1800MHz band.
- PCS is the abbreviation for Personal Communications Service. It is the name of the 1900MHz band.
- UMTS is the abbreviation for Universal Mobile Telecommunications System [30]. UMTS is one of the 3G mobile telecommunications technologies. The most common form of UMTS is W-CDMA. The Chinese version 3G system, TD-SCDMA, also belongs to the UMTS family. The main competitor of UMTS is CDMA2000, which is another 3G standard. As most countries allocate the 2100MHz band to 3G systems, UMTS is used as the 2100MHz band's alternative name. In fact, UMTS has been deployed in different bands, such as 850 and 900MHz bands.
- LTE is the abbreviation for Long-Term Evolution, commonly marketed as the 4G LTE [31]. LTE has allocated around 40 operating bands and many of them overlap with previous 2G and 3G bands. The allocated bands cover 700, 750, 800, 850, 900, 1800, 1900, 2100, 2300, 2500, 2600, and so on. Similar to what had happened to the 3G standard, most of the country adopts the LTE-FDD standard and China backs TD-LTE standard. However, two smaller carriers in China, which have a combined market share of 35% in 2014, adopted LTE-FDD. LTE bands are omitted in Figure 1.13.

- WLAN is the abbreviation for wireless local area network. WLAN actually involves several standards, such as 802.11b, 802.11g, 802.11a, and so on. WLAN is also known as Wi-Fi [32], which is the acronym for wireless fidelity. From the antenna point of view, the 802.11b/g uses the 2.4GHz band and the 802.11a uses the 5GHz band, which is omitted in Figure 1.13.
- Bluetooth [33] is a standard different from WLAN. It is an open wireless protocol for exchanging data over short distances. However, Bluetooth shares the same 2.4GHz frequency band with WLAN.

Besides the aforementioned bands, some other technologies, such as FM radio, analog TV, and digital TV, are also used in cellular phones. Their band allocations are omitted in Figure 1.13. Another point worth mentioning is that most technologies and band allocations used in Japan are different from the rest of the world. As the Japanese market is the most difficult one to penetrate, related information of that market is also omitted.

In this chapter, only the basic terminologies are introduced. For more in-depth information about different cellular communication technologies, Wikipedia [34] is a good place to start.

1.6 Quickly Building a Simple Antenna—a Practical Example

If an engineer must design an antenna in the shortest time, the antenna is most likely a 2.4GHz one. The 2.4GHz band is one of the industrial, scientific, and medical (ISM) bands. The 2.4GHz band is reserved internationally for short-range communications and it is a license-free band. Many technologies, such as WLAN, Bluetooth, Zigbee, ANT, and cordless phones, use this band.

Design of a 2.4GHz antenna is not a difficult task, because the relative bandwidth of the 2.4GHz band (2.4–2.483 GHz) is only 3.7%. Various ceramic chip antennas, which are discussed in Section 4.5, are marketed for these bands. However, for a product which is not space constrained, IFA is a better choice. Unlike chip antennas, an IFA can be integrated into the PCB and thus can be considered as a freebee. Detailed introductions of an IFA can be found in Section 4.1; here, we will carry out the design without going into theoretical details.

A network analyzer is essential to any antenna designing or tuning. Discussions of a network analyzer can be found in Section 5.1.1. If you work in a start-up and does have one on hand, you should convince your manager to buy one. Because you need to check the antenna and debug for problems during the whole life span of a product, renting one is not a good idea.

To be an advanced antenna designer, one should master the Smith chart and use it to design complex antennas. Detailed techniques related to the Smith chart and matching can be found in Chapter 2. Because a 2.4GHz antenna is a simple one, we will design the antenna without the Smith chart and only use reflection coefficient S_{11} .

Shown in Figure 1.14 is a network analyzer. Set the measurement type to [S11] and the display format to [Log Mag]. Set the start frequency to [2GHz] and the stop frequency to [3GHz]. Set the marker frequency to the center of the band [2.44GHz]. Although we only are concerned about 2.4–2.483GHz, it is a good practice to set the frequency span wide enough.

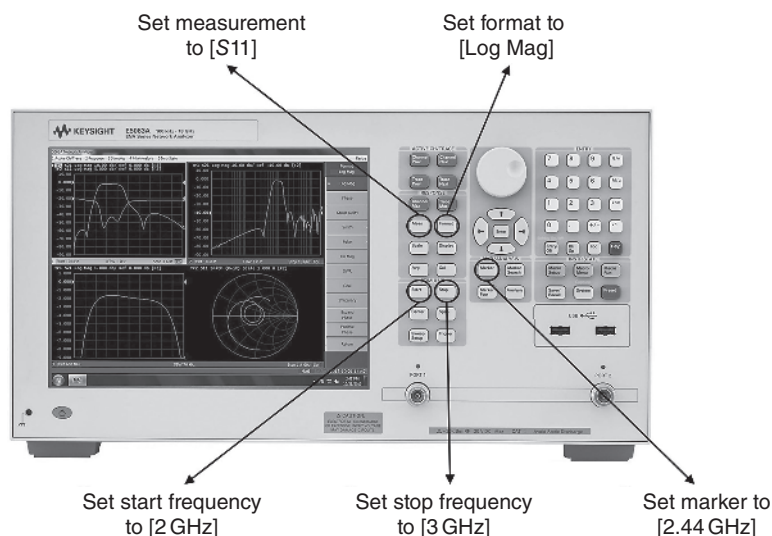


Figure 1.14 Network analyzer.

Thus, we can still observe an antenna's response even it is significantly off the design target, which happens a lot to a fresh engineer.

A network analyzer might have two or four ports. As we have selected [S11], the left-most port is the one to which the test cable should be attached. The coaxial connector on a network analyzer can be N-type, SubMiniature version A (SMA)-type, and so on. You might have to find an adaptor to mate a network analyzer to your cable. If you are not familiar with all these connectors, check a network analyzer's manual to decide which type of adaptor you need. You can order them online from the Digi-key Inc. [35]. There are various grades of coaxial cables, which range from tens of US dollars to thousands of US dollars. For the current project, a half-meter cheap cable (30–60\$) with SMA connectors, which normally has a maximum working frequency up to 18 GHz, will be good enough.

To make accurate measurement, the network analyzer to be used should be calibrated with the testing cable attached. However, in this practice we will proceed without calibration. Ideally, the response of a calibrated analyzer, which has one end of the test cable left open, should be a flat line which overlaps with the 0 dB grid line. Shown in Figure 1.15a is the response we should get without calibration. The line should be a slightly inclined curve. The reading at 2 GHz is a little higher than at 3 GHz, that is because a cable always introduces higher loss at the upper band. If the cable is not too long and the network analyzer is not that antique, the measured curve should all be above -1 dB. This will cause about 1 dB error in antenna measurement, which can be tolerated in this practice.

If there are large ripples or nulls in the measured result, as shown in the Figure 1.15b, the connection between the network analyzer and the cable is not secured. If the S_{11} reading is too low, say minus several dB, the cable is either too long or too lossy, and it should be replaced.

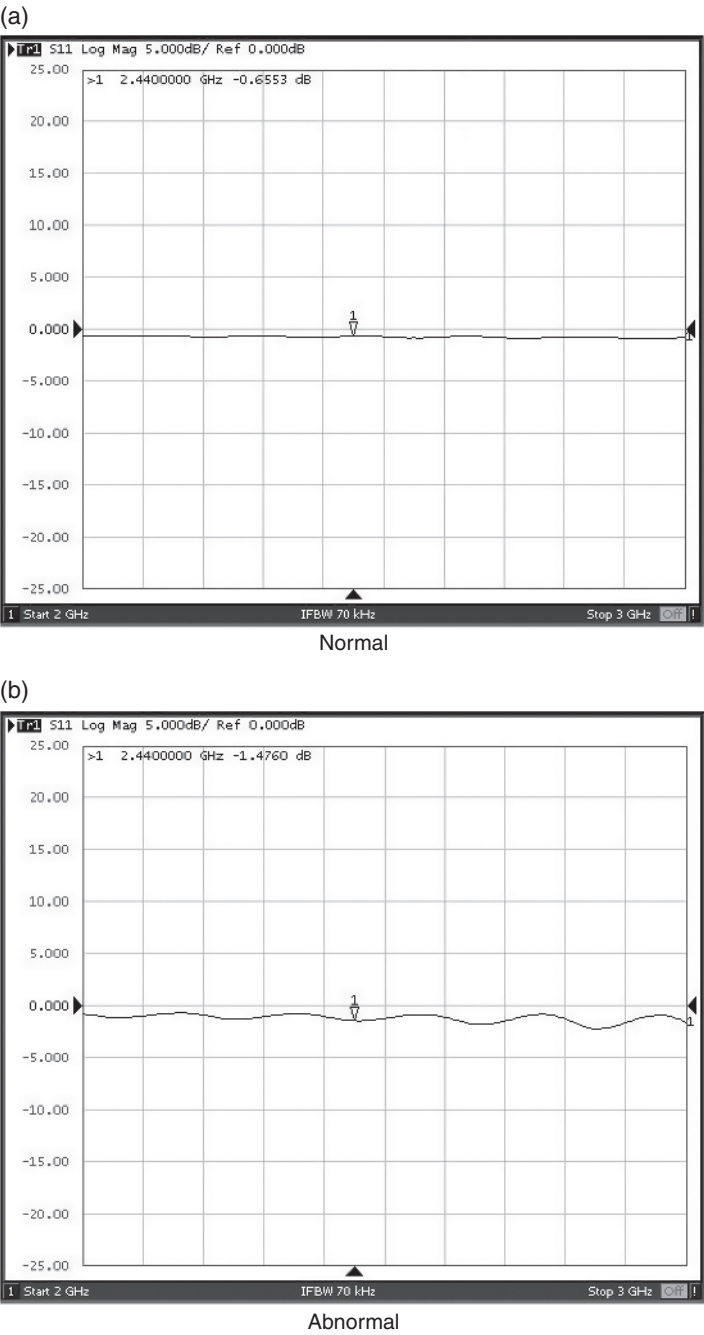


Figure 1.15 Response of an open-ended cable.

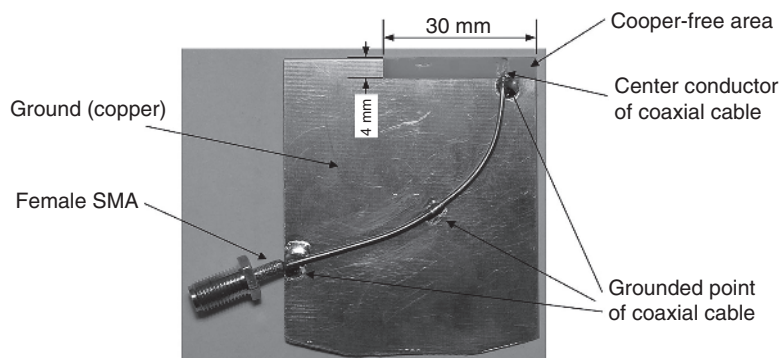


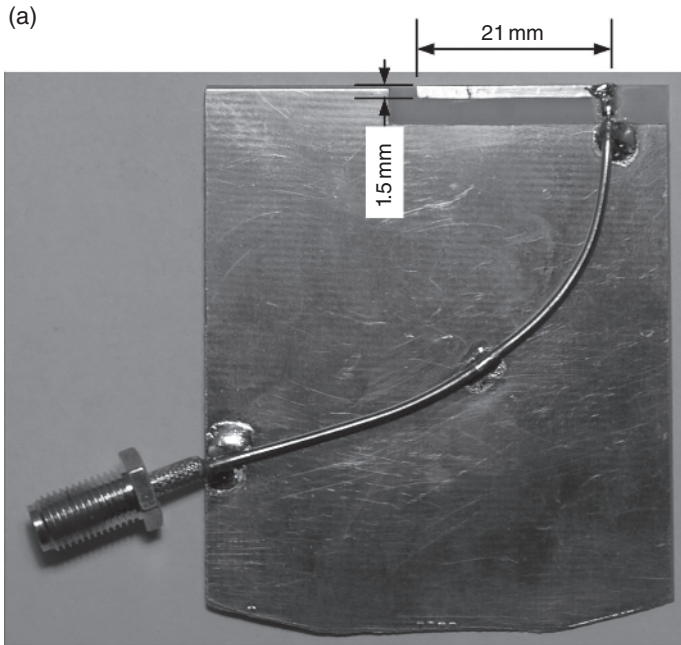
Figure 1.16 Antenna fixture.

Next, we need to find a single-side PCB, which has a solid copper layer only on one side of the board. When making antenna prototypes, try to avoid double side PCB, unless you wanted to spend time to manually make multiple connections between copper layers on top and bottom sides. Without proper connection between both sides, a double-side PCB might generate weird result. A heavy-duty scissor can be used to cut the PCB according to a mechanical design.

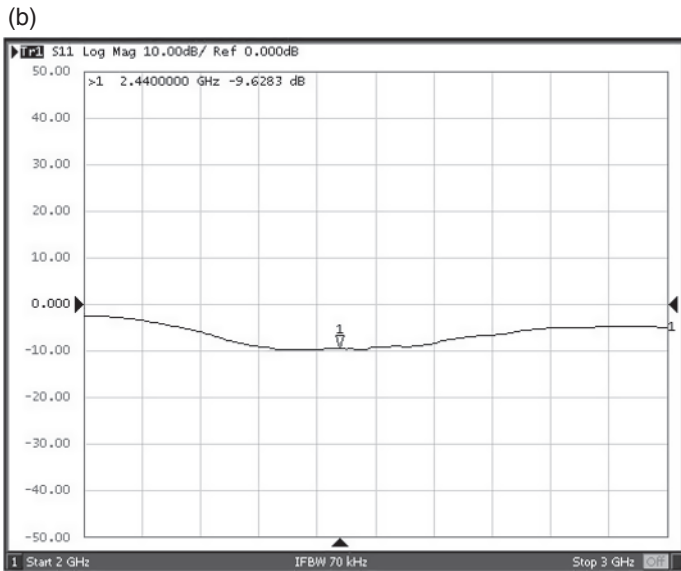
To place the antenna, a piece of copper measuring 30 mm × 4 mm should be removed from the PCB. A pigtail cable is then soldered to the PCB. Shown in Figure 1.16 is a prepared antenna fixture. The outer conductor of coaxial cable has been soldered to ground. The center conductor of coaxial cable has been left open. As the preparing and soldering of the pigtail cable is critical to obtain correct and constant results, it is strongly recommended that readers spend some time to go through Section 5.1.2 before continuing this practice.

Now it is time to actually design the antenna. A full wavelength of 2.4 GHz is 125 mm and a quarter of wavelength is 31.25 mm. Because commonly available PCBs use FR4 as its substrate, which has a permittivity around 4.4 and can shift antenna resonant frequency toward lower band, the finished antenna is always shorter than a quarter of wavelength. We can start with 21 mm. The antenna element is cut from a copper tape, which has glue on the bottom side and can be ordered from Digi-Key. Use finger nail to press the copper tape, until it is tightly attached to the PCB. Shown in Figure 1.17a is the half-finished prototype. The antenna has been soldered to the coaxial cable's center conductor. The measured S_{11} of the half-finished antenna has been shown in Figure 1.17b. A ferrite choke was used when measuring the antenna. To make a repeatable measurement, choke is very important. More discussions about choke can be found in Section 5.1.2.2. However, because the bandwidth of this example is quite wide and the PCB is big enough, one can move on without a choke.

As shown in Figure 1.17b, the measured S_{11} barely reaches -10 dB, so some matching work is required. There are various matching techniques, and Chapter 2 has been dedicated to this topic. In the following practice, a grounding branch method was used. As shown in Figure 1.18, one end of the branch was soldered to the antenna and the other end is soldered to the ground. Fresh engineers might wonder whether the grounding branch has shorted the antenna. Please relax, it isn't a short circuit, and it functions as a shunt inductor at the feeding point.



Prototype

 S_{11} **Figure 1.17** Make an antenna with copper tape.

Whenever we apply a new copper tape to an existing antenna structure, always use a solder to guarantee secured contact. Although copper tape is marketed as a conductive tape and can provide direct current (DC) connection, it can cause a lot of headache due to intermittent RF contact.

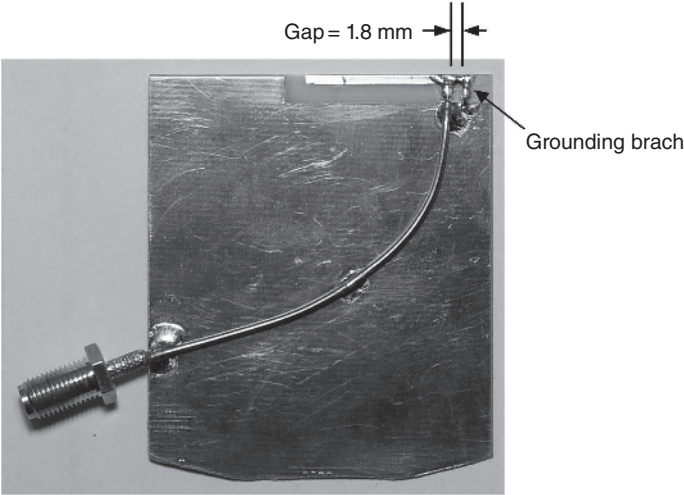


Figure 1.18 Match an IFA by grounding branch.

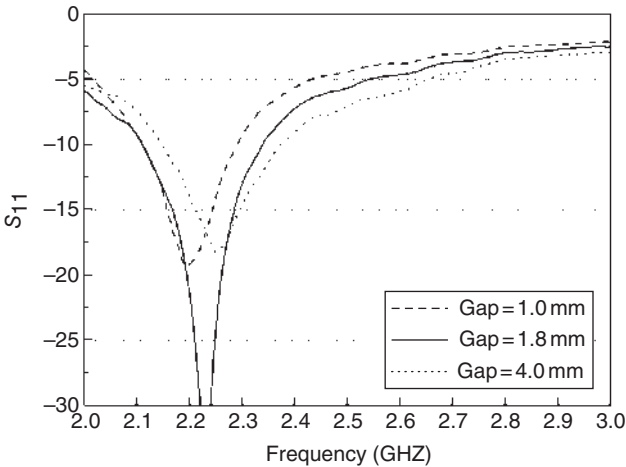


Figure 1.19 Impact of the grounding branch.

As we are not using the Smith chart, the matching effort will be a little less efficient. Fortunately, single-band IFA only has one tuning parameter, which is the gap between feeding strip and grounding strip. There is only one sweet spot for matching. Other than that point, the matching is always degraded no matter whether the gap is too wide or too narrow. Shown in Figure 1.19 are measured results of three different gap values. It is obvious that a 1.8 mm gap gives the best matching.

So far, the IFA has been matched. However, the resonant frequency is not at 2.44 GHz, which is the design target. Because the resonant frequency is lower than 2.44 GHz, we can shift it higher by shorting the antenna trace. The antenna can be tuned by cutting the antenna from 21 to 19 mm. Shown in Figure 1.20 is the measurement result. The center frequency is right at 2.44 GHz; however, the matching has degraded. It normally takes a few iterations to finalize a design.

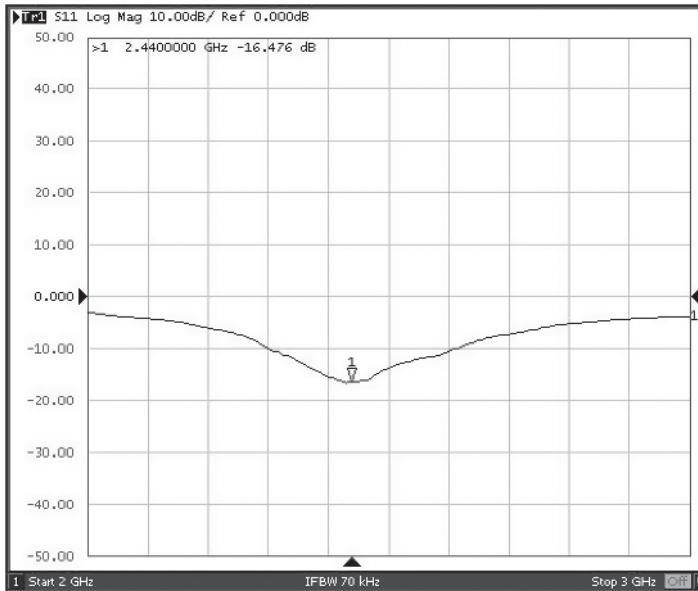


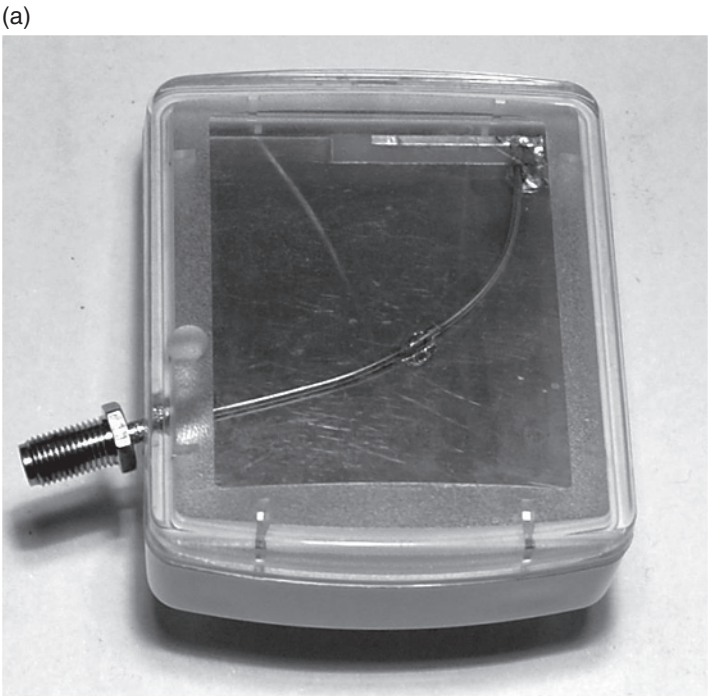
Figure 1.20 Tuning resonant frequency.

In real life, there is always an external plastic case to protect a PCB and components populated on it. Those plastic parts and various types of components around the antenna can have some impact on the antenna, which always requires some further fine-tuning. Shown in Figure 1.21a is a photo of a prototype. The sample antenna is at the top left corner. The plastic cover causes a frequency drift of 100 MHz toward lower frequency. After a few more iterations, the antenna was retuned. The length of the finalized antenna is 18 mm and the gap is 3.5 mm. Shown in Figure 1.21b is the measured S_{11} of the final design. The -10 dB bandwidth is around 500 MHz. Comparing with the measured results shown in Figure 1.19, the bandwidth is significantly increased. The wider bandwidth is due to the dielectric loss caused by the plastic cover. Although the bandwidth seems improved, the antenna efficiency is actually worse.

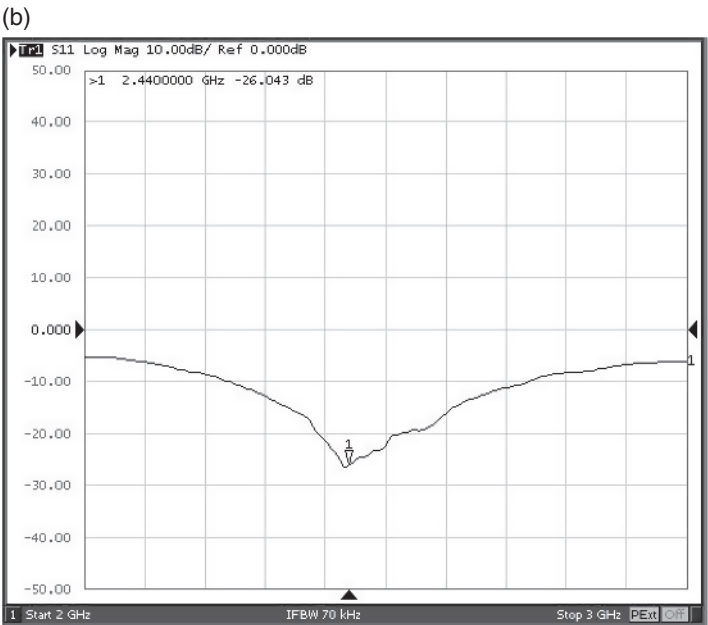
To make an IFA smaller, the common practice is to use meander line as an antenna element, as shown in Figure 1.22a. The antenna size is 14 mm \times 3 mm and the gap between grounding branch and feed is 1.2 mm. As a rule of thumb, whenever an IFA becomes smaller, its grounding branch always gets closer to the feed. Although the size of a meander antenna is smaller, the length of the metal line is always longer. More discussion can be found in Section 3.1.1.

The measured S_{11} has been given in Figure 1.22b. The -10 dB bandwidth is around 300 MHz. The reason for such a wide bandwidth is because the relative large ground plane. If the antenna was put on a much smaller PCB, the achievable bandwidth would shrink significantly. More discussion about the effect of ground plane can be found in Section 3.4.

The tuning procedure of meander line IFA is pretty much the same as the previous example. However, whenever an antenna is squeezed into a smaller area, the antenna bandwidth always becomes narrower and antenna efficiency gets worse. At some point, it will be a potential problem for an integrated IFA. Although the permittivity of FR4 substrate, which is the most commonly used PCB material, is marked as 4.4, the actual permittivity changes from vendor to vendor and from batch to batch. The permittivity can vary from 4.0 up to 4.8. If the bandwidth of a design is

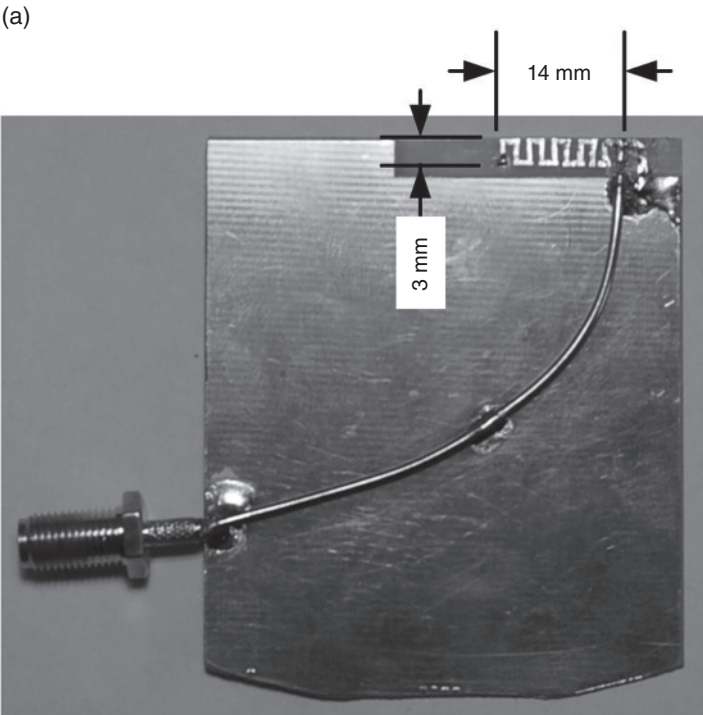


Prototype



S_{11} of the final design

Figure 1.21 Impact of plastic case.



Meander line antenna

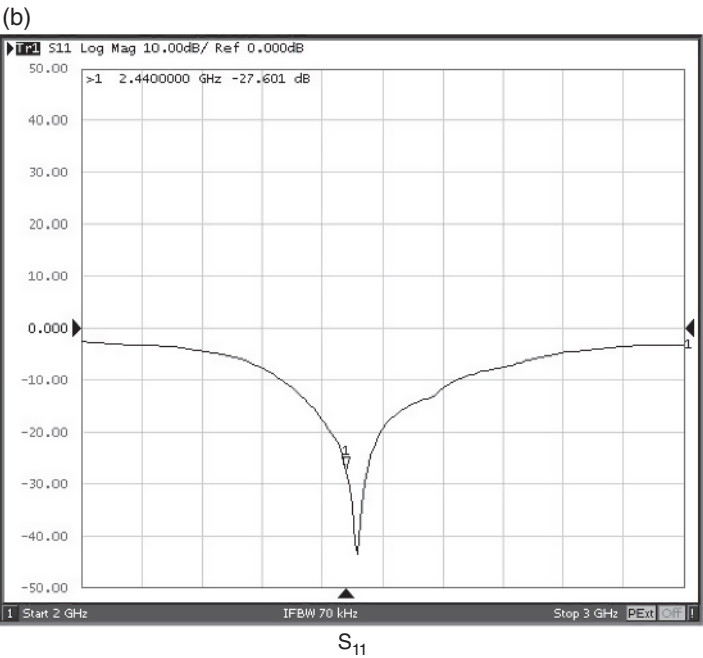


Figure 1.22 Making antenna smaller.

so tight that it can only cover 2.4–2.483 GHz, the yield will be an issue in mass production. When designing a product with very tight space constraints, ceramic antennas are better choices.

As the first practical example in the book, we will stop at here. I hope this example have relaxed you a little bit. After all, designing an antenna isn't as tough as everyone else said.

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