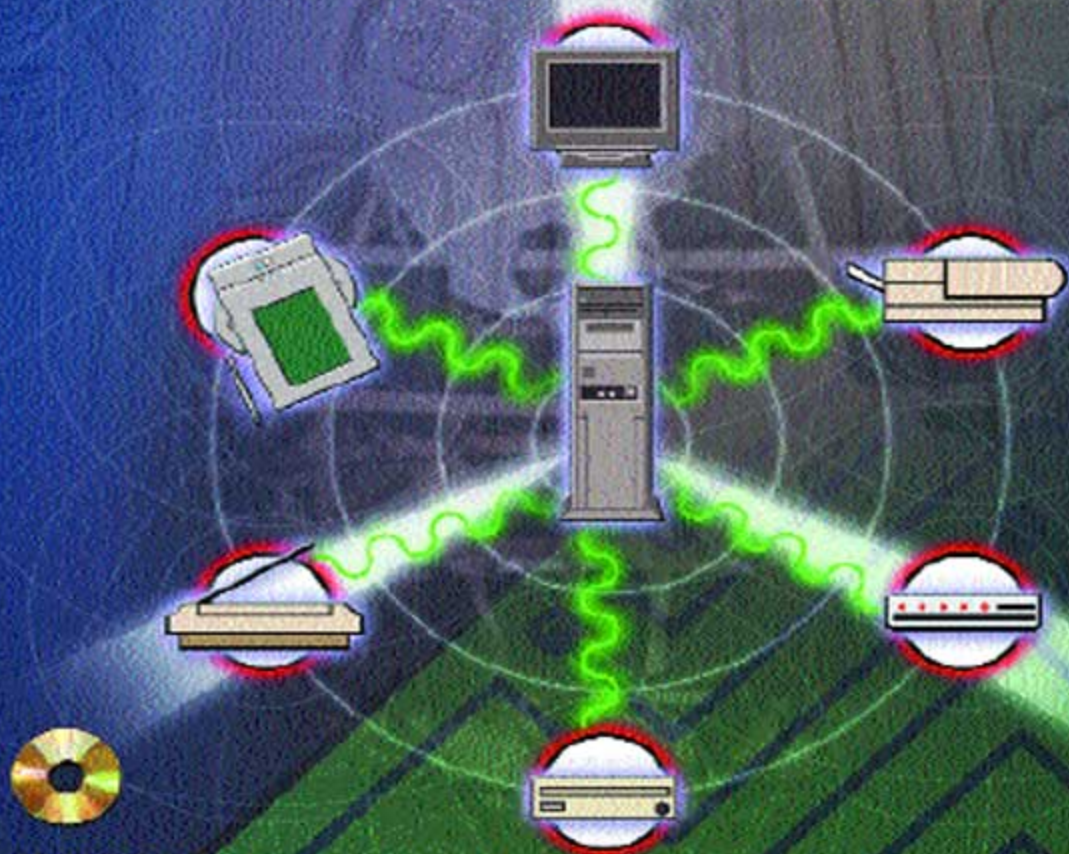


Short-range Wireless Communication

Fundamentals of RF System Design
and Application

Alan Bensky



CD-ROM Included
Contains Mathcad Worksheets
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Demystifying Technology Series

By Engineers, For Engineers

Short-range Wireless Communication

Fundamentals of RF System Design and Application

by Alan Bensky

A Volume in the DEMYSTIFYING TECHNOLOGY Series



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Dedication

To my wife Nuki,
and to daughters Chani, Racheli, and Ortal

Preface

Developers, manufacturers and marketers of products incorporating short-range radio systems are experts in their fields—security, telemetry, medical care, to name a few. Often they add a wireless interface just to eliminate wires on an existing wired product. They may adapt a wireless subsystem, which is easy to integrate electrically into their system, only to find that the range is far short of what they expected, there are frequent false alarms, or it doesn't work at all. It is for these adapters of wireless subsystems that this book is primarily intended.

Other potential readers are curious persons with varied technical backgrounds who see the growing applications for wireless communication and want to know how radio works, without delving deeply into a particular system or device. This book covers practically all aspects of radio communication including wave propagation, antennas, transmitters, receivers, design principles, telecommunication regulations and information theory. Armed with knowledge of the material in this book, the reader can more easily learn the details of specialized radio communication topics, such as cellular radio, personal communication systems (PCS), and wireless local area networks (WLAN).

The technical level of this book is suitable for readers with an engineering education or a scientific background, working as designers, engineering managers, or technical marketing people. They should be familiar with electrical circuits and engineering mathematics. Elementary probability theory is needed in some of the early chapters. Readers without an appropriate background or who need to brush up on probability are advised to jump ahead to chapter 10.

The book is organized as follows:

Chapter 1 is an introduction, presenting the focus of the book and the types of short-range radio applications that are covered.

Chapter 2 discusses radio propagation and factors that affect communication range and reliability.

Chapter 3 reviews the antennas used in short-range radio as well as transmission lines and circuit-matching techniques.

Chapter 4 covers the various forms of signals used for information transmission and modulation, and overall wireless system properties.

Chapters 5 and 6 describe the various kinds of transmitters and receivers.

Chapter 7 details the performance characteristics of radio systems.

Chapter 8 presents various component types that can be used to implement a short-range radio system.

Chapter 9 covers regulations and standards. It gives an overview of the conditions for getting approval of short-range radio systems in North America and Europe.

Chapter 10 is an introduction to probability and communication theory.

Chapter 11 reviews some of the most important new developments in short-range radio.

An introductory section describes the twelve Mathcad worksheets included on the CDROM accompanying the book, which are helpful for wireless design engineers in their daily work. A fully searchable pdf version of the book is also included on the CDROM.


Several terms in the book are used synonymously for varied expression, although there are subtle differences. “Wireless” and “radio” are used without distinction, although generally “wireless” also includes infrared communication and power line communication, which are not covered in this book. “Short-range radio” and “low-power radio” both refer to the area of unlicensed radio communication, although low power can be used to communicate over thousands of kilometers whereas short range, as used here, refers to several kilometers at the very most.

The book has a number of schematic diagrams, most of which do not include component values. Circuit design is more involved than just copying values from a schematic, and my intent is to explain concepts and give initial direction to engineers who have the ability to design a circuit to their own specific requirements. Many “cookbook” texts are available to assist in the actual circuit development as needed.

I wish to thank Professor Moe Bergman, who encouraged and assisted me from the time of my early interest in radio communication, for reviewing the manuscript and offering many helpful suggestions.

What's on the CDROM

Radio Engineering Worksheets

Included on the CDROM accompanying this book are twelve radio engineering worksheets. Throughout the text, sections that have an accompanying worksheet are indicated by this icon: . These worksheets will help you solve a wide variety of problems and should be of assistance to you in radio system design. The worksheets are based on Mathcad, a popular mathematics program published by MathSoft in which formulas and data are entered in familiar mathematical format, just as they would be when solving problems using pencil and paper or writing on the blackboard.

In order to use the worksheets you must have Mathcad 8 Professional version or higher installed on your computer. A free version of Mathcad Explorer, a read-only version of Mathcad 8 Professional, can be installed from MathSoft's website. A link to their site has been provided on the CDROM.

Once Mathcad Explorer has been installed on your system, run the program. Click "File", "Open...", from the tool bar, then select the "Mathcad Worksheets" folder from the CDROM. From "Files of type..." choose "Mathcad Files (*.mcd)." Open a worksheet.

The Mathcad web site, www.mathcad.com, has a library of engineering worksheets that you can access and work on using the Mathcad Explorer.

Using the Worksheets

As stated above, Mathcad formulas appear in normal written form on the worksheets. There are some small differences in interpretation of symbols. For example, a data entry expression is made up of a variable on the left, followed by a special equal sign which looks like a colon and an equals sign as follows := . An equals sign alone is followed by a calculated answer. It's worthwhile to study the HELP contents in order to benefit most from the worksheets, as well as to do your own mathematical calculations.

Text, interspersed with the mathematics, explains the organization of the worksheet and tells you where to enter data and where the answers

are. All worksheets have default data that you replace with your data to solve specific problems. Note the following:

- Yellow marked expressions on the worksheet indicate where to insert your data. Click the cursor on the default data and erase it using the delete and backspace keys. Type in your numerical data on the remaining small black rectangle.
- Blue marked expressions are the calculated answers. They change automatically when you change the data (see below).

Calculations are usually performed by the program automatically as soon as you change the data and press Enter. This can be annoying when you originally enter your data into the worksheet, so you can disable this feature by pressing “Math” on the upper bar and then “Automatic Calculation” to remove the check mark. When you finish entering data, press “Automatic Calculation” again. Now when you change your data, the answers and graphs will automatically update, as on a spreadsheet. You can also initiate calculation if it happens to be disabled by pressing F9.

Graphs

A couple of the worksheets have graphs. If you want to find a particular coordinate and the resolution of the axes is not sufficient, click on the graph with the right mouse button. Click on Trace. Move the cursor on the plot and see the coordinates in the Trace window.

Units of Measure

One of the special features of Mathcad is the ease of using units of measure. You don't have to use any conversion factors when changing units. For example, if the default unit of length in a yellow data input expression is cm (centimeters) and you prefer to enter your data in inches, simply insert the number of inches, then replace “cm” with “in.” Similarly, the units of measure in the blue solution expressions can also be replaced.

Worksheet Descriptions

Each worksheet has a basic description and text to help you use it. More detailed descriptions are given in the following sections.

Conversions.mcd — Impedance Transformations

This worksheet is intended for general use in circuit design. It is particularly helpful in designing impedance-matching networks, together with the worksheet “Matching.mcd.” Sections (6) and (7) can be used in impedance matching when the source and load impedances are not pure resistances. In these cases, combine the reactance with the adjacent reactance of the matching network.

Diffraction.mcd — Diffraction

Here you can see one reason why radio reception is possible in places that don't have a line-of-sight view to the transmitter. Note that the diffraction phenomenon affects the signal strength in line-of-sight paths as well. This worksheet is more tutorial than practical, since its results are accurate only where there is only one barrier that has the shape of a knife edge. In most real situations there are several barriers of various shapes, and signal strength is also affected by reflections. However, it is interesting and informative to see the effects of changing the frequency on wave penetration into shadowed regions. The calculations for the plot are complicated and take time, so be patient!

Helical.mcd — Helical Antennas

Helical antennas are commonly used for portable short-range transmitters and receivers, and you can get a good start on the design of one using this worksheet. After you insert the global parameters — frequency, antenna diameter, and wire diameter—you have two choices for the remaining data. If you know the turns per inch of the winding for the antenna, start from section (1) and insert the data. The antenna height will then be calculated. In section (2) right click on the yellow expression for height, then click “Disable Evaluation” in the pop-up window. Check sections (3) through (7) to see the results of your design.

If both the height and the diameter of the antenna are known, enter the height in the yellow expression under (2). (If the expression had been disabled as shown above, there will be a small black rectangle in it. Right click on it and click “Enable Evaluation.”) The required number of turns for resonance will be shown in the blue expression. Get more information from sections (3) through (7).

By changing the form factor of the antenna, you affect the radiation resistance and efficiency. Section (6) gives the total resistance that has to be matched.

The formulas in the worksheet assume a perfect ground plane, which is rarely the case for portable devices. So regard the results of the calculations as starting points in the design. Start with a few more turns than calculated, then trim the antenna until resonance, or maximum radiation or reception, is achieved.

Loop.mcd — Loop Antenna

The printed loop antenna is one of the most popular for small portable UHF transmitters. Enter your basic data — dimensions and frequency. Sections (1), (2) and (3) give results involving radiation efficiency. The result in (3) is most probably an understatement, since other factors not taken into account will reduce the efficiency. Among them are losses in the dielectric of the board and surrounding components and housing materials.

Section (4) of the worksheet gives an approximation of the loop inductance, helpful for matching to the transmitter output.

Matching.mcd — Impedance Matching

This worksheet presents several topologies for matching functional blocks of a radio circuit — antenna to receiver input, transmitter final stage to antenna, and matching between RF amplifier stages, for example. R_1 is the resistance seen looking into the network when it is terminated by R_2 . If a resistance R_1 is connected to the left side, then the resistance looking into the right side will be R_2 . Circuits (1) and (2) each have only one solution for a pair of values R_1 and R_2 , whereas in circuits (3) and (4) the values of the matching components depend on the value chosen for Q .

The losses of the matching circuit components, particularly the inductors, should be taken into consideration when choosing the matching circuit configuration. An inductor can be represented as having a small resistance in series with it or a large resistance in parallel. These resistances can be manipulated to be part of the resistances being

matched with the help of worksheet “Impedance Transformations.” See the impedance matching examples in Chapter 3.

Microstrip.mcd — Microstrip Transmission Lines

This worksheet tells you the characteristic impedance of a printed circuit board conductor when the width is known, or the required conductor width to get a specified characteristic impedance. Note that the conductor has to be backed by a ground plane on the opposite side. You have to specify the frequency, dielectric constant of the board insulating material, and board thickness. The actual dielectric constant needed for determining characteristic impedance is a function of the board thickness and conductor width. In section (2) it is the width we are trying to find, so we need to follow an iterative process to get a true solution. That is why the width that is determined from the first trial is used as the “guess value” for a second run that results in a closer estimate of the true width for the required characteristic impedance.

The results include the wavelength in the board for the particular conductor width. This value is needed when using the Smith chart for designing printed circuit matching networks or reactive components.

Patch.mcd — Microstrip Patch Antennas

You can design a square half-wave microstrip patch antenna using this worksheet. The formulas account for the “fringing distance,” which makes the patch length somewhat smaller than a half wavelength in the board. A result of the worksheet is the impedance at the center of a board edge to which you have to match the input impedance of a receiver or output impedance of a transmitter. This matching is usually done by printed microstrip distributed components. If you want to match directly to a coaxial cable, solder the cable’s shield to the groundplane on the opposite side of the board. Connect the center connector through a via insulated from the groundplane to the patch at the distance “ x ” from the center, which is displayed as a result in the last section of the worksheet.

Radiate.mcd — Radio Propagation Formulas

This worksheet is very handy for anyone dealing with wave propagation and antennas. Note that in section (1) a factor “ L ” is included, which contains circuit and system losses. This factor is not explicit in the other sections but such losses should be incorporated in the gain factors. For example, section (3) may be used to find the transmitter power needed to meet the FCC regulations for maximum field strength at a distance of 3 meters. When a loop antenna is used, the antenna losses may be 10 dB or more so G_t should be at the most 0.1 in this case.

Range.mcd — Open Field Range

Estimating the range of a low-power wireless communication system under open field conditions is much more relevant than using the free space equations. Using this worksheet you can see the nulls and the peaks of signal strength that are so often experienced in practice, and how they are influenced by operating frequency and antenna heights.

To use the worksheet you enter the operating frequency, transmitting and receiving antenna heights above ground, and polarity of the transmitting antenna. You also indicate the maximum distance for the plot. The calculations vectorily add the direct line-of-sight received signal strength and that of the signal reflected from the ground. “Normal” ground conductivity and permittivity are used, which you could change if you wish but usually it isn’t necessary. It’s assumed that the antennas have constant gain in elevation. The result is a plot of the isotropic path gain (the negative of the path loss) in decibels, representing the ratio of the power at the input of a receiver relative to the radiated transmitter power in the direction of the receiver with receiver antenna gain equal to zero dB. The open field path gain is calculated relative to the free space power at a reference distance, d_o , set to 3 meters. Then transmitter power is found from the free space power at d_o . Free space path gain is also plotted, for reference.

The last sections of the worksheet let you find, for a given transmitted power, the required receiver sensitivity for a given range in an open field, or the open field range when receiver sensitivity is known. Finding the sensitivity when power and range are known is straightforward, but

to get the range from given power and sensitivity you have to find the abscissa of the curve (the distance) when the ordinate (path gain) is known. The worksheet has instructions for doing it.

Translines.mcd — Transmission Lines

This worksheet solves various useful formulas for working with transmission lines. First you enter the operating frequency and transmission line parameters. The calculations account for line loss, whose value you have to enter, but if you don't know it, you can enter 0 dB with little effect on short low-loss lines. If you do use line loss, you have to know it for the frequency of operation, as the loss increases with frequency. From the cable velocity factor and frequency, which you provide, the wavelength in the cable is calculated and displayed.

Section (1) gives relationships between often-used matching parameters and uses only the line characteristic impedance that was entered. Section (2) gives the transformation of the load impedance to the impedance seen looking into the line from the source, as well as the required load impedance for a specified impedance in the line at the source. You only have to enter the line length. Section (3) lets you find line lengths needed, for shorted or open lines, to get desired inductive or capacitive reactances.

Probabilities.mcd — Probability of Detection

It's very useful to be able to find the probability of errorless detection, or the probability of error, of sending a sequence of a particular number of bits over a transmission system. You can do this, when the probability of error of each bit is known, using this worksheet. You can also find from the worksheet how much an error-correcting code can improve (reduce) the probability of error. The calculations use the Hamming bound for the minimum number of code letters required to correct all errors up to a given number.

The worksheet states that because of the increase of error-correcting bits in the sent message, the time to send the information is increased when bit rate is constant. Increasing the bit rate to bring the information rate up to its value without error correction entails increased bandwidth

and a consequential reduction of signal-to-noise ratio. The effect on bit error rate depends on the type of modulation used and, when the new probability of bit error is known, you can input it to the data sheet and get a better solution for the probability of error with error-correction coding.

The worksheet also calculates the probability of false alarms. False alarms occur when noise changes received bits so that a randomly received sequence is identical to an expected message when this message is not being sent.

A common way to improve the probability of detection of messages without using error-correction coding is to send the same message consecutively several times. You can see the degree of improvement of the probability of detection from the repetition of messages from the results displayed in the last section of the worksheet.

S-parameters.mcd — S-Parameters

Often manufacturers of active and passive components provide sets of s -parameters, which range over bands of operating frequencies and biasing currents and voltages. By plugging the relevant set of s -parameters into this worksheet, you can find the input and output impedances that you need to design the matching networks for these devices. The worksheet finds reflection coefficients and input and output impedances according to the corresponding load or source impedances applied to the components.

CHAPTER 1

Introduction

1.1 Historical Perspective

A limited number of short-range radio applications were in use in the 1970s. The garage door opener was one of them. An L-C tuned circuit oscillator transmitter and superregenerative receiver made up the system. It suffered from frequency drift and susceptibility to interference, which caused the door to open apparently at random, leaving the premises unprotected. Similar systems are still in use today, although radio technology has advanced tremendously. Even with greatly improved circuits and techniques, wireless replacements for wired applications—in security systems for example—still suffer from the belief that wireless is less reliable than wired and that cost differentials are too great to bring about the revolution that cellular radio has brought to telephone communication.

Few people will dispute the assertion that cellular radio is in a class with a small number of other technological advancements—including the proliferation of electric power in the late 19th century, mass production of the automobile, and the invention of the transistor—that have profoundly affected human lifestyle in the last century. Another development in electronic communication within the last 10 or so years has also impacted our society—satellite communication—and its impact is coming even closer to home with the spread of direct broadcast satellite television transmissions.

That wireless techniques have such an overwhelming reception is not at all surprising. After all, the wires really have no intrinsic use.

They only tie us down and we would gladly do without them if we could still get reliable operation at an acceptable price. Cellular radio today is of lower quality, lower reliability, and higher price generally than wired telephone, but its acceptance by the public is nothing less than phenomenal. Imagine the consequences to lifestyle when electric power is able to be distributed without wires!

Considering the ever-increasing influence of wireless systems in society, this book was written to give a basic but comprehensive understanding of radio communication to a wide base of technically oriented people who either have a curiosity to know how wireless works, or who will contribute to expanding its uses. While most chapters of the book will be a gateway, or even a prerequisite, to understanding the basics of all forms of radio communication, including satellite and cellular systems, the emphasis and implementations are aimed at what are generally defined as short-range or low-power wireless applications. These applications are undergoing a fast rate of expansion, in large part due to the technological fall-out of the cellular radio revolution.

1.2 Reasons for the Spread of Wireless Applications

One might think that there would be a limit to the spread of wireless applications and the increase in their use, since the radio spectrum is a fixed entity and it tends to be depleted as more and more use is made of it. In addition, price and size limitations should restrict proliferation of wire replacement devices. However, technological developments defy these axioms.

- We now can employ higher and higher frequencies in the spectrum whose use was previously impossible or very expensive. In particular, solid-state devices have recently been developed to amplify at millimeter wavelengths, or tens of gigahertz. Efficient, compact antennas are also available, such as planar antennas, which are often used in short-range devices. The development of surface acoustic wave (SAW) frequency-determining components allow generation of UHF frequencies with very simple circuits.
- Digital modulation techniques are replacing the analog methods of previous years, permitting a multiplication of the number of communication channels that can occupy a given bandwidth.

- We have seen much progress in circuit miniaturization. Hybrid integrated circuits, combining analog and digital functions on one chip, and radio-frequency integrated circuits are to a large part responsible for the amazingly compact size of cellular telephone handsets. This miniaturization is not only a question of convenience, but also a necessity for efficient design of very short-wavelength circuits.

1.3 Characteristics of Short-range Radio

“Short-range” and “low-power” are both relative terms, and their scope must be asserted in order to see the focus of this book. Hardly any of the applications that we will discuss will have all of these characteristics, but all of them will have some of the following features:

- RF power output of several microwatts up to 100 milliwatts
- Communication range of several centimeters up to several hundred meters
- Principally indoor operation
- Omnidirectional, built-in antennas
- Simple construction and relatively low price in the range of consumer appliances
- Unlicensed operation
- Noncritical bandwidth specifications
- UHF operation
- Battery-operated transmitter or receiver

Our focus on implementation excludes cellular radios and wireless telephones, although an understanding of the material in this book will give the reader greater comprehension of the principles of operation of those ubiquitous devices.

Short-range radio applications

The following table lists some short-range radio applications and characteristics that show the focus of this text.

<i>Application</i>	<i>Frequencies (MHz)</i>	<i>Characteristics</i>
Security Systems	300-500, 800, 900	Simplicity, easy installation
Emergency Medical Alarms	300-500, 800	Convenient carrying, long battery life, reliable
Computer Accessories—mouse, keyboard	UHF	High data rates, very short range, low cost
RFID (Radio Frequency Identification)	100 KHz – 2.4 GHz	Very short range, active or passive transponder
WLAN (Wireless Local Area Network)	900 MHz, 2.4 GHz	High continuous data rates, spread-spectrum modulation, high price
Wireless microphones; Wireless Headphones	VHF, UHF	Analog high-fidelity voice modulation, moderate price
Keyless Entry—Gate openers	UHF	Miniature transmitter, special coding to prevent duplication
Wireless bar code readers	900 MHz, 2.4 GHz	Industrial use, spread spectrum, expensive

A new direction in short-range applications is about to appear in the form of high-rate data communication devices for distances of several meters. This is being developed by the Bluetooth consortium of telecommunication and PC technology leaders for eliminating wiring between computers and peripherals, as well as wireless internet access through cellular phones. Mass production will eventually bring sophisticated communication technology to a price consumers can afford, and fallout from this development will surely reach many of the applications in the table above, improving their reliability and increasing their acceptance for replacing wiring.

1.4 Elements of Wireless Communication Systems

Figure 1-1 is a block diagram of a complete wireless system. Essentially all elements of this system will be described in detail in the later chapters of the book. A brief description of them is given below with special reference to short-range applications.

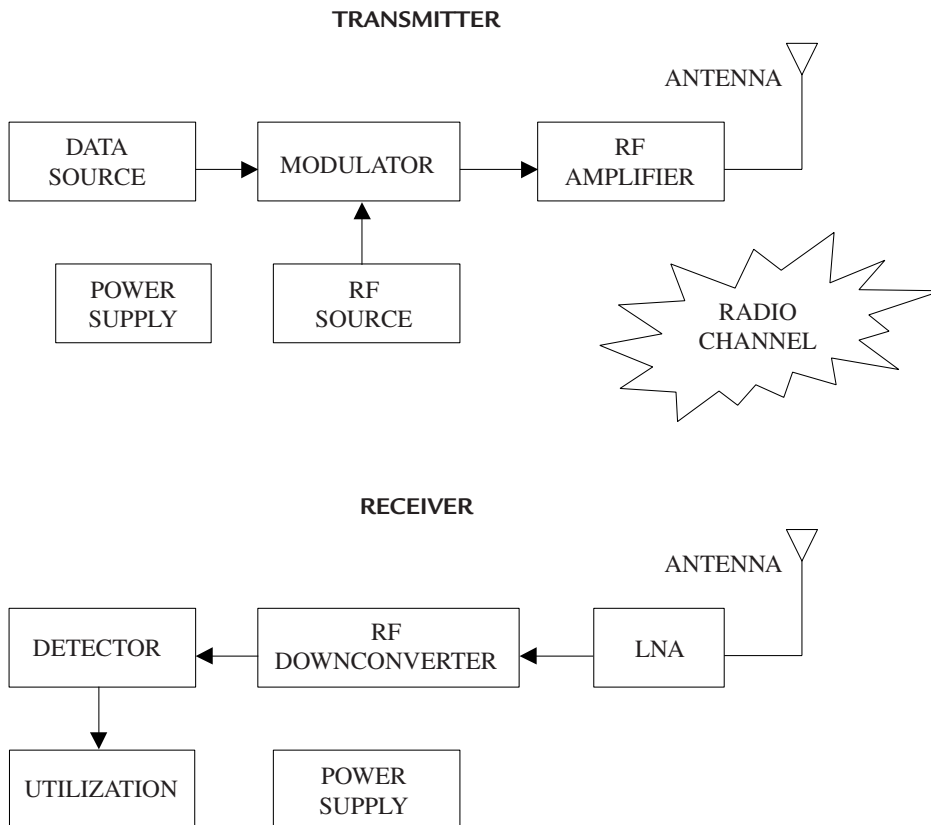


Figure 1-1: The Wireless System

Data source

This is the information to be conveyed from one side to the other. Each of the devices listed in the table on page 4 has its own characteristic data source, which may be analog or digital. In many of the cases the data may be simple on/off information, as in a security intrusion detector, panic button, or manually operated remote control unit. In this case, a change of state of the data will cause a message frame to be modulated on an RF carrier wave. In its simplest form the message frame may look like Figure 1-2. An address field identifies the unit that is transmitting and the data field conveys the specific information in on/off form. A parity bit or bits may be appended to allow detecting false messages.



Figure 1-2: Message Frame

Other digital devices have more complex messages. Computer accessories and WLANs send continuous digital data over the short-range link. These data are organized according to protocols that include sophisticated error detection and correction techniques (see Chapter 10).

Audio devices such as wireless microphones and headsets send analog data to the modulator. However, these data must be specially processed for best performance over a wireless channel. For FM transmission, which is universally used for these devices, a preemphasis filter increases the high frequencies before transmission so that, in the receiver, deemphasizing these frequencies will also reduce high-frequency noise. Similarly, dynamic range is increased by the use of a compandor. In the transmitter weak sounds are amplified more and strong signals are amplified less. The opposite procedure in the receiver reduces background noise while returning the weak sounds to their proper relative level, thus improving the dynamic range.

A quite different aspect of the data source is the case for RFIDs. Here, the data are not available in the transmitter but are added to the RF signal in an intermediate receptor, called a transducer. See Figure 1-3. This transducer may be passive or active, but in any case the originally

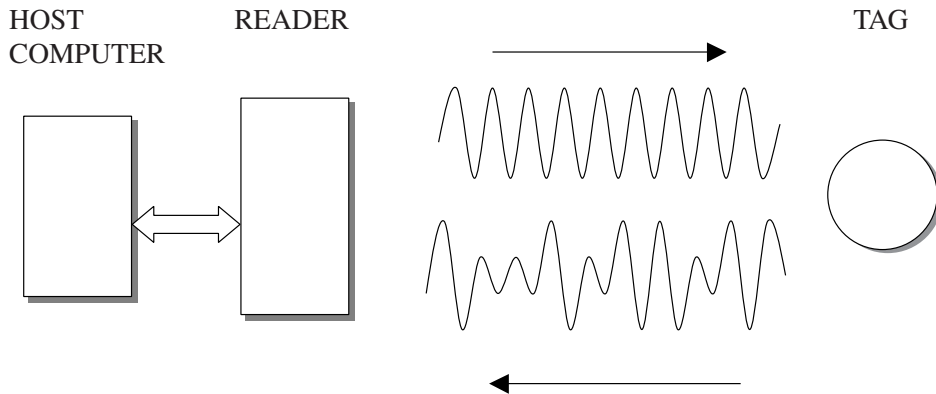


Figure 1-3: RFID

transmitted radio frequency is modified by the transducer and detected by a receiver that deciphers the data added and passes it to a host computer.

Radio frequency generating section

This part of the transmitter consists of an RF source (oscillator or synthesizer), a modulator, and an amplifier. In the simplest short-range devices, all three functions may be included in a circuit of only one transistor. Chapter 5 details some of the common configurations. Again RFIDs are different from the other applications in that the modulation is carried out remotely from the RF source.

RF conduction and radiation

Practically all short-range devices have built-in antennas, so their transmission lines are relatively short and simple. However, particularly on the higher frequencies, their lengths are a high enough percentage of wavelength to affect the transmission efficiency of the transmitter. Chapter 3 discusses the transmission lines encountered in short-range systems and the importance and techniques of proper matching. The antennas of short-range devices also distinguish them from other radio applications. They must be small—often a fraction of a wavelength—and omnidirectional for most uses.

Radio channel

By definition, the radio channel for short-range applications is short, and for a large part the equipment is used indoors. The allowed radio frequency power is relatively low and regulated by the telecommunication authorities. Also, the devices are often operated while close to or attached to a human (or animal) body, a fact which affects the communication performance. Reliable operating range is difficult to predict for these systems, and lack of knowledge of the special propagation characteristics of short-range radio by manufacturers, sellers, and users alike is a dominating reason for its reputation as being unreliable. Short-range devices are often used to replace hard wiring, so when similar performance is expected, the limitations of radio propagation compared to wires must be accounted for in each application. Chapter 2 brings this problem into perspective.

Receivers

Receivers are similar to transmitters, but their operation is reversed. They have an antenna and transmission line, RF amplifiers, and use oscillators in their operation. The ultimate purpose of the receiver is to convert the data source that was implanted on the RF wave in the transmitter back to its original form. While the transmitted power is limited by the authorities, receiver sensitivity is not, so the most obvious way to improve system performance is by improving the sensitivity and the selectivity to reduce interference from unwanted sources. This must be done under constraints of physics, cost, size, and often power consumption. Chapter 7 deals with these matters.

An important factor in low-power system design, and sometimes a controversial one, is the type of modulation to use. In the case of the simpler systems—security and medical alarms, for example—the choice is between amplitude shift keying (ASK), parallel to amplitude modulation in analog systems, and frequency shift keying (FSK), analogous to frequency modulation (FM). In Chapter 4 we'll look at the pros and cons of the two systems.

Power supplies

In most short-range devices, at least one side of the wireless link must be completely untethered—that's what wireless is for! When size is limited, as it is in hand-operated remote control transmitters and security detectors, battery size and therefore energy is limited. The need to change batteries often is not only highly inconvenient but also expensive, and this is an impediment to more widespread use of radio in place of wires. Thus, low-current consumption is an important design aim for wireless devices. This is usually harder to achieve for receivers than for transmitters. Many short-range applications call for intermittent transmitter operation, in security systems, for example. Transmitters can be kept in a very low-current standby status until data needs to be sent. The receiver, on the other hand, usually doesn't know when data will be sent so it must be alert all the time. Even so, there are techniques to reduce the receiver duty cycle so that it doesn't draw full current all the time. Another way to reduce receiver power consumption is to operate it in a reduced power standby mode, wherein operation goes to normal when the beginning of a signal is detected. This method often entails reduced sensitivity, however.

1.5 Summary

Short-range radio is developing as an expanding and distinct adjunct to wireless communication in general. While its basic operating characteristics are the same as all radio systems, there are many features and specific problems that justify dealing with it as a separate field. Among them are low power, low cost, small size, battery operation, uncertainty of indoor propagation, and unlicensed operation on crowded bands. The rest of this book will delve into the operational and design specialties of short-range radio communication from the electromagnetic propagation environment through antennas, receivers and transmitters, regulations and standards, and a bit of relevant information theory. The last chapter introduces some new developments that are apt to bring wireless into the home to an unprecedented extent.

Antennas and Transmission Lines

3.1 Introduction

The antenna is the interface between the transmitter or the receiver and the propagation medium, and it therefore is a deciding factor in the performance of a radio communication system. The principal properties of antennas—directivity, gain, and radiation resistance—are the same whether referred to as transmitters or receivers. The principle of reciprocity states that the power transferred between two antennas is the same, regardless of which is used for transmission or reception, if the generator and load impedances are conjugates of the transmitting and receiving antenna impedances in each case.

First we define the various terms used to characterize antennas. Then we discuss several types of antennas that are commonly used in short-range radio systems. Finally, we review methods of matching the impedances of the antenna to the transmitter or receiver RF circuits.

3.2 Antenna Characteristics

Understanding the various characteristics of antennas is a first and most important step before deciding what type of antenna is most appropriate for a particular application. While antennas have several electrical characteristics, often a primary concern in choosing an antenna type is its physical size. Before dealing with the various antenna types and the shapes and sizes they come in, we first must know what the antenna has to do.

Antenna impedance

As stated in the introduction, the antenna is an interface between circuits and space. It facilitates the transfer of power between space and the transmitter or receiver. The antenna impedance is the load for the transmitter or the input impedance to the receiver. It is composed of two parts—radiation resistance and ohmic resistance. The radiation resistance is a virtual resistance that, when multiplied by the square of the RMS current in the antenna at its feed point, equals the power radiated by the antenna in the case of a transmitter or extracted from space in the case of a receiver. It is customary to refer the radiation resistance to a current maximum in the case of an ungrounded antenna, and to the current at the base of the antenna when the antenna is grounded. Transmitter power delivered to an antenna will always be greater than the power radiated. The difference between the transmitter power and the radiated power is power dissipated in the ohmic resistance of the antenna conductor and in other losses. The efficiency of an antenna is the ratio of the radiated power to the total power absorbed by the antenna. It can be expressed in terms of the radiation resistance R_r and loss resistance R_l as

$$\text{Antenna Efficiency (\%)} = 100 \times (R_r / (R_r + R_l)) \quad (3-1)$$

The resistance seen by the transmitter or receiver at the antenna terminals will be equal to the radiation resistance plus the loss resistance only if these terminals are located at the point of maximum current flow in the antenna. The impedance at this point may have a reactive component, too. When there is no reactive component, the antenna is said to be resonant. Maximum power transfer between the antenna and transmitter or receiver will occur only when the impedance seen from the antenna terminals is the complex conjugate of the antenna impedance.

It is important to match the transmitter to the antenna not only to get maximum power transfer. Attenuation of harmonics relative to the fundamental frequency is maximized when the transmitter is matched to the antenna—an important point in meeting the spurious radiation requirements for license-free transmitters. The radiation resistance depends on the proximity of the antenna to conducting and insulating objects. In particular, it depends on the height of the antenna from the ground. Thus, the antenna-matching circuit of a transmitter with integral

antenna that is intended to be hand-held should be optimized for the antenna impedance in a typical operating situation.

Directivity and gain

The directivity of an antenna relates to its radiation pattern. An antenna which radiates uniformly in all directions in three-dimensional space is called an isotropic antenna. Such an antenna doesn't exist, but it is convenient to refer to it when discussing the directional properties of an antenna. All real antennas radiate stronger in some directions than in others. The directivity of an antenna is defined as the power density of the antenna in its direction of maximum radiation in three-dimensional space divided by its average power density. The directivity of the hypothetical isotropic radiator is 1, or 0 dB. The directivity of a half-wave dipole antenna is 1.64, or 2.15 dB.

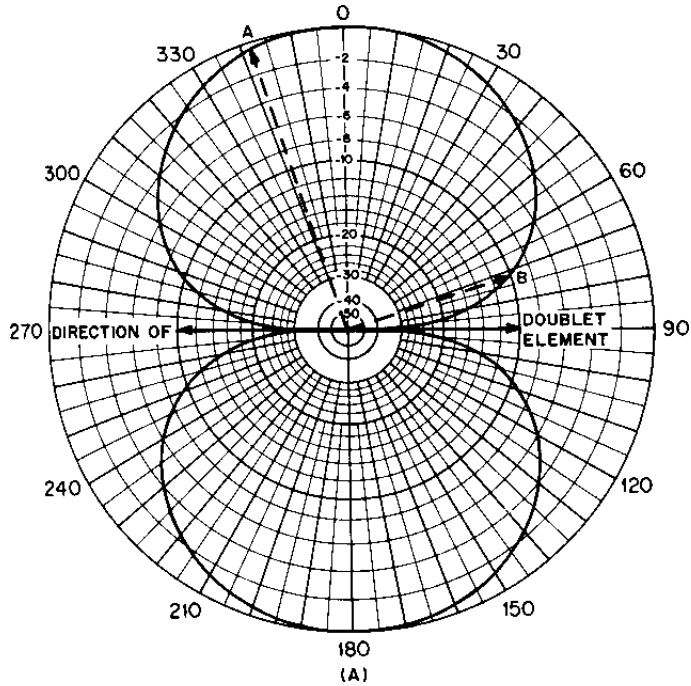
The radiation pattern of a wire antenna of short length compared to a half wavelength is shown in Figure 3-1a. The antenna is high enough so as not to be affected by the ground. If the antenna wire direction is parallel to the earth, then the pattern represents the intersection of a horizontal plane with the solid pattern of the antenna shown in Figure 3-1b. A vertical wire antenna is omnidirectional; that is, it has a circular horizontal radiation pattern and directivity in the vertical plane.

The gain of an antenna is the directivity times the antenna efficiency. When antenna losses are low, the two terms are almost the same. In general, when you are interested in the directional discrimination of an antenna, you will be interested in its directivity. Gain is used to find the maximum radiated power when the power into the antenna is known.

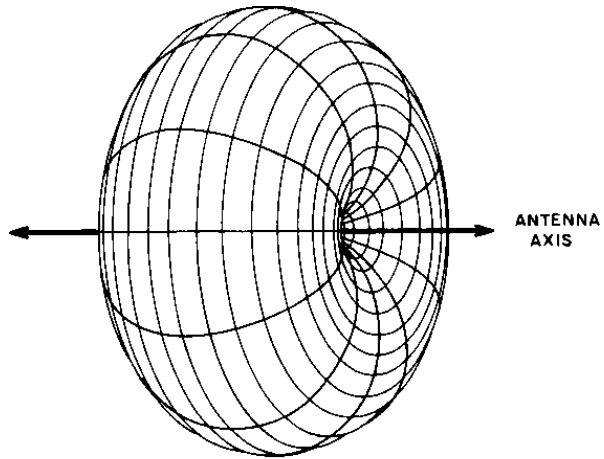
Effective area

Another term often encountered is the effective area of an antenna. Wave propagation can be described as if all of the radiated power is spread over the surface of a sphere whose area expands according to the square of the distance (in free space). The power captured by the receiving antenna is then the capture area, or effective area, of the antenna times the power density at that location. The power density is the radiated power divided by the surface area of the sphere.

Figure 3-1: Short Dipole Antenna (ARRL Antenna Book)



a) Directive pattern in plane containing antenna



(B)

b) Solid Diagram

Courtesy *Antenna Book*, 16th Edition, published by ARRL.

The effective area of an antenna related to gain and wavelength is shown in the following expression:

$$A_e = \frac{\lambda^2 \cdot G}{4\pi} \quad (3-2)$$

This expression shows us that the capture ability of an antenna of given gain G grows proportionally as the square of the wavelength. The antenna of a particular configuration captures less power at higher frequencies. (Remember that frequency is inversely proportional to wavelength λ .)

When the electric field strength E is known, the power density is

$$P_d = \frac{E^2}{120\pi} \quad (3-3)$$

Thus, received power can be found when field strength is known by multiplying (3-2) times (3-3):

$$P_R = \frac{E^2 \lambda^2 G}{480\pi^2} \quad (3-4)$$

It's intuitive to note that the effective antenna area has some connection with the physical size of the antenna. This is most obvious in the case of microwave antennas where the effective area approaches the physical aperture. From (3-4) it appears that for a given radiated power and thus field strength, the lower frequency (longer wavelength) systems will give stronger receiver signals than high-frequency equipment. However, short-range devices are often portable or are otherwise limited in size and their antennas may have roughly the same dimensions, regardless of frequency. The lower frequency antennas whose sizes are small fractions of a wavelength have poor efficiency and low gain and therefore may have effective areas similar to their high-frequency counterparts. Thus, using a low frequency doesn't necessarily mean higher power at the receiver, which Eq. (3-4) may lead us to believe.

Polarization

Electromagnetic radiation is composed of a magnetic field and an electric field. These fields are at right angles to each other, and both are in a plane normal to the direction of propagation. The direction of polarization refers to the direction of the electric field in relation to the earth. Linear polarization is created by a straight wire antenna. A wire antenna parallel to the earth is horizontally polarized and a wire antenna normal to the earth is vertically polarized.

The electric and magnetic fields may rotate in their plane around the direction of propagation, and this is called elliptical polarization. It may be created by perpendicular antenna elements being fed by coherent RF signals that are not in the same time phase with each other. Circular polarization results when these elements are fed by equal power RF signals which differ in phase by 90° , which causes the electric (and magnetic) field to make a complete 360° rotation every period of the wave (a time of $1/\text{freq.}$ seconds). Some antenna types, among them the helical antenna, produce elliptic or circular polarization inherently, without having two feed points. There are two types of elliptical polarization, right hand and left hand, which are distinguished by the direction of rotation of the electric field.

The polarization of a wave, or an antenna, is important for several reasons. A horizontally polarized receiving antenna cannot receive vertically polarized radiation from a vertical transmitting antenna, and vice versa. Similarly, right-hand and left-hand circular antenna systems are not compatible. Sometimes this quality is used to good advantage. For example, the capacity of a microwave link can be doubled by transmitting two different information channels between two points on the same frequency using oppositely polarized antenna systems.

The degree of reflection of radio signals from the ground is affected by polarization. The phase and amount of reflection of vertically polarized waves from the ground are much more dependent on the angle of incidence than horizontally polarized waves.

Except for directional, line-of-sight microwave systems, the polarity of a signal may change during propagation between transmitter and receiver. Thus, in most short-range radio applications, a horizontal antenna will receive transmissions from a vertical antenna, for example,

albeit with some attenuation. The term *cross polarization* defines the degree to which a transmission from an antenna of one polarization can be received by an antenna of the opposite polarization. Often, the polarization of a transmitter or receiver antenna is not well defined, such as in the case of a handheld device. A circular polarized antenna can be used when the opposite antenna polarization is not defined, since it does not distinguish between the orientation of the linear antenna.

Bandwidth

Antenna bandwidth is the range of frequencies over which the antenna can operate while some other characteristic remains within a given range. Very frequently, the bandwidth is related to the antenna impedance expressed as standing wave ratio. Obviously, a device that must operate over a number of frequency channels in a band must have a comparatively wide bandwidth antenna. Less obvious are the bandwidth demands for a single frequency device.

A narrow bandwidth or high Q antenna will discriminate against harmonics and other spurious radiation and thereby will reduce the requirements for a supplementary filter, which may be necessary to allow meeting the radio approval specifications. On the other hand, drifting of antenna physical dimensions or matching components could cause the power output (or sensitivity) to fall with time. Changing proximity of nearby objects or the “hand effect” of portable transmitters can also cause a reduction of power or even a pulling of frequency, particularly in low-power transmitters with a single oscillator stage and no buffer or amplifier stage.

Antenna factor

The antenna factor is commonly used with calibrated test antennas to make field strength measurements on a test receiver or spectrum analyzer. It relates the field strength to the voltage across the antenna terminals when the antenna is terminated in its specified impedance (usually 50 or 75 ohms):

$$AF = \frac{E}{V} \quad (3-5)$$

where $AF =$ antenna factor in (meters)⁻¹

$E =$ field strength in V/m

$V =$ load voltage in V

Usually the antenna factor is stated in dB:

$$AF_{\text{dB}}(m^{-1}) = 20 \log (E/V)$$

The relationship between numerical gain G and antenna factor AF is:

$$AF = \frac{4\pi}{\lambda} \cdot \sqrt{\frac{30}{R_L \cdot G}} \quad (3-6)$$

where R_L is the load resistance, usually 50 ohms.

3.3 Types of Antennas

In this section we review the characteristics of several types of antennas that are used in short-range radio devices. The size of the antenna is related to the wavelength, which in turn is found when frequency is known from

$$\text{wavelength} = (\text{velocity of propagation})/(\text{frequency})$$

The maximum velocity of propagation occurs in a vacuum. It is approximately 300,000,000 meters/second, with little difference in air. This figure is less in solid materials, so the wavelength will be shorter for antennas printed on circuit board materials or protected with a plastic coating.

Dipole

The dipole is a wire antenna fed at its center. The term usually refers to an antenna whose overall length is one-half wavelength. In free space its radiation resistance is 73 ohms, but that value will vary somewhat when the ground or other large conducting objects are within a wavelength distance from it. The dipole is usually mounted horizontally, but if mounted vertically, its transmission line feeder cable should extend from it at a right angle for a distance of at least a quarter wavelength.

In free space, the radiation pattern of a horizontal half-wave dipole at zero degrees elevation is very similar to that of the dipole shown in Figure 3-1a. It has a directivity of 1.64, or 2.15 dB. It would seem that this antenna would not be usable for short-range devices that need an omnidirectional radiation, but this isn't necessarily the case. The radiation pattern at an elevation of 30 degrees when the antenna is a half wavelength above a conductive plate is shown in Figure 3-2. The radiation is 8 dB down from maximum along the direction of the wire. When used indoors where there are a multitude of reflections from walls, floor and ceiling, the horizontal dipole can give good results in all directions.

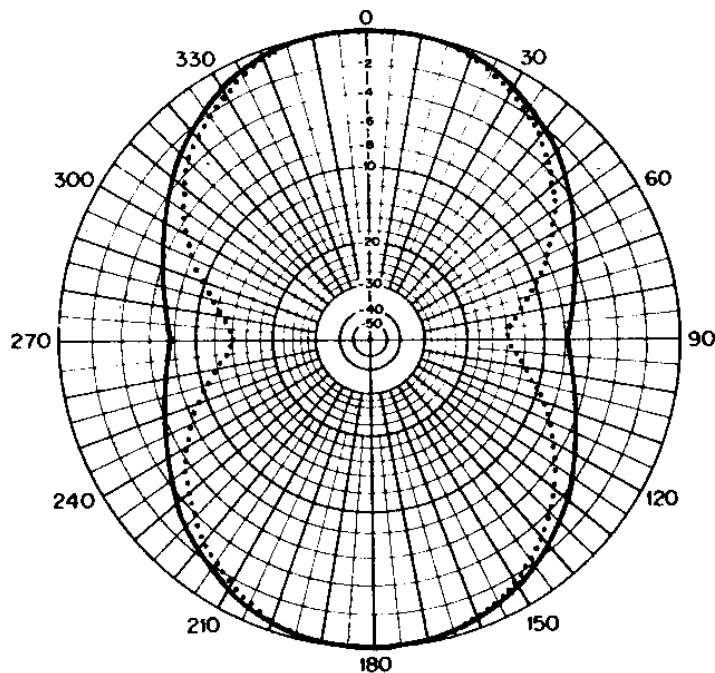


Figure 3-2: Dipole Pattern at 30° Elevation (solid line)

Courtesy 1990 ARRL *Handbook*.

The half-wave dipole antenna is convenient to use because it is easy to match a transmitter or receiver to its radiation resistance. It has high efficiency, since wire ohmic losses are only a small fraction of the radiation resistance. Also, the antenna characteristics are not much affected by the size or shape of the device it is used with, and it doesn't use a ground plane. Devices whose dimensions are small relative to the antenna size can directly feed the dipole, with little or no transmission line. For increased compactness, the two antenna elements can be extended at an angle instead of being in a straight line.

In spite of its many attractive features, the half-wave dipole is not commonly used with short-range radio equipment. On the common unlicensed frequency bands, it is too large for many applications, particularly portable devices. The antenna types below are smaller than the half-wave dipole, and generally give reduced performance.

Groundplane

We mentioned that the dipole can be mounted vertically. If we take one dipole element and mount it perpendicular to a large metal plate, then we don't need the bottom element—a virtual element will be electrically reflected from the plate. When the metal plate is approximately one-half wavelength square or larger, the radiation resistance of the antenna is 36 ohms, and a good match to the receiver or transmitter can be obtained.

The quarter-wave groundplane antenna is ideal if the receiver or transmitter is encased in a metal enclosure that has the required horizontal area for an efficient vertical antenna. However, in many short-range devices, a quarter-wave vertical element is used without a suitable groundplane. In this case, the radiation resistance is much lower than 36 ohms and there is considerable capacitance reactance. An inductor is needed to cancel the reactance as well as a matching circuit to assure maximum power transfer between the antenna and the device. The ohmic losses in the inductor and other matching components, together with the low radiation resistance, result in low antenna efficiency. When possible, the antenna length should be increased to a point where the antenna is resonant, that is, has no reactance. The electrical length can be increased and capacitive reactance reduced by winding the bottom

part of the antenna element into a coil having several turns. In this way, the loss resistance may be reduced and efficiency increased.

Loop

The loop antenna is popular for hand-held transmitters particularly because it can be printed on a small circuit board and is less affected by nearby conducting objects than other small resonant antennas. Its biggest drawback is that it is very inefficient.

A loop antenna whose dimensions are small compared to a wavelength—less than 0.1λ —has essentially constant current throughout. Its radiation field is expressed as

$$E(\theta) = \frac{120\pi^2 \cdot I \cdot N \cdot A}{r \cdot \lambda^2} \cdot \cos\theta \quad (3-7)$$

where

I is its current

A is the loop area

r is the distance

θ is the angle from the plane of the loop

N is the number of turns

From this expression we can derive the radiation resistance which is

$$R_r = 320 \cdot \pi^4 \cdot \frac{(A \cdot N)^2}{\lambda^4} \quad (3-8)$$

Loop antennas are frequently used in small hand-held remote control transmitters on the low UHF frequencies. The radiation resistance is generally below a tenth of an ohm and the efficiency under 10%. In order to match the transmitter output stage to the low antenna resistance, parallel resonance is created using a capacitor across the loop terminals. While it may appear that the radiation resistance and hence the efficiency could be raised by increasing the number of turns or the area of the loop, the possibilities with this approach are very limited. Increasing

the area increases the loop inductance, which requires a smaller value of resonating capacitance. The limit on the area is reached when this capacitance is several picofarads, and then we get the radiation resistance and approximate efficiency as mentioned above.

Because of the low efficiency of the loop antenna, it is rarely used in UHF short-range receivers. An exception is pager receivers, which use low data rates and high sensitivity to help compensate for the low antenna efficiency. One advantage of the loop antenna is that it doesn't require a ground plane.

In low-power unlicensed transmitters, the low efficiency of the loop is not of much concern, since it is the radiated power that is regulated, and at the low powers in question, the power can be boosted enough to make up for the low efficiency. A reasonably high Q is required in the loop circuit, however, in order to keep harmonic radiation low in respect to the fundamental. In many short-range transmitters, it is the harmonic radiation specification that limits the fundamental power output to well below the allowed level.

Example

We will design a loop antenna for a transmitter operating on 315 MHz. The task is easy using the Mathcad worksheet "Loop Antenna."



Given data: $f = 315$ MHz; G10 circuit board 1/16" thick, 1 oz. copper plating, and dielectric constant = 4.7; loop sides 25 mm and 40 mm, conductor width 2 mm.

Enter the relevant data in the worksheet.

The results of this example are:

Radiation resistance = .038 ohm

Loss resistance = .32 ohm

Efficiency = 10.6%

Resonating capacitance 3.65 pF

The results from using the loop antenna worksheet are not particularly accurate, but they do give a starting point for design. Efficiency can be expected to be worse than that calculated because circuit board losses

were not accounted for, nor were the effects of surrounding components. There will also be significant losses in the matching circuit because of the difficulty of matching the high output impedance of the low-power transmitter to the very low impedance of the loop. Transmitters designed to operate from low battery voltages can be expected to be better in this respect (see “Transmitter Output Impedance” later in this section).

Helical

The helical antenna can give much better results than the loop antenna, when radiation efficiency is important, while still maintaining a relatively small size compared to a dipole or quarter-wave ground plane.

The helical antenna is made by winding stiff wire in the form of a spring, whose diameter and pitch are very much smaller than a wavelength, or by winding wire on a cylindrical form. See Figure 3-3. This helical winding creates an apparent axial velocity along the “spring” which is much less than the velocity of propagation along a straight wire—approximately the speed of light in space. Thus, a quarter wave on the helical spring will be much shorter than on a straight wire. The antenna is resonant for this length, but the radiation resistance will be lower and consequently the efficiency is less than that obtained from a standard quarter-wave antenna. The helical antenna resonates when the wire length is in the neighborhood of a half wavelength. Impedance matching to a transmitter or receiver is relatively easy.

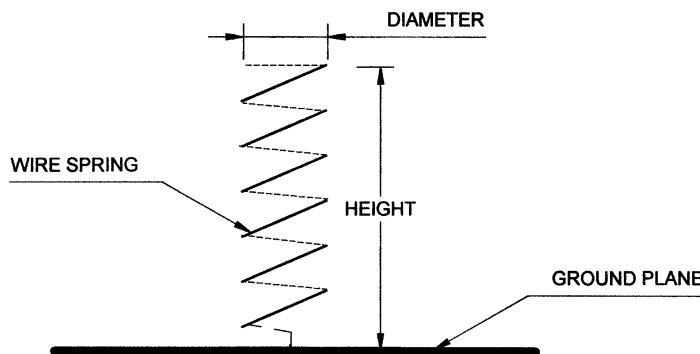


Figure 3-3: Helical antenna

The radiating surface of the helical antenna has both vertical and horizontal components, so its polarization is elliptic. However, for the form factors most commonly used, where the antenna length is several times larger than its diameter, polarization is essentially vertical.

The helical antenna should have a good ground plane for best and predictable performance. In hand-held devices, the user's arm and body serve as a counterpoise, and the antenna should be designed for this configuration.

The Mathcad worksheet "Helical Antenna" helps design a helical antenna. We'll demonstrate by an example.



Example

Our antenna will be designed for 173 MHz. We will wind it on a 10-mm form with AWG 20 wire. We want to find the number of turns to get a resonant antenna 16 cm high. We also want an approximation of the radiation resistance and the antenna efficiency.

Given: The mean diameter of the antenna $D = 10.8$ mm (includes the wire diameter). Wire diameter of AWG 20 is $d = .8$ mm. Antenna height $h = 160$ mm. Frequency $f = 173$ MHz.

We insert these values into the helical antenna worksheet and get the following results:

Number of turns = 26

Wire length = 89 cm = $.514 \lambda$

Radiation efficiency = 90 percent

Total input resistance = 6.1 ohm

The prototype antenna should have a few more turns than the design value so that the length can be gradually reduced while return loss is monitored, until a resonant condition or good match is obtained for the ground plane that results from the physical characteristics of the product. The input resistance of the antenna can be raised by grounding the bottom end of the antenna wire and tapping the wire up at a point where the desired impedance is found.

Patch

The patch antenna is convenient for microwave frequencies, specifically on the 2.4-GHz band and higher. It consists of a plated geometric form (the patch) on one side of a printed circuit board, backed up on the opposite board side by a groundplane plating which extends beyond the dimensions of the radiating patch. Rectangular and circular forms are the most common, but other shapes—for example, a trapezoid—are sometimes used. Maximum radiation is generally perpendicular to the board. A square half-wave patch antenna has a directivity of 7 to 8 dB.

A rectangular patch antenna is shown in Figure 3-4. The dimension L is approximately a half wavelength, calculated as half the free space wavelength (λ) divided by the square root of the effective dielectric constant (ϵ) of the board material. It must actually be slightly less than a half wavelength because of the fringing effect of the radiation from the two opposite edges that are L apart. As long as the feed is on the centerline, the two other edges don't radiate. The figure shows a microstrip feeder, which is convenient because it is etched on the board together with the patch and other component traces on the same side.

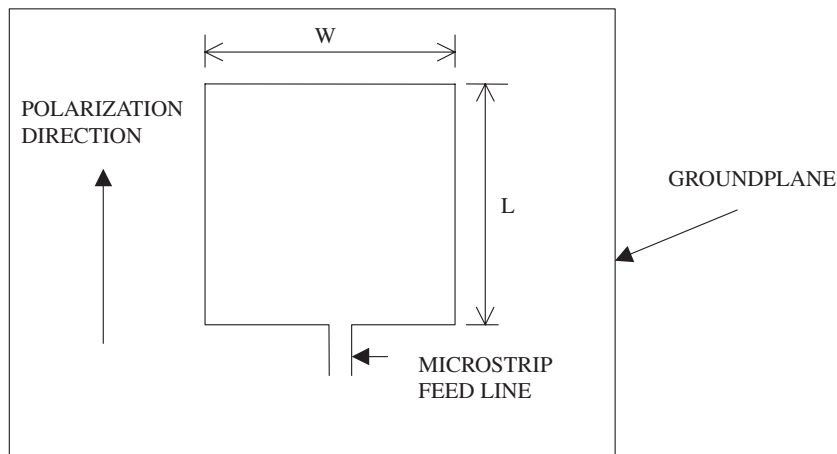


Figure 3-4: Patch Antenna

The impedance at the feed point depends on the width W of the patch. A microstrip transforms it to the required load (for transmitter) or source (for receiver) impedance. The feed point impedance can be made to match a transmission line directly by moving the feed point from the edge on the centerline toward the center of the board. In this way a 50-ohm coax transmission line can be connected directly to the underside of the patch antenna, with the center conductor going to the feed point through a via and the shield soldered to the groundplane.

The Mathcad “Patch Antenna” worksheet on the enclosed CDROM helps design a rectangular patch antenna. It includes calculations for finding the coax cable feed point location.



3.4 Impedance Matching

Impedance matching is important in transmitters and receivers for getting the best transfer of power between the antenna and the device. In a receiver, matching is often done in two stages—matching the receiver input to 50 ohms to suit a bandpass filter and to facilitate laboratory sensitivity measurements, and then matching from 50 ohms to the antenna impedance. Receiver modules most often have 50 ohms input impedance. Receiver integrated circuits or low-noise RF amplifiers may have 50 ohms input, or the input impedance may be specified for various frequencies of operation. Sometimes a particular source impedance is specified that the input RF stage must “see” in order to obtain minimum noise figure.

Impedances to be matched are specified in different ways in component or module data sheets. A complex impedance may be specified directly for the operating frequency or for several possible operating frequencies. Another type of specification is by a resistance with capacitor or inductor in parallel or in series. The degree of matching to a specified impedance, usually 50 ohms, can be expressed by the *reflection coefficient*. This will be discussed later.

There are various circuit configurations that can be used for impedance matching and we present some simple examples here to match a pure resistance to a complex impedance. First, you should be able to express an impedance or resistance-reactance combination in parallel or serial form, whichever is convenient for the matching topography you

wish to use. You can do this using the Mathcad worksheet “Impedance Transformations.” Then use the worksheet “Impedance Matching” to find component values to match a wide range of impedances. The parallel or series source reactance must be separated from the total adjacent derived reactance value to get the value of the component to use in the matching circuit. Example 1 demonstrates this for a parallel source capacitor.



Remember that coils and capacitors are never purely reactive. The losses in coils, specified by the quality factor Q , are often significant whereas those in capacitors are usually ignored. In a parallel equivalent circuit (loss resistance in parallel to the reactance), $Q = R/X$ (X is the reactance). In a series equivalent circuit, $Q = X/R$. If the loss resistance is within a factor of up to around 5 of a resistance to be matched, it should be combined with that resistance before using the impedance matching formula. Example 2 shows how to do it.

Use nearest standard component values for the calculated values. Variable components may be needed, particularly in a high Q circuit. Remember also that stray capacitance and inductance will affect the matching and should be considered in selecting the matching circuit components.

Example 1

Figure 3-5 shows a circuit that can be used for matching a high impedance, such as may be found in a low-power transmitter, to 50 ohms.

Let’s use it to match a low-power transmitter output impedance of 1000 ohms (see the section “Transmitter Output Impedance”) and 1.5-pF parallel capacitance to a 50-ohm bandpass filter or antenna. The frequency is 315 MHz. We use “Impedance Matching” worksheet, circuit 3.

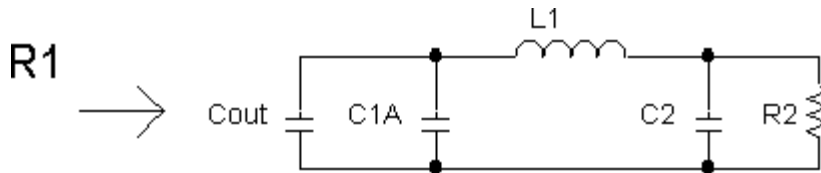


Figure 3-5: Impedance Transformation, Example 1

Given values are:

$$R_1 = 1000 \text{ ohms} \quad C_{out} = 1.5 \text{ pF} \quad R_2 = 50 \text{ ohms} \quad f = 315 \text{ MHz}$$

(a) At the top of the worksheet, set $f = 315 \text{ MHz}$. Under circuit (3) set R_1 and R_2 to 1000 and 50 ohms, respectively. Select a value for Q .

$$Q = 10$$

(b) Rounded off results are:

$$C_1 = 5.1 \text{ pF}$$

$$C_2 = 20.3 \text{ pF}$$

$$L_1 = 101 \text{ nH}$$

(c) C_1 of the worksheet is made up of the parallel combination of C_{out} and C_{1A} of Figure 3-5:

$$C_{1A} = C_1 - C_{out} = 5.1 \text{ pF} - 1.5 \text{ pF} = 3.6 \text{ pF}$$

Example 2

We want to match the input of an RF mixer and IF amplifier integrated circuit (such as Philips NE605) to a 50-ohm antenna at 45 MHz. The equivalent input circuit is 4500 ohms in parallel with 2.5 pF. We choose to use a parallel coil L_{1A} having a value of 220 nH and a Q_{L1A} of 50. See Figure 3-6.

$$\text{Given: } f = 45 \text{ MHz, } R_1 = 50 \text{ ohms, } R_{in} = 4.5\text{K ohms, } C_{in} = 2.5 \text{ pF, } L_{1A} = 220 \text{ nH, } Q_{1A} = 50$$

Find: C_1 and C_2

(a) Calculate RL_{1A}

$$XL_{1A} = 62.2 \text{ ohms (you can use "Conversions" worksheet)}$$

$$RL_{1A} = Q_{1A} \times XL_{1A} = 3110 \text{ ohms}$$

(b) Find equivalent input resistance to be matched, RL_1 :

$$RL_1 = RL_{1A} \parallel R_{in} = (3110 \times 4500)/(3110 + 4500) = 1839 \text{ ohms}$$

(c) Find equivalent parallel inductance L_1

$$XC_{in} = -1415 \text{ ohms (‘‘Conversions’’ worksheet)}$$

$$XL_1 = XL_{1A} \parallel XC_{in} = (62.2 \times (-1415))/(62.2 - 1415) = 65.06 \text{ ohms}$$

(d) Find Q , which is needed for the calculation of C_1 and C_2 using the ‘‘Impedance Matching’’ worksheet:

$$Q = RL_1/XL_1 = 28.27$$

(e) Use the worksheet ‘‘Impedance Matching’’ circuit (4) to find C_1 and C_2 , after specifying R_1 , R_2 , and Q :

$$R_1 = 50 \text{ ohms} \quad R_2 = RL_1 = 1839 \text{ ohms} \quad Q = 28.27$$

Results:

$$C_1 = 65 \text{ pF}$$

$$C_2 = 322 \text{ pF}$$

It may seem that the choice of the parallel inductor was arbitrary, but that’s the designer’s prerogative, as long as the resultant Q is greater than the minimum Q given in the worksheet example (in this case approximately 6). The choice of inductance determines the circuit Q , and consequently the bandwidth of the matching circuit. The total Q of the circuit includes the loading effect of the source resistance. Its value is one half the Q used in the design procedure, or $28.27/2 =$ approximately 14 in this example.

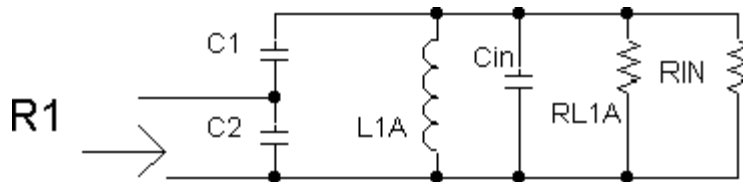


Figure 3-6: Impedance Transformation, Example 2

Example 3

We have a helical antenna with 15-ohm impedance that will be used with a receiver module having a 50-ohm input. The operating frequency is 173 MHz. The matching network is shown in Figure 3-7.

Given: $f = 173$ MHz, $R_1 = 50$ ohms, $R_2 = 15$ ohms

Use these values in the “Matching Impedance” worksheet, circuit (1), to get the matching network components:

$$L_1 = 21.1 \text{ nH}$$

$$C_1 = 28.1 \text{ pF}$$

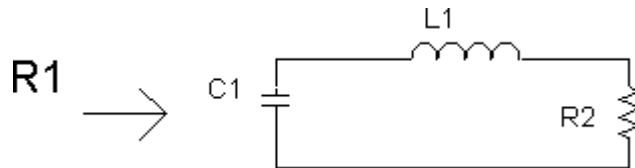


Figure 3-7: Impedance Transformation, Example 3

Transmitter output impedance

In order to get maximum power transfer from a transmitter to an antenna, the RF amplifier output impedance must be known, as well as the antenna impedance, so that a matching network can be designed as shown in the previous section. For very low-power transmitters with radiated powers of tens of microwatts at the most, close matching is not critical. However, for a radiated power of 10 milliwatts and particularly when low-voltage lithium battery power is used, proper matching can save battery energy due to increased efficiency, and can generally simplify transmitter design. Besides, an output bandpass filter needs reasonably good matching to deliver a predictable frequency response.

A simplified estimate of an RF amplifier’s output impedance R_L is given by the following expression:

$$R_L = \frac{(V_{CC} - V_{CE(sat)})^2}{2P} \tag{3-9}$$

V_{CC} is the supply voltage to the RF stage, $V_{CE(sat)}$ is the saturation voltage of the RF transistor at the operating frequency, and P is the power output.

Transmission lines

In many short-range radio devices the transmitter or receiver antenna is an integral part of the device circuitry and is coupled directly to the transmitter output or receiver input circuit through discrete components. This is particularly the case with portable equipment. Devices with an external antenna located away from the equipment housing need a transmission line to connect the antenna to the input or output circuit. The transmission line is an example of a *distributed circuit* and it affects the coupling or transfer of the RF signal between the device RF circuit and the antenna. At high UHF and microwave frequencies, even the short connection between an internal antenna and the RF circuit is considered a transmission line whose characteristics must be designed to achieve proper impedance matching.

The transmission line can take several forms, among them coaxial cable, balanced two-wire cable, microstrip, and waveguide (a special case, not considered below).

A basic characteristic of a transmission line is its *characteristic impedance*. Its value depends on the capacitance per unit length C and inductance per unit length L , which in turn are functions of the physical characteristics of the line and the dielectric constant of the material surrounding the conductors. In the ideal case when there are no losses in the line the relationship is

$$Z_0 = \sqrt{\frac{L}{C}}$$

where L is the inductance per unit length in henrys and C is the capacitance per unit length in farads. Another important characteristic is the velocity factor, which is the ratio of the propagation velocity, or phase velocity, of the wave in the line to the speed of light. The velocity factor depends on the dielectric constant, ϵ , of the material enclosing the transmission line conductors as

$$VF = \frac{1}{\sqrt{\epsilon}}$$

Also important in specifying a transmission line, particularly at VHF and higher frequencies and relatively long lines, is the attenuation or line loss.

For example, the characteristics of a commonly used coaxial cable, RG-58C, are:

Characteristic impedance	50 ohms
Inductance per meter	0.25 microhenry
Capacitance per meter	101 picofarad
Velocity factor	0.66
Attenuation at 50 MHz	3.5 dB per 30 meters
Attenuation at 300 MHz	10 dB per 30 meters

In the previous section we talked about matching the antenna impedance to the circuit impedance. When the antenna is connected to the circuit through a transmission line, the impedance to be matched, seen at the circuit end of the transmission line, may be different from the impedance of the antenna itself. It depends on the characteristic impedance of the transmission line and the length of the line.

Several terms which define the degree of impedance matching, usually relating to transmission lines and antennas, are presented below.

Standing Wave Ratio is a term commonly used in connection with matching a transmission line to an antenna. When the load impedance differs from the characteristic impedance of the transmission line, the peak voltage on the line will differ from point to point. On a line whose length is greater than a half wavelength, the distance between voltage peaks or between voltage nulls is one-half wavelength. The ratio of the voltage peak to the voltage null is the standing wave ratio, abbreviated *SWR*, or *VSWR* (voltage standing wave ratio). The ratio of the peak current to the minimum current is the same as the *VSWR*, or *SWR*.

When the load is a pure resistance, R , and is larger than the characteristic impedance of the line (also considered to be a pure resistance), we have

$$SWR = R/Z_0$$

If the load resistance is less than the line characteristic impedance, then

$$SWR = Z_0/R$$

In the general case where both the line impedance and the characteristic impedance may have reactance components, thus being complex, the voltage standing wave ratio is

$$SWR = \frac{1 + \left| \frac{Z_{load} - Z_0}{Z_{load} + Z_0} \right|}{1 - \left| \frac{Z_{load} - Z_0}{Z_{load} + Z_0} \right|} \quad (3-10)$$

Reflection Coefficient is the ratio of the voltage of the reflected wave from a load to the voltage of the forward wave absorbed by the load:

$$\rho = \frac{E_r}{E_f}$$

When the load is perfectly matched to the transmission line, the maximum power available from the generator is absorbed by the load, there is no reflected wave, and the reflection coefficient is zero. For any other load impedance, less power is absorbed by the load, and what remains of the available power is reflected back to the generator. When the load is an open or short circuit, or a pure reactance, all of the power is reflected back, the reflected voltage equals the forward voltage, and the reflection coefficient is unity. We can express the reflection coefficient in terms of the load impedance and characteristic impedance as

$$\rho = \frac{Z_{load} - Z_0}{Z_{load} + Z_0} \quad (3-11)$$

The relation between the standing wave ratio and the reflection coefficient is

$$SWR = \frac{1 + |\rho|}{1 - |\rho|} \quad (3-12)$$

Return Loss is an expression of the amount of power returned to the source relative to the available power from the generator. It is expressed in decibels as

$$RL = -20 \log(|\rho|) \quad (3-13)$$

Note that the return loss is always equal to or greater than zero.

Of the three terms relating to transmission line matching, the reflection coefficient gives the most information, since it is a complex number. As for the other two terms, *SWR* may be more accurate for large mismatches, whereas return loss presents values with greater resolution than *SWR* when the load impedance is close to the characteristic impedance of the line.

A plot of forward and reflected powers for a range of *SWR*s is given in Figure 3-8. This plot is convenient for seeing the effect of an impedance mismatch on the power actually dissipated in the load or accepted by the antenna, which is the forward power minus the reflected power.

Transmission line losses are not represented in the above definitions. Their effect is to reduce the *SWR* and increase the return loss, compared to a lossless line with the same load. This may seem to contradict the expressions given, which are in terms of load impedance, but that is not so. For instance, the load impedance in the expression for *SWR* (equation (3-10)) is *the impedance at a particular point on the line where the SWR is wanted* and not necessarily the impedance at the end of the line. Thus, a long line with high losses may have a low *SWR* measured at the generator end, but a high *SWR* at the load. Transmission line loss is specified for a perfectly matched line, but when a mismatch exists, the loss is higher because of higher peak current and a resulting increased I^2R power dissipation in the line.

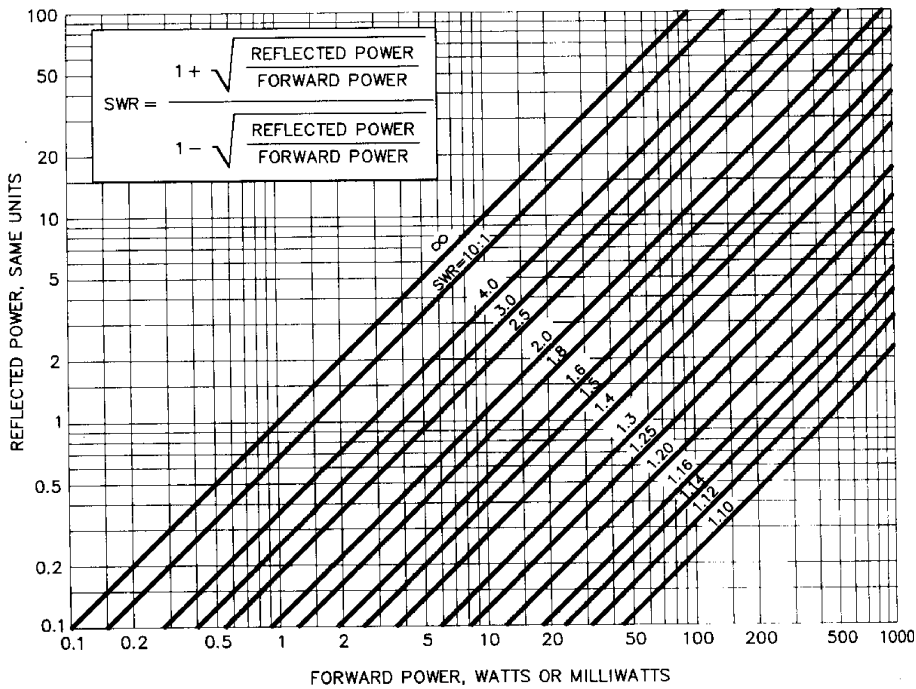


Figure 3-8: SWR, Forward and Reflected Power

Courtesy *Antenna Book*, 16th Edition, ARRL

Smith chart

A convenient tool for finding impedances in transmission lines and designing matching networks is the Smith chart, shown in Figure 3-9.

The Smith chart is a graph on which you can plot complex impedances and admittances (admittance is the inverse of impedance). An impedance value on the chart is the intersection of a resistance circle, labeled on the straight horizontal line in the middle, and a reactance arc, labeled along the circumference of the “0” resistance circle. Figure 3-10 gives an expanded view of the chart with some of the labels. The unique form of the chart was devised for convenient graphical manipulation of impedances and admittances when designing matching networks, particularly when transmission lines are involved. The Smith chart is useful for dealing with distributed parameters which describe the characteristics of circuit board traces at UHF and microwave frequencies.

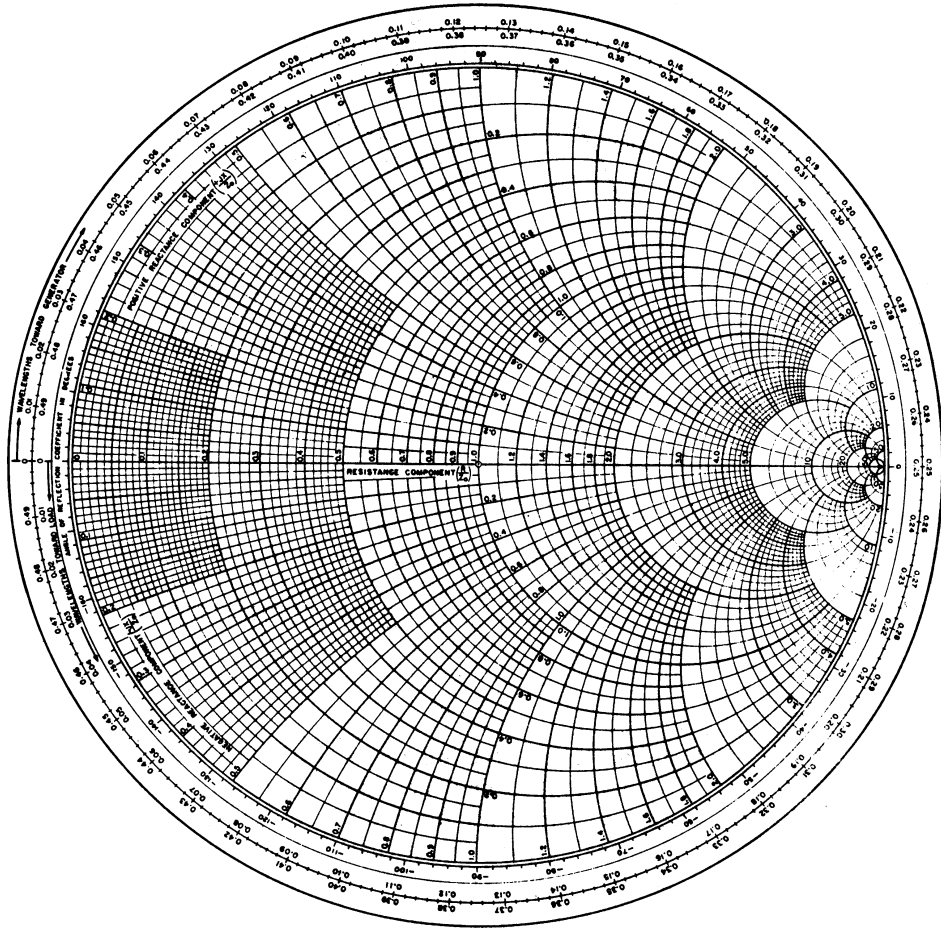


Figure 3-9: Smith Chart

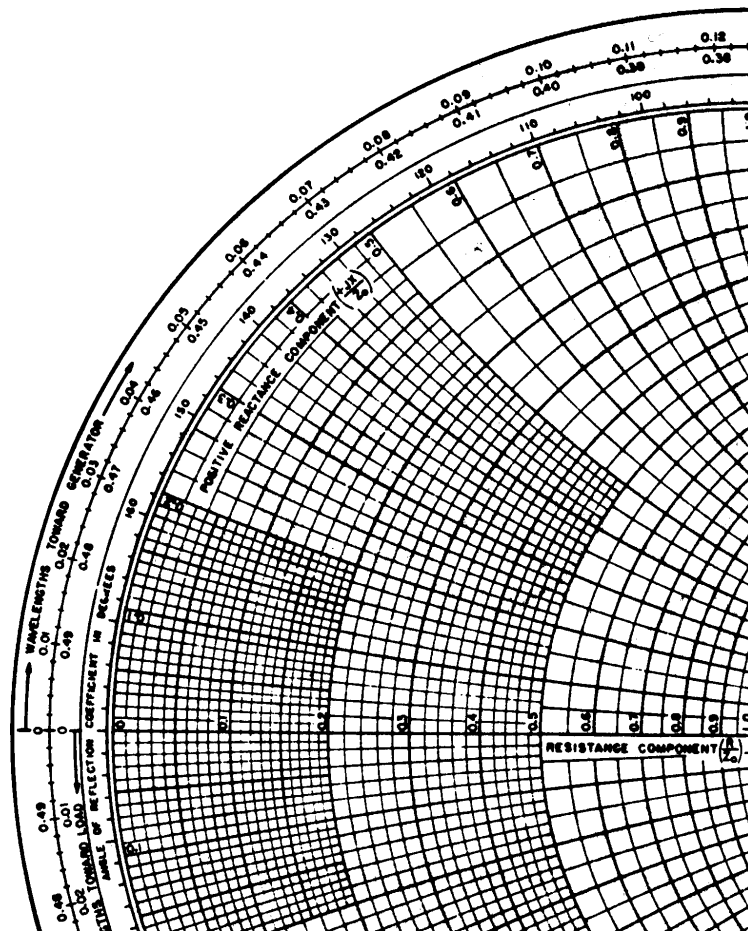


Figure 3-10: Expanded View of Smith Chart

We'll describe some features of the Smith chart by way of an example. Let's say we need to match an antenna having an impedance of 15 ohms resistance in series with a capacitance reactance of 75 ohms to a transmitter with 50 ohms output impedance. The operating frequency is 173 MHz. The antenna is connected to the transmitter through 73 cm of RG-58C coaxial cable. What is the impedance at the transmitter that the matching network must convert to 50 ohms? The example is sketched in Figure 3-11 and Figure 3-12 shows the use of the Smith chart.

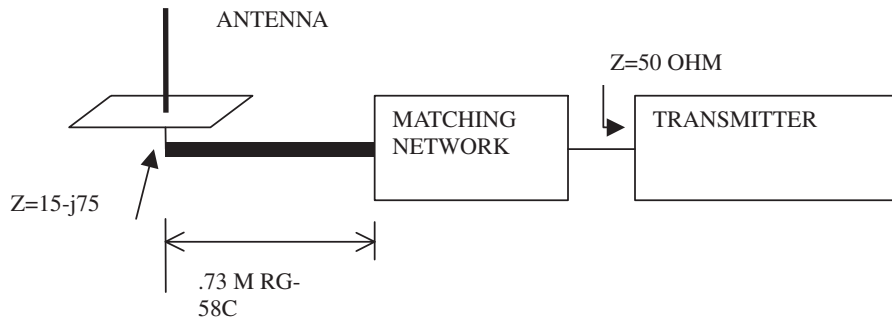


Figure 3-11: Antenna Matching Example

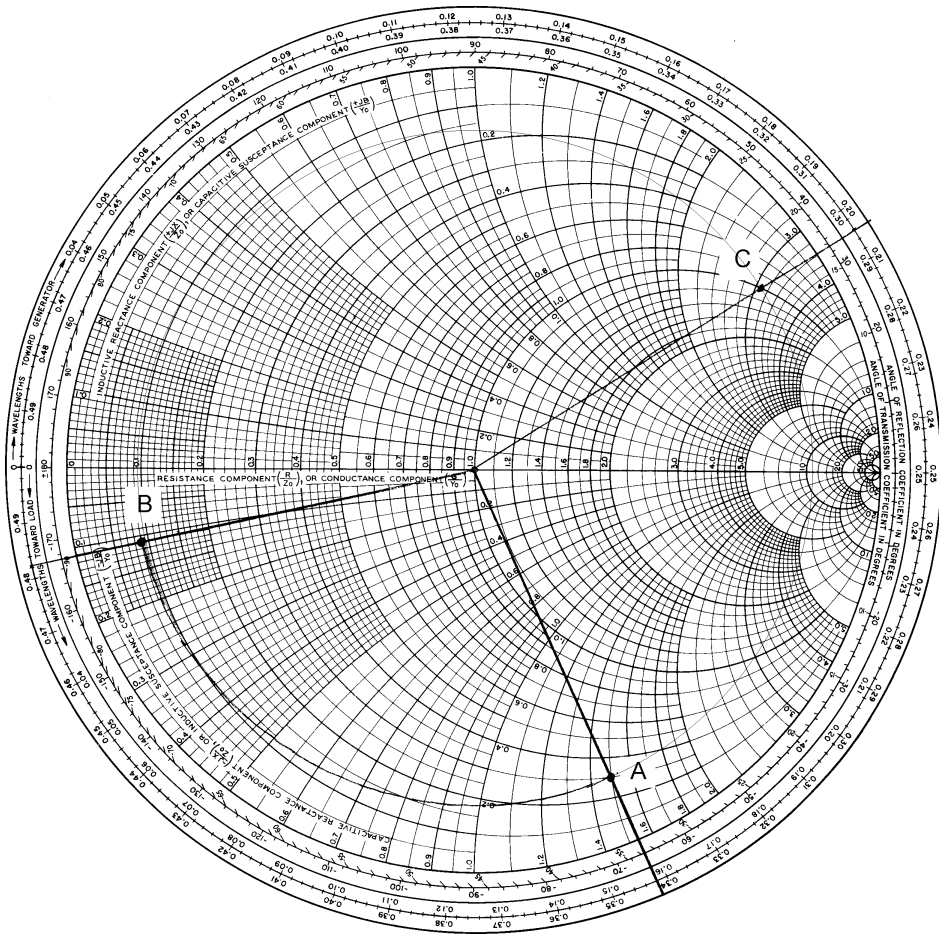


Figure 3-12: Using the Smith Chart

Step 1. First we mark the antenna impedance on the chart. Note that the resistance and reactance coordinates are normalized. The center of the chart, labeled 1.0, is the characteristic impedance of the transmission line, which is 50 ohms. We divide the resistance and capacitive reactance of the antenna by 50 and get, in complex form:

$$Z_{load} = 0.3 - j1.5$$

This is marked at the intersection of the 0.3 resistance circle with the 1.5 capacitive reactance coordinate in the bottom half of the chart. This point is marked “A” in Figure 3-12.

Step 2. The impedance at the transmitter end of the transmission line is located on a circle whose radius is the length of a line from the center of the chart to point “A” (assuming no cable losses). In order to find the exact location of the impedance on this circle for the 73-cm coax cable, we must relate the physical cable length, l , to the electrical length, L , in wavelengths.

$$L = \frac{l}{\eta\lambda}$$

where η is the velocity factor (.66) and λ is the wavelength in free space (3×10^8 /frequency). Inserting the values for this example we find the electrical length of the line is 0.64 wavelengths.

The Smith chart instructs us to move toward the generator in a clockwise direction from the load. The wavelength measure is marked on the outmost marked circle. Every 0.5 wavelengths, the load impedance is reflected to the end of the cable with no change, so we subtract a whole number of half wavelengths, in this case one, from the cable length, giving us

$$.64\lambda_c - .5\lambda_c = 0.14\lambda_c$$

where λ_c is the wavelength in the cable.

The line drawn on Figure 3-12 from the center through Z_{load} (point A) intersects the “wavelengths to generator” circle at 0.342. We add 0.14 to get 0.482 and draw a line from the center to this point. Mark the line at point B, which is the same distance from the center as point A. This is done conveniently with a compass.

Step 3. Read off point B. It is $0.1 - j0.113$. Multiplying by the 50-ohm characteristic impedance we get

$$Z_{gen} = 5 - j5.65 \text{ ohms.}$$

Step 4. Now using the procedure of Example 3 above, we can design a matching network to match the impedance seen at the coax cable to the 50-ohm impedance of the transmitter. You have to add the capacitive reactance, 5.65 ohms, to the reactance you find for L_1 . The resulting network components are $L_1 = 19 \text{ nH}$ and $C_1 = 55 \text{ pF}$.

By examining the Smith chart in Figure 3-12, we note that if we use a longer coaxial cable we can get an impedance at its end that has a real part, or resistance, of 50 ohms, and an inductive reactance of $50 \times 3.1 = 155$ ohms. This is point C in the figure. We attain this impedance by adding $.22\lambda_c = 25 \text{ cm}$ to the original transmission line, for a total coax cable length of 98 cm. Now the only matching component we need is a series capacitor to cancel out the inductive reaction of 155 ohms. Using the “Conversions” worksheet we find its capacitance to be approximately 6 pF.

Other transmission-line matching problems can be solved using the Smith chart. Using the chart, you can easily determine *SWR*, reflection coefficient and return loss. The chart also has provision for accounting for line losses.

The Smith chart is very handy for seeing at a glance the effects on impedance of changing transmission line lengths, and also for using transmission lines as matching networks. Computer programs are available for doing Smith chart plotting. The enclosed Mathcad worksheet “Transmission Lines” solves transmission line problems directly from mathematical formulas.



Microstrip

From around 800 MHz and higher, the lengths of printed circuit board conductors are a significant fraction of a wavelength, so they act as transmission lines. Thus, if the input to a receiver integrated circuit or low-noise amplifier is 50 ohms, and a conductor length of 6 cm connects to the antenna socket, the RF plug from the antenna will *not* see 50 ohms, unless the conductor is designed to have a characteristic impedance of 50

ohms. A printed conductor over a ground plane (copper plating on the opposite side of the board) is called microstrip. The transmission line characteristics of conductors on a board are used in UHF and microwave circuits as matching networks between the various components.

Using the attached Mathcad worksheet “Microstrip,” you can find the conductor width required to get a required characteristic line impedance, or you can find the impedance if you know the width. Then you can use the Smith chart to do impedance transformations and design matching networks using microstrip components. The “Microstrip” worksheet also gives you the wavelength on the pc board for a given frequency. In order to use this worksheet, you have to know the dielectric constant of your board material and the board’s thickness.



3.5 Measuring Techniques

If you happen to have a vector analyzer, you can measure the impedances you want to match, design a matching network, and check the accuracy of your design. When a matching network is designed and adjusted correctly, the impedance looking into the network where it is connected to the load or source is the complex conjugate of the impedance of the load or of the source impedance. The complex conjugate of an impedance has the same real part as the impedance and minus the imaginary part of the impedance. For example, if $Z_{source} = 30 - j12$ ohms, then the impedance seen at the input to the matching network should be $30 + j12$ ohms when its output port is connected to the load.

Without a vector analyzer, you need considerable cut-and-try to optimize the antenna and matching components. Other instruments, usually available in RF electronics laboratories, can be a big help. Here are some ideas for adjusting antennas and circuits for resonance at the operating frequency using relatively inexpensive equipment (compared to a vector analyzer).

A grid dip meter (still called that, although for years it has been based on a transistor oscillator, not a vacuum tube) is a simple, inexpensive tool, popular with radio amateurs. It consists of a tunable RF oscillator with external coil, allowing it to be lightly coupled to a resonant circuit, which can be an antenna of almost any type. When the dip meter is tuned across the resonant frequency of the passive circuit under test, its indicating

meter shows a current dip due to absorption of energy from the instrument's oscillator. A loop antenna with resonating capacitor is easy to adjust using this method. A dipole, ground plane, or helical antenna can also be checked for resonance by connecting a small one-turn loop to the antenna terminals with matching circuit components disconnected. Set the dip meter coil close to the loop and tune the instrument to find a dip.

The main limitation to the grid dip meter is its frequency range, usually no more than 250 MHz. Higher frequency resonances can be measured with a return loss bridge, also called directional bridge or impedance bridge. This device, which is an integral part of a scalar network analyzer, can be used with a spectrum analyzer and tracking generator or a noise source to give a relative display of return loss versus frequency.

The return loss bridge is a three-port device that indicates power reflected from a mismatched load. Figure 3-13 shows a diagram of the bridge. Power applied at the source port passes to the device under test at the test port with a nominal attenuation of 6 dB. Power reflected from the device under test appears at the measurement port, attenuated approximately 6 dB. If the tested circuit presents the same impedance as the characteristic impedance of the bridge, there will be no output at the measurement port, except for a leakage output on the order of 50 dB below the output of the source. If the test port sees an open or short circuit, all power will be reflected and the measurement port output will be around -12 dB. The return loss is the difference between the output measured in dBm at the measurement port when the test port is open or shorted, and the dBm output when the circuit under test is connected to the test port.

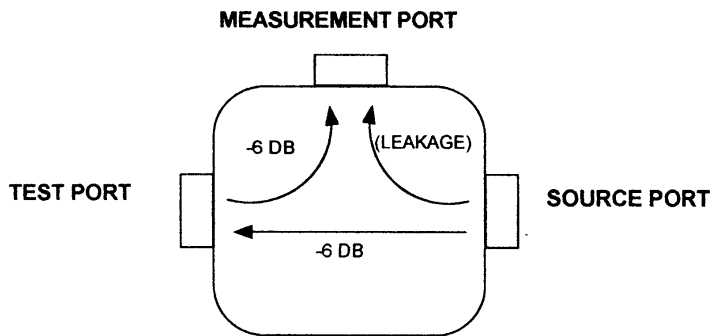


Figure 3-13: Return Loss Bridge

A setup to determine the resonant frequency of an antenna is shown in Figure 3-14 (a). The antenna is connected to the test terminal of the bridge through a short length of 50-ohm coaxial cable. A spectrum analyzer is connected to the measurement port and a tracking generator, whose frequency is swept in tandem with the frequency sweep of the spectrum analyzer, drives the source port.

When the swept frequency passes the resonant frequency of the antenna, the analyzer display dips at that frequency. At the resonant frequency, reactance is cancelled and the antenna presents a pure resistance. The closer the antenna impedance is to 50 ohms, the deeper the dip. Antenna parameters may be changed—length, loading coil or helical coil dimensions, for example—until the dip occurs at the desired operating frequency. Dips are usually observed at several frequencies because of more than one resonance in the system. By noting the effect of changes in the antenna on the various dips, as well as designing the antenna properly in the first place to give approximately the correct resonant frequency, the right dip can usually be correctly identified.

You can get an approximation of the resonant antenna resistance R_{ant} by measuring the return loss RL and then converting it to resistance using the following equations, derived from Equations (3-11) and (3-13), or by using the Mathcad “Transmission Lines” worksheet.



$$\rho = \pm 10^{\frac{-RL}{20}} \quad (3-14)$$

$$R_{ant} = Z_0 \cdot \frac{1 + \rho}{1 - \rho} \quad (3-15)$$

The return loss is a positive value, so when solving for the reflection coefficient in Eq. (3-14), ρ can be either plus or minus, and R_{ant} found in Eq. (3-15) has two possible values. For example, if the return loss is 5 dB, the antenna resistance is either 14 ohms or 178 ohms. You decide between the two values using an educated guess. A monopole antenna over a ground plane, helically wound or having a loading coil, whose length is less than a quarter wave will have an impedance less than 50 ohms. Once the resistance is known, you can design a matching network as described above.

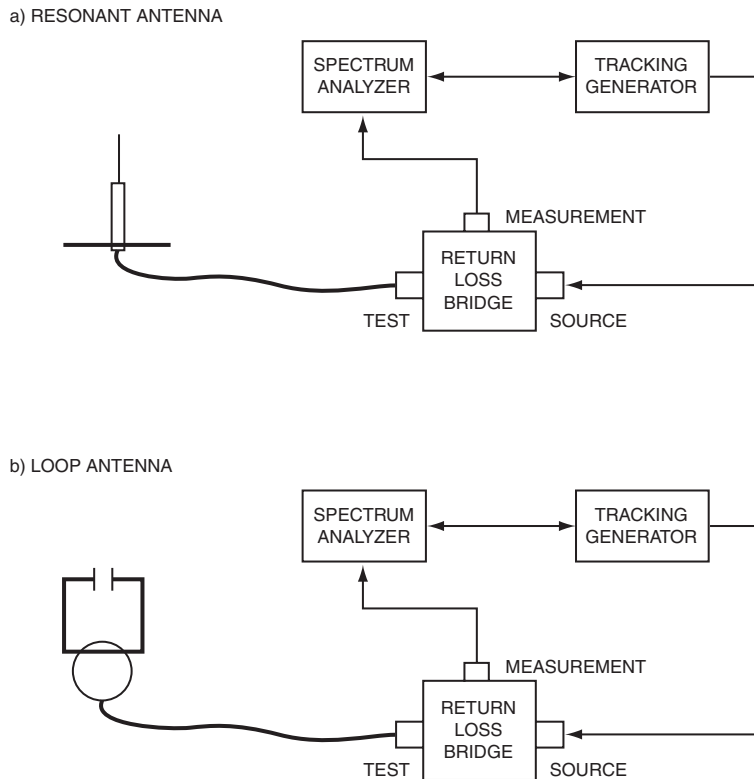


Figure 3-14: Resonant Circuit Test Setup

The arrangement shown in Figure 3-14(b) is convenient for checking the resonant frequency of a loop antenna, up to around 500 MHz. Use a short piece of coax cable and a loop of stiff magnet wire with a diameter of 2 cm. Use two or three turns in the loop for VHF and lower frequencies. At loop resonance, the spectrum analyzer display shows a sharp dip. Keep the test coil as far as possible from the loop, while still seeing the dip, to avoid influencing the circuit. You can easily tune the loop circuit, if it has a trimmer capacitor, by observing the location of the dip. The same setup can be used for checking resonance of tuning coils in the transmitter or receiver. There must be no radiation from the circuit when this test is made. If possible, disable the oscillator and apply power to the device being tested. The resonant frequency of a tuned circuit that is coupled to a transistor stage will be different when voltage is applied and when it is not.

3.6 Summary

We have covered in this chapter the most important properties of antennas and transmission lines that one needs to know to get the most from a short-range radio system. Antenna characteristics were defined. Then we discussed some of the types of antennas commonly used in short-range systems and gave examples of design. Impedance matching is imperative to get the most into, and out of, an antenna, and we presented several matching circuits and gave examples of how to use them. We introduced the Smith chart, which may not be as widely used now as it once was as a design tool, but understanding it helps us visualize the concepts of circuit matching, particularly with distributed components.

Finally, we showed some simple measurements which help in realizing a design and which considerably shorten the cut-and-try routine that is almost inevitable when perfecting a product.

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