Marco Zennaro
Carlo Fonda

Radio Laboratory Handbook

of the ICTP "School On Digital Radio Communications for Research and Training in Developing Countries"

Volume 1

Cables and Antennas

February 2004

Radio Laboratory Handbook

1 - Cables and Antennas

Contents

Foreword

Recently, modern radio has generated much interest because of its potential to facilitate access to the global information infrastructure, and to close the 'digital divide' as named it Kofi Annan, the UN Secretary General. Many projects have been launched to solve the problem, but without active involvement of young scientists and engineers in developing countries, without wide dissemination of the 'know-how', there is no hope to bridge the "digital gap" in the foreseeable future. Training activities on digital radio have been initiated at ICTP schools and colleges, some of which were carried out in collaboration with other entities, such as the International Union of Radio Science (URSI), and the International Telecommunication Union Telecommunication Development Bureau (ITU/BDT). These activities included tutorial lectures and laboratory work, where both computer networking and innovative digital radio techniques were experienced by some 1500 participants from all the continents since 1996. As a result, a series of concrete ICT projects have been initiated, developed and successfully completed in Nigeria, Sudan, Benin, Ghana and Romania.

This book was prepared for the participants in the 2004 School on Digital Radio Communications for Research and Training in Developing Countries, but also other people may found it useful. Following the request of the participants, the school program is focused on innovative solutions in design and implementation of 2.4 GHz low-cost wireless local area networks (WLANs) not only interconnecting computers, but also offering data, audio, and video communications at distances up to about 25 kilometers. The goal is to provide the participants with knowledge and skills needed to setup wireless networks for campus WLANs and links to remote internet service providers, using modest resources available locally in their home countries. Much of the school time is thus devoted to hands-on sessions of antenna building, installation, testing and measurements, and this volume guides through these activities step-by-step.

The book contains also some theoretical background and bases on the experience the authors gained at the previous schools and elsewhere. The contents of this volume will be available also on CDROM and at the webpage *http://wireless.ictp.trieste.it*. It will be complemented by other teaching material and documentation, tutorials, and open source software, as well as by reviews of the state-of-the-art technologies and will be updated from time to time. The free on-line access to lecture notes, hands-on guides, manuals and tutorials from previous schools has already enjoyed a daily average of some 450 visits and 260 MB of data retrieved.

We hope that the 2004 school and this material will contribute to advancing scientific development in academic and research institutions in Developing Countries, and it is up to the scientists and professors employed there to make use of information offered and to disseminate it further.

Comments on this book and on the school can be submitted to *sandro.radicella@ictp.trieste.it*

Prof. Dr. Sandro M. Radicella, Co-Director of the School
Prof. Dr. Ryszard Struzak, Co-Director of the School

Basic Concepts

RF Basics

The technology involving the generation, the manipulation, the transmission and the reception of radio waves, and the use of these to transmit information (both in analog and digital way), is called RF technology or, nowadays, *wireless* technology. The literal meaning of RF is *Radio Frequency*, but this term is often use in the figurative sense of "anything related to electromagnetic signals".

An electromagnetic or RF signal is a controlled variation of electrical energy over time. The simplest example of such a variation is when the intensity of the electric field grows to some maximum, then goes back to zero, becoming negative and reaching some minimum value, before returning back to zero and then starting the process again, following the shape of the trigonometric function called *sine*. The *sine wave* is the basic example of a signal that can be generated, transmitted and received with RF equipment. It may be characterized by its *frequency* and its *amplitude*:

- the frequency is the number of times a signal goes through a complete "up and down" cycle in one second of time, and is measured in *Hertz* (being 1 Hz the frequency of a signal that makes a complete cycle every second);

- the amplitude of a signal is the difference between its maximum and its minimum value during one cycle. It is measured with the same unit used for the intensity of the electric field, the *Volt* (V), and is related with the strength, or power, of the signal.

The units used to measure frequency and amplitude may become inadequate when the numeric values of such quantities become very small or very big, so that a different notation is needed, called the scientific notation, that use the powers of ten to multiply the values. It gives also standard names to the many prefixes associated with these multiplying factors.

Some are listed here:

milli (m)	1/1000	10 to the power of -3	ex.: 1 mV
micro (μ)	1/1000000	10 to the power of -6	ex.: 1 μV
kilo (k)	1000	10 to the power of 3	ex.: 1 kHz
Mega (M)	1 million	10 to the power of 6	ex.: 1 MHz
Giga (G)	1 billion	10 to the power of 9	ex.: 1 GHz

Frequency, bands and bandwidth

The concept of frequency is the key to understanding RF, because almost everything in the RF world is frequency-dependent. Signals can be distinguished on the basis of their different frequencies, and RF devices are almost always characterized by the range of frequencies they can generate, measure or handle.

The range of frequencies used is also the most common way to distinguish one wireless application from another. This is achieved using the concept of *frequency band*, that is a standard way to name a specific range of frequencies. A list of RF bands of common use is given here:

HF	High Frequency	3 MHz - 30 MHz
VHF	Very High Frequency	30 MHz - 300 MHz
UHF	Ultra High Frequency	300 MHz - 3 GHz
SHF	Super High Frequency	3 GHz - 30 GHz
EHF	Extra High Frequency	30 GHz - 300 GHz

While for the microwave range a more detailed band list is this one:

L band	1GHz - 2 GHz
S band	2GHz - 4GHz
C band	4GHz - 8GHz
X band	8GHz - 12GHz
Ku band	12GHz - 18GHz
K band	18GHz - 27GHz
Ka band	27GHz - 40GHz

The bands we are mostly interested in for this handbook are the ISM (Industrial, Scientific and Medical) radio bands, that were originally reserved internationally for non-commercial use of RF electromagnetic fields for industrial, scientific and medical purposes. The ISM bands are defined by the ITU-T in S5.138 and S5.150 of the Radio Regulations and are used for license-free error-tolerant digital communications applications such as wireless LANs and Bluetooth:

“900MHz” ISM band	902MHz - 928MHz (Americas only)
“2.4GHz” ISM band	2400MHz - 2483.5MHz
”5GHz” ISM band	5725MHz - 5875MHz

Many other RF bands and possible classifications and definitions exist, that we will not consider here.

Together with the concept of frequency, there is another useful one: the *bandwidth*. While in the telecommunications world the term bandwidth has a general meaning of how much information can be carried in a given period of time (usually a second) over a wired or wireless communications link, in the RF world the bandwidth is the width of the range of frequencies that an electronic signal occupies on a given transmission medium. Any RF signal has a bandwidth, expressed in terms of the difference between the highest-frequency signal component and the lowest-frequency signal component. A typical voice transmission like a phone call has a bandwidth of approximately 3 kHz; a stereo musical signal like a FM radio broadcast has a bandwidth of 200 KHz; an analog television (TV) broadcast video signal has a bandwidth of 6 MHz.

Wavelength

The wavelength is the distance a radio wave will travel during one cycle. The formula which relates the wavelength to the frequency is the following:

$$\lambda = \frac{c}{f}$$

where λ is the wavelength, expressed in meters , c is the speed of light, which is exactly 299793,07 meters/second, and f is the frequency. Following is a table with the wavelength for different ISM frequencies:

Frequency	Wavelength
900 MHz	0.33 m
2.4 GHz	0.125 m
5.0 GHz	0.06 m

The speed of propagation at a certain frequency in a coaxial cable is slower than in air, so the wavelength is shorter. The velocity of propagation of electromagnetic waves in coaxial cables is usually given as a percentage of the free space velocity, and it is different for different types of coaxial cables, and is called Velocity Factor (VF).

Amplitude and power

The amplitude of an RF signal, measured in Volts, is not of common use in the RF world, while the related concept of *power* of a signal is much more used and useful.

The power of a constant low-frequency signal is measured in *Watts*, symbolized by W, and is the product of the amplitude (or voltage, measured in Volts) and the current (measured in Amperes). One watt is also the power resulting from an energy dissipation, conversion, or storage process equivalent to one Joule per second. At high frequencies, in which energy is stored and released (as well as dissipated or converted), the relation between power, amplitude and current is more complex.

In a DC circuit, a source of E volts, delivering I Amperes, produces P Watts according to the formula:

$$P = E\,I$$

When a current of I Amperes (A) passes through a *resistance* of R Ohms (Ω), then the power in Watts dissipated or converted by that component is given by:

$$P = I^2R$$

When a potential difference of E Volts appears across a component having a resistance of R Ohms, then the power in Watts dissipated or converted by that component is given by:

$$P = E^2/R$$

In a DC circuit, power is a scalar (one-dimensional) quantity. In the general RF case, the determination of power requires two dimensions, because RF power is a vector quantity. Assuming there is no reactance (opposition to RF but not to DC) in an RF circuit, the power can be calculated according to the above formulas for DC, using root-mean-square values for the alternating current and voltage. If reactance exists, some power is alternately stored and released by the system. This is called apparent power or reactive power. The resistance dissipates power as heat or converts it to some other tangible form; this is called true power. The vector combination of reactance and resistance is known as impedance.

Decibels and dB math

The *decibel* (abbreviated as *dB*) is a logarithmic expression of the ratio between the power, voltage, or current of two signals. A decibel is one-tenth of a Bel, a seldom-used unit named for Alexander Graham Bell.

Suppose a signal has a power of P_1 watts, and a second signal has a power of P_2 watts. Then the power ratio in decibels, symbolized P_{dB}, is:

$$P_{dB} = 10 \log_{10} (P_2 / P_1)$$

Decibels can also be calculated in terms of the effective voltage if the load impedance remains constant. Suppose a signal has an RMS (root-mean-square) voltage of V_1 across a load, and a second signal has an RMS voltage of V_2 across another load having the same impedance. Then the voltage amplitude difference in decibels, symbolized V_{dB}, is:

$$V_{dB} = 20 \log_{10} (V_2 / V_1)$$

When a decibel figure is positive, then the second signal is stronger than the first signal and the power ratio is called *gain*. When a decibel figure is negative, then the second signal is weaker than the first signal and the power ratio is called *loss*. In amplifiers, the gain, also called the amplification factor, is often expressed in decibels.

For example, if a signal at the output of an amplifier is 100 times bigger then the signal at its input, the amplifier has a gain of 100 or, using the definition of decibel, of 20 dB. Some useful values to remember are:

+3 dB	means	two times bigger
+10 dB	means	ten times bigger
- 3 dB	means	one half
-10 dB	means	one tenth

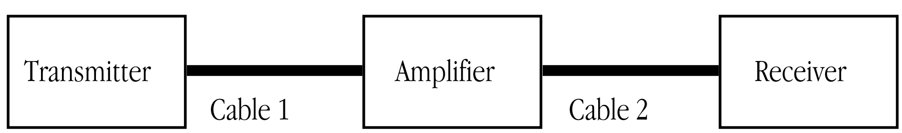
To express power using decibels we need a specific power to be assumed as a reference. In the RF world the common standard is to refer powers to 1 mW (0.001 Watts). Such power ratio, expressed in decibels, is called dBm. Following the definition of dB, we have:

$$P_{dBm} = 10 \log_{10} (P_{Watts} / 1\ mW)$$

A table of correspondence between Watts and dBm is given here:

1 μW	=	-30 dBm
10 μW	=	-20 dBm
100 μW	=	-10 dBm
1 mW	=	0 dBm
10 mW	=	10 dBm
100 mW	=	20 dBm
1 W	=	30 dBm
10 W	=	40 dBm
100 W	=	50 dBm

The advantage of using decibels instead of Watts to express the power of a signal along an *RF chain* (a chain composed by RF devices like transmitters, receivers, cables, amplifiers, attenuators, measurement instruments, loads, etc.) is that instead of dividing or multiplying powers to take care of amplifications and attenuations, we just add or subtract the gains and the losses expressed in decibels. An example follows:



Using amplification and attenuation factors and expressing the powers in Watts, we obtain the value of the power at the receiver's input in this way:

$$P_{\text{Receiver}} = P_{\text{Transmitter}} \times \frac{1}{\text{Attenuation}_{\text{Cable1}}} \times \text{Amplification} \times \frac{1}{\text{Attenuation}_{\text{Cable2}}}$$

If we use dB to express the gains and the losses and dBm to express the powers, the calculation becomes a simple addition:

$$P_{\text{Receiver}} = P_{\text{Transmitter}} + \text{Loss}_{\text{Cable1}} + \text{Gain}_{\text{Amplifier}} + \text{Loss}_{\text{Cable2}}$$

The procedure of adding gains and losses to obtain the resulting power for an RF chain is very commin and is called *Power Budget Calculation*.

Transmission Lines

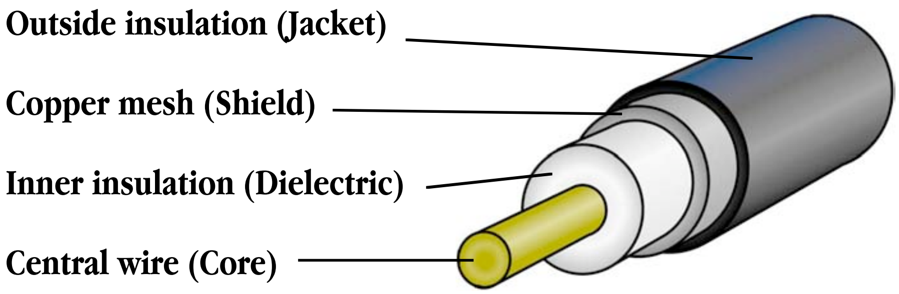
Introduction

The transmitter that generates the RF power to drive the antenna is usually located at some distance from the antenna terminals. The connecting link between the two is the *RF transmission line*. Its purpose is to carry RF power from one place to another, and to do this as efficiently as possible. From the receiver side, the antenna is responsible for picking up any radio signals in the air, and passing them to the receiver with the minimum amount of distortion so that the radio has its best chance to decode the signal. For these reasons, the RF cable has a very important role in radio systems: it must maintain the integrity of the signals in both direction.

There are two main categories of transmission lines: *cables* and *waveguides*.

Cables

RF cables are, for frequencies higher than HF, almost exclusively *coaxial cables* (or "coax" for short, derived from the words "of common axis"). Coax cables have a core wire, surrounded by a non-conductive material (which is called dielectric or insulation), and then surrounded by an encompassing shielding which is often made of braided wires. The dielectric keeps the core and the shielding apart. Finally, the coax is protected by an outer shielding which will generally be a PVC material. The inner conductor carries the RF signal and the outer shield is there to keep the RF signal from radiating to the atmosphere and to stop outside signals from interfering with the signal carried by the core. Another interesting fact is that the electrical signal always travels along the outer layer of the central conductor: the larger the central conductor, the better signal will flow. This is called the "skin effect".



In the following table the diameters of Core, Dielectric, Shield and Jacket of the most popular Coax cables can be found.

Cable Type	Core (mm)	Dielectric (mm)	Shield (mm)	Jacket (mm)
RG-58	0.9	2.95	3.8	4.95
RG-213	2.26	7.24	8.64	10.29
LMR-400	2.74	7.24	8.13	10.29
3/8" LDF	3.1	8.12	9.7	11

Even though the coaxial construction is good at containing the signal on the core wire, there is some resistance to the electrical flow: as the signal travels down the core, it will fade away. This fading is known as attenuation, and is measured in dB/m. The rate of attenuation is a function of the signal frequency and the physical construction of the cable itself., and a table of these values can be found in the next chapter. Obviously, we need to minimize the cable attenuation as much as possible, keeping the cable very short and using high quality cables.

Practical Hints: How to choose the proper cable

- "The shorter the better!": the first rule when you have to place a cable is to try to keep it as short as possible. The power loss is not linear, so doubling the cable length means that you are going to loose much more than twice the power. In the same way, halfening the cable length gives you more than twice the power at the antenna. The best solution is to place the transmitter as close as possible to the antenna, even when this means placing it on the top of a mast.

- “The cheaper the worse!”: the second golden rule is that the money you invest in buying a good quality cable is a bargain. Cheap cables are intended to be used at low frequencies, not higher than VHF. Microwaves require the highest quality cables, all other options are nothing else than a dummy load.

- always avoid *RG-58*. It is intended for thin Ethernet networking, CB or VHF radio, not for microwave.

- always avoid *RG-213*. It is intended for CB and HF radio. The cable diameter does not imply a high quality, or low attenuation.

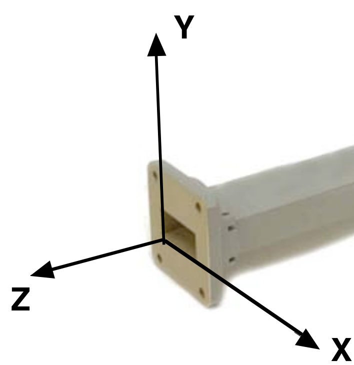
- always use “*Heliax*” (also called “*Foam*”) cables for connecting the transmitter to the antenna, and Semi-rigid cables to interconnect the other devices in the RF chain (i.e. instrumentation). Semi-rigid cables consist of a solid inner conductor (usually copper or silver/copper-plated steel), a solid PTFE dielectric and a solid copper outer pipe. They are sealed, and their rigid construction means that they cannot flex. However the loss is still relatively high due to the small diameter, and they are therefore rarely used as a feeder to an antenna. Heliax cables are basically larger diameter flexible versions of Semi-rigid cables, with a corrugated solid outer conductor to enable them to flex more easily. They can be built in two ways: using air or foam as dielectric. The first solution is the most expensive, guarantees the minimum loss but is very difficult to handle. The second solution is more lossy but less expensive and easier to install. A special procedure is required when soldering connectors, in order to maintain the foam dielectric dry and uncorrupted.

- never step over a cable, never bend it too much, never try to unplug a connector pulling directly the cable. All those behaviors may change the mechanical characteristic of the cable and therefore its impedance, shortcut the inner conductor with the shield, or even break the line. Those problems are difficult to track and recognize and can lead to unpredictable behavior of the radio link.

Waveguides

Above 2 GHz, the wavelength is short enough to allow practical, efficient energy transfer by different means. A waveguide is a conducting tube through which energy is transmitted in the form of electromagnetic waves. The tube acts as a boundary that confines the waves in the enclosed space. The skin effect prevents any electromagnetic effects from being evident outside the guide. The electromagnetic fields are propagated through the waveguide by means of reflections against its inner walls, which are considered perfect conductors. The intensity of the fields is greatest at the center along the X dimension, and must diminish to zero at the end walls because the existence of any field parallel to the walls at the surface would cause an infinite current to flow in a perfect conductor. Waveguides, of course, cannot carry RF in this fashion.

The X, Y and Z dimensions of a rectangular waveguide can be seen in the following figure:



There are an infinite number of ways in which the electric and magnetic fields can arrange themselves in a waveguide for frequencies above the low cutoff frequency. Each of these field configurations is called a *mode*. The modes may be separated into two general groups. One group, designated *TM (Transverse Magnetic)*, has the magnetic field entirely transverse to the direction of propagation, but has a component of the electric field in the direction of propagation. The other type, designated *TE (Transverse Electric)* has the electric field entirely transverse, but has a component of magnetic field in the direction of propagation. TM waves are sometimes called E waves, and TE waves are sometimes called H waves, but the TM and TE designations are preferred. The mode of propagation is identified by the group letters followed by two subscript numerals. For example, TE_{10}, TM_{11}, etc. The number of possible modes increases with the frequency for a given size of guide, and there is only one possible mode, called the *dominant mode*, for the lowest frequency that can be transmitted. In a rectangular guide the critical dimension is X. This dimension must be more than 0.5 λ at the lowest frequency to be transmitted. In practice, the Y dimension usually is made about equal to 0.5 X to avoid the possibility of operation in other than the dominant mode. Cross-sectional shapes other than the rectangle can be used, the most important being the circular pipe. Much the same considerations apply as in the rectangular case. Wavelength dimensions for rectangular and circular guides are given in the following table, where X is the width of a rectangular guide and r is the radius of a circular guide. All figures apply to the dominant mode.

Type of Guide	Rectangular	Circular
Cutoff Wavelength	2X	3.41r
Longest Wavelength transmitted with little attenuation	1.6X	3.2r
Shortest Wavelength before next mode becomes possible	1.1X	2.8r

Energy may be introduced into or extracted from a waveguide by means of either an electric or magnetic field. The energy transfer frequently is through a coaxial line. Two possible methods for coupling to a coaxial line are using the inner conductor of the coaxial line or through a loop. A probe which is simply a short extension of the inner conductor of the coaxial line can be oriented so that it is parallel to the electric lines of force. A loop can be arranged so that it encloses some of the magnetic lines of force. The point at which maximum coupling is obtained depends upon the mode of propagation in the guide or cavity. Coupling is maximum when the coupling device is in the most intense field. If a waveguide is left open at one end it will radiate energy. This radiation can be enhanced by flaring the waveguide to form a pyramidal horn antenna.

Connectors and Adapters

Connectors allow a cable to be connected to another cable or to a component of the RF chain. There is a wide variety of fittings and connectors designed to go with various sizes and types of coaxial lines. We will describe some of the most popular ones.

BNC connectors were developed in the late 40s, and BNC stands for Bayonet Neill Concelman after Amphenol's engineer Carl Concelman. The BNC product line is a miniature quick connect/disconnect connector. It features two bayonet lugs on the female connector, and mating is achieved with only a quarter turn of the coupling nut. BNC's are ideally suited for cable termination for miniature to subminiature coaxial cable (RG - 58 to RG - 179, RG - 316, etc.). They have acceptable performance up to few GHz.

Type N (Navy) connectors were originally developed during the Second World War. They are usable up to 18 Ghz, and very common for microwave and available for almost all types of cable. Both the plug/cable and plug/socket joints are waterproof, providing an effective cable clamp.

SMA is an acronym for SubMiniature version A and was developed in the 60s. 50 Ω SMA connectors are precision, subminiature units that provide excellent electrical performance up to 18 GHz. These high-performance connectors are compact in size and mechanically have outstanding durability.

The *SMB* name derives from SubMiniature B, and it is the second subminiature design. The SMB is a smaller version of the SMA with snap-on coupling. It provides broadband capability through 4 GHz with a snap-on connector design.

MCX connectors were introduced in the 80s. While the MCX uses identical inner contact and insulator dimensions as the SMB, the outer diameter of the plug is 30% smaller than the SMB. This series provides designers with options where weight and physical space are limited. MCX provides broadband capability though 6 GHz with a snap-on connector design.

The *MMCX* series is also called MicroMate™. It is one of the smallest RF connector line and was developed in the 90s. MMCX is a micro-miniature connector series with a lock-snap mechanism allowing for 360 degrees rotation enabling flexibility.

Adapters, which are also called coaxial adapters, are short, two-sided connectors which are used to join two cables or components which cannot be connected directly. In particular, there are two kinds of a adapters. The first one are adapters used to fit connectors of different types. For example an adapter can be used to connect a SMA connector to a BNC one.

Another kind of adapter is the one used to fit connectors of the same type but which cannot be directly joined because of their gender. For example a very useful adapter is the one which enables to join two Type N connectors, having socket (female) connectors on both sides. In this figure, one of these adapters is shown.

Practical Hints: How to choose the proper connector

- “The gender question”: connector do have a well-defined gender. Usually cables have male connectors at both sides, while RF devices (i.e. transmitters and antennas) have female connectors. Devices as directional couplers and line-through measuring devices may have both male and female connectors. Moreover, connectors have their own threading: it is usually right-hand, but left-hand thread exists as well, especially for WiFi devices due to some US regulations. Be careful about it.

- “The less the best!”: try to minimize the number of connectors/adapters in the RF chain, because each of them introduces some loss (even some dB for each connection!).

- “Buy, don’t build!”: if possible, buy cables that are already terminated with the connectors you need. Soldering connectors is not an easy task, and to do this job properly is almost impossible for small connectors as MCX and MMCX. Even terminating “Foam” cables is not an easy task.

- don’t use BNC for 2.4GHz or higher, use N type connectors (or SMA, SMB, MCX, etc.).

- microwave connectors are precision-made parts, and can be easily damaged by mistreatment. As a general rule, if the connectors have threaded sleeves, you should rotate these to tighten, leaving the rest of the connector (and cable) stationary. If other parts of the connector are twisted while tightening or loosening, damage can easily occur.

- never step over connectors, or drop connectors on the floor when disconnecting cables (this happens more often than what you may imagine, especially when working on a mast over a roof).

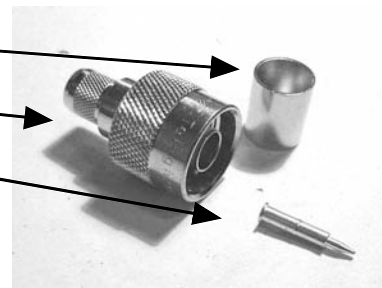
- never use tools like pliers to tighten connectors, use your hands. When working outside, remember that metals expand at high temperatures and reduce their size at low temperatures: a very tightened connector in the summer can even break in winter.

Experiment 1: How to put together an N Type connector

As an example, we will learn how to terminate an RG 213 like coaxial cable with an N type male connector.

Equipment Required:

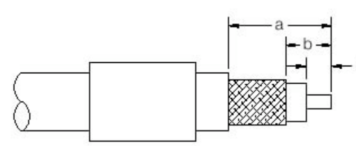
- the connector. It is provided in three parts: the outer ring (for crimping), the connector body and the inner pin (which can be soldered or crimped).
Other versions of the connector exist, intended for soldering;



- the cable. Remember to add to the required length of the cable at least 2 cm at each end, for the connectors;
- a cutter and/or a pair of scissors;
- a soldering iron with a small tip;
- some solder (1 mm of thickness, 60%-40%);
- a crimping tool for RG 213.

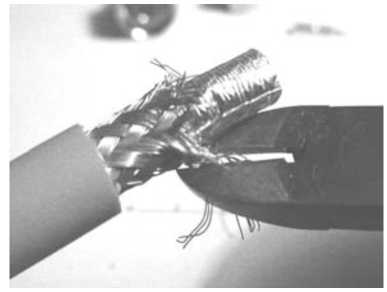
Procedure:

- Strip cable jacket, braid, and dielectric to the proper dimensions (there should be an instruction sheet included with the connector). All cuts are to be sharp and square.

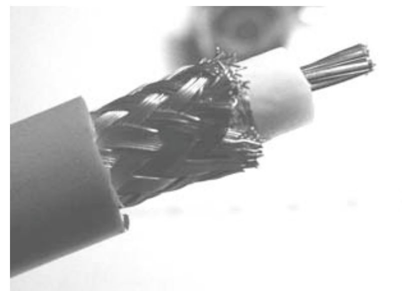


1) Trim the jacket with the cutter for a length of ‘a’ mm. Don’t put too much pressure in cutting the jacket, proceed gradually in order not to nick the braid.

2) Cut the braid with the scissors for a length of 'b' mm. Good quality cables have two layers of braid, with a thin metallic sheet inside. Cut also this sheet at the same length.

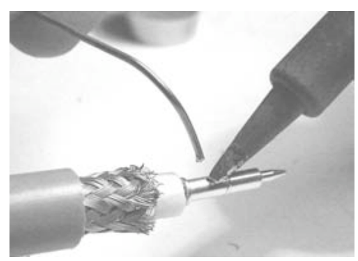


3) Cut the dielectric with the cutter for a length of 'c' mm. Do not nick the center conductor. Tinning of center conductor is not necessary if contact is to be crimped. For solder method, tin center conductor avoiding excessive heat.

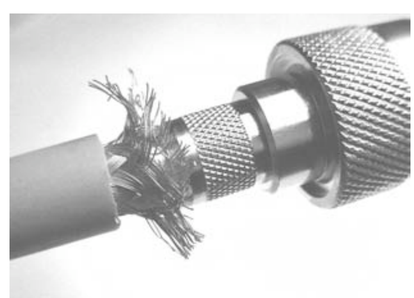


4) Slide outer ring onto cable as shown. Do not comb out braid.

5) Place the central pin on cable's center conductor so it butts against cable dielectric. Center conductor should be visible through inspection hole in the central pin. Solder (or crimp) the pin in place. Do not get any solder on outside surface of the pin. Avoid excessive heat to prevent swelling of dielectric.



6) Insert the cable into the connector body so the inner portion slides under the braid. Push cable assembly forward until the pin snaps into place. You should hear a 'click' sound.



7) Slide outer ring over braid and up against connector body.

8) Crimp outer ring using the crimping tool. It is a one-shot operation, so be careful in positioning the tool properly around the ring and press strongly. If necessary, you can crimp the ring few more times.

9) The final result should look like the picture.

10) Check with an Ohmmeter to assure you don't have a short circuit between the central pin and the connector body.

Impedance and Impedance Matching

Transmission system behavior differs at low and high frequencies, and the different behaviors are usually described in terms of lumped-constant and distributed-constant systems. Lumped-constant circuits involve components (coils, resistors, capacitors, etc.) whose physical dimensions are much less than the wavelength of the propagating electromagnetic wave and which can be located at discrete points. When circuit components and connecting wires are of dimensions comparable to a wavelength of the propagating electromagnetic wave, then the circuit components and the wires effectively become distributed constants. We may then think of a line as begin composed of a series of small inductors and capacitors, where each coil is the inductance of an extremely small section of wire, and the capacitance is that existing between the same two sections. Each series inductor acts to limit the rate at which current can charge the following shunt capacitor, and in so doing it establishes a very important property of a transmission line, its characteristic impedance. This is abbreviated by convention as Z_0.

The value of a the characteristic impedance is equal to $\sqrt{\frac{L}{C}}$ in a perfect line, one in which the conductors have no resistance and there is no leakage between them. L and C are respectively the inductance and capacitance per unit of length of line. The inductance decreases with increasing conductor diameter, and the capacitance decreases with increasing spacing between the conductors. Hence a line with closely spaced large conductors has a low characteristic impedance, while one with widely spaced thin conductors has a high one. Typical coaxial lines can have characteristic impedance's ranging from $30\,\Omega$ to $100\,\Omega$, but most common impedance values for coaxial cables are $50\,\Omega$ and $75\,\Omega$. Physical constraints on practical wire diameters and spacing limit Z_0 values to these ranges. The $50\,\Omega$ RG-58 cable was developed during World War II to connect antennas which had an impedance of $50\,\Omega$.

A line terminated in a purely resistive load equal to the characteristic line impedance is said to be *matched*. In a matched transmission line, the power is transferred outward from the source until it reaches the load, where it is completely absorbed. Thus with either an infinitely long line or a matched one, the impedance presented to the source of power is the same, regardless of the line length: it is equal to the characteristic impedance of the line. The current in such a line is given by the applied voltage divided by the characteristic impedance, according to Ohm's law.

If the terminating resistance R is not equal to Z_0, then the line is said to be *mismatched*. The more the R differs from Z_0, the greater the mismatch. The power reaching R is not totally absorbed, as it was when R was equal to Z_0, because R requires a voltage to current ratio that is different from the one traveling along the line. The result is that R absorbs only part of the power reaching it, the *incident or direct power*. The remainder goes back along the line toward the source, and it is knows as the *reflected power*. The greater the mismatch, the larger the percentage of the incident power that is reflected. In the extreme case when R is zero (a short circuit) or infinity (an open circuit), all of the power reaching the end of the line is reflected back toward the source. When there is a mismatch, power is transferred in both directions along the line. The voltage to current ratio must be the same for the reflected power and for the incident one, because this ratio is determined by the Z_0 of the line. The actual voltage at any point along the line is the vector sum of the incident voltage and of the reflected voltage, taking into account the phases of each component. The same is true for the current. The effect of the incident and reflected components on the behavior of the line can be understood by considering two limiting cases: the short-circuited line and the open-circuited line. If the line if short-circuited, the voltage at the end of the line must be zero. Thus the incident voltage must disappear at the short. Is can do this only if the reflected voltage is opposite in phase and of the same amplitude. The current, however, does not disappear in the short circuit. The incident current flows through the short and there is in addition the reflected component in phase with it and of the same amplitude. The reflected voltage and current must have the same amplitudes of the incident ones, because no power is dissipated in the short circuit. Reversing the phase of either the current or voltage reverses the direction of the power flow. If the line is open-circuited, the current must be zero at the end of the line. In this case the reflected current must be opposite in phase with the incident current, and with the same amplitude. The reflected voltage must be in phase with the incident voltage, and must have the same amplitude. When there is a finite value of resistance at the end of the line, only part of the power is reflected. That is, the reflected voltage and current are smaller than the incident ones. The amplitudes of the two components are therefore not equal, but the resultant current and voltage are in phase in R because R is a pure resistance.

The ratio of the reflected voltage at a given point on a transmission line to the incident voltage is called the *voltage reflection coefficient*. The voltage reflection coefficient is also equal to the ratio of the incident and reflected currents.

$$\rho = \frac{E_r}{E_i} = \frac{I_r}{I_i}$$

where

- ρ is the reflection coefficient
- E_r is the reflected voltage
- E_i is the incident voltage
- I_r is the reflected current
- I_i is the incident current

The reflection coefficient is determined by the relationship between the line's characteristic impedance and the actual load at the end of the line. In most cases, the load is not entirely resistive. It is a complex impedance, consisting of a resistance in series with a reactance. The reflection coefficient is thus a complex quantity, having both amplitude and phase. It can be designated with the letter ρ or with the letter Γ.

The relationship between R_a, the load resistance, X_a, the load reactance, Z_0, the line characteristic impedance with real part R_0 and reactive part X_0 and the complex reflection coefficient is given by:

$$\rho = \frac{Z_a - Z_0}{Z_a + Z_0} = \frac{(R_a \pm jX_a) - (R_0 \pm jX_0)}{(R_a \pm jX_a) + (R_0 \pm jX_0)}$$

For most transmission lines the characteristic impedance is almost completely resistive, meaning that $Z_0 = R_0$ and $X_0 = 0$. The magnitude of the complex reflection coefficient then simplifies to:

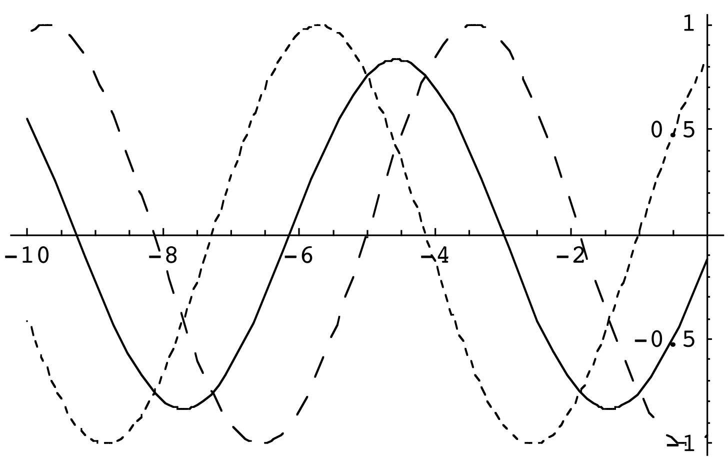
$$|\rho| = \sqrt{\frac{(R_a - R_0)^2 + X_a^{\,2}}{(R_a + R_0)^2 + X_a^{\,2}}}$$

Example: if the characteristic impedance of a coaxial line is $50\,\Omega$ and the load impedance is $140\,\Omega$ in series with a capacitive reactance of $-190\,\Omega$, the magnitude of the reflection coefficient is

$$|\rho| = \sqrt{\frac{(140 - 50)^2 + 190^2}{(140 + 50)^2 + 190^2}} = 0.782$$

If R_a is equal to R_0 and if X_a is zero, the reflection coefficient is also zero: this is the case of the matched line. On the other hand, if R_a is equal to zero, meaning that the load has no resistive part, then the reflection coefficient is equal to 1 regardless of the value of R_0. This means that all the forward power is reflected, since the load is completely reactive.

As a consequence of reflection, a standing wave may be visualized as an interference between the incident signal E_i at a given frequency, traveling in the forward direction, and the signal E_r, at the same frequency, traveling in the reverse direction. At the load, the relationship between the amplitudes of E_r and E_i and the phase angle between them are uniquely determined by the load impedance. The phase angle between E_r and E_i, however, will vary along the line as a function of the distance from the load. A wave is created that oscillates in amplitude but never moves laterally. That is why it is called *standing wave*. In the following figure, the E_r , E_i and the standing wave can be seen. The dashed lines are the E_r and the E_i, while the non dashed one represents the standing wave.



At a position 180° from the load ($\frac{1}{2}\lambda$), the voltage and current must have the same values they do at the load. At a position 90° from the load ($\frac{1}{4}\lambda$), the voltage and current must be inverted: if the voltage is lowest and the current is highest at the load, then at 90° from the load the voltage reaches its highest value and the current reaches its lowest value at the same point. Note that the conditions at 90° also exist at 270°, and the ones at 180° are valid at every point multiple of 180°.

In a matched line, all of the power that is transferred along the line is absorbed in the load if the load is equal to the characteristic impedance. None of the power is reflected back toward the source. As a result, no standing waves will be developed along the line. The voltage along the line is constant, so the matched line is also said the be flat.

The ratio of the maximum voltage, resulting from the interaction of incident and reflected voltages along the line, to the minimum voltage is defined as the *Voltage Standing-Wave Radio (VSWR)* or simply *Standing-Wave Radio (SWR)*. The ratio of the maximum current to the minimum current is the same as the VSWR, so either current or voltage can be measured to determine the standing-wave ratio.

$$SWR = \frac{E_{max}}{E_{min}} = \frac{I_{max}}{I_{min}}$$

In the case where the load contains no reactance, the SWR is equal to the ratio between the load resistance R and the characteristic impedance of the line. The standing-wave ratio is an index of many of the properties of a mismatched line. The SWR is related to the magnitude of the complex reflection coefficient by the following equation

$$SWR = \frac{1+|\rho|}{1-|\rho|}$$

where we can see that with $|\rho| = 0$ we get SWR=1, so we have maximum transmission, and with $|\rho| = 1$ we get $SWR = \infty$, so we have no transmission. And the reflection coefficient magnitude may be defined from a measurement of SWR as

$$|\rho| = \frac{SWR - 1}{SWR + 1}$$

We may also express the reflection coefficient in terms of forward and reflected power, quantities that can be easily measured using a directional RF wattmeter. The reflection coefficient may be computed as

$$\rho = \sqrt{\frac{P_r}{P_f}}$$

where P_f is the power in the forward wave and P_r is the power in the reflected wave. We can use this equation to calculate the SWR from a measurement of the forward and reflected power

$$\mathrm{SWR} = \frac{1+|\rho|}{1-|\rho|} = \frac{1+\sqrt{\frac{P_r}{P_f}}}{1-\sqrt{\frac{P_r}{P_f}}}$$

The relation between the *Return Loss* expresses in dB, which is the amplitude of the reflected wave to the amplitude of the incident wave, and the reflection coefficient is given by:

$$\text{Return Loss (dB)} = -20\log(\rho)$$

The relation between the power ratio and the reflection coefficient is given by:

$$\frac{P_r}{P_f} = 100\rho^2$$

For example, if we measure a return loss of 15 dB, then we can calculate the reflection coefficient as 0.178 and thus the SWR as 1.43.

Attenuation in Transmission Lines

Every transmission line will have some loss, because of the resistance of the conductors and because power is consumed in the dielectric used for insulating the conductors. Power lost in a transmission line is not directly proportional to the line length, but varies logarithmically with the length. For this reason line losses are expressed in terms of decibels per unit length, since the decibel is a logarithmic unit. Calculations are very simple because the total loss in a line is found by multiplying the decibel loss per unit length by the total length of the line.

The power lost in a matched line is called *matched-line loss*. It is usually expressed in decibels per 100 feet. It is necessary to specify the frequency for which the loss applies, because the loss varies with frequency. Conductor and dielectric losses increase with frequency, but not in the same way. The relative amount of each type of loss depends also on the construction on the line, so there is no specific relationship between loss and frequency valid for all types of lines. Actual loss values for practical lines can be found in the following table, expressed in $\frac{dB}{100m}$.

Cable Type	144 MHz	1.2 GHz	2.4 GHz	5.8 GHz
RG-58	20.3	69.2	105.6	169.2
RG-213	9.2	33.1	49.9	93.8
LMR-400	4.9	15.7	22.3	35.4
3/8" LDF	4.3	13.8	19.4	26.6

The power lost in a given line is minimum when the line is terminated in a resistance equal to its characteristic impedance. On non-matched lines there is an additional loss that increases with the increase of the SWR. This is because the effective values of both current and voltage become greater on lines with standing waves. This increase raises the ohmic losses (I^2R) in the conductors and the losses in the dielectric (E^2/R).

The total loss in a line, including matched-line and the additional loss due to standing waves may be calculated as follows

$$\text{Total Loss (db)} = 10\log\left[\frac{\alpha^2 - |\rho|^2}{\alpha(1-|\rho|^2)}\right]$$

where

- $\alpha = 10^{\frac{ML}{10}}$ = matched-line loss ratio
- $|\rho| = \frac{SWR - 1}{SWR + 1}$ =magnitude of reflection coefficient

ML is the matched-line loss for a particular length of the line, expressed in dB, and SWR is the standing-wave ratio at the load end of the line.

Thus the additional loss caused by the standing waves is calculated from

$$\text{Additional Loss (dB)} = \text{Total Loss} - \text{ML}$$

Example: let us consider a RG-213 coaxial cable at 2.4 GHz. The matched-line loss is rated at 49.9 dB per 100 meters. A 10-meter length of RG-213 would then have an overall matched-line loss of

$$\frac{49.9}{100} \times 10 = 4.99\text{dB}$$

If the SWR at the load end of the cable is 4:1, then

$$\alpha = 10^{\frac{4.99}{10}} = 3.155$$
$$|\rho| = \frac{4-1}{4+1} = 0.6$$

The total line loss can then be calculated as

$$\text{Total Loss (dB)} = 10\log\left[\frac{3.155^2 - 0.6^2}{3.155(1-0.6^2)}\right] = 15.5\text{dB}$$

The additional loss due to the SWR of 4:1 is then

15.5-4.99=10.51 dB

If the SWR at the load end of the cable is 2:1, then

$$|\rho| = \frac{2-1}{2+1} = 0.33$$

and the total line loss is then

$$\text{Total Loss (dB)} = 10\log\left[\frac{3.155^2 - 0.33^2}{3.155(1-0.33^2)}\right] = 12.5\text{dB}$$

The additional loss due to the SWR of 2:1 is then

12.5-4.99=7.51 dB

It is often desirable to know the voltages and currents that are developed in a line operating with standing waves. The voltage maximum may be calculated as follows

$$E_{max} = \sqrt{P \times Z_0 \times SWR}$$

where

- E_{max} is the voltage maximum along the line in the presence of standing waves

- P is the power delivered by the source to the line input, expressed in Watts

- Z_0 is the characteristic impedance of the line, expressed in Ohms

- SWR is the SWR at the load

The voltage determined is the RMS value, the voltage that would be measured with an ordinary RF voltmeter. To consider the risk of voltage breakdown, this value should be converted to an instantaneous peak voltage. This is done multiplying the RMS value by $\sqrt{2}$ if we assume the RF waveform to be a sine wave. The resultant value is the maximum possible value that can exist along a line, and it is useful in determining whether a particular line can operate safely with a given SWR.

Example: if 100 Watts of power are applied to a 50 Ω line with a SWR at the load of 4:1, then

$$E_{max} = \sqrt{100 \times 50 \times 4} = 141.4\ \mathrm{V}$$

$$E_{max}\ \text{(instantaneous peak)} = 141.1 \times \sqrt{2} = 199.4\ \mathrm{V}$$

Since

$$SWR = \frac{E_{max}}{E_{min}}$$

then

$$E_{min} = \frac{E_{max}}{SWR}$$

The current can be found using Ohm's law:

$$I_{max} = \frac{E_{max}}{Z_0} = 2.82\ A$$

$$I_{min} = \frac{I_{max}}{SWR} = 0.70\ A$$

It is very useful to relate the value of attenuation with the power lost along a line and with the values of voltage at the input and at the output of the line. We have

$$A(power) = 10\ \log_{10} \frac{P_{out}}{P_{in}}$$

$$A(voltage) = 20\ \log_{10} \frac{V_{out}}{V_{in}}$$

We can also use this equation to calculate the power that is going to be delivered to the load when we have a certain power at the input and a certain value of attenuation.

We can calculate this power as

$$P_{out} = P_{in}\ 10^{\frac{A}{10}}$$

A transmission line can be considered also to be an impedance transformer. A certain value of load impedance, consisting of a resistance and reactance, at the end of a particular transmission line is transformed into another value of impedance at the input of the line. The amount of this transformation is determined by the length of the line, its characteristic impedance, and by the losses in the line. The input impedance of a lossy transmission line of length *L* is calculated using the *Transmission Line Equation*:

$$Z_{in} = Z_0 \frac{Z_L \cosh(\gamma L) + Z_0 \sinh(\gamma L)}{Z_L \sinh(\gamma L) + Z_0 \cosh(\gamma L)}$$

where

- Z_{in} is the complex impedance at the input of the line
- Z_L is the complex load impedance at the end of the line
- Z_0 is the characteristic impedance of the line
- γ is the complex loss coefficient, $\gamma = \alpha + \beta$
- α is the matched line attenuation constant, expressed in nepers/unit length (1 neper=8.688 dB)
- β is the phase constant of line in radians/unit length (2π =one wavelength). In particular:

$$\beta = \frac{2\pi}{VF \times \frac{983.6}{f(MHz)}}$$

where VF is the velocity factor and L is the electrical length in the same units as α and β. The velocity factor is related to the dielectric constant ε by

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

and is usually given by the cable manufacturer. It is an adimensional value always lower than 1 which represents the relation between the propagation speed of an electromagnetic wave in the dielectric and in vacuum. It shows the delay to be expected during signal propagation along the line coming from the usage of the dielectric as a support and electric insulation for the conductors, so its value depends on the dielectric constant.

Example: an antenna terminates a 50 feet long piece of RG-213 coaxial cable, and we want to calculate the impedance value at the input. The antenna is assumed to have an impedance of $43 + j30\Omega$ at 7.15 MHz. Its velocity factor is 0.66. The matched line loss of the line at 7.15 MHz is 0.27 dB/ 100 feet. The characteristic impedance for this type of cable is 50Ω. We must first calculate the values of α and β as:

$$\alpha = \frac{1\ \text{neper} \times 0.27}{8.688} \times \frac{1}{100} = 0.000310773$$

$$\beta = \frac{2\pi}{0.66 \times \frac{983.6}{7.15}} = 0.0692029$$

The complex loss coefficient is then:

$$\gamma = 0.000310773 + j0.0692028$$

We can finally calculate the complex impedance at the input of the line as:

$$Z_{in} = 65.6563 + j33.2804$$

A special case of impedance transformation is a line which is an exact multiple of 1/4 λ. Such a line will have a purely resistive input impedance when the termination is a pure resistance. When the line losses are low, a short circuit as load is seen as an inductor at the input, while an open circuit is seen as a capacitor.

When the line length is an even multiple of 1/4 λ (i.e. a multiple of 1/2 λ), the input resistance is equal to the load resistance, regardless of the line Z_0. A line which is an exact multiple of 1/2 λ simply repeats at its input whatever impedance exists at its output. Sections of lines having such length can be added or removed without changing any of the operating conditions, when the losses are negligible. When the line length is an odd multiple of 1/4 λ the input impedance of the line becomes

$$Z_{in} = \frac{Z_0^{\ 2}}{Z_l}$$

where Z_{in} is the input impedance and Z_l is the load impedance. If Z_l is a pure resistance, Z_{in} will also be a pure resistance. Rearranging the equation gives

$$Z_0 = \sqrt{Z_{in} \times Z_l}$$

This means that if we have two values of impedance that we wish to match, we can connect them together by a 1/4 λ transmission line having a characteristic impedance equal to the square root of their product. A 1/4 λ transmission line is, in effect, a transformer.

By knowing the parameters Z_0, α and β, one can extract the parameters R (series resistance per unit length of line), L (series inductance per unit length of line), C (shunt capacitance per unit length of line) and G (shunt conductance per unit length of line) which define the transmission line. The equations are the following

$$R = R_0\alpha - x_0\beta\left(\frac{\Omega}{m}\right)$$

$$L = \frac{R_0\beta + x_0\alpha}{\omega}\left(\frac{H}{m}\right)$$

$$G = \frac{R_0\alpha + x_0\beta}{R_0^{\ 2} + x_0^{\ 2}}\left(\frac{\Omega^{-1}}{m}\right)$$

$$C = \frac{R_0\beta - x_0\alpha}{(R_0^{\ 2} + x_0^{\ 2})\omega}\left(\frac{F}{m}\right)$$

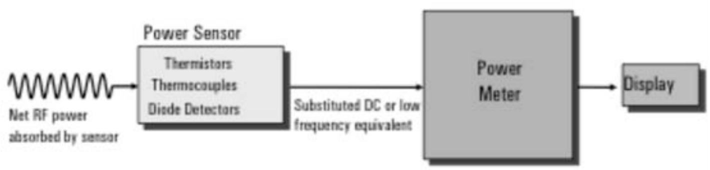
Measurements on Transmission Lines

Power and Attenuation Measurements

Although a variety of instruments measure power, the most accurate instrument is a *power meter* and a *power sensor*. The sensor is an RF power-to-voltage transducer. The power meter displays the detected voltage as a value of power in log (dBm) or linear (watts) units. Typical power meter instrumentation accuracy will be in the order of hundredths of a dB, while other instruments (i.e., *spectrum analyzers*, *network analyzers*) will have power measurement accuracies in the tenths of dBs or more. One of the main differences between the instruments is that of frequency selective measurements. Frequency selective measurements attempt to determine the power within a specified bandwidth. The traditional Power Meter is not frequency selective in the sense that it measures the average power over the full frequency range of the sensor and will include the power of the carrier as well as any harmonics which may be generated. A Spectrum Analyzer provides a frequency selective measurement since it measures in a particular Resolution Bandwidth. The lack of frequency selectivity is the main reason why Power Meters measure down to around -70 dBm and instruments such as a Spectrum Analyzer can measure much lower than this if narrow resolution bandwidths are used.

Average Power provides the average power delivered over several cycles and this is the most common power measurement performed. Average power is defined as the energy transfer rate averaged over many periods of the lowest frequency in the signal. Average power is also defined as the power averaged over a specified time interval. The power meter with sensor only allow to measure the average power, while the Spectrum Analyzer may be used also for more sophisticated power measurements (i.e. peak and pulse power, time-gated power, etc.). We are just interested in average power measurements in the microwave frequency range.

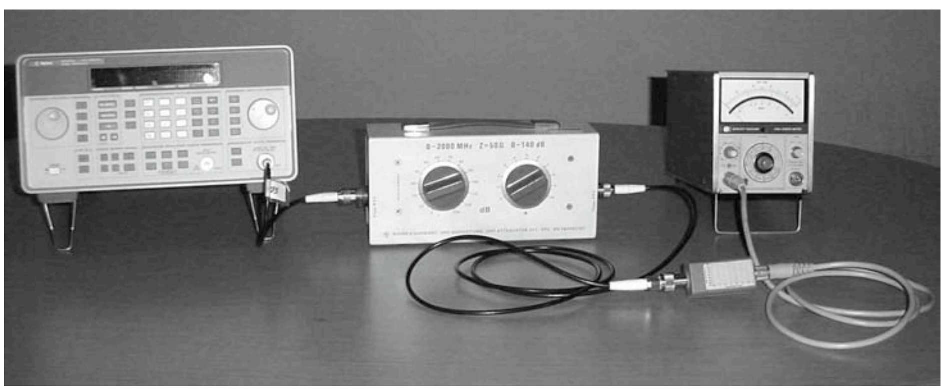
Regarding the hardware used in average power measurements, the basic idea behind the power sensor is to convert high frequency power to a DC or low frequency signal that the power meter can then measure and relate to a certain RF power level. There are two types of power sensor: the end-line power sensor which has just one RF input and a connection to the power meter and basically behaves as a dummy load, and the line-throught power sensor, less common, which has an RF input, and RF output and a connection to the power meter and therefore behaves like a coupler. Often the second type of sensor is integrated in the power meter (line-through power meter).



Experiment 2: Power Measurement with a Power Meter and Power Sensor.

Objective:
We want to use a power meter to measure a reference signal produced by a signal generator.

Equipment Required:
- a signal generator
- a power meter
- an end-line power sensor
- a variable attenuator
- a couple of cables for interconnection



Procedure:
- Before starting the experiment, remember that overloading a device like the power meter may lead to damages or injury. Always estimate the power you are going to apply to the device before connecting it and be sure it fits in the accepted range. If you are not sure, adopt a safe setting.

1) Set the signal generator to output a carrier signal with a value of 0 dBm of average power and a frequency of 2.4 GHz. Disable any modulation. If possible, disable the output of the generator ("RF OFF").

2) Connect the power sensor to the power meter following its instructions before switching it on. Follow the calibration procedure for the power meter, as indicated in its manual. The general procedure consists in switching on the meter for some time in order to stabilize the temperature of the circuits. Then, use the internally generated reference signal to calibrate the gain of the sensor. After the calibration, the instrument should not be switched off. Exit from the calibration mode of the power meter.

3) Set the variable attenuator to an attenuation of -20 dB.

4) Check again the output level of the generator (it should be 0 dBm or 1mW) and the attenuation of the variable attenuator (-20 dB). Estimate the losses of the cables at the working frequency and compute the expected power level at the input of the power meter.

$$\begin{aligned}\mathrm{Power}_{\mathrm{Expected}}(\mathrm{dBm}) = \mathrm{Power}_{\mathrm{Generated}}\ (\mathrm{dBm}) + \mathrm{Losses}_{\mathrm{Cable}}(\mathrm{dB}) \\ + \mathrm{Losses}_{\mathrm{Connector}}(\mathrm{dB}) + \mathrm{Attenuation}(\mathrm{dB})\end{aligned}$$

In our case the expected value cannot exceed -20 dBm.

5) Be sure that this estimated value fits in the actual measurement range of the power meter, setting the range knob.

6) Connect the signal generator to the power meter passing through the attenuator. Enable the output of the signal generator if it was disabled.

7) If everything is correct, the power meter should indicate the expected value of the power. If you don't read the expected value or a near one, switch off immediately the generator and check carefully the connections, the setting of the instruments, the calculations and ask for assistance before repeating the measurement.

8) You may observe a small difference, of the order of a few dB, between the estimated and measured value. This difference is given by the losses of the connectors in the RF chain and eventually by the inaccuracy of the instruments. The signal generator is not supposed to be a reference source of power, if not stated explicitly in the manual. You can therefore use this procedure to estimate roughly the losses of the cables and connectors, but you cannot expect to get the exact value.

9) Disable the output of the signal generator, if possible, or reduce the power at the minimum level, then switch the generator off. Disconnect the RF cable from the power sensor but not switch off the power meter.

10) Repeat the calibration procedure for the power meter, in order to validate the measurements. If you notice that the instrument calibration has changed, repeat the whole measurement procedure. Finally switch off the power meter and disconnect the power sensor.

Experiment 3: Power Measurement with a Spectrum Analyzer.

Objective:

We want to use a Spectrum Analyzer to measure a signal produced by a signal generator.

Equipment Required:

- a signal generator
- a Spectrum Analyzer
- a variable attenuator
- a couple of cables for interconnection

Procedure:

- Before starting the experiment, remember that overloading a device like the Spectrum Analyzer may lead to damages or injury. Always estimate the power you are going to apply to the device before connecting it and be sure it fits in the accepted range. If you are not sure, adopt a safe setting.

1) Set the signal generator to output a sine wave (carrier) signal with a value of -20 dBm of average power and a frequency of 2.4 GHz. Disable any modulation. If possible, disable the output of the generator ("RF OFF").

2) Set the variable attenuator to an attenuation of -20 dB.

3) Check again the output level of the generator (it should be -20 dBm or $10\,\mu W$) and the attenuation of the variable attenuator (-20 dB). Estimate the losses of the cables at the working frequency and compute the expected power level at the input of the power meter.

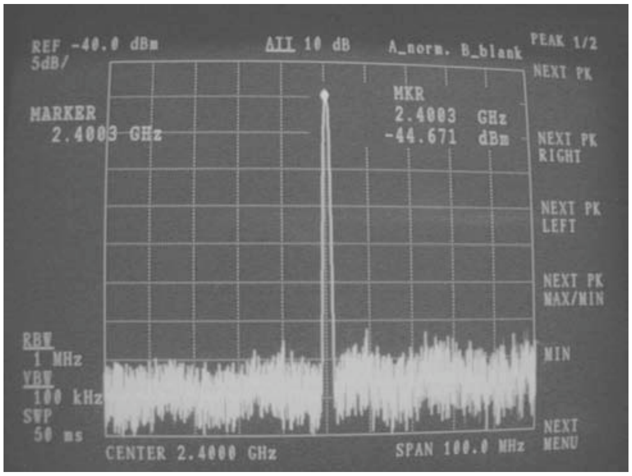
$$\begin{aligned}\mathrm{Power}_{\mathrm{Expected}}(\mathrm{dBm}) = \mathrm{Power}_{\mathrm{Generated}}\,(\mathrm{dBm}) + \mathrm{Losses}_{\mathrm{Cable}}(\mathrm{dB}) \\ + \mathrm{Losses}_{\mathrm{Connector}}(\mathrm{dB}) + \mathrm{Attenuation}(\mathrm{dB})\end{aligned}$$

In our case the expected value cannot exceed -40 dBm.

4) Switch on the Spectrum Analyzer and set the input attenuation of the Spectrum Analyzer to 20dB, the center frequency at 2.4 GHz, the frequency span at 100 MHz, the reference level at -40 dBm, RBW at 1 MHz, VBW at 100 kHz.

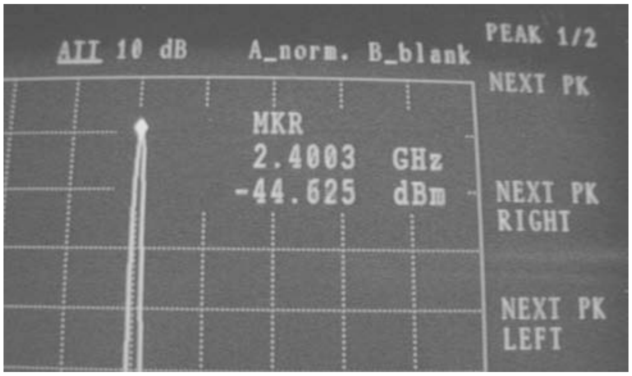
5) Connect the signal generator to the Spectrum Analyzer passing through the attenuator. Enable the output of the signal generator if it was disabled.

6) If everything is correct, the Spectrum Analyzer should display a peak signal centered at 2.4 GHz as shown in figure.



If you don't see any signal, switch off immediately the generator and check carefully the connections, the setting of the instruments, the calculations and ask for assistance before repeating the measurement.

7) You can read the power level of the signal directly on the screen of the Spectrum Analyzer using the grid as a reference. For a better reading, you may use the marker facilities provided by some Spectrum Analyzers. Check on the instruction manual the correct procedure.



8) You may observe a small difference, of the order of a few dB, between the estimated and measured value. This difference is given by the losses of

the connectors in the RF chain and eventually by the inaccuracy of the instruments. The signal generator is not supposed to be a reference source of power, if not stated explicitly in the manual. You can therefore use this procedure to estimate roughly the losses of the cables and connectors, but you cannot expect to get the exact value.

9) Disable the output of the signal generator, if possible, or reduce the power at the minimum level, then switch the generator off. Disconnect the RF cable from the Spectrum Analyzer and switch it off.

Experiment 4: Measurement of Cable Loss with Power Meter.

Objective:
We want to use the same procedure as experiment number 2 to measure the loss of a cable at a given frequency.

Equipment Required:
- a signal generator
- a power meter
- a power sensor
- the cable under measurement
- eventually, a reference cable with a known loss
- connectors/gender adapters if required

Procedure:
- Be familiar with the procedure of power measurement with the power meter following the instructions of exercise number 2.

In this type of measurement, different scenarios are possible:

1) The power sensor can be plugged directly at the output of the signal generator, and the cable under measurement can also be inserted between the signal generator and the power sensor. In this case, you should first calibrate the signal generator connecting directly its output to the power meter and follow the procedure for power measurement

without any cable in between. Then, you should place the cable under measurement between the signal generator and the power sensor without changing any of the settings of the two instruments. The difference between the two measurements will give a precise value for the loss of the cable (including the losses of the connectors). This method works also if the power meter is not perfectly calibrated because it is based on a difference of values of power, thus eliminating the *bias*.

2) The power sensor cannot be plugged directly at the output of the signal generator or the cable under measurement cannot be inserted between the signal generator and the power sensor. In this case, you should use one or more adapters to match the connector type and gender. In this case you cannot avoid to take into consideration in the total cable loss also the loss of the adapters, possibly using good quality calibrated adapters.

3) In some cases you can measure the loss of a cable relatively to a cable of known loss value. This procedure is also useful in measuring the loss of a very long cable in comparison with a very short one, which is supposed to have a very low loss compared to the long one.

Experiment 5: Measurement of Cable Loss with Spectrum Analyzer and Signal Generator.

Objective:
We want to use the same procedure as experiment number 3 to measure the loss of a cable at different frequencies (called *Frequency Response* of the cable)

Equipment Required:
- a signal generator
- a Spectrum Analyzer
- the cable under measurement
- an interconnection cable
- connectors/gender adapters if required

Procedure:
- Be familiar with the procedure of power measurement with the Spectrum Analyzer following the instructions of exercise number 3.

- This measurement technique works in the same way as the previous one, it just requires an additional cable. It should be a short, good-quality cable. One end of the cable should always be connected to the Spectrum Analyzer, while the other will act like the power sensor of the power meter. With this scheme, the loss of the cable under test can be measured for different values of frequency, varying the frequency of the signal generator and of the Spectrum Analyzer. The calibration of the signal generator should be repeated for the different frequencies used. With enough measurements, you can plot a curve showing the loss at different frequencies: this curve is known as Frequency Response of the cable.

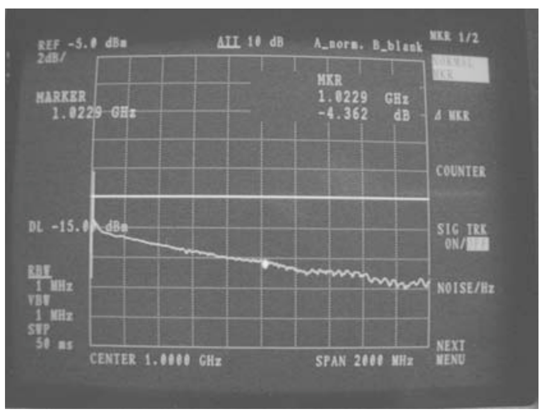
Experiment 6: Measurement of Cable Loss with Spectrum Analyzer and Tracking Generator.

Objective:
We want to use a Spectrum Analyzer with its own Tracking Generator to measure the loss of a cable in a continuous range of frequencies (called *Frequency Response* of the cable)

Equipment Required:
- a tracking generator which can be internal to the Spectrum Analyzer or an external accessory
- a Spectrum Analyzer
- the cable under measurement
- an interconnection cable
- connectors/gender adapters if required

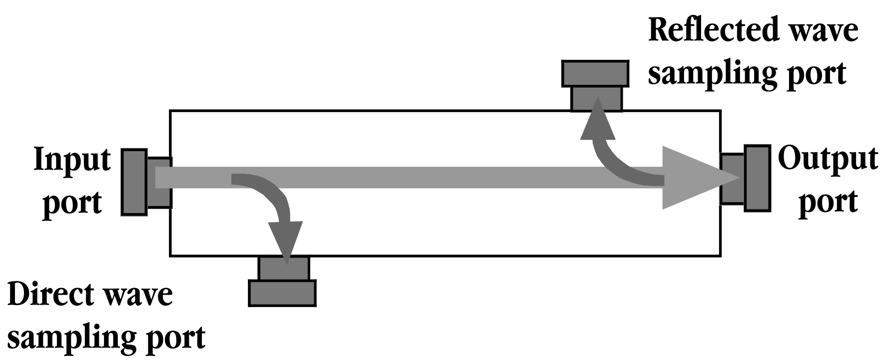
Procedure:
- Be familiar with the procedure of power measurement with the Spectrum Analyzer following the instructions of exercise number 3.
This measurement technique works in the same way as the previous one, but uses the tracking generator instead of the signal generator. It requires

an initial calibration of the tracking generator, usually performed connecting the output of the tracking generator and the input of the Spectrum Analyzer with a short cable. Some devices, anyway, do not require this cable and perform automatically the calibration. After the calibration and the proper setting of the Spectrum Analyzer, simply connecting the tracking generator to the Spectrum Analyzer with the cable under test allows to get directly the frequency response of the cable in the chosen frequency range on the display. The difference between this measurement technique and the one with the signal generator is that in this case just one measurement is required instead of many. The usual attention should be given in taking into account the loss of the adapters in the total loss of the cable.



Use of the Directional Coupler for the measurement of Direct Power, Reflected Power and SWR

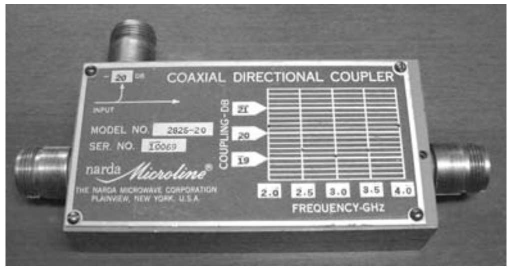
A *directional coupler* is a passive device used to separately extract, through a known *coupling loss*, either the incident (direct) or the reflected wave in a transmission line. The sampling ports have an output 10 to 30 dB less than the signal passing through it, while the pass-through signal is subject to negligible loss, called *insertion loss*.



The coupling factor represents the primary property of a directional coupler and is defined as

$$\text{Coupling factor (dB)} = -10\log\frac{P_c}{P_i}$$

where P_i is the input power and P_c is the output power at the coupled port. Coupling is not constant, but varies with frequency. While different designs may reduce the variance, a perfectly flat coupler theoretically cannot be built. The the graph of the coupling value at different frequencies, given in dB, is usually reproduced on the coupler itself.



A *unidirectional coupler* has available connections for extracting only one direction of transmission; a *bidirectional coupler* has available terminals for extracting both directions.

A function for which couplers offer an ideal solution is the measuring of RF power and comparing incident and reflected signals to calculate the SWR. Common properties desired for all directional couplers are wide operational bandwidth and a good impedance match at all ports when the other ports are terminated in matched loads.

Experiment 7: Measurement of Direct Power, Reflected Power and SWR with Signal Generator, Power Meter and Directional Coupler.

Objective:

We want to use a Directional Coupler to sample the direct and reflected signal to measure its power with a Power Meter. This will allow us to check if the line and the load are matched, having the correct value of impedance.

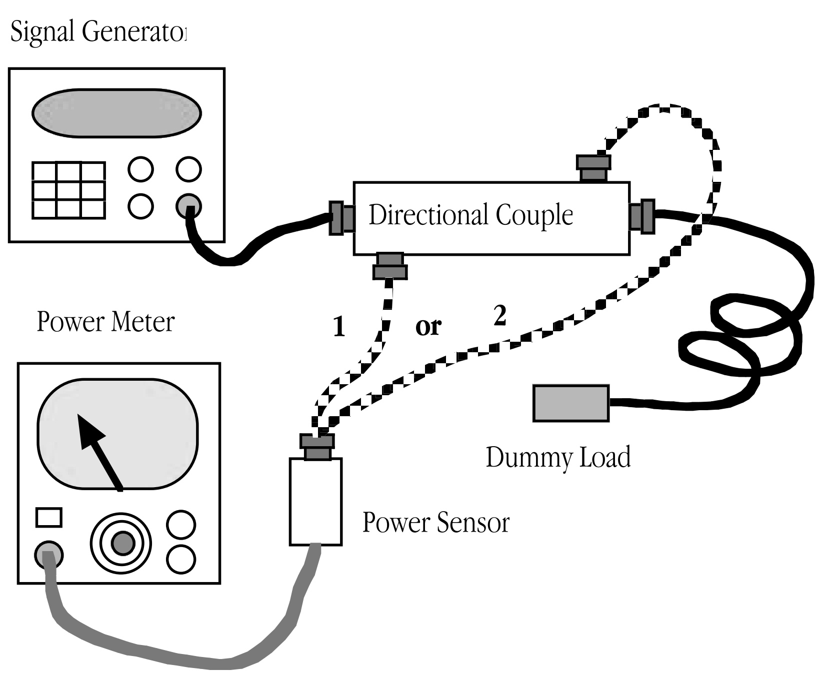
Equipment Required:

- a power meter
- a power sensor
- a signal generator
- an uni-directional coupler
- a bi-directional coupler
- a cable with an impedance of 50 Ω
- a cable with an impedance of 75 Ω
- a dummy load with an impedance of 50 Ω

- a dummy load with an impedance of 75 Ω
- connectors/gender adapters if required

Procedure:

- Be familiar with the procedure of power measurement with the Power Meter following the instructions of exercise number 2.



- Before starting the experiment, remember that overloading a device like the power meter may lead to damages or injury. Always estimate the power you are going to apply to the device before connecting it and be sure it fits in the accepted range. If you are not sure, adopt a safe setting.

1) Set the signal generator to output a carrier signal with a value of 0 dBm of average power and a frequency of 2.4 GHz. Disable any modulation. If possible, disable the output of the generator ("RF OFF").

2) Connect the power sensor to the power meter and calibrate them.

3) Connect the output of the signal generator to the input port of the directional coupler with a 50 Ω cable.

4) Connect the output port of the directional coupler to the 50 Ω dummy load.

5) Connect another 50 Ω dummy load to the reflected signal coupling port of the directional coupler.

6) Check the output level of the generator (it should be 0 dBm or 1mW). Estimate the coupling loss of the directional coupler and the losses of the cables at the working frequency and compute the expected power level at the direct coupling port of the directional coupler.

7) Be sure that this estimated value fits in the actual measurement range of the power meter, setting the range knob.

8) Connect the power sensor of the power meter to the direct signal coupling port of the directional coupler.

9) Enable the output of the signal generator.

10) If everything is correct, the power meter should indicate the expected value of the power. If you don't read the expected value or a near one, switch off immediately the generator and check carefully the connections, the setting of the instruments, the calculations and ask for assistance before repeating the measurement.

11) Disable the output of the signal generator. Disconnect the power sensor from the direct signal coupling port of the directional coupler. Disconnect the dummy load from the reflected signal coupling port of the directional coupler.

12) Connect the power sensor to the reflected signal coupling port of the directional coupler. Connect the 50 Ω dummy load to the direct signal coupling port of the directional coupler.

13) Enable the output of the signal generator, and measure the power with the power meter.

14) Being very low the expected value of the power of the reflected signal, due to the fact that the line is properly matched, modify gradually the setting of the power meter to reach the maximum sensitivity. You should still expect to read a value near to zero.

15) You can repeat the same procedure with a 75 Ω dummy load connected to the output of the directional coupler, or use a 75 Ω cable connected to the output of the directional coupler and terminated with a 50 Ω dummy load, or any other configuration which has an impedance mismatch after the directional coupler. In this case you should measure a reflected power different from zero.

16) With the mismatched configuration you may compute the SWR from the measured values of power of the forward and reflected waves as

$$SWR = \frac{1 + \sqrt{\frac{P_r}{P_f}}}{1 - \sqrt{\frac{P_r}{P_f}}}$$

Use of the SWR meter for the measurement of SWR

An *SWR meter*, also called *Directional Wattmeter*, is a measuring device that contains a directional coupler for sensing the forward and reflected components of the signal that pass through it. Usually a meter sensitivity control is provides so that when sensing forward power the meter can be set for a full-scale reading. The meter scale can be calibrated to show SWR directly when switched to sense the reflected component. In modern instruments the signal processing and display circuits compute and display the SWR.

One of the most common SWR meters family is the “Bird” one. They provide an easy way to switch between frequency and power ranges by using different plug-in elements, also called “slugs”, which have an arrow over them to indicate the direction of the measured power. The power range goes from 0 to 10kW, and the frequency range is from 450 kHz to 2.7 GHz. There can be place for one or two slugs. With only one slug, two measurements are required to compute the SWR (and you have to rotate the slug of 180°), while in the model with two slugs only one measurement is required to measure both the forward and reflected power and therefore the SWR. An SWR meter can also be used to measure the power as a through-line power meter.

Measures of Impedance of a Coaxial Cable

We are going to calculate the characteristic impedance of a coaxial cable using three different methods:

- Measuring the physical characteristics of the cable

- Using Time Domain Pulse Reflection. With this method we are also going to locate a disturbance along the cable

- Using an SWR meter

To calculate the characteristic impedance of a coaxial cable using its *physical characteristics*, we must consider the values of the distributed capacity and of the distributed inductance. For a coaxial cable, the distributed capacity is equal to

$$C = \frac{2\pi\varepsilon_0}{\log_{10}\frac{b}{a}}\left(\frac{\text{farads}}{\text{meter}}\right)$$

and the distributed inductance is

$$L = \frac{\mu_0}{2\pi}\log_{10}\left(\frac{b}{a}\right)\left(\frac{\text{henries}}{\text{meter}}\right)$$

where b is the inside radius of the outer conductor and a is the outside radius of the inner conductor.

At radio frequency the characteristic impedance becomes a pure resistance if we neglect the ohmic resistance and the shunt conductance of the line. We then have

$$Z_0 = \sqrt{\frac{L}{C}} = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\log_{10}\left(\frac{b}{a}\right)\frac{1}{\sqrt{\varepsilon_r}}$$

The characteristic impedance becomes

$$Z_0 = \frac{1}{2\pi} 377 \log_{10}\left(\frac{b}{a}\right) \frac{1}{\sqrt{\varepsilon_r}}$$

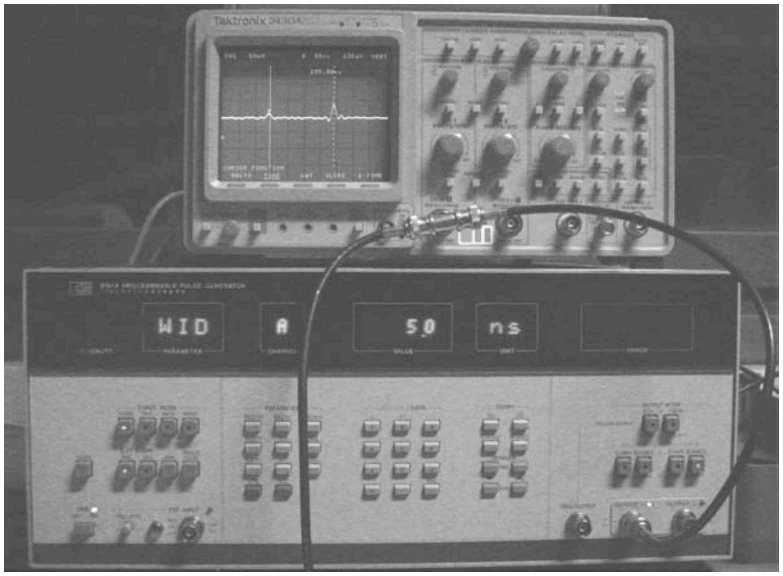
where ε is the dielectric constant of the insulation between the conductors.

For example, if we measure the physical dimensions of the RG-58/U coaxial cable, we find the following values: the inner conductor diameter is 0.8 millimeters and the outer conductor diameter is 5 millimeters. We know that the relative dielectric constants of the polyethylene used in the RG-58/U is equal to 2.3. We then have

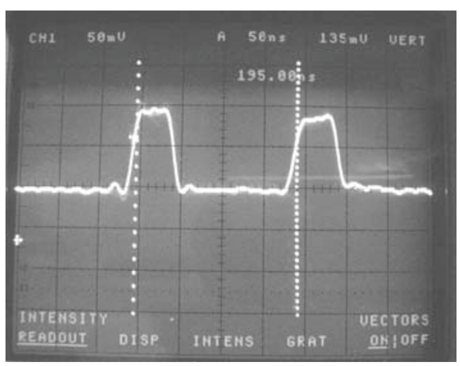
$$Z_0 = 49.7359\Omega$$

This result is very near to the known value of $\mathbf{50\Omega}$.

A *Time Domain Reflectometer (TDR)* is a simple but powerful tool to evaluate transmission lines. The technique used in time-domain reflectometer consists of feeding an impulse of energy into the system and then observing that energy as it is reflected by the system at the point of insertion. A TDR may be assembled using a square wave (or pulse) generator and an oscilloscope.



The generator sends a sequence of pulses down a transmission line, and with the oscilloscope it is possible to sample the signal and observe the incident and reflected pulses. When the fast-rise input pulse meets with a discontinuity or impedance mismatch, the resultant reflections are compared in time and amplitude with the original pulse.



By analyzing the magnitude and shape of the reflected waveform, you can determine the nature of the impedance variation in the transmission system. Also, since distance is related to time and the amplitude of the reflected step is directly related to impedance, the comparison indicates the distance to the fault as well as the nature of the fault. In addition to this, time-domain reflectometer also reveals the characteristic impedance of the line. After the round trip delay of the cable, the reflected voltage arrives back to the oscilloscope and is added to the incident voltage on the oscilloscope to produce the measured voltage value V_m. If we know the impedance of the load Z_l and if we call V_r the value of the reflected voltage and V_i the value of the incident voltage, we can use the following equations to calculate the characteristic impedance of the line:

$$\frac{V_r}{V_i} = \frac{Z_l - Z_0}{Z_l + Z_0}$$

$$\frac{V_m}{V_i} = \frac{V_r + V_i}{V_i} = 1 + \frac{V_r}{V_i} =$$

$$= 1 + \frac{Z_l - Z_0}{Z_l + Z_0} = \frac{Z_l + Z_0 + Z_l - Z_0}{Z_l + Z_0} = \frac{2Z_l}{Z_l + Z_0}$$

A TDR can be also used to determine the position of a disturbance along a line, for example the position of a short circuit. The location of the disturbance is calculated with a simple proportional method. The round-trip time to the disturbance can be read from the oscilloscope grid. Thus, you need only to read the time, multiply it by the velocity of the radio wave on the specific cable (which is given by the speed of light multiplied by a factor called the velocity factor of the cable, VF) and divide it by two. The distance of the disturbance is then calculated as

$$l = \frac{300 \times VF \times t}{2}$$

Where *l* is the length in meters, *t* is the time delay in microseconds and VF is the velocity factor of the line.

Experiment 8: Measurement of the characteristic impedance of a coaxial cable with a TDR.

Objective:
We want to measure the characteristic impedance of a coaxial cable with a TDR.

Required equipment:
- a piece of RG-58/U coaxial cable with connectors
- a square wave generator
- an oscilloscope
- a load impedance of known value

Procedure:
We must first of all know the value of the load impedance. For example, it can be a 75Ω impedance. We must then set the Amplitude of the incident voltage waveform on the square wave generator. To make calculations easier, we can set this value to 1 V. The oscilloscope has then to be synchronized to the pulses. We are now ready to measure the value of the resulting step. If we measure a step of 1.2 V on the oscilloscope, we can use the formulas and obtain:

$$\frac{1.2}{1} = \frac{2 \times 75}{75 + Z_0}$$

The value of the unknown characteristic impedance is then 50Ω.

Experiment 9: Location of a disturbance along a coaxial cable with a TDR.

Objective:
We want to determine the position of a disturbance along a line with a TDR, for example the position of a short circuit.
Required equipment:
- a piece of RG-58/U coaxial cable with connectors
- a square wave generator
- an oscilloscope
- a pair of scissors

Procedure:
- If we want to determine the position of a disturbance, we must first of all create a "simulated" disturbance, for example with an open circuit at the end of the cable. We must use a pulse generator capable of generating short and fast rising pulses. For cable lengths in the order of meters, the pulses width should be in the range of 10 ns. We must synchronize the oscilloscope with the pulses. We can then measure on the oscilloscope grid the time it takes at the incident pulse to come back from the disturbance. If we measure a time of 0.16 μs, we are able to determine the position of the disturbance as

$$l = \frac{300 \times 0.66 \times 0.16}{2} = 15.84 \text{ meters}$$

where 0.66 is the velocity factor of the coaxial cable.

To calculate the characteristic impedance of a coaxial cable using an SWR meter, we must find the relationship between the value of the SWR and the characteristic impedance. We know that

$$r = \frac{Z_a - Z_0}{Z_a + Z_0} = \frac{(R_a \pm jX_a) - (R_0 \pm jX_0)}{(R_a \pm jX_a) + (R_0 \pm jX_0)}$$

In most cases, the characteristic impedance is completely resistive, meaning that $Z_0=R_0$ and $X_0=0$. We can choose a known load impedance which is resistive too, meaning that $Z_a=R_a$ and $X_a=0$. In this way we have

$$|\rho| = \sqrt{\frac{(R_a - R_0)^2}{(R_a + R_0)^2}}$$

We know that the relationship between the absolute value of ρ and the SWR is

$$|\rho| = \frac{SWR - 1}{SWR + 1}$$

Combining the two equations, we have

$$\frac{SWR - 1}{SWR + 1} = \sqrt{\frac{(R_a - R_0)^2}{(R_a + R_0)^2}}$$

$$\left(\frac{SWR - 1}{SWR + 1}\right)^2 = \frac{(R_a - R_0)^2}{(R_a + R_0)^2}$$

$$\frac{(SWR - 1)^2}{(SWR + 1)^2} = \frac{(R_a - R_0)^2}{(R_a + R_0)^2}$$

$$\gamma = \frac{(SWR - 1)}{(SWR + 1)} = \frac{(R_a - R_0)}{(R_a + R_0)}$$

If we measure the SWR with an SWR meter, and we indicate the ratio on the left as γ, we can calculate the value of R_0 as

$$R_0 = R_a \frac{1 - \gamma}{1 + \gamma}$$

For example, if we want to determine the characteristic impedance with an SWR meter, we must first of all place a $50\,\Omega$ load at the end of the cable. Using the SWR meter, we measure the value of SWR. Assuming that it is 1.4, then we calculate γ as

$$\gamma = \frac{(\mathrm{SWR}-1)}{(\mathrm{SWR}+1)} = \frac{0.4}{2.4} = 0.166$$

We can then determine the characteristic impedance as

$$R_0 = R_a \frac{1-\gamma}{1+\gamma} = 35.7143\Omega$$

Antenna Basics

Introduction

Antennas are a very important component of communication systems. By definition, an antenna is a device used to transform an RF signal, traveling on a conductor, into an electromagnetic wave in free space. Antennas demonstrate a property known as *reciprocity*, which means that an antenna will maintain the same characteristics regardless if it is transmitting or receiving. Most antennas are resonant devices, which operate efficiently over a relatively narrow frequency band. An antenna must be tuned to the same frequency band of the radio system to which it is connected, otherwise the reception and the transmission will be impaired. When a signal is fed into an antenna, the antenna will emit radiation distributed in space in a certain way. A graphical representation of the relative distribution of the radiated power in space is called a *radiation pattern*.

Antenna Glossary

Before we talk about specific antennas, there are a few common terms that must be defined and explained:

- Input Impedance

For an efficient transfer of energy, the impedance of the radio, of the antenna and of the transmission cable connecting them must be the same. Transceivers and their transmission lines are typically designed for 50 Ω impedance. If the antenna has an impedance different from 50 Ω, then there is a mismatch and an impedance matching circuit is required.

- Return loss

The return loss is another way of expressing mismatch. It is a logarithmic ratio measured in dB that compares the power reflected by the antenna to the power that is fed into the antenna from the transmission line. The relationship between SWR and return loss is the following:

$$\text{Return Loss (in dB)} = 20\log_{10}\frac{\text{SWR}}{\text{SWR}-1}$$

- **Bandwidth**

The bandwidth of an antenna refers to the range of frequencies over which the antenna can operate correctly. The antenna's bandwidth is the number of Hz for which the antenna will exhibit an SWR less than 2:1.

The bandwidth can also be described in terms of percentage of the center frequency of the band.

$$BW = 100 \times \frac{F_H - F_L}{F_C}$$

where F_H is the highest frequency in the band, F_L is the lowest frequency in the band, and F_C is the center frequency in the band.

In this way, bandwidth is constant relative to frequency. If bandwidth was expressed in absolute units of frequency, it would be different depending upon the center frequency. Different types of antennas have different bandwidth limitations.

- **Directivity and Gain**

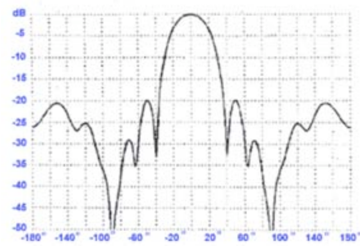
Directivity is the ability of an antenna to focus energy in a particular direction when transmitting, or to receive energy better from a particular direction when receiving. In a static situation, it is possible to use the antenna directivity to concentrate the radiation beam in the wanted direction. However in a dynamic system where the transceiver is not fixed, the antenna should radiate equally in all directions, and this is known as an omni-directional antenna.

Gain is not a quantity which can be defined in terms of a physical quantity such as the Watt or the Ohm, but it is a dimensionless ratio. Gain is given in reference to a standard antenna. The two most common reference antennas are the isotropic antenna and the resonant half-wave dipole antenna. The isotropic antenna radiates equally well in all directions. Real isotropic antennas do not exist, but they provide useful and simple theoretical antenna patterns with which to compare real antennas. Any real antenna will radiate more energy in some directions than in others. Since it cannot create energy, the total power radiated is the same as an isotropic antenna, so in other directions it must radiate less energy. The gain of an antenna in a given direction is the amount of energy radiated in that direction compared to the energy an isotropic antenna would radiate in the same direction when driven with the same input power. Usually we are only interested in the maximum gain, which is the gain in the direction in which the antenna is radiating most of the power. An antenna gain of 3 dB compared to an isotropic antenna would be written as 3 dBi. The resonant half-wave dipole can be a useful standard for comparing to other antennas at one frequency or over a very narrow band of frequencies. To compare the dipole to an antenna over a range of frequencies requires a number of dipoles of different lengths. An antenna gain of 3 dB compared to a dipole antenna would be written as 3 dBd.

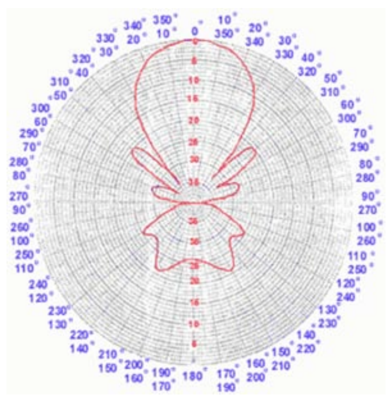
The method of measuring gain by comparing the antenna under test against a known standard antenna, which has a calibrated gain, is technically known as a gain transfer technique. Another method for measuring gain is the 3 antennas method, where the transmitted and received power at the antenna terminals is measured between three arbitrary antennas at a known fixed distance.

- **Radiation Pattern**

The radiation or antenna pattern describes the relative strength of the radiated field in various directions from the antenna, at a constant distance. The radiation pattern is a reception pattern as well, since it also describes the receiving properties of the antenna. The radiation pattern is three-dimensional, but usually the measured radiation patterns are a two-dimensional slice of the three-dimensional pattern, in the horizontal or vertical planes. These pattern measurements are presented in either a *rectangular* or a *polar* format. The following figure shows a rectangular plot presentation of a typical 10 element Yagi. The detail is good but it is difficult to visualize the antenna behavior at different directions.

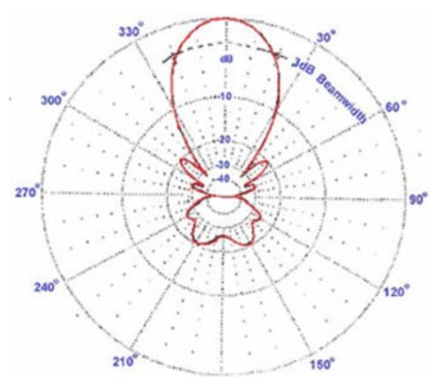


Polar coordinate systems are used almost universally. In the polar-coordinate graph, points are located by projection along a rotating axis (radius) to an intersection with one of several concentric circles. Following is a polar plot of the same 10 element Yagi antenna.



Polar coordinate systems may be divided generally in two classes: *linear* and *logarithmic*. In the linear coordinate system, the concentric circles are equally spaced, and are graduated. Such a grid may be used to prepare a linear plot of the power contained in the signal. For ease of comparison, the equally spaced concentric circles may be replaced with appropriately placed circles representing the decibel response, referenced to 0 dB at the outer edge of the plot. In this kind of plot the minor lobes are suppressed. Lobes with peaks more than 15 dB or so below the main lobe disappear because of their small size. This grid enhances plots in which the antenna has a high directivity and small minor lobes. The voltage of the signal, rather than the power, can also be plotted on a linear coordinate system. In this case, too, the directivity is enhanced and the minor lobes suppressed, but not in the same degree as in the linear power grid.

In the logarithmic polar coordinate system the concentric grid lines are spaced periodically according to the logarithm of the voltage in the signal. Different values may be used for the logarithmic constant of periodicity, and this choice will have an effect on the appearance of the plotted patterns. Generally the 0 dB reference for the outer edge of the chart is used. With this type of grid, lobes that are 30 or 40 dB below the main lobe are still distinguishable. The spacing between points at 0 dB and at -3 dB is greater than the spacing between -20 dB and -23 dB, which is greater than the spacing between -50 dB and -53 dB. The spacing thus correspond to the relative significance of such changes in antenna performance.



A modified logarithmic scale emphasizes the shape of the major beam while compressing very low-level (>30 dB) sidelobes towards the center of the pattern.

There are two kinds of radiation pattern: absolute and relative. Absolute radiation patterns are presented in absolute units of field strength or power. Relative radiation patterns are referenced in relative units of field strength or power. Most radiation pattern measurements are relative to the isotropic antenna, and then the gain transfer method is then used to establish the absolute gain of the antenna.

The radiation pattern in the region close to the antenna is not the same as the pattern at large distances. The term near-field refers to the field pattern that exists close to the antenna, while the term far-field refers to the field pattern at large distances. The far-field is also called the radiation field, and is what is most commonly of interest. Ordinarily, it is the radiated power that is of interest, and so antenna patterns are usually measured in the far-field region. For pattern measurement it is important to choose a distance sufficiently large to be in the far-field, well out of the near-field. The minimum permissible distance depends on the dimensions of the antenna in relation to the wavelength. The accepted formula for this distance is:

$$r_{min} = \frac{2d^2}{\lambda}$$

where r_{min} is the minimum distance from the antenna, d is the largest dimension of the antenna, and λ is the wavelength.

- **Beamwidth**

An antenna's beamwidth is usually understood to mean the half-power beamwidth. The peak radiation intensity is found and then the points on either side of the peak which represent half the power of the peak intensity are located. The angular distance between the half power points is defined as the beamwidth. Half the power expressed in decibels is —3dB, so the half power beamwidth is sometimes referred to as the 3dB beamwidth. Both horizontal and vertical beamwidths are usually considered.

Assuming that most of the radiated power is not divided into sidelobes, then the directive gain is inversely proportional to the beamwidth: as the beamwidth decreases, the directive gain increases.

-**Sidelobes**

No antenna is able to radiate all the energy in one preferred direction. Some is inevitably radiated in other directions. The peaks are referred to as sidelobes, commonly specified in *dB down from the main lobe*.

- **Nulls**

In an antenna radiation pattern, a *null* is a zone in which the effective radiated power is at a minimum. A null often has a narrow directivity angle compared to that of the main beam. Thus, the null is useful for several purposes, such as suppression of interfering signals in a given direction.

- **Polarization**

Polarization is defined as the orientation of the electric field of an electromagnetic wave. Polarization is in general described by an ellipse. Two special cases of elliptical polarization are linear polarization and circular polarization. The initial polarization of a radio wave is determined by the antenna.

With linear polarization the electric field vector stays in the same plane all the time. Vertically polarized radiation is somewhat less affected by reflections over the transmission path. Omnidirectional antennas always have vertical polarization. With horizontal polarization, such reflections cause variations in received signal strength. Horizontal antennas are less likely to pick up man-made interference, which ordinarily is vertically polarized.

In circular polarization the electric field vector appears to be rotating with circular motion about the direction of propagation, making one full turn for each RF cycle. This rotation may be righthand or lefthand. Choice of polarization is one of the design choices available to the RF system designer.

- **Polarization Mismatch**

In order to transfer maximum power between a transmit and a receive antenna, both antennas must have the same spatial orientation, the same polarization sense and the same axial ratio.

When the antennas are not aligned or do not have the same polarization, there will be a reduction in power transfer between the two antennas. This reduction in power transfer will reduce the overall system efficiency and performance.

When the transmit and receive antennas are both linearly polarized, physical antenna misalignment will result in a polarization mismatch loss which can be determined using the following formula:

$$\text{Polarization Mismatch Loss (dB)} = 20 \log (\cos \vartheta)$$

where ϑ is the misalignment angle between the two antennas. For 15° we have a loss of 0.3 dB, for 30° we have 1.25 dB, for 45° we have 3 dB and for 90° we have an infinite loss.

The actual mismatch loss between a circularly polarized antenna and a linearly polarized antenna will vary depending upon the axial ratio of the circularly polarized antenna.

If polarizations are coincident no attenuation occurs due to coupling mismatch between field and antenna, while if they are not, then the communication can't even take place.

- **Front-to-back ratio**

It is useful to know the *front-to-back ratio* that is the ratio of the maximum directivity of an antenna to its directivity in the rearward direction. For example, when the principal plane pattern is plotted on a relative dB scale, the front-to-back ratio is the difference in dB between the level of the maximum radiation, and the level of radiation in a direction 180 degrees.

Types of Antennas

A classification of antennas can be based on:

- **Frequency and size**

antennas used for HF are different from the ones used for VHF, which in turn are different from antennas for microwave. The wavelength is different at different frequencies, so the antennas must be different in size to radiate signals at the correct wavelength. We are particularly interested in antennas working in the microwave range, especially in the 2.4 GHz and 5 GHz frequencies. At 2.4 GHz the wavelength is 12.5 cm, while at 5 Ghz it is 6 cm.

- Directivity

antennas can be omnidirectional, sectorial or directive. Omnidirectional antennas radiate the same pattern all around the antenna in a complete 360 degrees pattern. The most popular types of omnidirectional antennas are the Dipole-Type and the Ground Plane. Sectorial antennas radiate primarily in a specific area. The beam can be as wide as 180 degrees, or as narrow as 60 degrees. Directive antennas are antennas in which the beamwidth is much narrower than in sectorial antennas. They have the highest gain and are therefore used for long distance links. Types of directive antennas are the Yagi, the biquad, the horn, the helicoidal, the patch antenna, the Parabolic Dish and many others.

- Physical construction

antennas can be constructed in many different ways, ranging from simple wires to parabolic dishes, up to coffee cans.

When considering antennas suitable for 2.4 GHz WLAN use, another classification can be used:

- Application

we identify two application categories which are Base Station and Point-to-Point. Each of these suggests different types of antennas for their purpose. Base Stations are used for multipoint access. Two choices are Omni antennas which radiate equally in all directions, or Sectorial antennas, which focus into a small area. In the Point-to-Point case, antennas are used to connect two single locations together. Directive antennas are the primary choice for this application.

A brief list of common type of antennas for the 2.4 GHz frequency is presented now, with a short description and basic information about their characteristics.

1/4 Wavelength Ground Plane

The 1⁄4 Wavelength Ground Plane antenna is very simple in its construction and is useful for communications when size, cost and ease of construction are important. This antenna is designed to transmit a vertically polarized signal. It consists of a 1⁄4 wave element as half-dipole and three or four 1⁄4 wavelength ground elements bent 30 to 45 degrees down. This set of elements, called *radials*, is known as a *ground plane*. This is a simple and effective antenna that can capture a signal equally from all directions. To increase the gain, however, the signal can be flattened out to take away focus from directly above and below, and providing more focus on the horizon. The vertical beamwidth represents the degree of flatness in the focus. This is useful in a Point-to-Multipoint situation, if all the other antennas are also at the same height. The gain of this antenna is in the order of 2 - 4 dBi.

Yagi antenna

A basic Yagi consists of a certain number of straight elements, each measuring approximately half wavelength. The driven or active element of a Yagi is the equivalent of a center-fed, half-wave dipole antenna. Parallel to the driven element, and approximately 0.2 to 0.5 wavelength on either side of it, are straight rods or wires called reflectors and directors, or passive elements altogether. A reflector is placed behind the driven element and is slightly longer than half wavelength; a director is placed in front of the driven element and is slightly shorter than half wavelength. A typical Yagi has one reflector and one or more directors. The antenna propagates electromagnetic field energy in the direction running from the driven element toward the directors, and is most sensitive to incoming electromagnetic field energy in this same direction. The more directors a Yagi has, the greater the gain. As more directors are added to a Yagi, however, it becomes longer. Following is the photo of a Yagi antenna with 6 directors and one reflector.

Yagi antennas are used primarily for Point-to-Point links, have a gain from 10 to 20 dBi and a horizontal beamwidth of 10 to 20 degrees.

Horn

The horn antenna derives its name from the characteristic flared appearance. The flared portion can be square, rectangular, cylindrical or conical. The direction of maximum radiation corresponds with the axis of the horn. It is easily fed with a waveguide, but can be fed with a coaxial cable and a proper transition. Horn antennas are commonly used as the active element in a dish antenna. The horn is pointed toward the center of the dish reflector. The use of a horn, rather than a dipole antenna or any other type of antenna, at the focal point of the dish minimizes loss of energy around the edges of the dish reflector. At 2.4 GHz, a simple horn antenna made with a tin can has a gain in the order of 10 - 15 dBi.

Parabolic Dish

Antennas based on parabolic reflectors are the most common type of directive antennas when a high gain is required. The main advantage is that they can be made to have gain and directivity as large as required. The main disadvantage is that big dishes are difficult to mount and are likely to have a large windage.

The basic property of a perfect parabolic reflector is that it converts a spherical wave irradiating from a point source placed at the focus into a plane wave. Conversely, all the energy received by the dish from a distant source is reflected to a single point at the focus of the dish. The position of the focus, or focal length, is given by:

$$f = \frac{D^2}{16 \times c}$$

where D is the dish diameter and c is the depth of the parabola at its center.

The size of the dish is the most important factor since it determines the maximum gain that can be achieved at the given frequency and the resulting beamwidth. The gain and beamwidth obtained are given by:

$$G = \frac{(\pi \times D)^2}{\lambda^2} \times n$$

$$BW = \frac{70\lambda}{D}$$

where D is the dish diameter and n is the efficiency. The efficiency is determined mainly by the effectiveness of illumination of the dish by the feed, but also by other factors. Each time the diameter of a dish is doubled, the gain is four times, or 6 dB, greater. If both stations double the size of their dishes, signal strength can be increased of 12 dB, a very substantial gain. An efficiency of 50% can be assumed when hand-building the antenna.

The ratio f/D (focal length/diameter of the dish) is the fundamental factor governing the design of the feed for a dish. The ratio is directly related to the beamwidth of the feed necessary to illuminate the dish effectively. Two dishes of the same diameter but different focal lengths require different design of feed if both are to be illuminated efficiently. The value of 0.25 corresponds to the common focal-plane dish in which the focus is in the same plane as the rim of the dish.

Dishes up to one meter are usually made from solid material. Aluminum is frequently used for its weight advantage, its durability and good electrical characteristics. Windage increases rapidly with dish size and soon becomes a severe problem. Dishes which have a reflecting surface that uses an open mesh are frequently used. These have a poorer front-to-back ratio, but are safer to use and easier to build. Copper, aluminum, brass, galvanized steel and iron are suitable mesh materials.

BiQuad

The BiQuad antenna is simple to build and offers good directivity and gain for Point-to-Point communications. It consists of a two squares of the same size of 1⁄4 wavelength as a radiating element and of a metallic plate or grid as reflector. This antenna has a beamwidth of about 70 degrees and a gain in the order of 10-12 dBi. It can be used as stand-alone antenna or as feeder for a Parabolic Dish. The polarization is such that looking at the antenna from the front, if the squares are placed side by side the polarization is vertical.

Other Antennas

Many other types of antennas exist and new ones are created following the advances in technology.

Sector or Sectorial antennas: they are widely used in cellular telephony infrastructure and are usually built adding a reflective plate to one or more phased dipoles. Their horizontal beamwidth can be as wide as 180 degrees, or as narrow as 60 degrees, while the vertical is usually much narrower. Composite antennas can be built with many Sectors to cover a wider horizontal range (*multisectorial antenna*).

Panel or Patch antennas: they are solid flat panels used for indoor coverage, with a gain up to 20 dB.

Antennas Construction

Quarter wave omnidirectional antenna for 2.4 *GHz*

This is a simple and cheap omnidirectional antenna good for surveying signal strength using wlan tools. It is built using an N-type female chassis mount connector and five short lengths of copper or brass wire. The driven element is the wire soldered into the central conductor of the connector, with a length of one quarter wavelength. The four radials are also one quarter wavelength long, and are soldered into each corner hole of the connector. Each groundplane is cut to length and then bent over at 30 degrees from the horizontal to attempt to match the impedance to 50 Ohms. The gain of this antenna will be between 3 dBi and 4 dBi depending on final tuning.

Parts list:

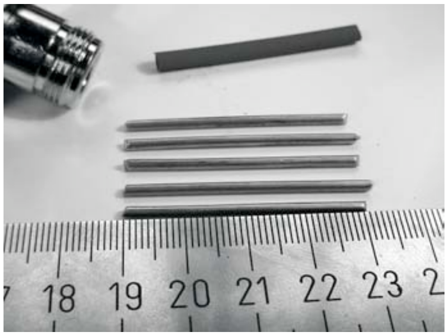
- one N-type chassis mount female connector with four-holes flange (good quality one with teflon insulator is recommended)
- 20 cm of copper or brass wire of 2 mm of diameter

Tools required:

- ruler and goniometer
- pliers
- a file for metal
- a small rat-tail file for metal
- one powerful soldering iron of about 80 -100 W
- one soldering iron
- solder
- vice
- hammer

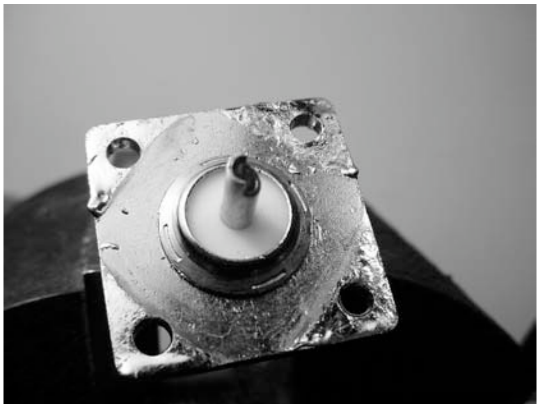
Construction:

1) With the pliers, cut the wire in 5 pieces of 4 cm each.

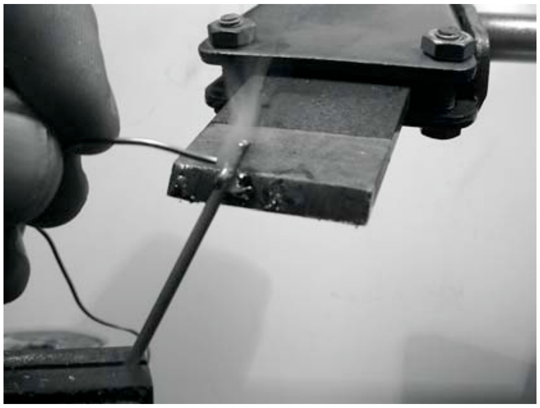


2) File the flange of the connector near the holes in order to remove the plated surface. Use the rat-tail file to do the same on the internal part of the holes. This is done to prepare the surface of the connector for tinning.

3) Power on the high power soldering iron and let it heat for a couple of minutes. Apply the soldering iron to the connector until it gets hot (really hot! Be very careful!), but avoid melting the dielectric. Then tin the area around and inside the holes by applying solder until it flows. Avoid filling the holes with solder. Tinning is required to facilitate the process of soldering the wires to the connector.



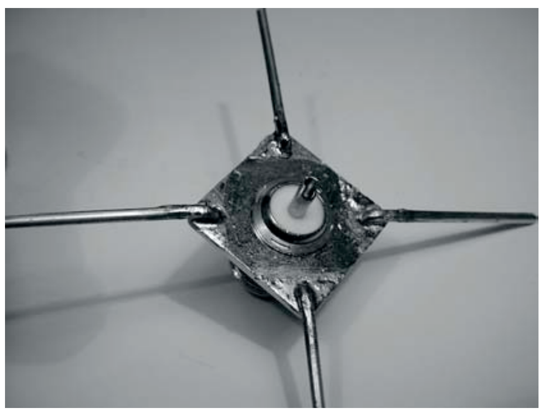
4) Smooth with the file one side of each of the wires. Tin the wires for around 1 cm at the smoothed end, using the high power soldering iron.



5) Bend at 90 degrees 0.5 cm of the tinned side of the wires with the pliers. Do it for four of the wires, leaving one straight. Help yourself with the vice and the hammer.

6) Place firmly the connector in the vice, avoiding damaging the screw. Place the tinned bend side of one wire in a hole of the flange. Keeping it with the pliers, position the wire horizontally and along the direction of the diagonal. Apply the high power soldering iron shortly to the connector and with a small amount of solder, solder the wire to the connector. Avoid melting the dielectric of the connector. You may find useful getting somebody else keeping the wires in place with the pliers while you are soldering.

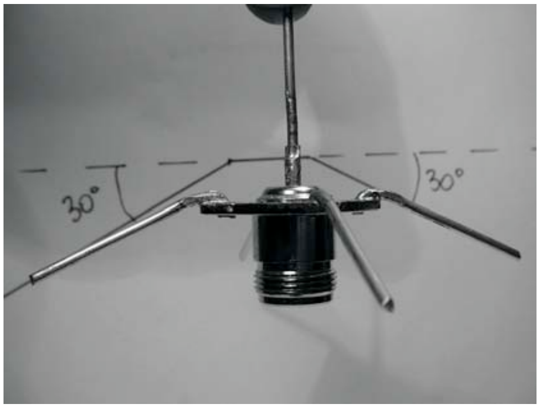
Repeat the same procedure for the four wires.



7) With the low power soldering iron, tin the central pin of the connector. Keeping the straight wire vertical with the pliers, solder its tinned side in the hole of the central pin.

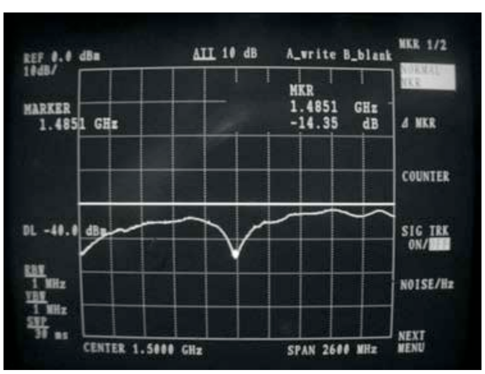
8) Trim the exceeding part of the wires under the flange.

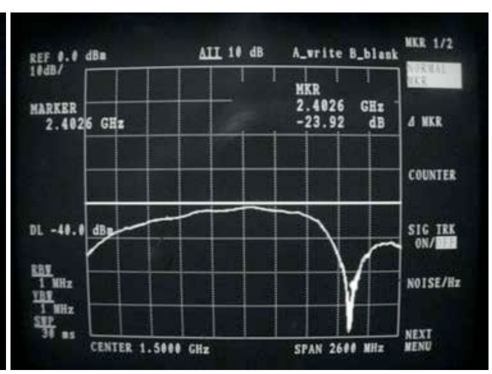
9) With the pliers, bent over the four radials at 30 degrees from the horizontal plane. This is done to match the impedance to 50 Ohms. To facilitate this operation, you may draw the 30 degrees angle on paper, and compare the antenna with it as shown.



10) Trim the radial at a length of 3,05 cm measured from the corner of the flange. Smooth the end of the wires with the file.

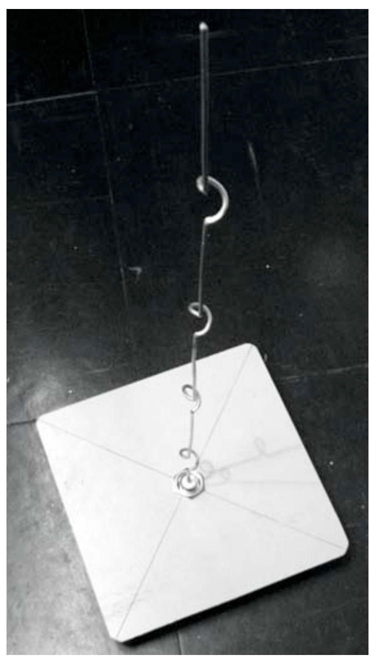
11) Trim the central wire at 3.05 cm measured from the flange surface. If you have a Spectrum Analyzer with Tracking Generator and a Directional Coupler, you can leave the central wire 0.5 cm longer and check the curve of the reflected power of the antenna. Trimming the wire at steps of 0.1 cm or less, you can tune the antenna to have the minimum reflected power at a frequency of 2.44 GHz. The pictures below show the display of the Spectrum Analyzer at the beginning and at the end of the tuning procedure. A difference of a few millimeters changes the frequency of resonance of the antenna of some hundred MHz. You are done!





Omnidirectional collinear antenna for 2.4 *GHz*

This antenna is very simple to build, requiring just a piece of wire, an N socket and a square metallic plate. It can be used for indoor or outdoor Point-to-MultiPoint short distance coverage. The plate has a hole drilled in the middle to accommodate an N type chassis socket that is screwed into place. The wire is soldered to the center pin of the N socket and has coils to separate the active phased elements. Two versions of the antenna are possible: one with two phased elements and two coils and another with four phased elements and four coils. For the short antenna the gain will be around 5dBi, while the long one with four elements will have 7 to 9 dBi of gain. We are going to describe how to build the long antenna only.



Parts list:

- one screw-on N-type female connector
- 50 cm of copper or brass wire of 2 mm of diameter
- 10x10 cm or greater square metallic plate

Tools required:

- ruler
- pliers
- file
- one soldering iron
- drill with a set of bits for metal (with a 1.5 cm diameter bit)
- a piece of pipe or a drill bit with a diameter of 1 cm
- solder
- vice or clamp
- hammer
- spanner or monkey wrench

Construction:

1) Straighten the wire using the vice.

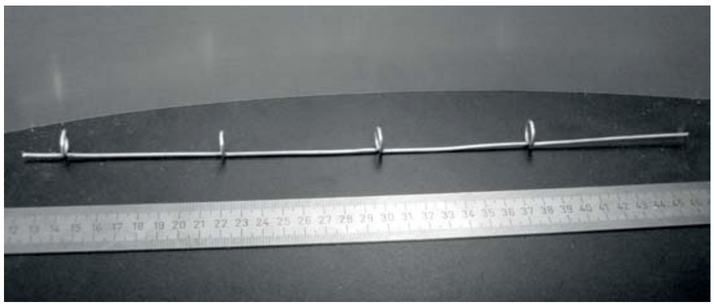
2) With a marker, draw a line at 2.5 cm starting from one end of the wire. On this line, bend the wire at 90 degrees with the help of the vice and of the hammer.

3) Draw another line at a distance of 3.6 cm from the bend. Using the vice and the hammer, bend once again the wire over this second line at 90 degrees, in the opposite direction to the first bend but in the same plane. The wire should look like a 'Z'.

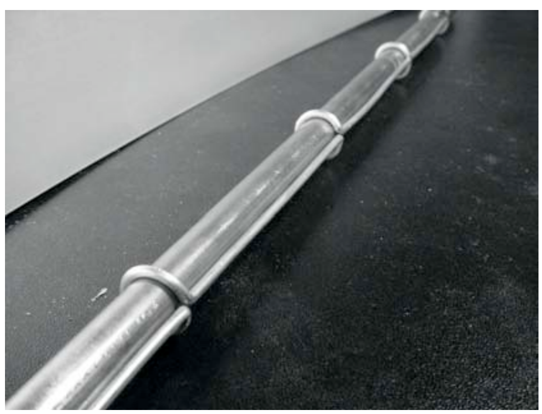
4) We will now twist the 'Z' portion of the wire to make a coil with a diameter of 1 cm. To do this, we will use the pipe or the drill bit and curve the wire around it, with the help of the vice and of the pliers.

The coil will look like this:

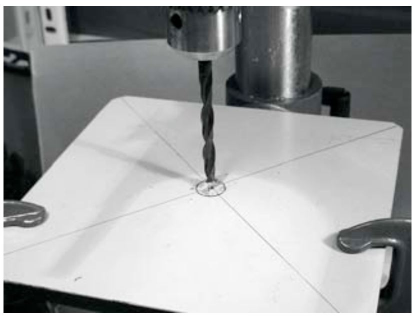
5) You should make a second coil at a distance of 7.8 cm from the first one. Both coils should have the same turning direction and should be placed on the same side of the wire. Make a third and a fourth coil following the same procedure, at the same distance of 7.8 cm one from each other. Trim the last phased element at a distance of 8.0 cm from the fourth coil.



If the coils have been made correctly, it should now be possible to insert a pipe through all the coils as shown.



6) With a marker and a ruler, draw the diagonals on the metallic plate, finding its center. With a small diameter drill bit, make a hole at the center of the plate. Increase the diameter of the hole using bits with an increasing diameter.



The hole should fit exactly the N connector. Use the file if needed.

7) To have an antenna impedance of 50 Ohms, it is important that the visible surface of the internal insulator of the connector (the white area around the central pin) is at the same level as the surface of the plate. For this reason, cut 0.5 cm of copper pipe with an external diameter of 2 cm, and place it between the connector and the plate.

8) Screw the nut to the connector to fix it firmly on the plate using the spanner.

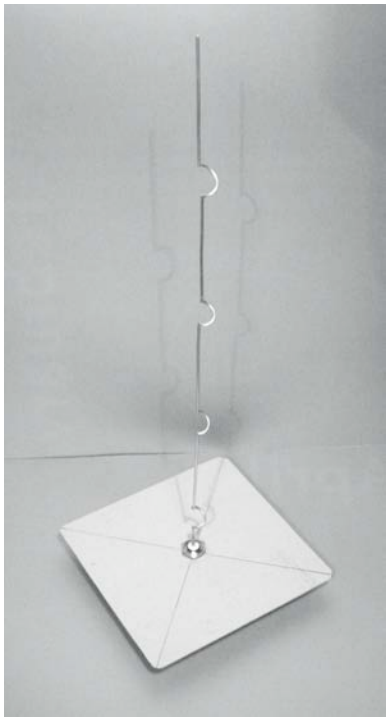
9) Smooth with the file the side of the wire which is 2.5 cm long, from the first coil. Tin the wire for around 0.5 cm at the smoothed end helping yourself with the vice.

10) With the soldering iron, tin the central pin of the connector. Keeping the wire vertical with the pliers, solder its tinned side in the hole of the central pin. The first coil should be at 2.0 cm from the plate.

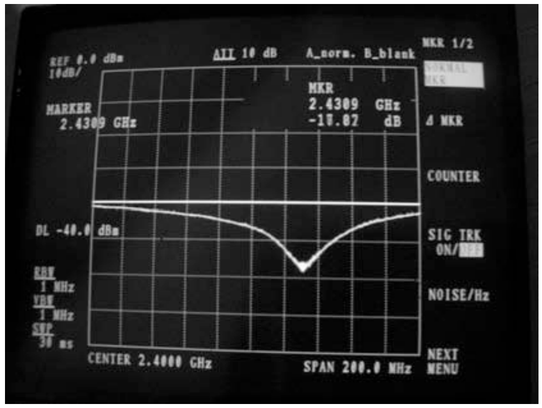
11) We are now going to stretch the coils extending the total vertical length of the wire. Using the use the vice and the pliers, you should pull the cable so that the final length of the coil is of 2.0 cm.

12) Repeat the same procedure for the other three coils, stretching their length to 2.0 cm

13) At the end the antenna should measure 41.5 cm from the plate to the top.

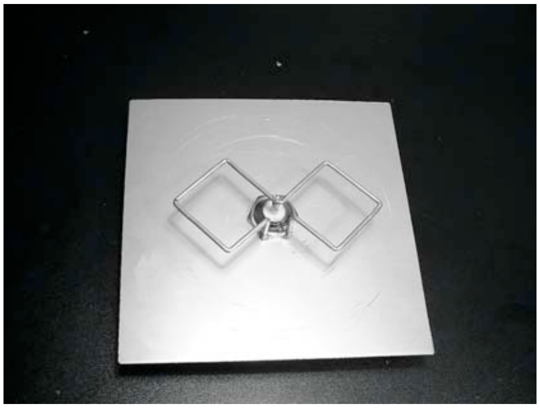


14) If you have a Spectrum Analyzer with Tracking Generator and a Directional Coupler, you can check the curve of the reflected power of the antenna. The picture below shows the display of the Spectrum Analyzer.



Biquad antenna for 2.4 GHz for stand-alone use

This antenna is a directive one, useful for a short distance Point-to-Point link. It may be also used as a feeder for a Parabolic Dish or Grid. It is very cheap and quite easy to build, requiring just a piece of wire, an N socket and a metallic plate. The plate has a hole drilled in the middle to accommodate an N type socket. The wire is shaped as an '8', but with squared angles and then soldered to the N socket. For this antenna the gain will be in the order of 10 to 12 dBi, with a beamwidth of around 60 degrees.



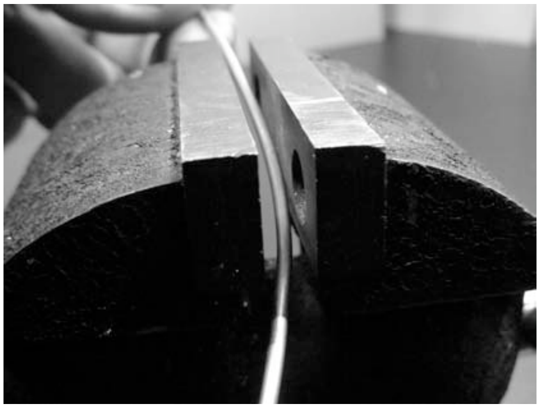
Parts list:

- one screw-on N-type female connector
- 30 cm of copper or brass wire of 2 mm of diameter
- a square metallic plate of at least 12.3x12.3 cm (aluminum is preferable)

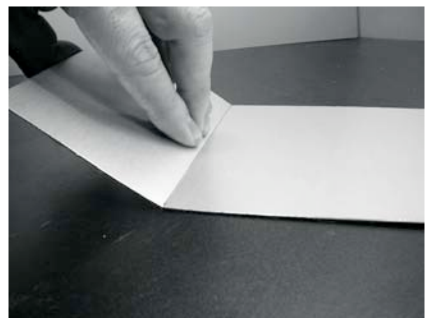
Tools required:
- ruler
- pliers
- file for metal
- small rat-tail file
- cutter
- saw for metal
- soldering iron
- solder
- drill with a set of bits for metal (with a 1.5 cm diameter bit)
- vice or clamp
- hammer
- spanner or monkey wrench

Construction:

1) Straighten the wire using the vice.

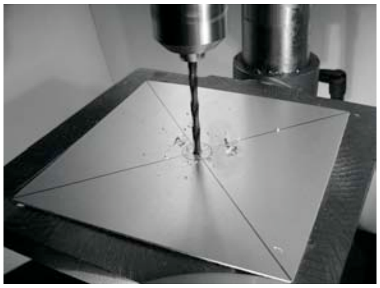


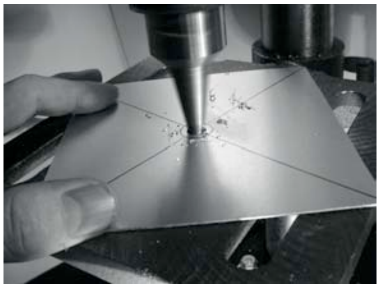
2) Cut the metallic plate to have a square shape of 12.3x12.3 cm. To do this, you may use the saw, but we suggest to use a thin (0.8 to 1.5 mm) aluminum plate, which can be cut with a cutter. Draw the correct dimensions on both sides of the plate with a marker. Carve the drawn lines with the cutter pressing firmly, helping yourself with the ruler. Do this a couple of times, on both sides of the plate. Bend the plate over the lines until it breaks.



3) The edges can be now very sharp. Be careful when handling the plate. Use the file to smooth the edges all around.

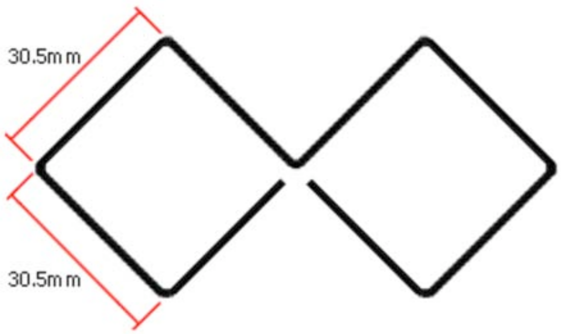
4) With a marker and a ruler, draw the diagonals on the metallic plate, finding its center. With a small diameter drill bit, make a hole at the center of the plate. Increase the diameter of the hole using bits with an increasing diameter.



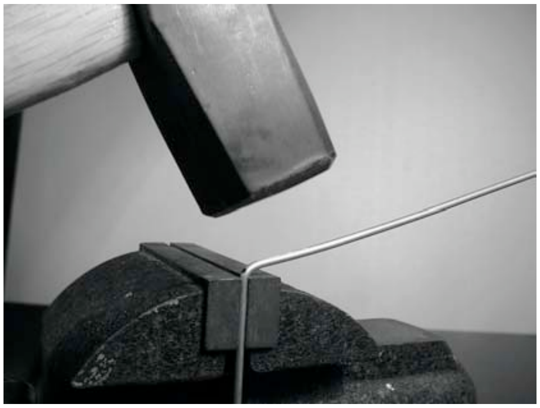


The hole should fit exactly the N connector. Use the file if needed.

5) Now we want to shape the wire as an '8', composed by two squares connected on one edge. The two squares have a side of 3.05 cm.

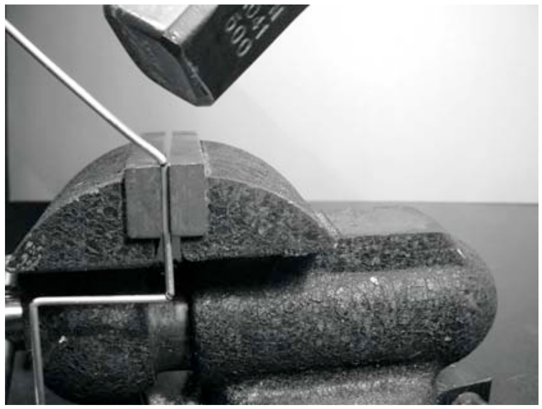


Bend the wire at 90 degrees in his central point using the vice and the hammer.



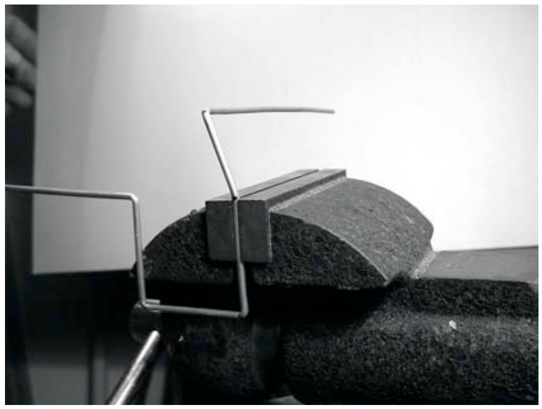
6) With a marker, draw a line at 3.05 cm from the edge, and bend the wire at 90 degrees in this point with the vice and the hammer as before, but in the opposite direction (it should look like a ‘Z’).

7) Draw another line at 3.05 cm from this new edge, and bend the wire at 90 degrees in this point, in the same direction as before.

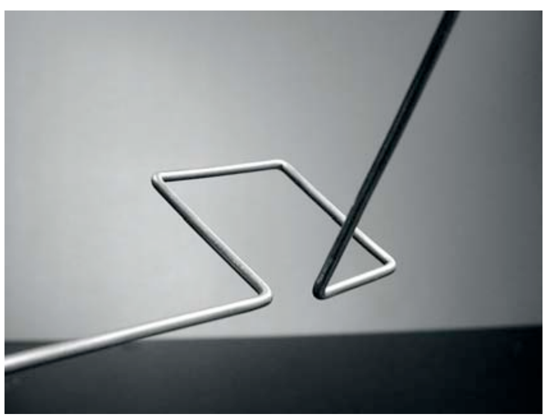


8) Draw now a line at 3.05 cm from the last edge, and a second line after 2.3 cm from the first one. Bend the wire at 90 degrees in the second line, in a direction orthogonal to the plane containing the wire, as shown.

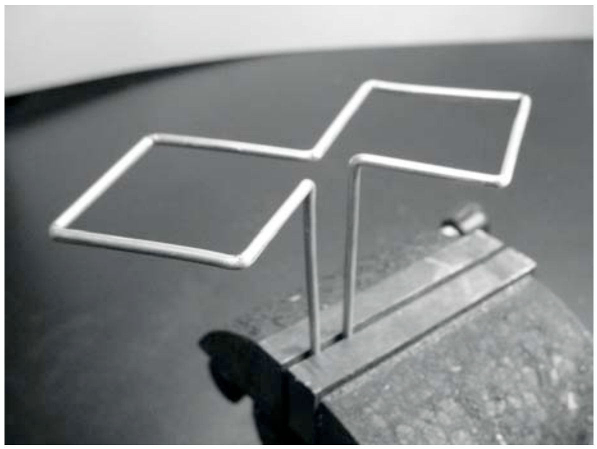
9) Bend the wire at 90 degrees in the first line drawn in the previous step in order to "close" the square, as shown.



The wire at this point should now look like this:



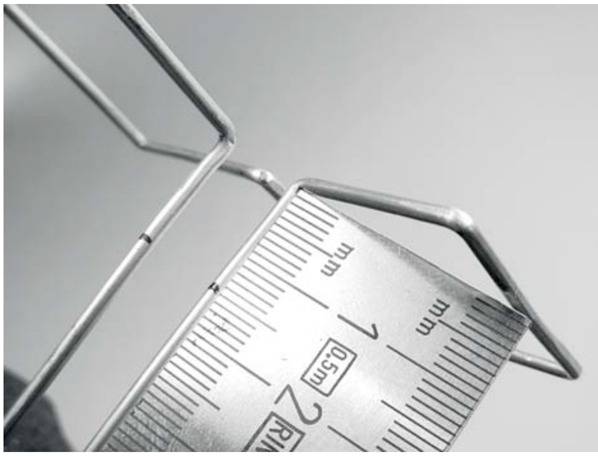
10) Shape the second half of the wire to obtain another square, repeating the procedure described in steps from 6 to 9. The result should be this one:



11) With the saw and the rat-tail file make two small, half-round shaped cuts in the connector's nut at 60 degrees one from each other. The cuts should be on two contiguous edges of the nut, and should be large enough to fit half of the wire's diameter. File also around the cuts.

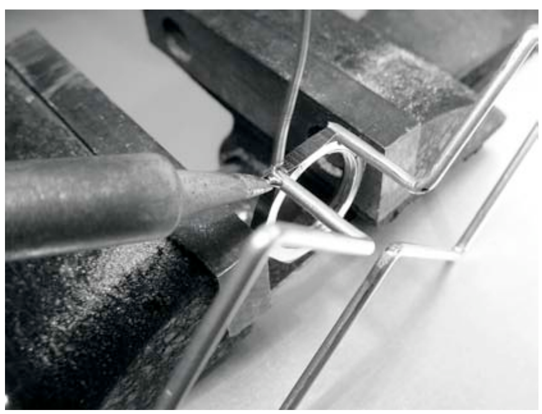
Be careful not to cut too deeply inside the nut: enough metal should remain to ensure its robustness.

12) Trim the two ends of the wire at a length of 1.5 cm.

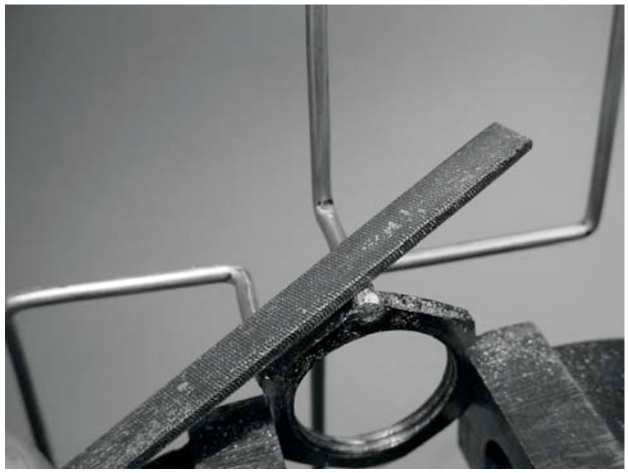


13) The wires should now fit in the nut's cuts as shown.

14) Tin the ends of the wire for 0.5 cm. Tin around and inside the cuts of the nut with a small amount of solder, and then solder the wires to the nut.



15) Remove the exceeding solder with the file, so that the nut can be screwed correctly.



16) Insert the connector into the hole of the metallic plate and screw the nut with the wire soldered on it.

Rotate the nut so that the diagonals of the two wire squares are parallel to the side of the metallic plate. Then screw it firmly with the spanner.

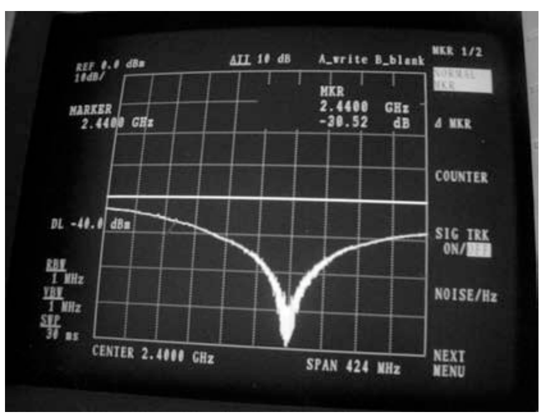
17) We now want to solder the central pin of the connector to the center of the shaped wire. You may have either a short or long type of N connector, as shown.

The central pin of the long type may be soldered directly on the shaped wire, while the short type of connector needs ad additional short piece of straight wire to be soldered into the central pin.

We are going to use the long type of N connector.

18) Tin the central pin of the connector and solder the center of the shaped wire to it.

19) The antenna is now completed. If you have a Spectrum Analyzer with Tracking Generator and a Directional Coupler, you can check the curve of the reflected power of the antenna. The picture below shows the display of the Spectrum Analyzer.

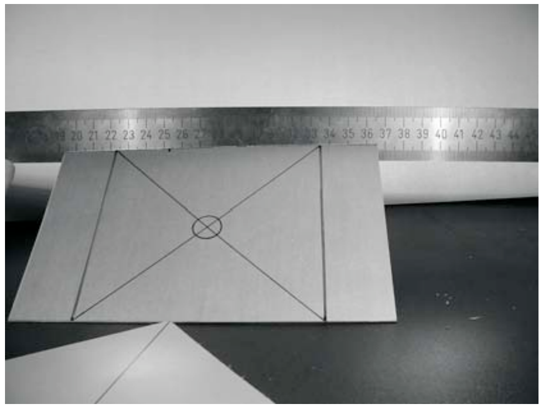


Biquad antenna as a 2.4 GHz feeder for a Parabolic Dish

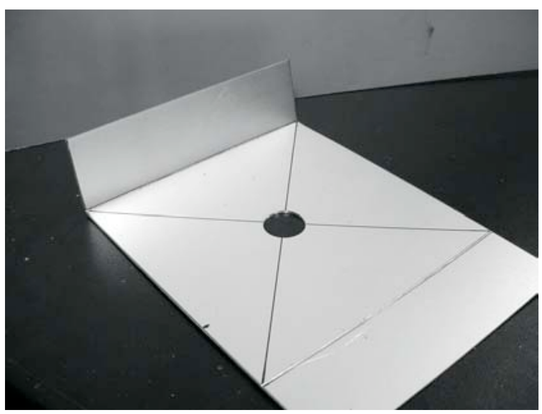
This antenna is essentially the same as the stand-alone Biquad, but with a modified reflector plate allowing it to be used as a feeder for small Parabolic Dishes. You can use one of the very cheap dishes that are used to receive Satellite TV. These dishes may have a centered feeder (called LNB for Satellite TV) or an off-set one. This Biquad feeder can be used in both cases with a reasonable efficiency. The gain will of course vary according to the size and characteristics of the dish.

The construction is the same as the stand-alone Biquad antenna, but the shape of the metallic plate is different. The reflector has two side 'lips' which are 3 cm high, used to minimize coupling with the mounting bar of the feeder. These lips cut down radiation from the rear lobes of the biquad.

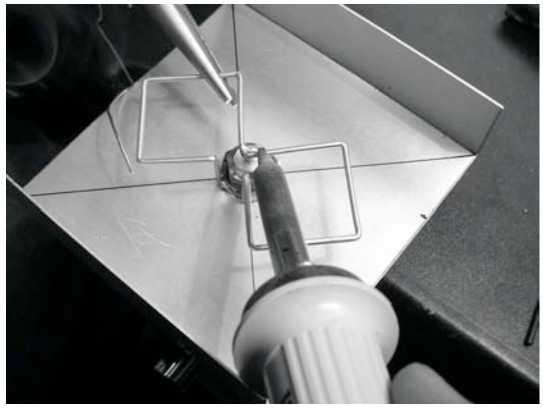
The plate is composed by three parts: a central square of 11x11 cm, and two side rectangles of 11x 3 cm.



The lines between the central square and the two side rectangles should not be carved deeply on both sides with the cutter, but only on the upper side and just enough to facilitate the bending of the plate. The two lips should be folded at 90 degrees. Use the vice if needed.



The procedure to shape the wire and to solder it to the connector is the same as for the stand-alone version.



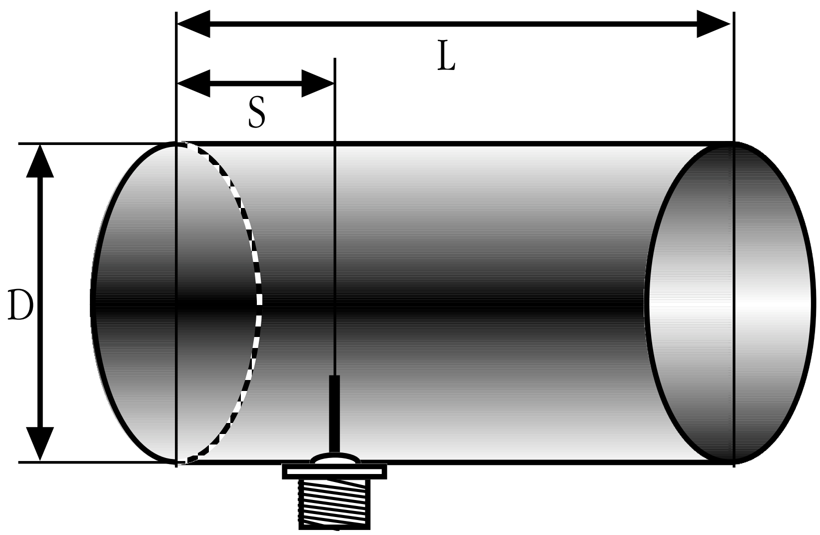
The procedure to fit the Biquad on the mounting bar may vary according to the shape of the original LNB fitting provided with the Parabolic Dish. It is usually round shaped, so it may be possible to use a rubber or plastic ring around the N connector to fix the Biquad in place.

Other types of home-made directive antennas may be used as feeders for Parabolic Dishes. The important point is to match the beamwidth of the feeder with the dish size, and to place the feeder exactly in the focus of the dish.

Can antenna for 2.4 *GHz*

This antenna, called *Cantenna*, uses a tin can as a waveguide and a short wire soldered on an N connector as a probe for coaxial-cable-to-waveguide transition. It can be easily built at just the price of the connector, recycling a food, juice, or other tin can. It is a directive antenna, useful for short to medium distance Point-to-Point links. It may be also used as a feeder for a Parabolic Dish or Grid.

Not all the cans are good to build the antenna because there are dimension constraints:



a) The acceptable values for the diameter D of the feed are between 0.60 and 0.75 wavelength in air at the design frequency. At 2.44 GHz the wavelength λ is 12.2 cm, so the can diameter should be in the range of 7.3 - 9.2 cm.

b) The length L of the can preferably should be at least 0.75 λ_G, where λ_G is the *guide wavelength* and is given by:

$$\lambda_G = \frac{\lambda}{\sqrt{1-\left(\frac{\lambda}{1.706\,D}\right)^2}}$$

For D=7.3 cm, we need a can of at least 56.4 cm, while for D=9.2 cm we need a can of at least 14.8 cm. Generally the smaller is the diameter, the longer the can should be. We will use oil cans, which have a diameter of 8.3 cm and a height of about 21 cm.

c) The probe for coaxial-cable-to-waveguide transition should be positioned at a distance S from the bottom of the can, given by:

$$S = 0.25\ \lambda_G$$

Its length should be 0.25 λ, which at 2.44 GHz corresponds to 3.05 cm.

For this antenna the gain will be in the order of 10 to 14 dBi, with a beamwidth of around 60 degrees.

Parts list:
- one screw-on N-type female connector
- 4 cm of copper or brass wire of 2 mm of diameter
- an oil can of 8.3 cm of diameter and 21 cm of height

Tools required:
- can opener
- ruler
- pliers
- file for metal
- soldering iron
- solder
- drill with a set of bits for metal (with a 1.5 cm diameter bit)
- vice or clamp
- spanner or monkey wrench
- hammer
- punch

Construction:

1) With the can opener, remove carefully the upper part of the can.

The circular dish has a very sharp edge. Be careful in handling it! Empty the can and wash it with soap.

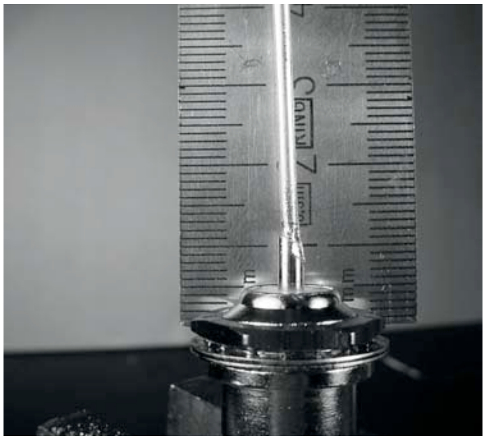
2) With the ruler, measure 6.2 cm from the bottom of the can and draw a point. Be careful to measure from the inner side of the bottom. Use a punch (or a small drill bit or a Phillips screwdriver) and a hammer to mark the point. This makes it easier to precisely drill the hole. Be careful not to change the shape of the can doing this: help yourself with a piece of wood and the vice.

3) With a small diameter drill bit, make a hole at the center of the plate. Increase the diameter of the hole using bits with an increasing diameter. The hole should fit exactly the N connector. Use the file to smooth the border of the hole and to remove the painting around it in order to ensure a better electrical contact with the connector.

4) Smooth with the file one end of the wire. Tin the wire for around 0.5 cm at the same end helping yourself with the vice.

5) With the soldering iron, tin the central pin of the connector. Keeping the wire vertical with the pliers, solder its tinned side in the hole of the central pin.

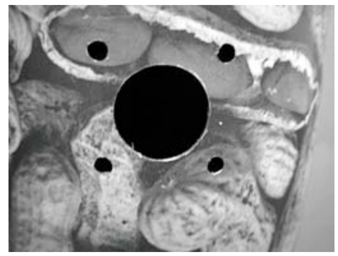
6) Insert a washer and screw gently the nut on the connector. Trim the wire at 3.05 cm measured from the bottom part of the nut.



7) Unscrew the nut from the connector, leaving the washer in place. Insert the connector into the hole of the can. Screw the nut on the connector from inside the can.

8) Use the pliers or the monkey wrench to screw firmly the nut on the connector. You are done!

9) It is also possible to use an N-type chassis mount female connector with four-holes flange, that will make the building procedure someway more complex. In addition to the central hole, you should drill four more small holes to accommodate the screws necessary to fix the connector.



You should also use some additional washers (or thin metallic plates) in order to fit the flange on the curved surface of the can without changing its shape.

10) You can use this cantenna as a feeder for a Parabolic Dish. To match the feeder with the optimal dish size, keep in mind that the horizontal and vertical 3dB beamwidths are given by:

$$\text{Horizontal Beamwidth (degrees)} = 29.4\frac{L}{D}$$

$$\text{Vertical Beamwidth (degrees)} = 50.0\frac{L}{D}$$

where L and D are expressed in the same unit.

Antenna Modifications for Outdoor Use

To use the antennas outdoor, some sort of protection and waterproofing must be provided. You can use some kind of plastic box, like the ones used to store food in the refrigerator, or pipe. The material they are made of should be transparent to the microwaves at 2.4 GHz in order to avoid any attenuation of the signal or modification of the antenna's characteristics. You may check this in two ways:

1) Testing if the insertion of the protective plastic around the antenna modifies in any way the signal's strength in an existing radiolink.

2) Checking if the plastic heats when placed in a microwave oven at the maximum power for a couple of minutes. Be very careful not to damage the oven and always insert a glass with water in the oven so that it will not run empty.

Waterproofing can be obtained sealing carefully the plastic box or pipe on the antenna with hot glue or silicone.

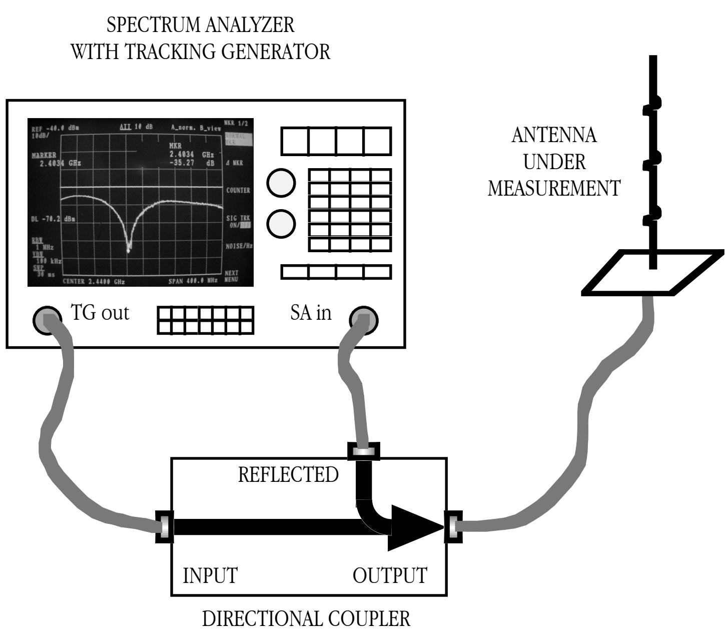
Antenna Measurements

The electrical characteristics of an antenna that are of interest to obtain by direct measurement are:

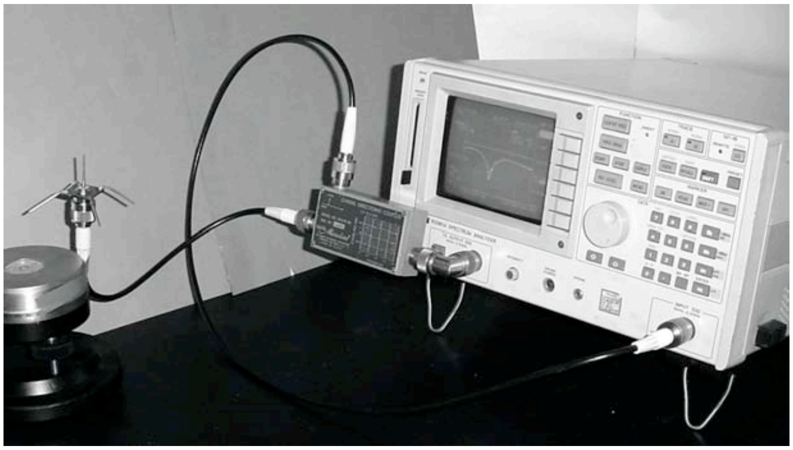
1) The frequency at which the antenna is tuned.
2) The gain.
3) The radiation pattern.

Tuning of an antenna.

To check if an antenna is tuned at the correct frequency, we can use a Directional Coupler and a Spectrum Analyzer. The signal is internally generated by the Tracking Generator of the Spectrum Analyzer, which is connected to the input port of the Directional Coupler. The antenna is connected to the output port of the Directional Coupler.

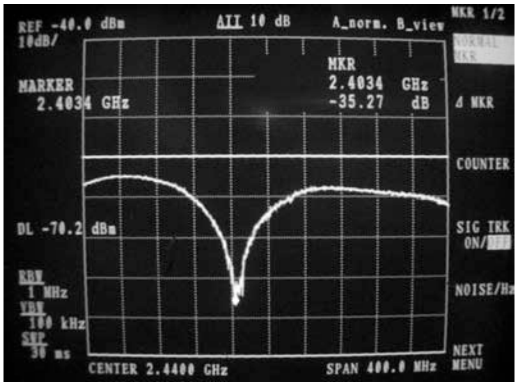


The signal reflected by the antenna is sampled at the reflected port of the Directional Coupler and displayed on the Spectrum Analyzer. We can then check if the minimum amount of reflected power corresponds to the correct frequency value, and if the amount of reflected power is low enough. Be careful to correctly terminate the other ports with 50 Ω dummy loads if the Directional Coupler is of the bidirectional type and to keep the cables as short as possible to avoid any resonance effect. The best electric length for cables is a N times the half wavelength.



To easily read the value of the reflected power, a calibration of the Spectrum Analyzer is required. In a first step, the reflected power when no antenna is connected to the output port of the Directional Coupler should be measured, and this value should be set as the reference value. In a second step, the power reflected by the antenna under test should be measured. In this way, we measure how much lower the reflected power is, in comparison to the case in which all the power is reflected.

For our quarter-wave omnidirectional antenna we got the following graph on the Spectrum Analyzer's screen:



We can see that the antenna is correctly tuned at 2.4 GHz, and the reflected power is about 35 dB less than the case without the antenna. This is a good result.

Measuring the gain.

To be consistent in comparing different antennas, it is necessary to have a standard environment surrounding the antenna. Ideally, measurements should be made with the measured antenna so far removed from any objects causing environmental effects that it can be considered in open space. This is an impractical situation. Professional laboratories use electromagnetic anechoic chambers (also called echo-free chambers) that simulate almost perfectly the open space situation. These are very expensive and for our purposes can be substituted by a roof, a terrace or an open field. The place should be as far as possible (at least 50 m) from power lines, aerials and microwave radio transmitters and without any metallic structure or conductive surface, concrete walls, other building, trees, etc. This is often difficult to achieve, but the environment should be controlled so that successful and accurate measurements can be made in a reasonable wide area.

To measure the gain of an antenna, three antennas are required:

a) The antenna under test
b) An antenna of known gain, that we will call Reference Gain
c) A third antenna which can be of unknown gain

Two measurements are required to determine the gain of the antenna under test. In each measurement, one antenna is connected to a transmitter, which can be a Signal Generator, and the other one is connected to a receiver, which can be a Spectrum Analyzer or a Power Meter. In our case, the receiver will be a Spectrum Analyzer. The antennas are mounted over tripods at fixed positions. The distance between the tripods should be more than a couple of meters to measure the far field. It is assumed that the three antennas have been carefully matched to the appropriate impedance and accurately calibrated and matched devices are being used. The antenna with known gain may be any type of antenna, which has been calibrated either by direct measurement or in special cases by accurate construction according to computed dimensions.

To prepare the measurement, switch on the Signal Generator and the Spectrum Analyzer well in advance and let them stabilize. Set the frequency of the Signal Generator to 2.44 GHz, with no modulation and disable the RF output until you connect the antenna. Set also the Spectrum Analyzer for a center frequency of 2.44 GHz and a frequency span of 20 MHz.

In the first measurement, the antenna of known gain is connected to the transmitter and the third antenna is connected to the receiver. Switch on the RF output of the Signal Generator and set its level high enough so that on the Spectrum Analyzer you can see the peak of the signal well over the noise floor. After arranging the two antennas to read the maximum value for the received signal, record this value on paper. This will be your Reference Level.

Without changing the position of the tripods nor the cables or connector/adapters, you should now exchange the antenna of known gain with the antenna under test. The value of the received signal must be read and recorded on paper as Measured Level.

The gain of the antenna under test is then given by:

Gain (dBi) = Reference Gain + (Measured Level - Reference Level)

The gains are expressed in dBi and the levels are expressed in dBm.

In our lab we have a 10 dBi calibrated directional antenna which we used as reference antenna.

As third antenna we used an omnidirectional antenna. According to the datasheet it has a 4 dBi gain, but as explained the knowledge of the gain of this antenna is not necessary. A photo of the omnidirectional antenna mounted on the tripod is shown.

Following the first measurement of the described procedure, we found a Reference Level of -64 dBm for the antenna of known gain.

We then exchanged the reference antenna with:

- the quarter wave omnidirectional antenna
- the collinear omnidirectional antenna
- the biquad antenna
- the cantenna

We obtained the results shown in this table.

	Measured Level (dBm)	Gain (dBi)
Reference Antenna	-64	10
Quarter Wave Omni	-70	4
Collinear Omni	-66	8
BiQuad	-62	12
Cantenna	-60	14

Measuring the antenna radiation pattern.

Of all antenna measurements considered, the radiation pattern is the most demanding in measurement steps and most difficult to interpret. Any antenna radiates to some degree in all directions into the space surrounding it. Therefore, the radiation pattern of an antenna is a three-dimensional representation of the magnitude, phase and polarization of the electromagnetic field. In most cases the radiation in one particular plane is of interest, usually the plane corresponding to that of the earth's surface, regardless of the polarization of the antenna. Measurements of radiation pattern should therefore be made in a plane nearly parallel to the earth's surface.

The technique to obtain radiation patterns is very similar in procedure to the one used to measure gain, but requires more equipment and time. For a relative antenna pattern measurement, just one antenna is needed in addition to the antenna under test and its gain does not necessarily need to be known. The antenna under test is connected to a transmitter, which can be a Signal Generator, and the other one is connected to a receiver, which can be a Spectrum Analyzer or a Power Meter. In our case, the receiver will be a Spectrum Analyzer. The antennas are mounted over tripods at fixed positions. For the antenna under test, a suitable mount is required which can be rotated in the horizontal plane with some degree of accuracy in terms of azimuth angle positioning. In the photo, one of such mounts is shown.

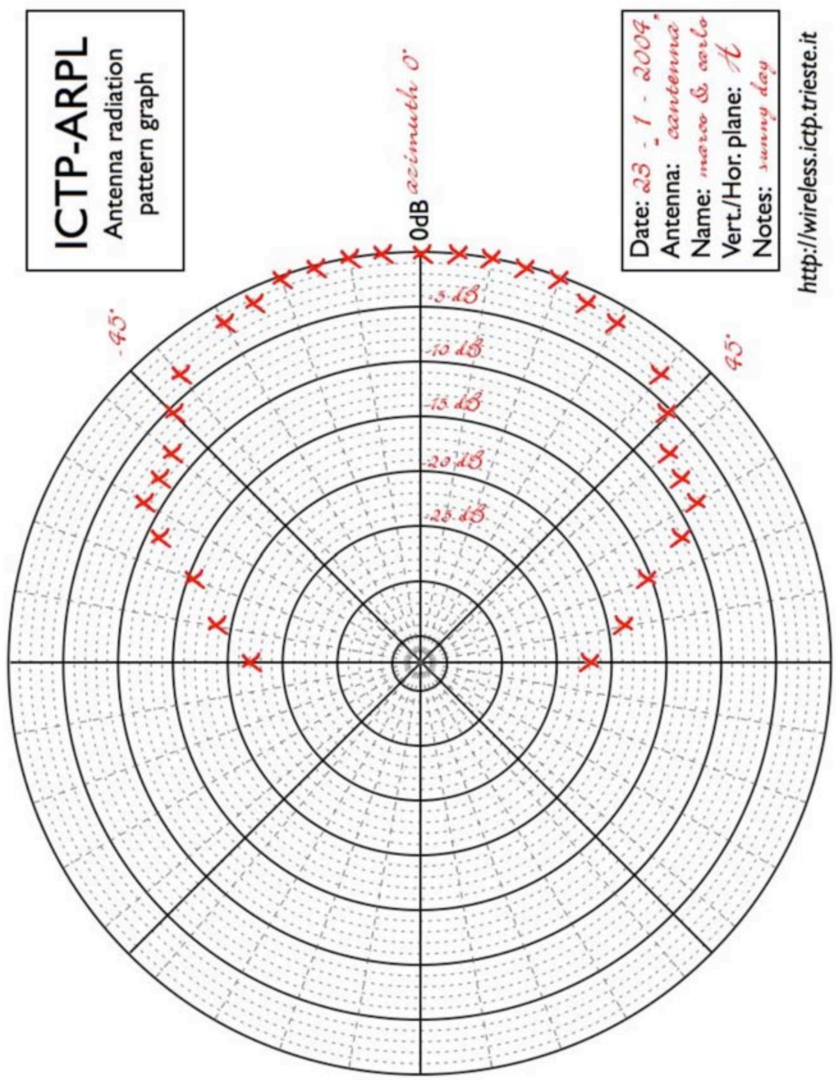
The distance between the tripods should be more than a couple of meters to measure the far field. It is assumed that the antennas have been carefully matched to the appropriate impedance and accurately calibrated and matched devices are being used.

To prepare the measurement, switch on the Signal Generator and the Spectrum Analyzer well in advance and let them stabilize. Set the frequency of the Signal Generator to 2.44 GHz, with no modulation and disable the RF output until you connect the antenna. Set then the Spectrum Analyzer for a center frequency of 2.44 GHz and a frequency span of 20 MHz. Align the geometrical axis of the antenna under test so that it points to the reference antenna. Set the zero of the azimuth scale. The elevation angle of the antenna under test should be also zero, and the two antennas should be at the same height. Connect the antennas, switch on the RF output of the Signal Generator and set its level high enough so that on the Spectrum Analyzer you can see the peak of the signal well over the noise floor. Record the value you read on the Spectrum Analyzer's screen on paper. This will be your Reference Level.

Without changing the elevation setting, carefully rotate the antenna in azimuth in small steps of 5 degrees. You can alternatively rotate the antenna to permit signal-level readout of 3 dB per step. These points of signal level corresponding with an azimuth angle are recorded and then plotted either manually on polar coordinate paper or printed with the use of a computer. On the polar paper, the measured points are marked with an X and a continuous line is then drawn by hand, since the pattern is a continuous curve.

Following the described procedure, we measured the radiation pattern of the cantenna. We aligned the cantenna with the receiving one, that in our case was a 4 dBi omnidirectional one. We reset the azimuth angle to zero. The value read on the Spectrum Analyzer, which was used as Reference Level, was -60 dBm. In the following pages, there is a table with the values read rotating the antenna of 5 degrees at a time in both directions and the hand-made graph of the radiation pattern. From the radiation pattern graph, the 3 dB beamwidth can be estimated in the order of 70 degrees. Due to obstacles near the area of measurement, the angle range was limited to 180 degrees.

Angle (degrees)	Measured Level (dBm)	Rel. Gain (dB)
0	-60	0
5	-60	0
10	-60	0
15	-60.25	0.25
20	-60.25	0.25
25	-61.37	1.37
30	-61.87	1.87
35	-63.25	3.25
40	-64.75	4.75
45	-65.5	5.5
50	-67.75	7.75
55	-68.37	8.37
60	-68.37	8.37
65	-71.35	11.35
70	-75.62	15.62
80	-78.75	18.75
90	-82	22
-5	-60	0
-10	-60	0
-15	-60.45	0.45
-20	-60.45	0.45
-25	-61.58	1.58
-30	-61.95	1.95
-35	-63.63	3.63
-40	-65	5
-45	-65.8	5.8
-50	-68	8
-55	-68.7	8.7
-60	-68.75	8.75
-65	-71.5	11.5
-70	-76	16
-80	-78.9	18.9
-90	-82	22


ICTP-ARPL
Antenna radiation pattern graph
0dB
azimuth 0°
-5 dB
-10 dB
-15 dB
-20 dB
-25 dB
-45°
45°
Date: 23 - 1 - 2004
Antenna: cantenna
Name: marco & carlo
Vert./Hor. plane: H
Notes: sunny day
http://wireless.ictp.trieste.it

Web Links

Basic Concepts

- Introduction to Analog and Digital Communication Theory
http://www.ee.byu.edu/ee/class/ee444/ComBook/ComBook/ComBook.html
- RF Glossary
http://www.hyperlinktech.com/web/glossary.php
- Agilent Technologies RF Corner
http://www.educatorscorner.com/index.cgi?CONTENT_ID=2601
- EM Wave Movies
http://www.ee.iastate.edu/~hsiu/em_movies.html
- Mathematica's Electromagnetic Notebooks
http://library.wolfram.com/infocenter/MathSource/801/

Transmission Lines

- Transmission Lines Interactive Java Applets
http://www.amanogawa.com/transmission.html
- Transmission Line Calculator
http://fermi.la.asu.edu/w9cf/tran/index.html
- Basic Soldering Guide
http://www.ee.byu.edu/ee/class/ee444/ComBook/ComBook/ComBook.html
- Soldering Tutorial
http://www.seas.upenn.edu/ese/rca/funstuff/soldering/soldering.html
- Wave Propagation Along a Transmission Line
http://www.educatorscorner.com/index.cgi?CONTENT_ID=2483
- Amphenol RF (a cable and connector producer)
http://www.amphenolrf.com

Antenna Basics

- MicroWave Antenna Book Online
http://www.qsl.net/n1bwt/contents.htm
- Antenna Types
http://www.netnimble.com/antennas.html
- RF Cafe Antenna Patterns and Gains
http://www.rfcafe.com/references/electrical/antenna_patterns.htm

Antennas Construction

- Quarter Wave Omnidirectional Antenna
http://flakey.info/antenna/omni/quarter/
- Collinear Omnidirectional Antenna
http://www.frars.org.uk/cgi-bin/render.pl?pageid=1071
- Trevor Marshall BiQuad Antenna
http://www.trevormarshall.com/biquad.htm
- BiQuad Antenna as Feeder
http://www.weijand.nl/wifi/
- The original Pringles Antenna
http://www.oreillynet.com/cs/weblog/view/wlg/448
- Cantenna Calculator
http://www.flakey.info/antenna/waveguide/
- Helicoidal Antenna Project
http://www.wireless.org.au/~jhecker/helix/
- Helicoidal Antenna CookBook
http://helix.remco.tk/
- Antenna Construction in French
http://reseaucitoyen.be/

Antenna Measurements

- Understanding and Using Antenna Patters
http://www.astronantennas.com/radiation_patterns.html
- Getting the Most Out of Antenna Patterns
http://www.cebik.com/p.html