Antennas

Antenna Fundamentals

Student Manual
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Lab-Volt®
ANTENNAS

ANTENNA FUNDAMENTALS

by
the Staff
of
Lab-Volt (Quebec) Ltd.

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Foreword

Although mankind has always strived to find new ways of communicating, it is only recently that we have been able to use radio waves for that purpose.

In 1886, Heinrich Hertz, a German physicist, experimentally demonstrated the existence of electromagnetic waves. These had been predicted earlier by the mathematical equations of James Clerk Maxwell. In his work, Hertz constructed several different types of antennas, including dipole and loop antennas.

The discovery of electromagnetic waves and the rapid development of radios and antennas ushered in a new era of communications. Today many different types of antennas are used in a wide variety of applications. Indeed, antennas are so prevalent that they are largely taken for granted. Yet every antenna in use has its own specific characteristics and is the fruit of many design considerations.

It is the purpose of the Lab-Volt Antenna Training and Measuring System and the associated manuals to explain the underlying principles of the different antenna types, and to allow students to measure and compare their fundamental characteristics.
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We Value Your Opinion!
Introduction

This laboratory manual accompanies the Lab-Volt Antenna Training and Measuring System. Together, the manual and the system provide hands-on instruction in the construction and characteristics of various types of antennas, and allow the student to make quantitative measurements without using expensive measuring instruments.

The manual is divided into three units. Unit 1, Basic Antenna Measurements, introduces two basic antenna types and allows the student to measure a number of important antenna characteristics.

Unit 2, Experimentation with Different Antenna Types, presents several commonly used antennas and their characteristics.

Unit 3, Microstrip and Array Antennas, introduces microstrip technology, a state-of-the-art technology used to create small and versatile antennas of the type used in many aviation and military applications.

Reflections

During measurements, the transmitted signal can be reflected by objects lying in the propagation path, and this may affect the results. Even objects not directly in the path may reflect part of the transmitted signal. To reduce these reflections, make sure that the site chosen for the exercises is clear of obstacles and metallic objects. For optimal results, perform the exercises in an anechoic chamber.

Safety with RF fields

When studying antennas, it is very important to develop good safety habits. Although microwaves are invisible, they can be dangerous at high levels or for long exposure times. The most important safety rule when working with microwave equipment is to avoid exposure to dangerous radiation levels.

The radiation levels in the Antenna Training and Measuring System are too low to be dangerous. The power radiated by the RF Generator is typically 2 mW at 1 GHz and 10 mW at 10 GHz. For comparison, a cellular telephone can radiate 300 mW at 850 Mhz. The maximum power density produced by the Lab-Volt Antenna Training and Measuring System is 0.14 mW/cm² at 10 GHz.

In order to develop good safety habits, you should, whenever possible, set the RF POWER switch to the OFF position before placing yourself in front of the transmitting antenna. Your instructor may have additional safety directives for this system.

WARNING

For your safety, do not look directly into the waveguides or Horn Antennas while power is being supplied to the Gunn Oscillator.
Basic Antenna Measurements

UNIT OBJECTIVE

When you have completed this unit, you will be familiar with two basic types of antennas: the wire antenna and the aperture antenna. You will also be familiar with a number of important antenna characteristics such as radiation pattern, beamwidth, gain, impedance, and polarization.

DISCUSSION OF FUNDAMENTALS

The study of antennas involves measuring and comparing the fundamental characteristics of different antennas and antenna types. In this unit, the dipole is used as an example of a wire antenna, and the horn is used as an example of an aperture antenna.

The physical size of an antenna is related to its operating frequency or wavelength. For this reason, the size of an antenna is frequently given in wavelengths.

The first exercise in this unit examines the radiation pattern and half-power beamwidth of the half-wavelength ($\lambda/2$) dipole antenna operating at 1 GHz.

The second exercise examines the radiation pattern of an open waveguide and defines a number of useful terms. This is an important preparation for Exercise 1-3, which presents the pyramidal horn antenna. The 10 GHz range is used in both of these exercises.

The fourth exercise examines dipole antennas of different lengths and shows how the length affects the radiation pattern and the input impedance of the antenna.

The fifth exercise presents a special type of dipole—the folded dipole. This antenna actually consists of two parallel dipoles connected into a narrow loop. This type of antenna can be considered to be a type of multiple-element antenna, or array. It also lends itself very well to the study of impedance transformation.
EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the radiation pattern of a half-wavelength (\(\lambda/2\)) dipole antenna in the E and H planes.

DISCUSSION

An antenna is a device for radiating or receiving radio waves. Antennas are the transition devices between waveguides or transmission lines and free space.

In general, a given antenna can be used to transmit or receive a signal. The orientation of the antenna is important. When receiving, the strength of the received signal will be stronger in some directions than in others. If the same antenna is used to transmit a signal, the radiated power will be greater in some directions than in others. It turns out that, for the same antenna, the direction of maximum power transmission coincides with the direction of maximum power reception.

An isotropic source is a hypothetical antenna which is nondirectional, that is, which has equal radiation intensity in all directions. Although a perfectly isotropic antenna does not exist in practice, the concept is very useful in the study of antennas. This concept gives a convenient reference for discussing the directional properties of antennas.

The dipole antenna and the ideal dipole

The dipole antenna is a simple type of antenna consisting of two rods or wires aligned as shown in Figure 1-1. The length of this antenna is \(L\). The dipole is connected at the centre to the transmitter through a transmission line.

The transmitter supplies an alternating current signal to the antenna. At a given instant, the current \(I\) flows into one terminal of the dipole and out of the other, as shown in the figure. The direction of current is then reversed.

The current distribution, that is, the magnitude of the alternating current along the length of the dipole antenna, is not uniform. Instead, it is zero at the ends, and may be highest at the centre or at other points, depending on the length of the dipole and the frequency of the signal from the transmitter.
An ideal dipole is another hypothetical antenna which is useful in the study of antennas. It can be considered to be a dipole of infinitesimal length with a uniform current distribution. The theoretical characteristics of an ideal dipole approximate those of electrically small dipole antennas.

**Radiation patterns**

A radiation pattern is a three-dimensional, graphical representation of the far-field radiation properties of an antenna as a function of space coordinates. The far-field region is a region far enough for the radiation pattern to be independent of the distance from the antenna. The radiation pattern of a particular antenna can be measured by experiment or can be calculated, if the current distribution is known.

A radiation pattern represents the energy distribution as a function of direction of the signal transmitted by the antenna. It indicates the relative level of transmitted power as a function of direction. Although the term "radiation" pattern is used, it applies just as well to receiving antennas. The reception pattern of an antenna is identical to its radiation pattern. This is a general rule, known as the **reciprocity theorem**.

Although the complete radiation pattern is a three-dimensional function, two two-dimensional patterns are usually sufficient to characterize the directional properties of an antenna. In most cases, the two radiation patterns are measured in planes which are perpendicular to each other. A plane parallel to the electric field is chosen as one plane and the plane parallel to the magnetic field as the other. The two planes are called the **E-plane** and the **H-plane**, respectively (see Figure 1-2).

The radiation pattern in one plane can be measured by rotating the antenna in that plane while measuring the level of received power as a function of the antenna orientation. To obtain a valid pattern, the surrounding environment should be free from objects which could reflect the transmitted signal towards the antenna being tested and cause errors in the results.
Radiation Pattern of a \( \lambda/2 \) Dipole at 1 GHz

Figure 1-2. E plane (y-z) and H plane (x-y) of a dipole

Figure 1-3 shows the E-plane radiation pattern of an ideal dipole. This pattern shows that the ideal dipole is directional because the radiation is stronger in some directions than in others. The H-plane pattern is shown in Figure 1-4. In this plane, the radiation is uniform.

Figure 1-3. Theoretical E-plane radiation pattern of an ideal dipole
Radiation Pattern of a \(\lambda/2\) Dipole at 1 GHz

Figure 1-4. Theoretical H-plane radiation pattern of an ideal dipole

The half-power beamwidth (HPBW) of an antenna is the angular separation of the points in the main beam where the power equals one-half (-3 dB) the power radiated in the direction of maximum power.

\[
\text{HPBW} = |\theta_{\text{HPBW left}} - \theta_{\text{HPBW right}}|
\]

The HPBW of an ideal dipole in the E plane is 90°, as indicated in Figure 1-3.

A practical dipole antenna has a finite length \(L\). Common lengths are \(\lambda/2\), \(\lambda\), and \(3\lambda/2\), where \(\lambda\) is the wavelength of the signal. The current distribution in a \(\lambda/2\) dipole has a half-sinusoidal shape, as shown in Figure 1-5. The current is highest at the centre, tapering off to zero at the ends.
Radiation Pattern of a $\lambda/2$ Dipole at 1 GHz

Figure 1-5. Current distribution in a $\lambda/2$ dipole

Figure 1-6 shows the E-plane radiation pattern for both a $\lambda/2$ dipole and an ideal dipole. The $\lambda/2$ dipole has a HPBW of $78^\circ$ in the E plane and is therefore slightly more directional than the ideal dipole. The H-plane radiation for a $\lambda/2$ dipole antenna is circular, as in Figure 1-4.

Figure 1-6. E-plane radiation pattern for a $\lambda/2$ dipole (solid line) and an ideal dipole (dotted line)
Antenna polarization

The polarization of an antenna describes the direction in space of the electric field of the electromagnetic wave transmitted by the antenna, in the far field. More exactly, it describes the direction where the field intensity is maximum.

Many antennas are linearly polarized, that is, during one cycle, the displacement of the electric field vector describes a straight line in space. Such antennas are referred to as being horizontally or vertically polarized. There are also polarizations called circular or elliptical. These will be seen in a later exercise.

It is often possible to deduce the polarization of an antenna from its geometry. In the case of wire antennas composed of one or several elements aligned parallel to each other (dipoles and Yagi antennas, for example), one can assume that the electric field is linearly polarized and is parallel to the elements. Other types of antennas are also linearly polarized although this is not obvious from their geometry. This is the case for horns, loops, and slits.

In order to obtain a received signal of the highest quality possible, it is important that the reception antenna have the same polarization as the incoming signal. When a signal loss occurs because of poor alignment of the polarizations (for example, a vertically polarized signal received by a horizontally polarized antenna), we speak of cross-polarization isolation.

Procedure Summary

In this exercise you will set up a 1 GHz λ/2 dipole and measure its radiation pattern in the E and H planes. You will become familiar with the concept of polarization for the Yagi and the dipole antennas. Using the cursors option of the LVDAM-ANT program, you will calculate the half-power beamwidth of the λ/2 dipole antenna.
PROCEDURE

Setting up the equipment

1. The main elements of the Antenna Training and Measuring System, that is the Data Acquisition Interface/ Power Supply, the RF Generator, the Antenna Positioner and the computer, must be properly set up before beginning this exercise. Refer to Section 4 in the User Manual for setting up the Antenna Training and Measuring System, if this has not already been done.

2. Place the antenna mast with horizontal clips on the transmission support and clip the Yagi antenna onto it. Orient the elements so they are horizontal; the transmission antenna is horizontally polarized, as shown in Figure 1-8.

![Figure 1-8. Set-up of the Yagi antenna horizontally polarized](image)

3. Using the following equation, calculate the length of a λ/2 dipole at 1 GHz. Note that the exact transmission frequency of the RF Generator is 915 MHZ.

\[ \lambda = \frac{c}{f} \]

where \( c \) is the velocity of light
\( f \) is the transmission frequency

\[ \lambda = \underline{\text{_______}} \text{ m} \]
then

\[ \lambda/2 = \quad m \]

To correctly evaluate the antenna length, the ratio of the length of the conductor to its diameter, the *end effect* (a loading effect at the end of the wires), and the impedance mismatch resulting from the presence of the balun should be considered. To respect these considerations, the antenna length must be shortened. In the present case, a length of 0.45 \( \lambda \), rather than 0.50 \( \lambda \), is a good approximation.

Then

\[ 0.45 \lambda = \quad m \]

☐ 4. Using the answer of your calculation as a reference, choose the appropriate pair of wires to set up the \( \lambda/2 \) dipole. Adjust the dipole length in accordance with your last result, as shown in Figure 1-9.

![Figure 1-9. \( \lambda/2 \) dipole assembly](image)

☐ 5. Place the antenna mast with vertical clips on the sliding support of the Antenna Positioner, then clip on the \( \lambda/2 \) dipole; the antenna is horizontally polarized. Using the sliding support, ensure that the antenna is in line with the rotation centre of the Antenna Positioner. Refer to Figure 1-10 to check your set-up.
Radiation Pattern of a $\lambda/2$ Dipole at 1 GHz

Screw the 10 dB attenuator to the RF input on top of the Antenna Positioner. Connect the antenna to the attenuator using the short SMA cable.

6. Referring to Figure 1-11, position the antennas a distance of $r = 1$ m apart. Adjust them so that they are at the same height and directly facing each other.

Figure 1-10. Set-up of the receiving antenna horizontally polarized.

Figure 1-11. Distance $r$ between the antennas.
7. Make the following adjustments:

On the RF Generator

1 GHz OSCILLATOR MODE ..................... 1 kHz
1 GHz OSCILLATOR RF POWER ............... OFF
10 GHz OSCILLATOR RF POWER .............. OFF

Power up the RF Generator and the Power Supply.

Turn on the computer and start the LVDAM-ANT software.

Radiation pattern acquisition and polarization

8. Set the 1 GHz OSCILLATOR RF POWER switch on the RF Generator to the ON position.

Use the Attenuation control to optimize the acquisition of your radiation pattern (refer to Section 4 in the User’s Manual).

9. Start the first acquisition.

When the acquisition is completed, turn OFF the RF POWER on the RF Generator.

Store the radiation pattern as the E plane of antenna1. Use the Information box to clearly identify the pattern.

Orient the pattern so that the MSP (maximum signal position) is at 0°.

10. Rotate the transmission antenna so it is perpendicular with respect to its initial position, as shown in Figure 1-12. Do not modify the orientation of the receiving antenna.

Note: Remember to loosen the connectors before you rotate an antenna; when it is correctly positioned, screw the connectors tightly together to avoid power loss.
Radiation Pattern of a $\lambda/2$ Dipole at 1 GHz

Figure 1-12. Rotation of the transmission antenna

Keep the same attenuation level. Start a new acquisition and store this pattern as the E plane of antenna2.

Figure 1-13. Set-up of the dipole
11. Remove the dipole antenna, and change the receiving mast for the one with horizontal clips. Install the $\lambda/2$ dipole on the mast, as shown in Figure 1-13.

Using the intermediate SMA cable, connect the antenna to the attenuator on top of the Antenna Positioner.

**Note:** Depending on its position in space, the receiving cable may collect part of the transmitted signal. To avoid distortion during the plotting of the radiation patterns, you will sometimes have to alternate between the short length and the intermediate length cables to connect the receiving antenna. Try to maintain the shortest section of cable possible between the antenna and the detector. Also, to ensure good symmetry, try to install the cable so that it lies close to the mast. Figure 1-14 shows the correct way of installing the cable. This will allow more reliable plotting of the radiation patterns.

12. Using the same attenuation level, perform another acquisition and store the pattern as the H plane of antenna1.

Orient the pattern so that the MSP is at $0^\circ$.

13. Observe your three radiation patterns. Did you expect the result of the second acquisition? Explain.

14. Referring to steps 2 and 5, redo the set-up using the transmission and the receiving antennas with horizontal polarization. Position the antennas a distance of $r = 1.25$ m apart, directly facing each other.

DO NOT change the attenuation level, and make sure that the environment (including your position) around the antennas is the same as for the first acquisition. Acquire the radiation pattern of the dipole E plane and store it in the antenna3 data box.

According to theory, except for its size which is affected by the power loss, this diagram should have the same shape as the first one. If this is not the case, try to find where reflections could have occurred and, if possible, prevent them. Then, do another acquisition and replace the old pattern in the antenna3 data box.
Radiation Pattern of a $\lambda/2$ Dipole at 1 GHz

Half-power beamwidth

15. Click the Cursors button on the tool bar. Two cursors appear, one on each side of the 0° angle. The values displayed on the right part of the screen will also change. These now include two power levels (in dB), the maximum value of the main beam (in dB) and, at the bottom right of the window, the

Figure 1-14. Appropriate cable installation
Radiation Pattern of a $\lambda/2$ Dipole at 1 GHz

positions of the cursors and the difference between these positions (in degrees).

Select and drag the green cursor. When you move this cursor around the window, the Curs2 value changes. This is the difference (in dB) between the maximum of a pattern and the position where the cursor crosses the pattern. You can do the same with the other cursor.

☐ 16. Using these two cursors, find the angles where the power level of the main beam drops to one half on the E-plane pattern of the antenna1 data box.

Note: Remember that a power decrease of one half is equivalent to an attenuation of 3 dB: $10 \log 0.5 = -3 \text{ dB}$

Using the following equation, calculate the E-plane half-power beamwidth (HPBW) of the $\lambda/2$ dipole antenna.

Note: If the left and right HPBW points are positioned on each side of the $0^\circ$ angle, you should add $360^\circ$ to the $\theta_{\text{HPBW, right}}$ in the following equation.

$$\text{HPBW}_E = |\theta_{\text{HPBW, left}} - \theta_{\text{HPBW, right}}|$$

$$\text{HPBW}_E = \quad ^\circ$$

☐ 17. Repeat Step 16 with the radiation pattern of the third data box.

$$\text{HPBW}_E = \quad ^\circ$$

☐ 18. Close the cursor option (the window returns to the initial display). Compare your answers with the values given by LVDAM-ANT (you will find the HPBW value of each antenna in the third column of the antenna data box). If your results do not agree with those values (i.e. the difference exceeds $7^\circ$), redo the procedure steps and your calculations.

Note: The half-power position estimated by LVDAM-ANT may sometimes differ slightly from the exact -3 dB point. To observe the cursor positions selected by the software, open the cursors option, then select the pattern you wish to evaluate. Click the Options, Set Cursors at -3 dB command; the cursors will be positioned automatically. In the next exercises, you can use this command for a rapid approximation of the half-power beamwidth. This can then be adjusted with more accuracy if necessary.

☐ 19. Save the antenna1 and antenna3 data, then print your results. Your printout should show the radiation patterns of these two data boxes with the main display.
OPTIONAL EXPERIMENT

The following experiment can be performed if you have the optional 1 GHz directional coupler.

Note: We have seen previously that the efficiency of a λ/2 dipole is improved when the length of the antenna is slightly shortened. This adjustment produces an impedance that is closely matched to the transmission line.

Using Standing-Wave Ratio (SWR) measurements, you will evaluate the impedance match between the dipole antenna and the transmission line for the two lengths of interest, that is, 0.5λ and 0.45λ.

20. Using the intermediate SMA cable, connect the second output of the directional coupler directly to the 10 dB attenuator still screwed on the RF input on top of the Antenna Positioner. Connect its first output to the 1 GHz OUTPUT of the RF Generator using the long SMA cable. Finally, connect the short SMA cable to its input. Refer to Figure 1-15 for the correct set-up.

21. Set the 1 GHz OSCILLATOR RF POWER switch on the RF Generator to the ON position. Set the Attenuation control to 10 dB and note the value of the received signal.

   \[ P_1 = \text{______ dB} \]

22. Adjust the length of the dipole to 0.5\( \lambda \), then fix this antenna onto the mast with vertical clips. Connect the \( \lambda/2 \) dipole to the open end of the short cable. Figure 1-16 illustrates the set-up of the antenna.
Radiation Pattern of a $\lambda/2$ Dipole at 1 GHz

Figure 1-16. Connection of the antenna to the directional coupler.

*Note:* The antenna is fixed onto the mast to avoid any type of reflection that could occur if it was left on the table during the measurement.

□ 23. Without modifying the attenuation level, record the new signal level.

\[ P_2 = \text{_______ dB} \]

□ 24. Use the following equations to calculate the SWR of this antenna.

\[ X_{\text{dB}} = 10 \log P_1 - 10 \log P_2 = P_1(\text{dB}) - P_2(\text{dB}) \]

\[ X = \text{_______ dB} \]

Knowing that \( X = -20 \log |\Gamma| \)

you can then calculate the voltage reflection coefficient

\[ \Gamma = 10^{\frac{X}{20}} = \text{_______} \]
Radiation Pattern of a $\lambda/2$ Dipole at 1 GHz

Hence, you obtain

$$\text{SWR} = \frac{V_{\text{max}}}{V_{\text{min}}} = \frac{1 + \Gamma}{1 - \Gamma} = \ldots$$

☐ 25. Adjust the length of the dipole to $0.45 \lambda$. Using the same attenuation level, record the signal level.

$$P_2 = \ldots \text{dB}$$

Evaluate the SWR of this antenna.

$$X = \ldots$$

$$\Gamma = \ldots$$

$$\text{SWR} = \ldots$$

☐ 26. Knowing that, for a perfect matching, the SWR = 1, which dipole offers better matching with the 50 $\Omega$ transmission line?

☐ 27. Make sure you have saved your radiation patterns if you expect to use them in the future, then exit the LVDAM-ANT software. Place all power switches in the O (off) position, turn off the computer, disassemble the setup, and return all components to their storage compartments.

CONCLUSION

In this exercise, you learned to calculate the length of a dipole antenna by using the frequency of the transmission signal. You learned to recognize the horizontal and vertical polarizations of the Yagi and the dipole antennas. You plotted the radiation patterns of the E and the H planes of a $\lambda/2$ dipole and observed that the shape of an antenna pattern is not affected by the strength of the signal. Finally, you learned to use the power pattern of an antenna to evaluate its half-power beamwidth (HPBW).

REVIEW QUESTIONS

1. What is the purpose of an antenna?

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________
Radiation Pattern of a $\lambda/2$ Dipole at 1 GHz

2. What is an isotropic source and why it is so useful?

3. What is a radiation pattern? Give the difference between the receiving and the transmission radiation patterns of an antenna.

4. Describe the dipole antenna.

5. What is meant by antenna polarization? How is the dipole antenna polarized?
EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the characteristics of the half-wave folded dipole antenna and with the use of baluns for impedance transformation.

DISCUSSION

Description of the half-wave folded dipole

The folded dipole antenna consists of two parallel dipoles connected into a narrow wire loop. Figures 1-41 and 1-42 illustrate the differences between a half-wave dipole and a half-wave folded dipole.

(a) physical configuration, (b) current distribution

Figure 1-41. The half-wave dipole
In the half-wave dipole of Figure 1-41, the current is forced to zero at both ends of the dipole. The current distribution is sinusoidal with a maximum of $I_D$ at the centre.

The current distribution on a dipole can be expressed as

$$I(z) = I_D \sin \left( \frac{2\pi}{\lambda} \left( \frac{L}{2} - |z| \right) \right), \quad |z| < \frac{L}{2}$$

where $z$ and $L$ are as shown in Figure 1-41.

The half-wave folded dipole of Figure 1-42 has the same sinusoidal current distribution on wire 1, except that the maximum value at the centre is $I_D/2$ instead of $I_D$. The sinusoidal current falls to zero at both ends of wire 1, then increases again as wire 1 turns into wire 2. The current goes through another maximum at the centre of wire 2.

The two current distributions on wire 1 and wire 2 of the folded dipole, added together, are the same as the current distribution on the half-wave dipole. The radiating power is also the same.

$$P_D = \frac{1}{2} Z_D I_D^2 = P_F = \frac{1}{2} Z_F I_F^2 = \frac{1}{2} Z_F \left( \frac{I_D}{2} \right)^2$$

where $P_D$, $Z_D$, $I_D$ are the power, impedance and current of the dipole, respectively.

$P_F$, $Z_F$, $I_F$ are the power, impedance and current of the folded dipole, respectively.
Consequently, the input impedance of the folded dipole is four times larger than that of the half-wave dipole, which is 73 Ω.

\[ Z_F = (4)Z_D = (4)(73) = 292 \ \Omega \]  

(3)

**Note:** Different authors quote slightly different values for the input impedance of the half-wave dipole, for instance, 70, 72, or 73 Ω. Consequently, the input impedance of the folded dipole is also quoted at different values from 280 Ω to 300 Ω.

**Impedance matching**

For optimum power transfer, the source impedance must be equal to the load impedance. This is illustrated in Figure 1-43 for a simple circuit with a voltage source \( V_S \), a source resistance \( R_S \), and a load resistance \( R_L \). Maximum power transfer occurs when \( R_S = R_L \).

![Diagram](image)

**Figure 1-43. Matching source and load impedance for maximum power transfer**

For an antenna system, the same rule prevails. For optimum power transfer, the antenna impedance \( Z_{ant} \) must be equal to the transmission line or waveguide impedance \( Z_L \), as shown in Figure 1-44.
Figure 1-44. Impedance at transmission line and antenna junction

If the match between the transmission line and the antenna is not perfect, part of the power transmitted will be reflected back instead of being radiated by the antenna. In the case of a receiving antenna, part of the signal received by the antenna will not be forwarded to the receiver.

When there is an impedance mismatch, Equation (4) relates the power transmitted through the impedance junction to the power reflected.

\[
P_T = 1 - P_{Rfl} = 1 - \left| \frac{\text{SWR} - 1}{\text{SWR} + 1} \right|^2 = 1 - \left| \frac{Z_{\text{ant}} - Z_L}{Z_{\text{ant}} + Z_L} \right|^2
\]  

(4)

where
- \(P_T\) is the power transmitted through the impedance junction
- \(P_{Rfl}\) is the power reflected at the impedance junction
- \(\text{SWR}\) is the voltage standing wave ratio (SWR = \(Z_{\text{ant}}/Z_L\))

For instance, if there is a perfect match, \(Z_{\text{ant}} = Z_L\) and there is no standing wave since \(\text{SWR} = Z_{\text{ant}}/Z_L = 1\). In this case, there is no reflected power.

\[
P_{Rfl} = \left| \frac{\text{SWR} - 1}{\text{SWR} + 1} \right|^2 = \left| \frac{0}{1} \right|^2 = 0
\]  

(5)

and all the power is transmitted.

In the case of a 73 Ω transmission line feeding into a half-wave folded dipole with four times the line impedance (4 \times 73 = 292 Ω), a standing wave is produced and the SWR is

\[
\text{SWR} = \frac{Z_{\text{ant}}}{Z_L} = \frac{4}{1} = 4
\]  

(6)
Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

\[ P_T = 1 - P_{RE} = 1 - \frac{\text{SWR} - 1^2}{\text{SWR} + 1} = 1 - \frac{3^2}{5} = 0.64 \quad (7) \]

In this case, 64% of the power would be transmitted and 36% would be reflected.

This effect is not necessarily catastrophic (although it might be at high power levels), but it is undesirable. It would be preferable to obtain good impedance matching between the line and the antenna, as shown in Figure 1-45.

Figure 1-45. Impedance matching between transmission line and antenna

Connecting balanced to unbalanced transmission lines through a balun

A problem which is related to the problem of impedance matching is to connect a balanced antenna (such as a centre-fed dipole) to an unbalanced transmission line (such as a coaxial cable).

If the centre-fed dipole is connected to a balanced transmission line, such as a parallel-wire pair, the question of balanced to unbalanced connection does not arise.

If the centre-fed dipole is connected to a coaxial cable, however, the balance is upset. One side of the dipole is connected to the inner conductor while the other side is connected to the shield, and a current will flow on the outside of the shield. This current creates a field which cannot be cancelled by the fields from the current on the inner conductor, because of the shielding. Therefore there will be radiation from the current on the outside shield of the coaxial cable.

This problem can be resolved by using an extra length (λ/4) of coaxial cable as illustrated in Figure 1-46, connecting the outside shields together at a point λ/4 below the antenna terminals. A second current is then induced on the outside shield and the two currents cancel each other. This arrangement is called a balun, which is a contraction of "balanced to unbalanced."
The principle is that the $\lambda/4$ transmission line appears as an infinite impedance to the dipole and does not affect its operation. However, the current which flows on it balances the current which flows on the outside of the coaxial cable.

There are a number of types of baluns. The dipole connectors in the Antenna Training and Measuring System are equipped with baluns similar to that shown in Figure 1-46. There are also baluns which, in addition to a balanced-to-unbalanced connection, offer impedance transformation.

In the next section, you will study a half-wave folded dipole connected to a coaxial cable, in one case without a balun, and in the second case, through a balun which offers a 4-to-1 impedance transformation.

**The Lab-Volt half-wave folded dipole**

The Antenna Training and Measuring System includes a 1-GHz half-wave folded dipole. As shown previously, this type of dipole has an input impedance of 292 $\Omega$.

The transmission lines used for connecting to the 1 GHz antennas in the Lab-Volt system are 50-\(\Omega\) coaxial cables.

The Lab-Volt system offers two types of transitions from the 50-\(\Omega\) coaxial cable to the 292-\(\Omega\) folded dipole antenna, one without a balun and one with a "four-to-one" impedance transformation balun.
Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

Transition without a balun

Figure 1-47 illustrates a transition without a balun from a 50-Ω coaxial cable to a 300-Ω parallel wire pair balanced transmission line and then to the approximately 300-Ω half-wave folded dipole.

![Diagram of transition without a balun](image)

Note: The impedance of a parallel wire pair is a function of the ratio D/d, where D is the distance between the two wires and d is the diameter of each wire. For 300 Ω, D/d = 6, for 75 Ω, D/d = 1.25.

In the case of Figure 1-47, due to the impedance mismatch between 50 Ω and 300 Ω, the SWR will be 300/50 = 6.

The relationship between the transmitted power $P_T$ and the reflected power $P_{RiL}$ will be

$$P_T = 1 - P_{RiL} = 1 - \left| \frac{\text{SWR} - 1}{\text{SWR} + 1} \right|^2 = 1 - 0.51 = 0.49$$

(8)

With perfect impedance matching, 100% of the power would be transmitted. In this case, however, only about 50% of the power will be transmitted. The other half will be reflected—a loss of 3 dB relative to the perfect impedance matching case.

Transition by a four-to-one impedance transformation balun

Figure 1-48 illustrates the transition from a 50-Ω coaxial cable to a 300-Ω half-wave folded dipole using a four-to-one impedance transformation balun. Folded dipole-balun assemblies may occasionally be connected to a 72 Ω coaxial cable such as RG-59U.
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Figure 1-48. Transition from a 50-Ω coaxial cable to a 300-Ω half-wave folded dipole through a four-to-one impedance transformation balun.

Note that the four-to-one transformation is not quite ideal in this case. Ideally, a 6-to-1 impedance transformation would be required to go from 50 to 300 Ω.

Although imperfect, this four-to-one impedance transformation offers substantial improvement. The impedance transformer transforms the 300-Ω impedance into a 75-Ω impedance so that the impedance transition from the 50-Ω coaxial cable causes a SWR of 75/50 = 1.5.

The relation between the transmitted and the reflected power is now

\[
P_T = 1 - P_{\text{ref}} = 1 - \left( \frac{\text{SWR} - 1}{\text{SWR} + 1} \right)^2 = 1 - 0.04 = 0.96
\]

(9)

Therefore, 96% of the power is transmitted and only 4% is reflected, which is not far from the ideal 100% transmission.

The half-wave folded dipole with balun is almost twice as efficient as the one without a balun. This will result in a difference of approximately 3 dB in measurements.

Operation of the four-to-one impedance transformation balun

The operation of the balun can be explained as follows.

Suppose that there is a voltage \( V_1 = V_0 \cos (ut) \) between the centre connector of the coaxial cable and the grounded outside shield. This is in particular the case at the unbalanced end at point c of Figure 1-49.
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Figure 1-49. Operation of the four-to-one impedance transformation balun

Since there is no significant loss in the cable, the voltage between the centre conductor and the grounded shield will again be $V_b = V_o \cos(\omega t)$ at point b some distance away.

Between point b and point a, however, there is exactly a distance of $\lambda/2$. Between these two points a phase shift of $\pi$ or $180^\circ$ will occur and the voltage between the centre conductor and the grounded shield at point a will be

$$V_a = V_o \cos(\omega t + \pi) = -V_o \cos(\omega t)$$

(10)

Then

$$V_2 = V_b - V_a = 2V_o \cos(\omega t)$$

(11)

Since there is no significant loss in the coaxial cable, the radiated power $P_2$ measured at the balanced end (antenna end, i.e., points a and b) will be the same as the power $P_1$ measured at the unbalanced end (cable end, i.e., point c).

Using the relationship $P = \frac{V_{rms}^2}{Z}$, one can then write

$$P_1 = \frac{(V_{1rms})^2}{Z_1} = P_2 = \frac{(V_{2rms})^2}{Z_2}$$

(12)

or

$$\frac{Z_2}{Z_1} = \frac{(V_{2rms})^2}{(V_{1rms})^2} = 2^2 = 4$$

(13)

Thus, $Z_2 = 4 Z_1$.

Using a folded dipole antenna with a metal mast

In principle, the radiation pattern of the dipole and the folded dipole are both circular in the H plane. This is also the case in practice but the circular radiation pattern can be elongated by using a metal mast, as shown in Figure 1-50.
Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

As shown in Figure 1-51, a quarter-wave spacing between the dipole and the mast will cause the radiation pattern to be elongated in the broadside direction (0°) whereas a half-wave spacing will cause the circular radiation pattern to elongated towards the sides (+90° and -90°). The gain in directivity can be 3 to 5 dB, which is quite appreciable.
Procedure Summary

In this exercise you will plot the radiation patterns of a folded dipole with and without a balun. You will then better understand the increase in gain resulting from the use of a 4:1 balun on an antenna having an input impedance of 300 Ω. You will learn the meaning of gain expressed in dBd and use this concept to evaluate the gain of the folded dipole. Finally, you will observe how a metal boom placed behind a dipole affects its directivity.

PROCEDURE

Setting up the equipment

1. The main elements of the Antenna Training and Measuring System, that is the Data Acquisition Interface/Power Supply, the RF Generator, the Antenna Positioner and the computer, must be properly set up before beginning this exercise. Refer to Section 4 of the User Manual for setting up the Antenna Training and Measuring System, if this has not already been done.
2. Place an antenna mast with horizontal clips on the transmission mast support. Clip the Yagi antenna on the mast, oriented for an acquisition in the E plane, and connect it to the 1 GHz OSCILLATOR OUTPUT of the RF Generator, using the long SMA cable.

3. Select the folded dipole connector with balun and the folded wire, then set up a folded dipole antenna, as shown in Figure 1-52.

4. Place the antenna mast with vertical clips on the sliding support of the Antenna Positioner. Attach the folded dipole to the mast.

   Using the sliding support, ensure that the antenna is in line with the rotation centre of the Antenna Positioner and oriented to rotate in the E plane (the folded dipole has the same polarization as that of the basic dipoles in Exercise 1-4).

   Screw the 10 dB attenuator onto the RF input on top of the Antenna Positioner. Connect the antenna to the attenuator using the short SMA cable.

5. Position the antennas a distance of \( r = 1 \) m apart. Adjust them so that they are at the same height and directly facing each other.
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6. Make the following adjustments:

On the RF Generator

1 GHz OSCILLATOR MODE ......................... 1 kHz
1 GHz OSCILLATOR RF POWER ................... OFF
10 GHz OSCILLATOR RF POWER ................... OFF

Power up the RF Generator and the Power Supply.

Turn on the computer and start the LVDAM-ANT software.

Radiation pattern

7. Set the 1 GHz OSCILLATOR RF POWER switch on the RF Generator to the ON position. Use the Attenuation control to optimize reception of the signal.

Start your acquisition and store the radiation pattern in the antenna1 data box, making sure you have selected the correct plane.

8. Rotate the Yagi antenna so that it is vertically polarized.

Remove the antenna mast with vertical clips from the sliding support and replace it with the other mast that uses horizontal clips. Making sure that it rotates in the H plane, install the folded dipole on this new mast and replace the short SMA cable with the intermediate one, as in Figure 1-53.

Figure 1-53. Set-up for a rotation in the H plane
Perform a new acquisition and store it as the H plane of antenna1.

9. Remove the complete folded dipole assembly from the receiving mast. Use the folded wire of this antenna, and set up another antenna using the folded dipole connector without the balun. Clip this new antenna onto the mast.

   Note: Make sure that the set-up here is the same as that in the preceding step - otherwise you won’t be able to compare the two. This remark also applies to acquisitions made in the E plane.

10. Do not modify the attenuation level; start an acquisition of the H-plane pattern.

   Make the appropriate modifications (including the replacement of the receiving cable), then perform an acquisition of the E plane. Store these two patterns in the antenna2 data box.

11. Observe the patterns carefully. Which antenna gives the better gain and what is the difference (in dB) between them? To obtain a convenient graph for your comparison, print the H plane patterns of both antennas on the same sheet (remember to save the patterns stored in the antenna1 and antenna2 data boxes before printing).

Gain of a folded dipole

12. Set-up a \( \lambda/2 \) dipole to replace the folded dipole antenna. Without changing the attenuation level, perform an acquisition of the E plane. Store this pattern in the antenna3 data box.

13. In Exercise 1-2, you saw that the antenna gain, which equals directivity multiplied by antenna efficiency, is a value expressed in dB relative to a hypothetical isotropic antenna. In antenna literature, you will often encounter antenna gain expressed in dBi, which is the gain relative to an isotropic radiator. Antenna gain can also be expressed relative to a half-wave dipole, thus gain in dBd, as shown in Figure 1-54. This figure shows the E-plane radiation patterns of a half-wave dipole (the 0-dB reference) and an example antenna, AntX. As can be seen from these patterns, the MSL of AntX is about 8.4 dB greater than the MSL of the dipole. Therefore, the gain of AntX is 8.4 dBd with respect to the 0-dB reference plot of the half-wave dipole.

   If the gain in dBi of a half-wave dipole is known, then it is easy to convert from a gain in dBd to a gain in dBi. The typical, measured gain in dBi of the half-wave dipole in the Lab-Volt system is 1.9 dBi (the theoretical value for...
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a half-wave dipole is 2.14 dBi. Therefore the gain of AntX expressed in dBi equals $8.4 + 1.9 = 10.3$ dBi.

In theory, the gain of the half-wave dipole and the folded dipole are supposed to be the same; in practice, however, differences sometimes occur. Using the typical dBi gain of the Lab-Volt half-wave dipole, express the gain of the folded dipole with balun in both dBd and dBi.

\[ G = \text{ dBd} = \text{ dBi} \]

\[ 8.4 \text{ dBd} = 10.3 \text{ dBi} \]

\[ 14. \] Print the 3-D representation of the radiation pattern of the folded dipole with balun and observe its similarity to that of the $\lambda/2$ dipole printed in Exercise 1-4.

Improving the directivity

**Note:** Be sure that the receiving antenna has the same orientation in Steps 16, 17 and 19, so that you can compare the different patterns you acquire.
15. Save any patterns you expect to use in the future, then select the File, Close All command to make the antenna1, antenna2, antenna3 data boxes available again.

16. Remove the \( \lambda/2 \) dipole and the receiving mast. Set up the mast with horizontal clips on the sliding support and install the folded dipole with balun on this mast, polarized vertically. Orient the Yagi antenna in the H plane. Adjust the attenuation level to get a maximum signal level of approximately -5 dB. Start an acquisition. Store the radiation pattern as the H plane of antenna1.

17. Add another sliding support onto the sliding support track. Insert the mast with vertical clips into this support and attach the aluminum mast included with the system to it. Position the support at a distance of \( \lambda/4 \) between the antenna and the mast. Refer to Figure 1-55.
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Figure 1-55. Set-up with an aluminum mast placed behind the antenna

Perform an acquisition WITHOUT changing the attenuation level. Store this H plane in antenna2.

☐ 18. You should notice a difference between the two acquired patterns; the second set-up should have improved the directivity of the folded dipole. Give the value of this increase.

Increase of ______ dB

☐ 19. Modify your set-up to obtain a distance of \( \lambda/2 \) between the antenna and the mast, then plot the radiation pattern. You will probably have to rotate one
of the sliding supports to perform this manipulation. Store your last acquisition as the H plane of antenna3 and compare this antenna pattern with that of the standard folded dipole. Does this correspond to the expected result?

☐ 20. Make sure you have saved your radiation patterns if you expect to use them in the future, then exit the LVDAM-ANT software. Place all power switches in the O (off) position, turn off the computer, disassemble the set-up, and return all components to their storage compartments.

CONCLUSION

In this exercise, you saw the radiation pattern of a folded dipole and observed the efficiency of a 4:1 balun used on an unmatched antenna. Using the gain of a $\lambda/2$ dipole antenna as a reference, you evaluated the gain of a folded dipole; you saw that these two gains are very similar. Finally, you improved the directivity of the folded dipole antenna by placing a metal boom behind it.

REVIEW QUESTIONS

1. Why is the impedance of the folded dipole four times greater than that of a $\lambda/2$ dipole?

2. What does the expression “perfect impedance match” mean? Why is it important for the antenna and the transmission line impedances to match, and what happens when a transmitting antenna is not correctly matched with the transmission line?
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3. An antenna has a $\text{HPBW}_E = 28^\circ$ and a $\text{HPBW}_H = 32^\circ$. Calculate the gain of this antenna referenced to a theoretical half-wave dipole.

4. The use of a 4:1 balun improves the gain of a folded dipole fed by a 75 $\Omega$ transmission line. Explain why.

5. Is there any reason to attach a folded dipole to a metal mast? Does the distance between the antenna and the mast have any importance?