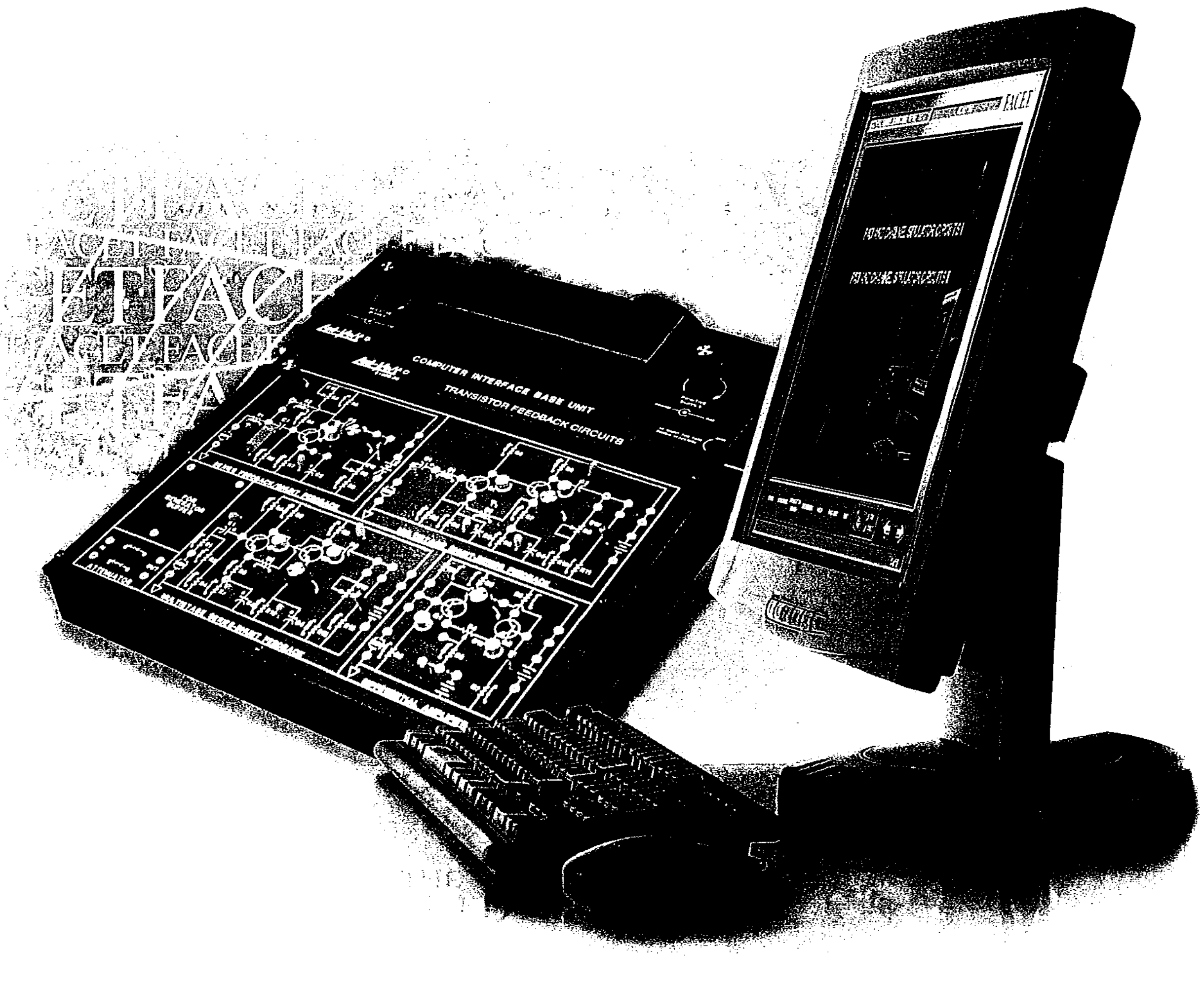
Lab-Volt® Communications Systems

Transmission Lines

FACET®



Student Workbook

36970-J0
Edition 1

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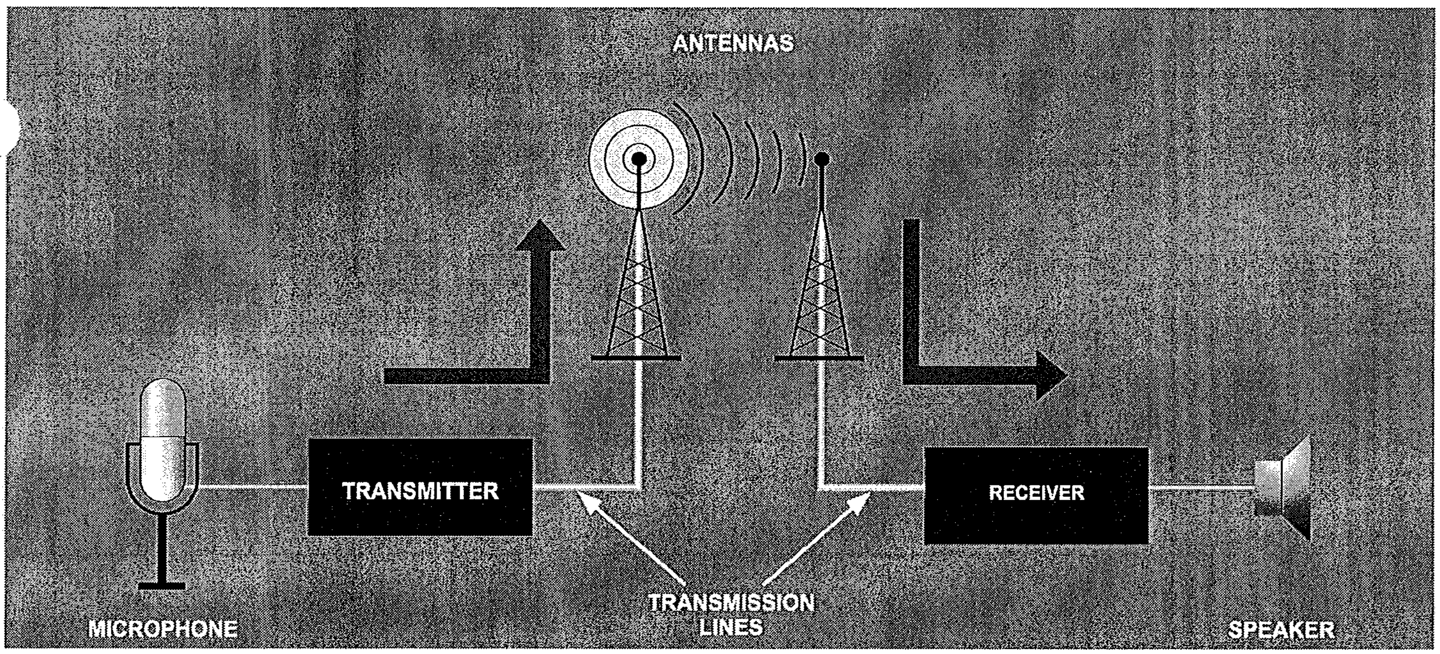
UNIT 1 – CHARACTERISTICS OF TRANSMISSION LINES

UNIT OBJECTIVE

Upon completion of this unit, you will be familiar with the basics of transmission lines. You will be able to describe different types of transmission lines and how they are used. You will know how to determine the equivalent circuit of a transmission line. You will be familiar with the concepts of characteristic impedance and impedance mismatch. You will know how a transmission line terminated by different resistive loads behaves when voltage steps are launched into the line.

UNIT FUNDAMENTALS

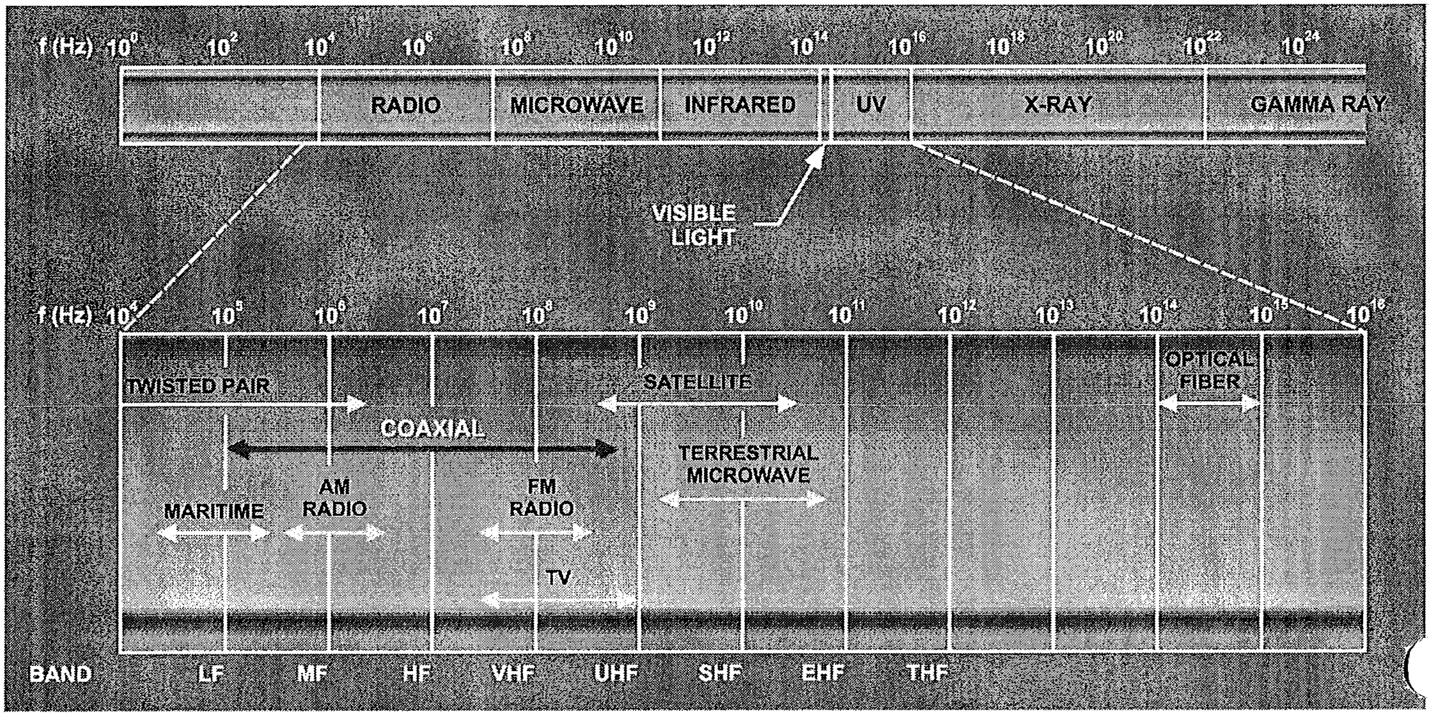
A transmission line is a conducting device used to transfer energy in the form of **electromagnetic waves** from a source (generator) to a load. In television and radio systems, for example, transmission lines are used to connect transmitters to antennas, or antennas to receivers.



There are several different types of transmission lines. Each type of line has different properties that affect transmission: the bandwidth, the attenuation, and the noise or interference.

Depending on the type of transmission line and on the communication requirements, different parts of the **electromagnetic frequency** spectrum are used.

Most of the electromagnetic spectrum is invisible. The lower frequencies of the spectrum include radio waves, microwaves, and infrared radiations. Visible light falls within a very narrow range. The highest frequencies include ultraviolet (UV) light, X-rays, and gamma rays.



The following types of transmission lines are commonly used:

- two-wire open line;
- twisted-pair line;
- shielded pair line;
- coaxial line;
- waveguide;
- optical fiber.

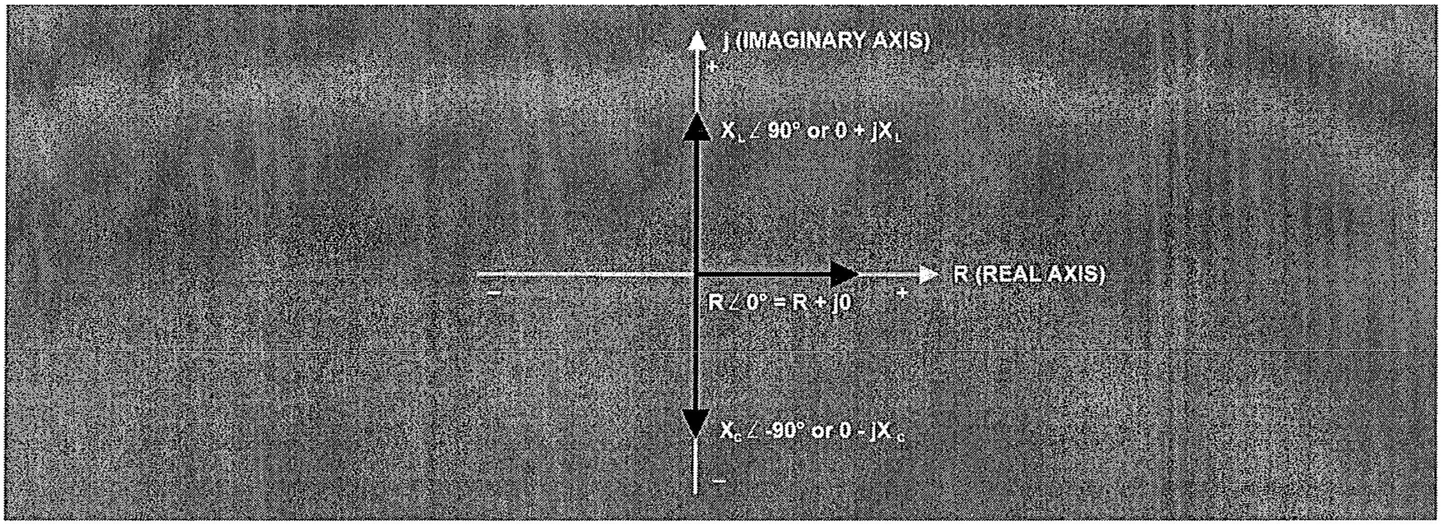
In alternating-current (AC) circuits, the resistance of a component to the flow of current is called **impedance**. Impedance is symbolized by a capital Z. Impedance is measured in ohms (Ω). Impedance is quantified by a complex number that can be expressed in either of the following forms:

- in **polar form**, with some resistance value R, expressed in ohms (Ω), and a given angle, θ, in degrees or radians (° or rad): $R \angle \theta$.

- in **rectangular form**, with a true or **purely resistive** component R, and a **reactive** component (jX), both expressed in ohms (Ω): $R \pm jX$.

When the impedance is

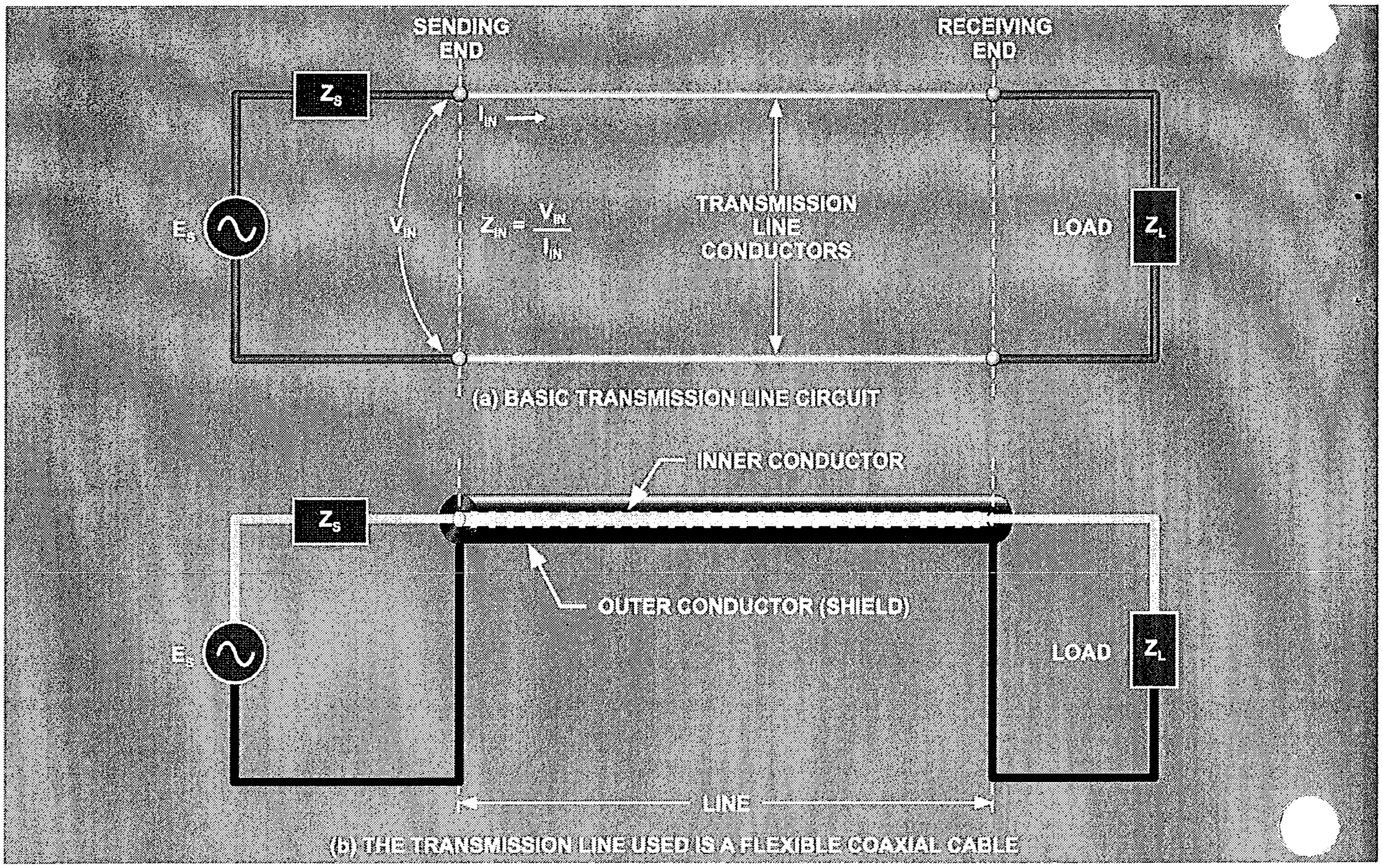
- purely resistive, then $Z = R + j0$, or $R \angle 0°$
- purely inductive, then $Z = 0 + jX_L$, or $X_L \angle 90°$
- purely capacitive, then $Z = 0 - jX_C$, or $X_C \angle -90°$



The upper section of the figure that follows shows a basic transmission line circuit. The transmission line consists of two conductors.

- The sending end of the line is connected to an AC voltage source, E_S, having an internal impedance Z_S. The receiving end of the line is connected to a load having a certain impedance, Z_L.

- The impedance seen at the sending end of the transmission line, Z_{IN}, is the ratio of the voltage to current (V_{IN}/I_{IN}) at that point of the circuit. Z_{IN} corresponds to the impedance presented to the voltage source by the transmission line and the load.



The lower section of the figure shows the circuit when the transmission line used is a flexible coaxial line. This is the type of transmission line used on the TRANSMISSION LINES circuit board. The inner conductor is insulated from the outer conductor by solid, dielectric material. The outer conductor consists of a braided copper shield. Since the source provides an AC voltage, the polarity of the two conductors is always opposite, since the current in the circuit alternates from positive to negative.

NEW TERMS AND WORDS

Attenuation - (in a transmission line): the gradual decrease in the level of a transmitted signal as the signal travels down the transmission line. The attenuation per unit length of a line increases with frequency, due to the skin effect.
Back-and-forth trip time - see Round-trip time (2T).
Bandwidth - (of a transmission line): range of frequencies throughout which a line meets specific performance characteristics (e.g., the frequency range for which attenuation is less than a specific value).
Braid - a woven fibrous protective outer covering over an insulated conductor or cable.
Characteristic impedance - theoretically speaking, the input impedance of a transmission line of infinite length. Practically speaking, the input impedance of a transmission line of finite length when the impedance of the load is perfectly equal to the characteristic impedance. The

characteristic impedance is determined mainly by: the diameter and shape of the conductors; the relative spacing between the conductors; and the type of insulating material that separates the conductors.
Cladding - (of an optical fiber): the light-transmitting material that surrounds the core of an optical fiber, and which has an index of refraction different from that of the core.
Coaxial line - a transmission line consisting of an inner conductor surrounded by a tubular outer conductor. The coaxial line comes in two types: rigid and flexible.
Conductors - materials within which electric current can flow by application of a voltage between points on or within the materials.
Core - (of an optical fiber): the central portion of an optical fiber through which light is transmitted.
Dielectric material - a material which is a poor conductor of electric current, but which can maintain an electrostatic field while dissipating minimal power in the form of heat.
Dispersion - phenomenon by which the fundamental and harmonics of a signal propagate at differing velocities down a transmission line. Dispersion is due to the fact that relative permittivity varies with frequency.
Distortion - the change in shape of a transmitted signal as it travels down a transmission line, due to unequal velocity of propagation and unequal attenuation of the fundamentals and harmonics that compose the signal.
Distortionless - said of a signal at the receiving end of a transmission line when this signal is a faithful reproduction of the transmitted signal.
Distributed parameters - when viewing a transmission line as many tiny sections distributed evenly along the entire length of the line, the value of each discrete component in a same combination per unit length: that is, the series resistance; the series inductance; the parallel resistance (reciprocal of the distributed conductance); and the parallel capacitance.
Electrical shield - a material used to reduce the tendency of a cable to produce electromagnetic interference and reduce the sensitivity of the cable to outside interference.
Electromagnetic frequency spectrum - the entire range of frequencies at which electromagnetic waves can travel. Most of the electromagnetic spectrum is invisible. The lower frequencies of the spectrum include radio waves, microwaves, and infrared radiations. Visible light falls within a very narrow range. The highest frequencies include ultraviolet (UV) light, X-rays, and gamma rays.
Electromagnetic waves - waves of energy produced by oscillation of an electric charge that propagate at a very high speed. They include radio waves, infrared, visible, and ultraviolet light waves, as well as X-, gamma, and cosmic rays.
Eye-pattern method - a popular method of evaluating signal quality in digital transmission systems. This method requires that a pseudo-random binary signal be applied to the vertical input of an oscilloscope. The oscilloscope horizontal sweep is triggered by a signal of the same frequency as the binary signal. The time base is adjusted so as to see about one period of the pseudo-random signal. In this way, the oscilloscope display is a pattern that resembles an eye, due to the superposition of the transitions and constant bit levels that occur randomly on successive periods of the signal. The width of the eye opening indicates the degree of distortion. The narrower the eye opening, the greater the signal distortion and, therefore, the lower the probability of error-free data recovery.
Fourier series - when performing the mathematical analysis of a periodic signal, the expansion of this signal as an infinite sum of sines and cosines of different amplitudes and frequencies.

Fundamental - the component of order 1 of the Fourier series of a periodic signal. A pure sinusoidal wave is composed of a single frequency component, which is the fundamental. However, periodic signals usually consist of a superposition of several frequency components, including a fundamental, or first harmonic, at the frequency of the signal, and several higher-order harmonics whose frequencies are multiples of the fundamental frequency.

Harmonic - frequency component of a signal whose frequency is a whole multiple of the fundamental frequency.

Imaginary axis - on a rectangular coordinate chart representing impedance as a vector, the vertical axis that corresponds to the reactance (jX) axis.

Impedance - in alternating-current (AC) circuits, the opposition of a component to the flow of current. Impedance is measured in ohms, and is quantified by a complex number that can be expressed in polar form (i.e., a resistance value, R, and an angle in degrees or radians) or rectangular form (i.e., a resistance value, R, and a reactive component, jX).

Impedance match - ideal condition under which the impedance of the load connected to a transmission line is perfectly equal to the characteristic impedance of the line. This is the preferred condition, by far, because the energy that reaches the receiving end of the line is perfectly absorbed by the load. The line therefore appears infinitely long from the perspective of the source, because the load has the ability to continually absorb all the received energy.

Impedance mismatch - condition under which the impedance of the load connected to a transmission line is not equal to the characteristic impedance of the line. In this case, not all the received energy is absorbed by the load. Instead, part of this energy is reflected back toward the source, resulting in a loss due to reflection. If, additionally, an impedance mismatch occurs at the source (the impedance of the source is not equal to characteristic impedance of the line), the reflected energy, when it gets back to the source, will be partly re-reflected down the line. The reflected energy will continue to bounce back and forth on the line for a certain time, increasing the losses between the point of transmission and the point of use, and resulting in transmission inefficiency.

Insulating material - a material for preventing or reducing the passage of electric current.

Lossless - said of a transmission line whose distributed series resistance can be neglected, and whose distributed parallel resistance is very high.

Lossy - said of a transmission line whose distributed series resistance is significant, and whose distributed parallel resistance is relatively low. This causes some part of the transmitted power to be lost through R'_s due to losses (series losses), and also through R'_p due to insulation leakage losses (shunt losses). The losses are converted into heat.

Non-return-to-zero (NRZ) data - a binary code with two logic states (1 and 0) and no neutral state between bits.

Optical fiber - a transmission line designed specifically for transmitting light, which can be modeled as an electromagnetic wave. The optical fiber consists of a central conductor, or core, made of glass or plastic surrounded by a protective cladding. The whole assembly is housed in a protective sheath.

Permittivity - a measure of the ability of the dielectric material to maintain a difference in electrical charge over a given distance. The permittivity of the dielectric material used to construct a transmission line is the determinant of the velocity of propagation of a signal in the line.

Polar form - a way of expressing impedance, with some resistance value R, in ohms, and a given angle in degrees or radians.

Pseudo-random binary signal (PRBS) - said of a binary code whose two logic states (1 and 0) occur randomly on successive periods of the signal.
Purely resistive - said of a device, such as a load, that consists mainly of resistor(s), without inductors or capacitors, causing the voltage and current waveforms to be in phase with one another.
Radio-frequency (RF) range - part of the frequency spectrum including frequencies of 20 kHz and higher.
Reactive - said of a device, such as a load, that consists mainly of inductor(s) or capacitor(s), causing the voltage and current waveforms to be out of phase.
Real axis - on a rectangular coordinate chart representing impedance as a vector, the horizontal axis that corresponds to the resistance (R) axis.
Rectangular form - a way of expressing impedance, with a true or purely resistive component R, and a reactive component (jX), both expressed in ohms.
Relative permittivity - (or dielectric constant): the permittivity of a particular dielectric material expressed in relation to that of vacuum.
Round-trip time - when the step response method is used, time required for the launched voltage step to travel to the receiving end of the transmission line and then back to the generator. The round-trip time is equal to twice the transit time, 2T. 2T is therefore synonymous with round-trip time, or back-and-forth trip time.
Sheath - a covering material surrounding a transmission line for insulation and protection purposes.
Skin effect - the non-uniform distribution of currents in a conductor. At direct current (DC) or low frequency, the current density is quite uniform across the conductor. At higher frequencies, the current density tends to concentrate near the surface (hence the term "skin") of the conductor, thereby increasing the resistance to current flow.
Spectrum analyzer - a device used to display the voltage of the frequency components of a signal as a function of frequency.
Steady-state - said of a system or conditions exhibiting only negligible change over a relatively long period of time. For example, transmission lines used to carry sinusoidal signals are said to operate under steady-state conditions if the carried signals, which consist of a sum of homogeneous frequency components that repeat periodically, show only negligible change over a relatively long period of time.
Step response method - method commonly used to measure various transmission line parameters: velocity of propagation, nature and magnitude of the load impedance, as well as detection and location of discontinuities. This method requires that a step generator and a high-impedance oscilloscope probe be both connected to the sending end of the line, using a bridging connection. The signal at the sending end of the line is called the step response signal.
Step response signal - signal observed at the sending end of a transmission line under test as a function of time, when using the step response method.
Thevenin's theorem - theorem named after the French engineer M.L. Thevenin. This theorem allows any electrical linear circuit seen at two terminals to be represented by a Thevenin equivalent circuit. The Thevenin equivalent circuit consists of a voltage source, E_{TH}, and an impedance in series with this source, Z_{TH}. The figure shows how a simple circuit is thevenized.
Transient - said of a temporary phenomenon occurring in a system before a steady-state condition is reached. For example, transmission lines used to carry digital signals, such as

telephone or computer network lines, are said to operate under transient conditions because it takes a certain time, or transitional period, for the pulses in digital signals to reach a steady value.
Transit time, T - when using the step response method, time required for the voltage step launched by the generator to reach the receiving end of the transmission line.
Velocity factor - the velocity of propagation of a signal in a transmission line, expressed as a percentage of the velocity of light in free space. For example, a transmission line with a velocity factor of 66% will transmit signals at about 66% of the velocity of light.
Waveguide - a transmission medium that confines and guides propagating electromagnetic waves. The waveguide normally consists of a hollow metallic conductor, usually cylindrical, rectangular, or elliptical in cross section.

EQUIPMENT REQUIRED

FACET Base Unit
TRANSMISSION LINES circuit board
Oscilloscope, dual trace, 40 MHz, (Lab-Volt P/N 797 or equivalent)

Exercise 1 – Introduction to the Circuit Board

EXERCISE OBJECTIVE

Upon completion of this exercise, you will be familiar with the various sections of the TRANSMISSION LINES circuit board. You will know how to replace the STEP GENERATOR of this board by its Thevenin equivalent circuit. You will be able to determine the voltage across a load connected to this generator, using the voltage divider rule.

DISCUSSION

The five sections that make up the TRANSMISSION LINES circuit board are as follows:

- TRANSMISSION LINEs A and B each consists of a 50-Ω RG-174 coaxial cable having a length of 24 meters (78.7 feet). These lines can be connected end-to-end to obtain a total line length of 48 meters (158 feet).
- The AUXILIARY POWER INPUT section is used to power the TRANSMISSION LINES circuit board with an external ±15 VDC power supply, if the board is operated in stand-alone mode (without a FACET Base Unit).
- The STEP GENERATOR delivers a 50-kHz signal consisting in a rectangular pulse that occurs every 20 µs.
- The SIGNAL GENERATOR delivers a sinusoidal signal whose frequency can be adjusted between 5 kHz and 5 MHz.
- The LOAD section consists of a network of resistors, inductors, and capacitors that can be configured in various ways, through the setting of toggle switches.
- Thevenin's theorem allows any electrical linear circuit seen at two terminals to be represented by a Thevenin equivalent circuit. The Thevenin equivalent circuit consists of a voltage source, E_{TH}, and an impedance in series with this source, Z_{TH}.
- The STEP GENERATOR of the TRANSMISSION LINES circuit board can be represented by its Thevenin equivalent. To do so, the Thevenin voltage is measured with no load connected to the generator output. The Thevenin impedance is determined by connecting a variable load resistance to the generator output.

NOTES

In Review Questions, the correct answer to Q# 1 is given by the software as "c. having frequency of 5 kHz"

Actually, this answer is incorrect (i.e., there is no correct answer provided by the system) because the frequency of the Step Generator is 50 kHz

Exercise 2 – Velocity of Propagation

EXERCISE OBJECTIVE

Upon completion of this unit, you will know how to measure the velocity of propagation of a signal in a transmission line, using the step response method. Based on the measurements, you will know how to determine the relative permittivity of the dielectric material used to construct this line.

DISCUSSION

- A radio signal travels in free space at the velocity of light (approximately $3.0 \cdot 10^8$ m/s, or $9.8 \cdot 10^8$ ft/s).
- In a transmission line, a signal will travel at a relatively lower speed. This is due mainly to the presence of the dielectric material used to construct the line.
- The velocity of propagation of a signal in a transmission line can be measured by using the **step response method**.
- This method requires that a step generator and a high-impedance oscilloscope probe be both connected to the sending end of the line, using a bridging connection.
- The signal at the sending end of the line, as a function of time, is the **step response signal**.
- The velocity of propagation of a signal in a transmission line is usually expressed as a percentage of the velocity of light in free space. This percentage is called the **velocity factor.**
- The velocity of propagation of a signal in a transmission line is determined mainly by the **permittivity** of the dielectric material used to construct the line.
- The permittivity of a particular dielectric material is normally expressed in relation to that of vacuum. This ratio is called **relative permittivity.**

Exercise 3 – Line Under Load Impedances

EXERCISE OBJECTIVE

Upon completion of this unit, you will know how a transmission line terminated by various types of loads behaves when voltage steps are launched into the line. You will also know about two methods of determining the characteristic impedance of a line.

DISCUSSION

- When a transmission line is terminated by a load of unknown impedance, the step response method can be used to determine the nature of this impedance (whether purely resistive or complex).
- The measurements are performed by using the step response method.
- When Z_L is purely resistive, the reflected voltage has the same shape as the incident voltage.
- When Z_L is both resistive and inductive, the reflected voltage in the step response signal has the same shape as the voltage across a capacitor discharging through a series resistor.
- When Z_L is both resistive and capacitive, the reflected voltage in the step response signal has the same shape as the voltage across a capacitor charging through a series resistor.
- The step response method can be used to measure the characteristic impedance of a line. To do this, a purely resistive load, Z_L, whose resistance can be varied, is connected to the receiving end of the line.
- When the receiving end of the line is not accessible for connection to a variable-resistance load, there is another way of determining the characteristic impedance of the line. This method consists in measuring the voltage of the rising edge, V_{re}, of the incident step in the step response signal.

Exercise 4 – Attenuation and Distortion

EXERCISE OBJECTIVE

Upon completion of this unit, you will know what attenuation and distortion are, and how they can affect the shape of the transmitted signal. You will be able to explain what causes attenuation and distortion. You will know about a method of evaluating signal quality in high-speed transmission systems.

DISCUSSION

- In transmission lines that are lossy, the transmitted signals lose some energy as they travel down the line. This occurs because the energy gradually dissipates in each series resistance, R'_S, and parallel resistance, R'_P, per unit length of the line.
- The decrease in signal level over distance is called **attenuation**.
- Attenuation increases as the distance from the transmission point increases.
- Attenuation is normally expressed in decibels (dB).
- At higher frequencies, the attenuation per unit length, instead of being constant, increases with frequency due, among other things, to a phenomenon known as skin effect.
- Periodic signals usually consist of a superposition of several frequency components. These components are waves that are all sinusoidal in shape, but are of different frequencies and amplitudes.
- These components include a fundamental, or first **harmonic**, at the frequency of the signal, and several higher-order harmonics whose frequencies are multiples of the fundamental frequency.
- In a transmission line, the velocity of propagation of the fundamental and harmonics that compose a transmitted signal is determined mainly by the relative permittivity of the line dielectric material.
- In lines that are **lossless** or that have very low losses, relative permittivity stays approximately constant with frequency. As a result, the signal at the receiving end of the line is a faithful reproduction of the transmitted signal.
- In lines that are **lossy**, however, relative permittivity varies with frequency. Consequently, the signal at the receiving end of the line has a shape that is quite different than that of the transmitted signal (distorted) due to **dispersion**.
- A popular method of evaluating signal quality in digital transmission systems is the **eye-pattern method**.
- The oscilloscope display is a pattern that resembles an eye, the width of the eye opening indicating the degree of distortion.

UNIT 2 – TRANSIENT (STEP TESTING) CONDITIONS

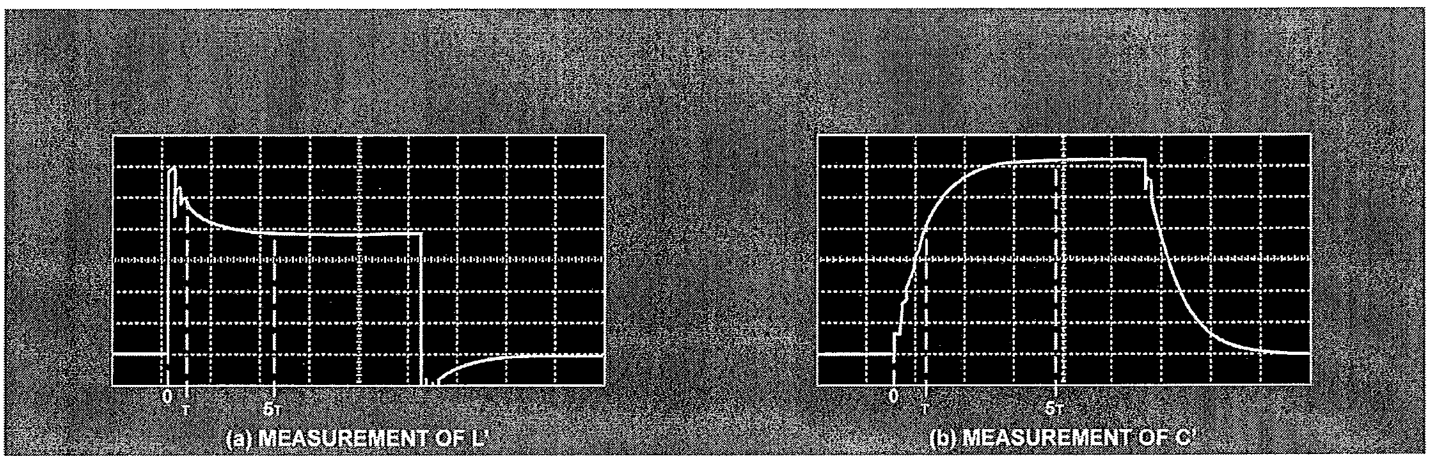
UNIT OBJECTIVE

Upon completion of this unit, you will be able to measure the distributed inductance and distributed capacitance of a line, and then use the measured values to determine the characteristic impedance and velocity of propagation through the line. You will be familiar with the concept of voltage reflection coefficient. You will know how to represent the creation of reflections and the distribution of the voltage along a line, using a graph called the voltage reflection diagram. You will know how a line terminated by complex load impedances behaves when voltage steps are launched into the line. Finally, you will learn how to use time-domain reflectometry (TDR) to locate and identify discontinuities (faults) introduced by your instructor along the transmission lines of the circuit board.

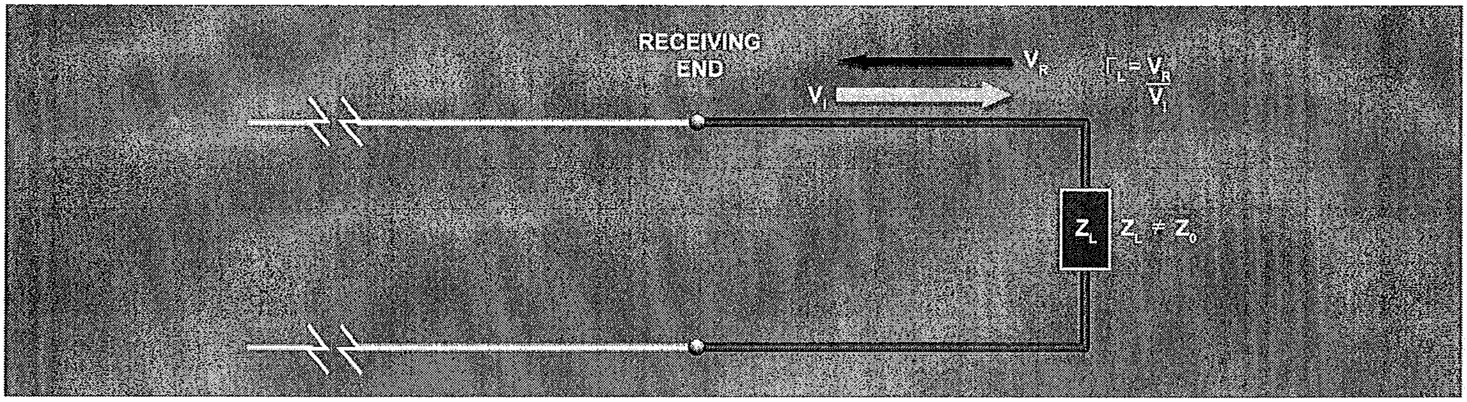
UNIT FUNDAMENTALS

The characteristic impedance, Z_0, of a line is constant, regardless of how long the line may be. This occurs because Z_0 is determined by the geometrical and physical characteristics of the line. Thus, a relationship exists between the value of Z_0 and the value of its distributed parameters, L', C', R'_S, and R'_P.

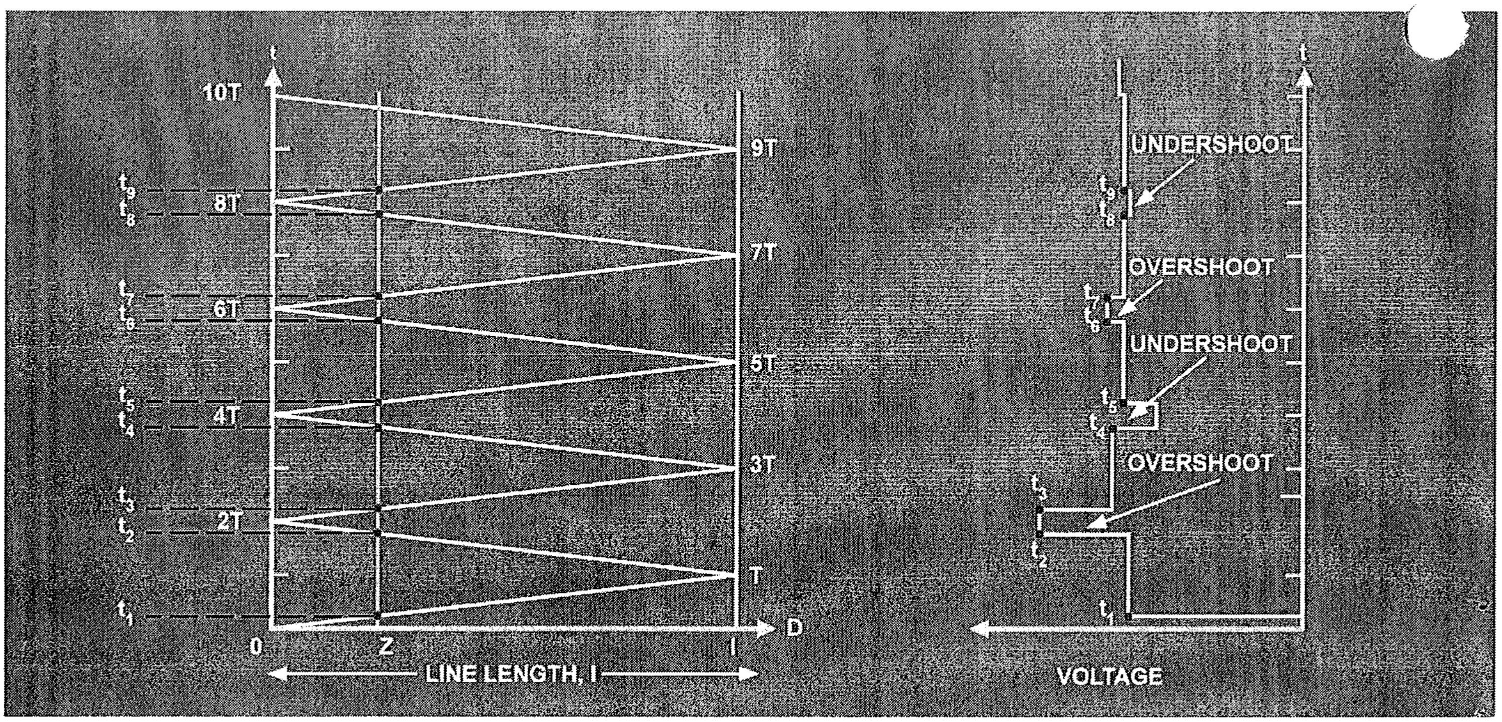
When the losses in a line are low and the frequency of the carried signals is relatively high, Z_0 is considered to be purely resistive. In this condition, L' and C' can be measured by creating an **impedance mismatch at both ends** of the line in order to obtain a step response signal with measurable time constant, as the figure below shows.



Whenever the signal carried by a transmission line encounters a change in impedance, or **discontinuity**, a reflection is created. The reflection causes part of the signal energy to be reflected in a direction opposite to the direction of travel of the signal. The ratio of the reflected voltage, V_R, to incident voltage V_I at a discontinuity is called the **voltage reflection coefficient**. This coefficient is usually represented by Γ, the Greek capital letter "gamma".

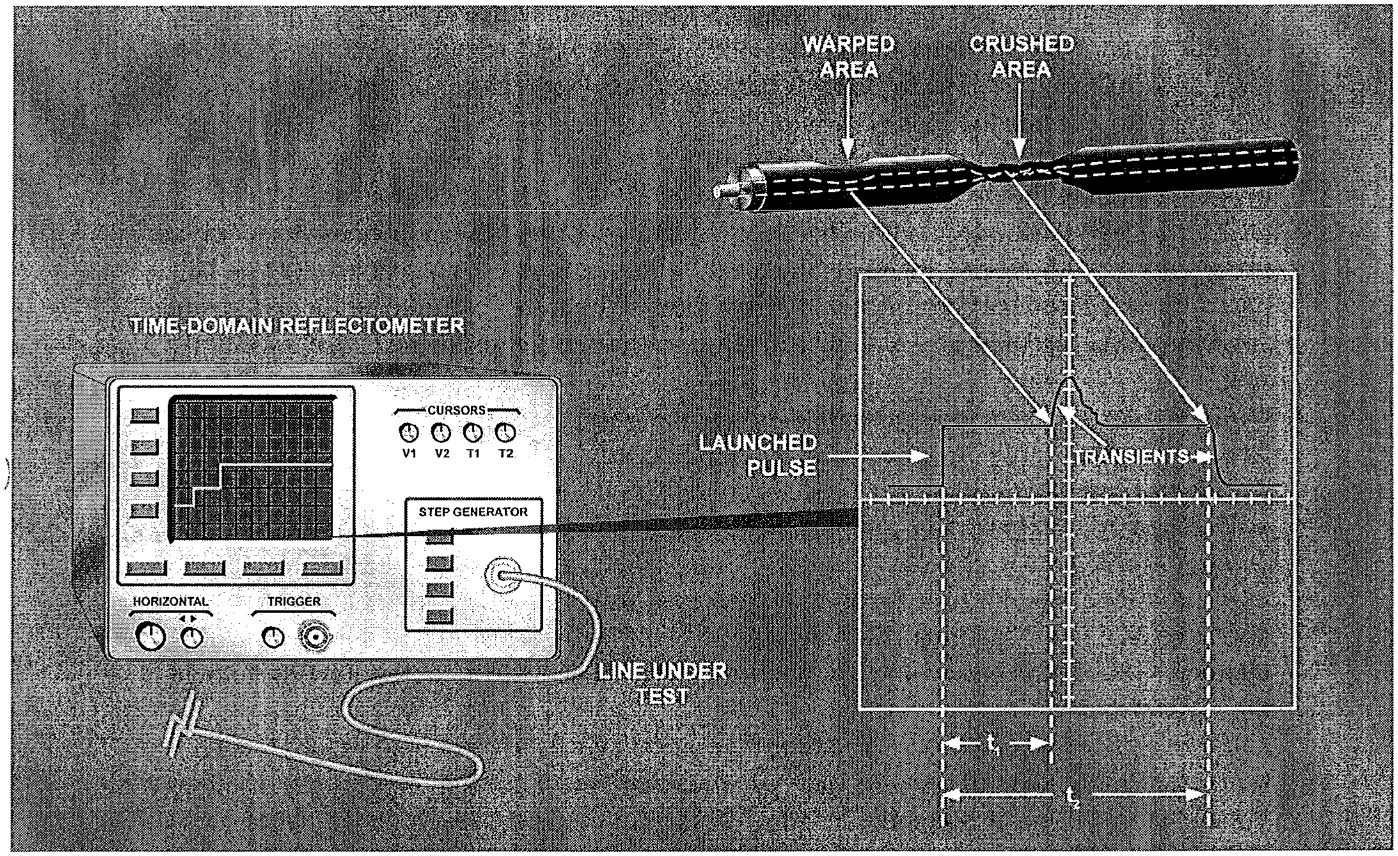


When multiple successive reflections occur on a line, a convenient way of representing the resulting distribution of the voltage along the line as a function of time is by using a **voltage reflection diagram**, as the figure below shows. The voltage reflection diagram can be used conveniently to graph the voltage as a function of time at any arbitrary point, z, along the line.



When the load connected to the end of a transmission line does not match the characteristic impedance of the line, and the load impedance is not purely resistive, the voltage reflected back toward the step generator varies with time, so that it does not have the same shape as the incident voltage. For example, the step response signal of a line terminated by an inductive load impedance corresponds to the step response of an RL circuit, and that of a line terminated by a capacitive load impedance corresponds to the step response of an RC circuit.

Time-domain reflectometry (TDR) is a technique used to detect, locate, and identify the nature of discontinuities (impedance changes) along a transmission line. TDR requires the use of a device called a time-domain reflectometer, as the figure shows. Conventional time-domain reflectometers consist of a built-in step generator and an oscilloscope.



NEW TERMS AND WORDS

Discontinuity - any change in impedance encountered by a signal traveling down a transmission line, resulting in the creation of a reflection. Discontinuities can be due, for example, to a broken conductor, a loose connector, a shorted conductor, or a sheath fault.
Overshoots - transient exaggerations of a voltage from a lower value to a higher value (the transitory higher value exceeding the final, steady-state value).
Signature - (of a line): the signal displayed by a TDR, that is, the algebraic sum of the incident pulse voltage and reflected voltage. The signature reveals the presence and nature of discontinuities, if any, along the line under test. (Nowadays, digital TDR's are

available that use digital techniques to automatically provide information on the location and magnitude of the major discontinuities on a digital readout).

Time-domain reflectometer - instrument used to detect and locate discontinuities along transmission lines. A TDR consists of a step generator and a high-speed oscilloscope combined in a single unit. The step generator launches a pulse into the line under test. When the pulse encounters a discontinuity along the line, or a mismatched load at the end of the line, part of the pulse energy is reflected back to the TDR for display on the oscilloscope. The signal displayed by the TDR is, therefore, the algebraic sum of the incident pulse voltage and reflected voltage.

Time-domain reflectometry (TDR) - a technique used to detect, locate, and identify the nature of discontinuities (impedance changes) along a transmission line. To permit the detection and location of discontinuities, time-domain reflectometry uses the same technique as bats or radars: the echo technique: a step generator launches a pulse into the line under test; when the pulse encounters a discontinuity along the line, part of the pulse energy is reflected back to the step generator for display on an oscilloscope. In the displayed signal, the discontinuities encountered by the pulse appear in the form of transients. By measuring the time between the rising edge of the launched pulse and the transient caused by a discontinuity, the location (distance) of the discontinuity can be determined. Moreover, the shape and magnitude of the transient indicate the nature and severity of the discontinuity and, therefore, give clues to the probable cause(s) of the fault.

Undershoots - transient exaggerations of a voltage from a higher to a lower value (the transitory lower value being less than the final, steady-state value).

Voltage excursion - the difference (in absolute value) between the final and initial voltages of an exponentially-rising or exponentially-decreasing voltage.

Voltage reflection coefficient - the ratio of the reflected voltage to incident voltage at a discontinuity along a transmission line. This coefficient is usually represented by the Greek capital letter "gamma". It is determined by the relationship between the characteristic impedance of the line and the new impedance encountered by the signal at the discontinuity.

Voltage reflection diagram - (or lattice diagram): a vertically oriented graph used to represent the creation of the multiple reflections and the resulting distribution of the voltage along a line as a function of time. This graph indicates each instant when a sudden change (voltage step) occurs in the line voltage. This graph can be used conveniently to graph the voltage as a function of time at any arbitrary point along the line.

EQUIPMENT REQUIRED

FACET Base Unit
TRANSMISSION LINES circuit board
Oscilloscope, dual trace, 40 MHz, (Lab-Volt P/N 797 or equivalent)

Exercise 1 – Distributed Capacitance and Inductance

EXERCISE OBJECTIVE

Upon completion of this exercise, you will know how to measure the distributed capacitance and distributed inductance of a line. You will use the measured values to determine the characteristic impedance of the line and the velocity of propagation of the signals along the line.

DISCUSSION

- The characteristic impedance, Z_0, of a line is an intrinsic property of the line. Because of this, Z_0 is determined by the geometrical and physical characteristics of the line—not by the length of the line.
- Consequently, a relationship exists between the value of Z_0 and the value of the distributed parameters.
- The theoretical values of C' and L' are normally specified by the line's manufacturer.
- However, these values can also be measured by using the step response method.
- To do so, a step generator and a high-impedance oscilloscope probe are both connected to the sending end of the line, using a bridging connection.
- To measure the distributed capacitance, the resistive component of the step generator impedance, R_{TH}, is set to a value that is much greater than the characteristic impedance of the line, while the receiving end of the line is left unconnected (open-circuit condition). This creates an impedance mismatch at both the sending and receiving ends of the line, and permits a step response signal with measurable time constant.
- A similar method is used to measure the distributed inductance of the line, except that this time, the resistive component of the step generator impedance, R_{TH}, is set to a value that is much lower than the characteristic impedance of the line, while the impedance of the load at the receiving end of the line is placed in the short-circuit condition (0 Ω).
- Once the distributed capacitance, C', and distributed inductance, L', of a line have been measured, the characteristic impedance, Z_0 of this line can be calculated by using a simple formula.
- Moreover, the velocity of propagation of the signals, v_P, in this line can also be calculated, using another equation.

Exercise 2 – Reflection Coefficients

EXERCISE OBJECTIVE

Upon completion of this exercise, you will know what is the concept of voltage reflection coefficient and why it is useful in analyzing the transient behavior of a transmission line mismatched at both ends by purely resistive impedances. You will also learn how to calculate the transient voltage anywhere on a transmission line, using a reflection diagram.

DISCUSSION

- It is important that the impedances of the load, Z_L, and of the step generator, Z_{TH}, both match the characteristic impedance of the line, Z_0, in order to prevent multiple successive reflections from occurring on the line.
- In a lossless transmission line where neither Z_L nor Z_{TH} matches $Z_{0,}$ Z_L and Z_{TH} are purely resistive the incident step voltage at the load is reflected by a coefficient $\Gamma_{L.}$
- The reflected step voltage then travels to the generator, where it is reflected back into the line by a coefficient Γ_g.
- The process goes on for a certain time, a new reflection being created at the load or generator at multiples of the transit time, T.
- At the **load**, reflections are created at **odd multiples of time** T.
- At the **generator**, reflections are created at **even multiples of time T**.
- Each newly created reflection is weaker than the preceding one, which eventually leads to a **steady-state** condition where the step voltage becomes stable.
- The voltage present at any given point and time on the line is the algebraic sum of the successive reflected voltages present on the line at that point and time.
- The voltage reflection diagram is used to represent the creation of the reflections and the distribution of the voltage along the line as a function of time. It indicates each instant when a sudden change (voltage step) occurs in the line voltage.
- The voltage reflection diagram can be used conveniently to graph the voltage as a function of time at any arbitrary point on the line.

Exercise 3 – Complex Load Impedances

EXERCISE OBJECTIVE

In this exercise, you will study the transient behavior of a transmission line terminated by various complex load impedances. To do so, you will observe the step response signal of a line terminated by inductive and capacitive loads.

DISCUSSION

- When an impedance mismatch exists at the load end of a line, and the load impedance is complex (either capacitive or inductive), the voltage reflected back toward the generator does not have the same shape as the incident voltage.
- When the load impedance consists of a **resistor** in **series** or in **parallel** with an inductor, the reflected voltage, after going through a fast-rising edge, decreases exponentially over time, at a rate determined by the time constant of the RL circuit of the load.
- When the load consists of a **resistor** in series with a **capacitor**, the reflected voltage, after going through a fast-rising edge, **increases exponentially** over time, at a rate determined by the time constant of the RC circuit of the load.
- When the load consists of a **resistor** in parallel with a **capacitor**, the reflected voltage, after going through a fast-falling edge, **increases exponentially** over time, at a rate determined by the time constant of the RC circuit of the load.
- Depending on whether the line is lossless or lossy, the step response signal of the line may differ significantly in regard to the initial level, final level, and time constant of the signal voltage. However, the general shape of the signal remains the same, regardless of the type of line.

Exercise 4 – Time-Domain Reflectometry (TDR)

EXERCISE OBJECTIVE

In this exercise, you will learn how discontinuities along transmission lines are detected and located, using techniques based on time-domain reflectometry (TDR).

DISCUSSION

- A **discontinuity** is a change in impedance along a transmission line.
- Discontinuities can be due, for example, to broken conductors, loose connectors, shorted conductors, sheath faults, mismatched load, etc.
- A **time-domain reflectometer** is an instrument used to detect and locate discontinuities along transmission lines. A TDR consists of a step generator and a high-speed oscilloscope combined in a single unit.
- To detect and locate discontinuities, a TDR uses the same technique as bats or radars: the echo technique.
- The signal displayed by the TDR is the algebraic sum of the incident pulse voltage and reflected voltage.
- The TDR signal is often called the **signature** of the line, because it reveals the presence and nature of discontinuities, if any.
- Discontinuities cause voltage transients of different shapes that add up to or subtract from the voltage in the TDR signal.
- The distance from the TDR to a discontinuity can easily be determined by measuring, on the TDR oscilloscope, the time between the rising edge of the incident voltage and the rising or falling transient caused by the reflecting discontinuity.
- The shape of a rising or falling transient in the TDR signal indicates the nature of the discontinuity that causes this transient: purely resistive, mostly inductive, or mostly capacitive.
- Moreover, the magnitude of the transient reveals how significant the discontinuity is.

Troubleshooting

EXERCISE OBJECTIVE

In this exercise, you will locate and identify the nature of discontinuities (faults) introduced by the software along the transmission lines of the circuit board, using time-domain reflectometry.

DISCUSSION

- The Transmission Line circuit is first setup under normal operating condition, and the load impedance is matched to the characteristic impedance of the line.
- The round-trip time of the pulse is then measured and recorded, under normal operating condition, for comparison purposes during troubleshooting.
- Thereafter, faults are automatically introduced at the proper moment by the software as you go through the troubleshooting exercise.

UNIT 3 – SINUSOIDAL (STEADY-STATE) CONDITIONS

UNIT OBJECTIVE

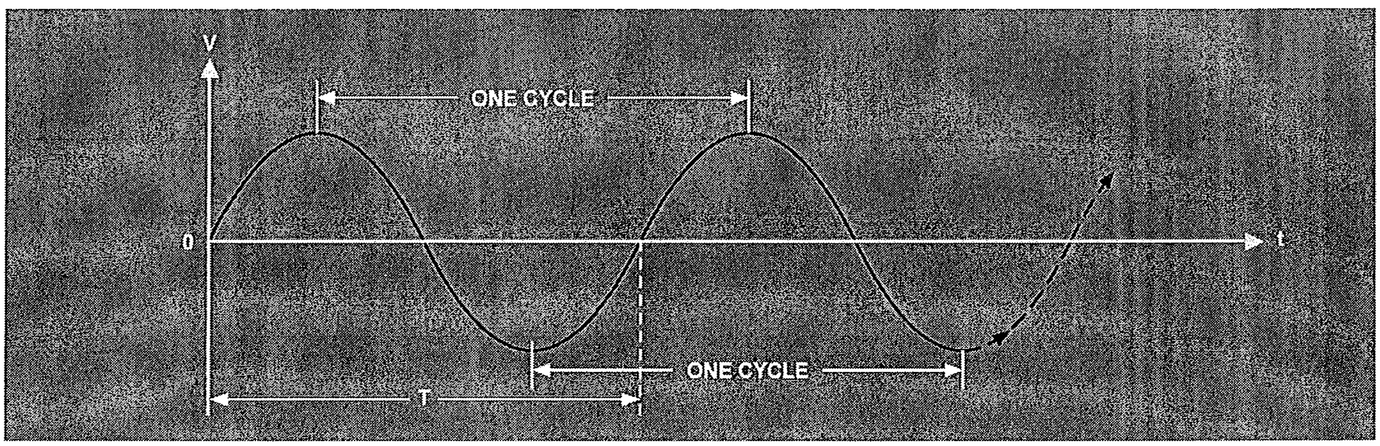
Upon completion of this unit, you will know what standing waves are and how the voltage standing wave ratio (VSWR) can be used to determine if a line is properly matched to a line. You will be able to define and calculate important parameters related to the transfer and loss of power in transmission losses: insertion loss, return loss, and mismatch loss. You will know what a Smith Chart is, and how to use it to determine the impedance at any point along a mismatched line, for various electrical lengths and load impedances. Finally, you will know how quarter-wavelength ($\lambda/4$) line sections are used for impedance transformation and matching.

UNIT FUNDAMENTALS

In many applications, such as telephone or computer networks, transmission lines are used to carry digital signals. These lines are said to operate under **transient** conditions, because it takes a certain time, or transitional period, for the pulses in digital signals to reach a steady value. In other applications, transmission lines are used to carry analog signals. These lines are said to operate under **steady-state** conditions when the carried signals, which consist of a sum of homogeneous frequency components that repeat periodically, show only negligible change over a relatively long period of time.

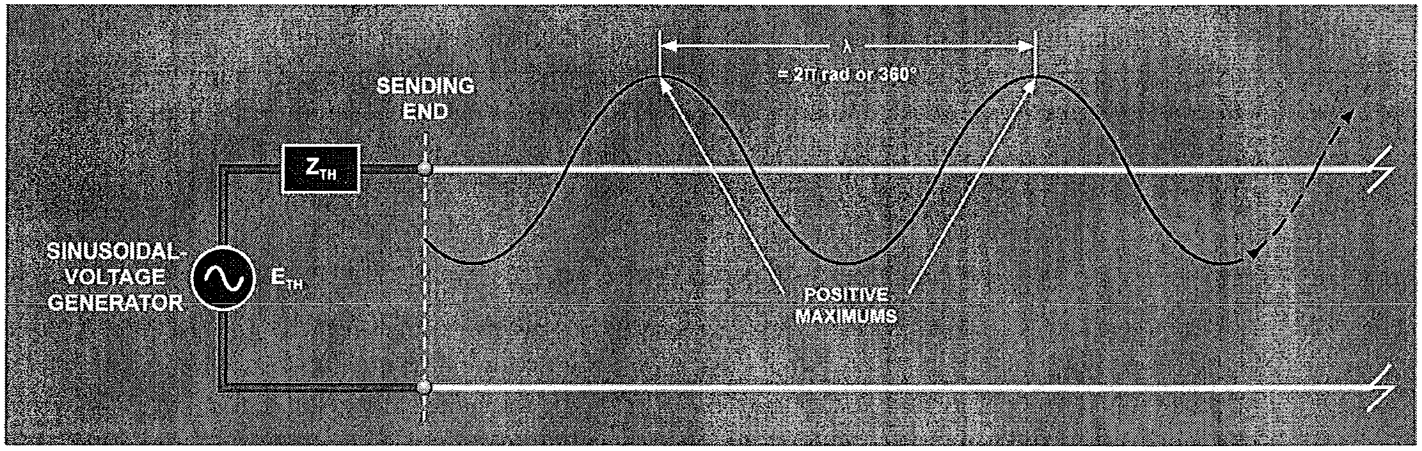
The basic concepts of distributed parameters and characteristic impedance studied under transient conditions remain applicable under steady-state conditions.

A sinusoidal voltage cyclically varies as a function of time, following a sinusoidal pattern, as the figure shows. The time required for one cycle of variation to occur is called the period, T.



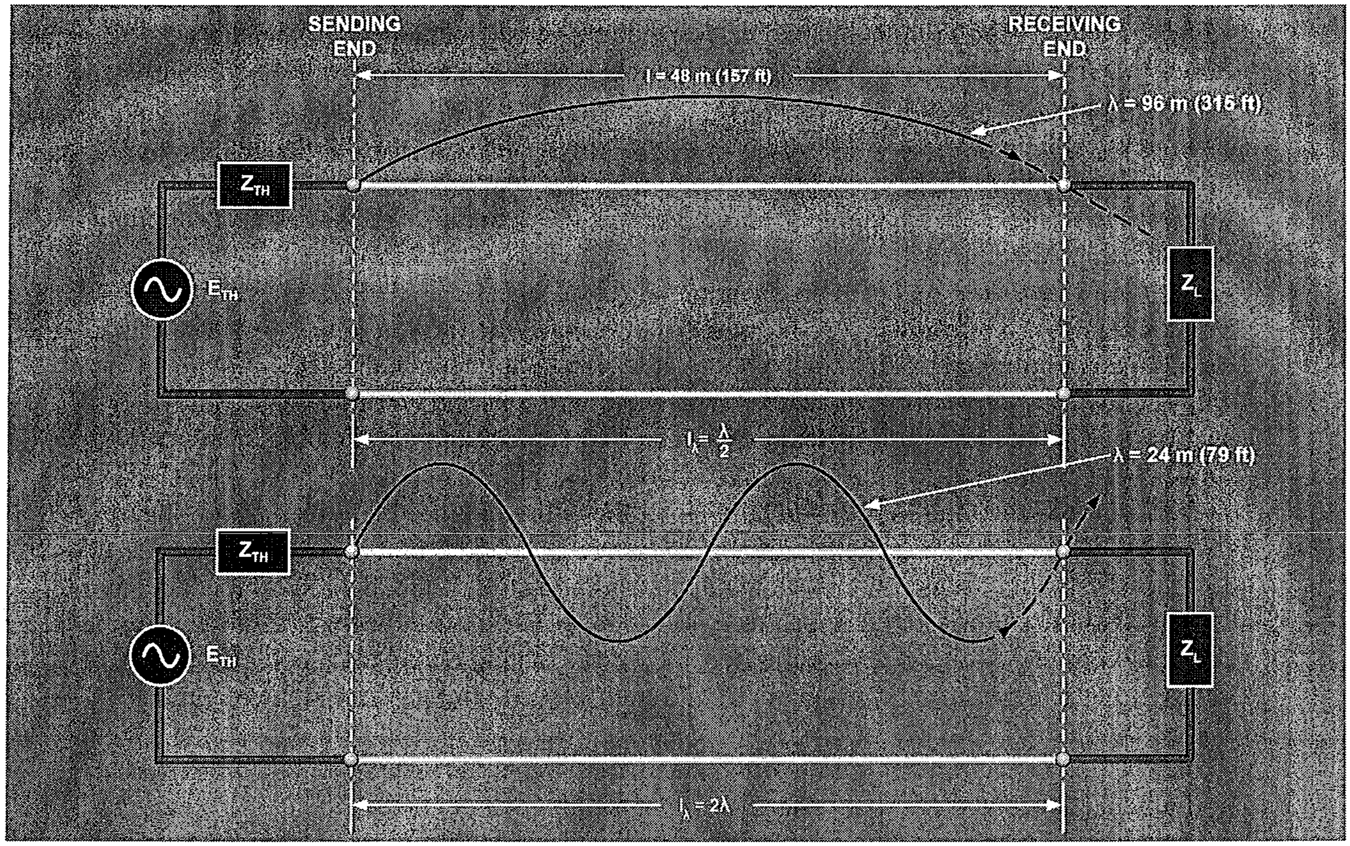
In the context of transmission lines, the variation of a sinusoidal voltage traveling down a line is usually considered as a function of distance rather than time.

The distance over which one cycle of variation occurs is called the **wavelength**. Wavelength is represented by the Greek lowercase letter λ. For every wavelength traveled along the line, the sinusoidal voltage goes through a phase change of 2Π radians, or 360°, as the figure shows.



An important characteristic of a transmission line is its **electrical length,** l_λ. The electrical length is the ratio of the actual physical length of the line to the wavelength of the signal it carries.

The electrical length is expressed as a fraction or multiple of the wavelength, λ. Any given electrical length corresponds to a single, specific frequency. For example, the figure that follows shows the electrical length of a 48-meter (157.4-foot) line for two different wavelengths of a sinusoidal voltage.



The electrical length of a line (rather than its actual physical length) determines whether the line is short or long with respect to the frequency of the signal it carries.

NEW TERMS AND WORDS

Antinodes - the points of maximum voltage in a standing wave. When the load impedance is higher than the characteristic impedance, loops occur at even multiples of lambda/4 from the receiving end of the transmission line. When the load impedance is lower than the characteristic impedance, loops occur at odd multiples of lambda/4 from the receiving end of the line.

Attenuation constant - the attenuation per unit length of a transmission line. Usually expressed as "decibels (dB) per unit length", or "nepers (Np) per unit length". The attenuation constant is determined by the geometrical and physical characteristics of the line. It increases with frequency. For this reason, manufacturers usually provide graphs or tables indicating the attenuation constant as a function of frequency.

Center point - the point marked "1.0" (i.e., 1 + j0) on the horizontal centerline of the chart.

Common point, or infinity point - the point of tangency of the circles of constant resistance (R) values, and also the originating point of the arcs of constant reactance values. The common point is located at the rightmost of the centerline of the chart.
Electrical length - the ratio of the actual physical length of a transmission line to the wavelength of the signal it carries.
Flat, or nonresonant - said of a line whose input impedance is equal to the characteristic impedance and to the load impedance. In this case, the maximum possible power is transmitted to the load. Changing the frequency of the generator will not change the input impedance of the line.
Horizontal centerline - a horizontal line in the middle of the chart representing pure resistance, or zero reactance. The normalized values for the ratio of R to the characteristic impedance are marked on this line. These values range between 0 and 50.
Impedance transformation and matching - the use of a lambda/4 or lambda/2 line section to change or adapt impedance between two devices and obtain a better transfer of power between them.
Insertion loss - the total loss that occurs along the entire length of a transmission line, in decibels (dB).
Loops - the points of maximum voltage in a standing wave. When the load impedance is higher than the characteristic impedance, loops occur at even multiples of lambda/4 from the receiving end of the transmission line. When the load impedance is lower than the characteristic impedance, loops occur at odd multiples of lambda/4 from the receiving end of the line.
Lossless - said of a transmission line whose distributed series resistance can be neglected, and whose distributed parallel resistance is very high.
Lossy - said of a transmission line whose distributed series resistance is significant, and whose distributed parallel resistance is relatively low. This causes some part of the transmitted power to be lost through the distributed series resistance due to the series losses, and also through the distributed parallel resistance due to insulation leakage losses (shunt losses). The losses are converted into heat.
Mismatch loss - the difference between the power or voltage incident at the line load and the power or voltage reflected at this load, in decibels (dB). When there is no impedance mismatch, there is no reflection, so that all the power received at the load is absorbed by the load.
Nodes - the points of minimum voltage in a standing wave. The minimum voltage is null only for a lossless line. When the load impedance is higher than the characteristic impedance, nodes invariably occur at odd multiples of lambda/4 from the receiving end of the transmission line. When the load impedance is lower than the characteristic impedance, nodes invariably occur at even multiples of lambda/4 from the receiving end of the line.
Normalized - said of the resistance and reactance values on a Smith Chart. These impedances are normalized to the characteristic impedance of the line: resistance values therefore correspond to the ratio of R to the characteristic impedance, while reactance values correspond to the ratio of jX to the characteristic impedance. This allows the chart to be used with transmission lines of any characteristic impedance.

Purely resistive - said of a device, such as a line or load, that consists mainly of resistor(s), without inductors or capacitors, causing the voltage and current waveforms to be in phase with one another.
Reactive - said of a device, such as a transmission line or load, that consists mainly of inductor(s) or capacitor (s), causing the voltage and current waveforms to be out of phase.
Resonant - said of a line whose load impedance is not perfectly equal to the characteristic impedance. In this case, the line may appear like a parallel or resonant circuit, or as an off-resonance or reactive circuit to the generator input, depending on the electrical length of the line. Consequently, the input impedance of the line will vary as a function of the electrical length and, therefore, of the frequency of the carried signal.
Return loss - the ratio of the power or voltage incident at the line load to the power or voltage reflected at this load, in decibels (dB). Since the power or voltage ratio is always lower than 1 (except when the impedance of the load is 0 ohm or infinite), the return loss always has a negative value. The greater the absolute value of the return loss, the lower the power or voltage lost by reflection at the load.
Set of arcs - all arcs representing constant reactance values on the chart. The upper half of the chart contains the arcs of inductive reactance. The lower half of the chart contains the arcs of capacitive reactance.
Set of circles - all circles representing constant resistance (R) values on the chart. The largest circle, which outlines the chart, corresponds to a constant R value of 0 ohms. The smaller circles correspond to higher, constant R values.
Smith Chart - a graphical computation tool developed by Dr. P.H. Smith in 1939 that greatly simplifies evaluation of transmission line parameters, such as the VSWR caused by a given load and the impedance at any point along a line for various line lengths and various load impedances.
Standing wave - a stationary wave on a transmission line mismatched at its load. This wave is produced by the vectorial summing of the incident and reflected voltages traveling through each other, but in opposite directions, along the line.
Steady-state - said of a system or conditions exhibiting only negligible change over a relatively long period of time. For example, transmission lines used to carry sinusoidal signals are said to operate under steady-state conditions if the carried signals, which consist of a sum of homogeneous frequency components that repeat periodically, show only negligible change over a relatively long period of time.
Transient - said of a temporary phenomenon occurring in a system before a steady-state condition is reached. For example, transmission lines used to carry digital signals, such as telephone or computer network lines, are said to operate under transient conditions because it takes a certain time, or transitional period, for the pulses in digital signals to reach a steady value.
Voltage standing-wave ratio - the ratio of the loop voltage to the node voltage of a standing wave. The VSWR is comprised between 1 (no standing wave) and infinite (open- or short-ended lossless line). The higher the VSWR, the more severe the impedance mismatch at the load. In lines that are lossy, attenuation improves the VSWR. The improvement in VSWR by attenuation is greater at the sending end of the line than at the receiving end.
VSWR circle - circle having its origin at the center point of the Smith Chart and representing a lossless line of known load impedance. Moving around the VSWR circle

corresponds to traveling down the lossless line. Consequently, the impedance at any point along the line can be read off on the chart, using this circle.

Wavelength - (of a signal traveling down a line): the distance over which one cycle of variation of the signal occurs. Wavelength is represented by the Greek lowercase letter lambda.

Wavelength circle - circle located just beneath the outer rim of the Smith Chart. This circle has an outer and an inner scales that permit measurement of the distance between any two points of a line, in wavelength (lambda) units.

EQUIPMENT REQUIRED

FACET Base Unit
TRANSMISSION LINES circuit board
Oscilloscope, dual trace, 40 MHz, (Lab-Volt P/N 797 or equivalent)

Exercise 1 – Standing Waves and VSWR

EXERCISE OBJECTIVE

Upon completion of this exercise, you will know how standing waves are created on transmission lines. You will be able to describe the characteristics of a standing wave based on the nature of the impedance mismatch at the origin of this wave. You will know what is the standing-wave ratio and how to measure it.

DISCUSSION

- When a line is mismatched at its load, standing waves are created along the line. A **standing wave** does not move or travel, hence the term "standing".
- The standing wave is the algebraic sum of the instantaneous values of the incident and reflected voltages at each point all along the line.
- The points of **maximum** voltage in a standing wave are called **loops**, or antinodes.
- The points of **minimum** voltage in a standing wave are called **nodes**.
- When the impedance of the load is **higher** than the characteristic impedance, **loops** occur at **even multiples of λ/4** from the receiving end, and **nodes** at **odd multiples of λ/4** from the receiving end. Consequently, the input impedance of an open-ended lossless line is null when the line is λ/4 long, and infinite when the line is λ/2 long.
- When the impedance of the load is **lower** than the characteristic impedance, **nodes** occur at **even multiples of λ/4** from the receiving end, and **loops** at **odd multiples of λ/4** from the receiving end. Consequently, the input impedance of an short-ended lossless line is infinite when the line is λ/4 long, and null when the line is λ/2 long.
- The ratio of the loop voltage to node voltage is called the **voltage standing-wave ratio (VSWR)**.
- The VSWR is comprised between **1** (no standing wave) and ∞ (short- or open-circuit load).
- The closer the VSWR is to 1, the better the impedance match between the line and load and, therefore, the better the efficiency of power transfer on the line.

Exercise 2 – Effect of Attenuation on the VSWR

EXERCISE OBJECTIVE

Upon completion of this exercise, you will know what the attenuation constant is and how to measure it. You will be able to define important terms related to the transfer and loss of power in mismatched transmission lines: insertion loss, return loss, and mismatch loss. You will know how to calculate the VSWR in a lossless line in terms of the reflection coefficient at the load. Finally, you will know how attenuation modifies the VSWR in lines that are lossy.

DISCUSSION

- As for transient (pulsed) signals, sinusoidal signals undergo attenuation as they travel down a line.
- The distributed series resistance of the line, R'_S, is responsible for most of the losses.
- The attenuation constant of a line is a measure of the attenuation per unit length of the line.
- The attenuation constant varies with frequency. Consequently, manufacturer's provide graphs or tables indicating the attenuation constant of a line as a function of frequency.
- Important terms relating to the loss of power in a transmission line are: the insertion loss, the return loss, and the mismatch loss, all expressed in decibels (dB).
- The **insertion loss** is the total loss occurring along the line.
- The **return loss** is the ratio of the voltage incident at the load to the voltage reflected at the load.
- The **mismatch loss** is the difference between the voltage incident at the load and the voltage reflected at the load.
- When a standing wave is present on a line, the VSWR can be calculated in terms of the reflection coefficient at the load, Γ_L, if the line is lossless or the losses can be neglected.
- In lines that are lossy, the VSWR becomes better and better as we approach the sending end of the line, due to attenuation. Consequently, a VSWR measurement made at the sending end of the line can give an illusion of having a good VSWR and, therefore, an efficiency that is better than reality.
- It is therefore preferable to measure the VSWR at the receiving end of the line, or to measure the insertion loss of the line rather than the VSWR per se.

Exercise 3 – The Smith Chart

EXERCISE OBJECTIVE

Upon completion of this exercise, you will know how the input impedance of a mismatched line varies as a function of the electrical length of the line. You will know what a Smith Chart is, and how it is used to determine the input impedance of a line that is not terminated by its characteristic impedance. You will know how quarter-wavelength ($\lambda/4$) line sections can be used for impedance transformation and matching. Throughout this exercise and for the rest of the unit, you can make copies of the Smith Chart found in the Appendix Section of this manual as often as necessary.

DISCUSSION

- When the input impedance of a transmission line is equal to the characteristic impedance and the load impedance, there are no standing waves on the line. The line is said to be **flat**, or **nonresonant**. The maximum possible power is transmitted to the load.
- When the impedance of the load is not perfectly equal to the characteristic impedance of the line, the input impedance of the line varies as a function of the electrical length and, therefore, of the frequency of the carried signal. The line is said to be **resonant**.
- When the line is open-ended, the input impedance of the resonant line is minimum for lengths that are odd multiples of $\lambda/4$; it is maximum for lengths that are even multiples of $\lambda/4$.
- When the line is short-ended, the input impedance of the resonant line is maximum for lengths that are even multiples of $\lambda/4$; it is minimum for lengths that are odd multiples of $\lambda/4$.
- The **Smith Chart** is a graphical computation tool that permits evaluation of the VSWR and impedance at any point along a line, for various electrical lengths and load impedances.
- The Smith Chart consists of a set of impedance coordinates used to represent normalized impedance. The "R" coordinates are represented by circles of constant resistance values. The "±jX" coordinates are represented by arc of constant reactance values.
- The Smith Chart can be used to determine the VSWR of a line or the impedance at any point along a line. It can also be used to correct mismatch conditions.
- When the line load is purely resistive, quarter-wavelength ($\lambda/4$) line sections can be used to perform **impedance transformation** and **impedance matching**, in order for the generator to transmit the maximum possible power to the load.

APPENDIX A – SAFETY

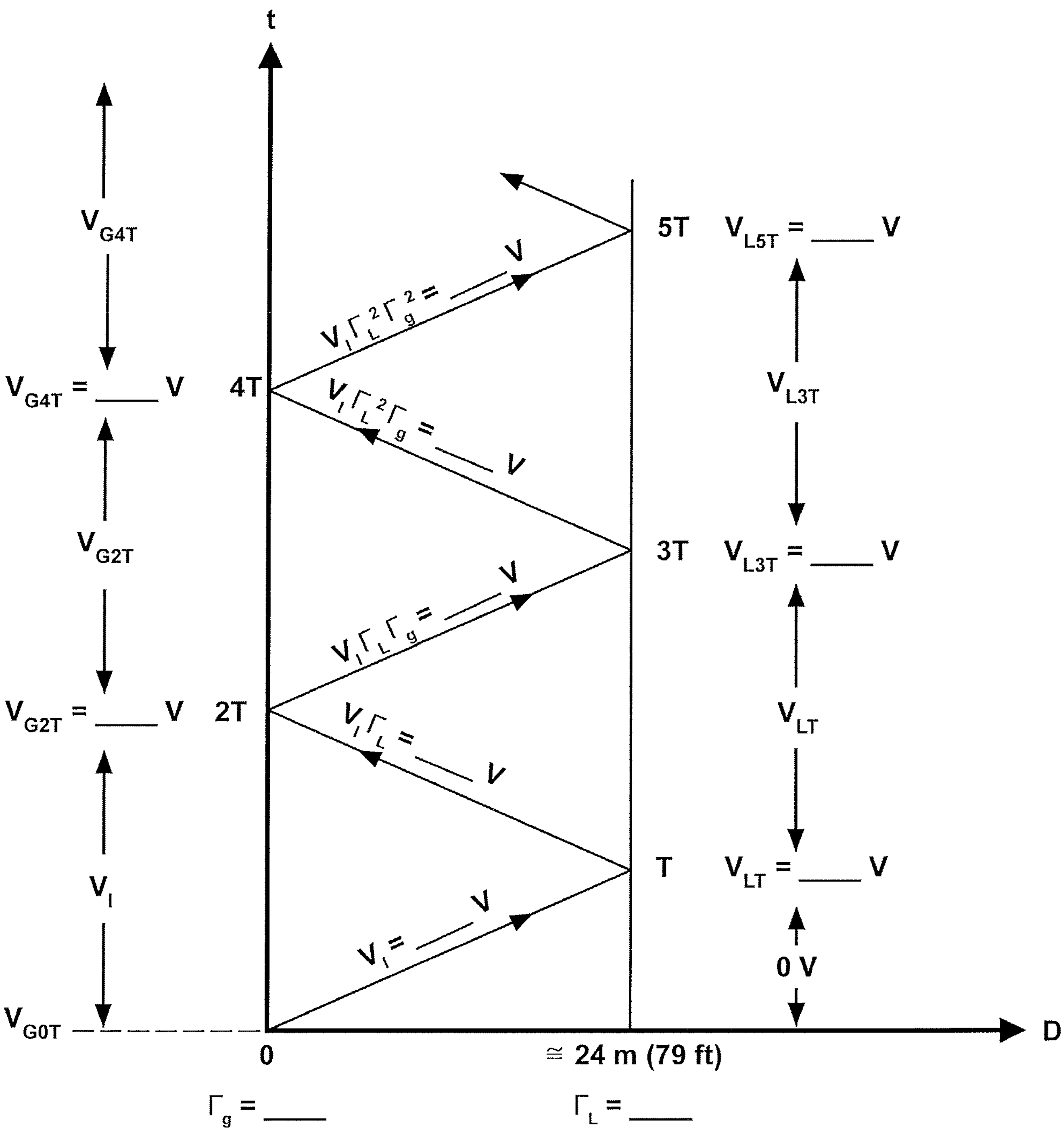
Safety is everyone's responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The FACET computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the FACET equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

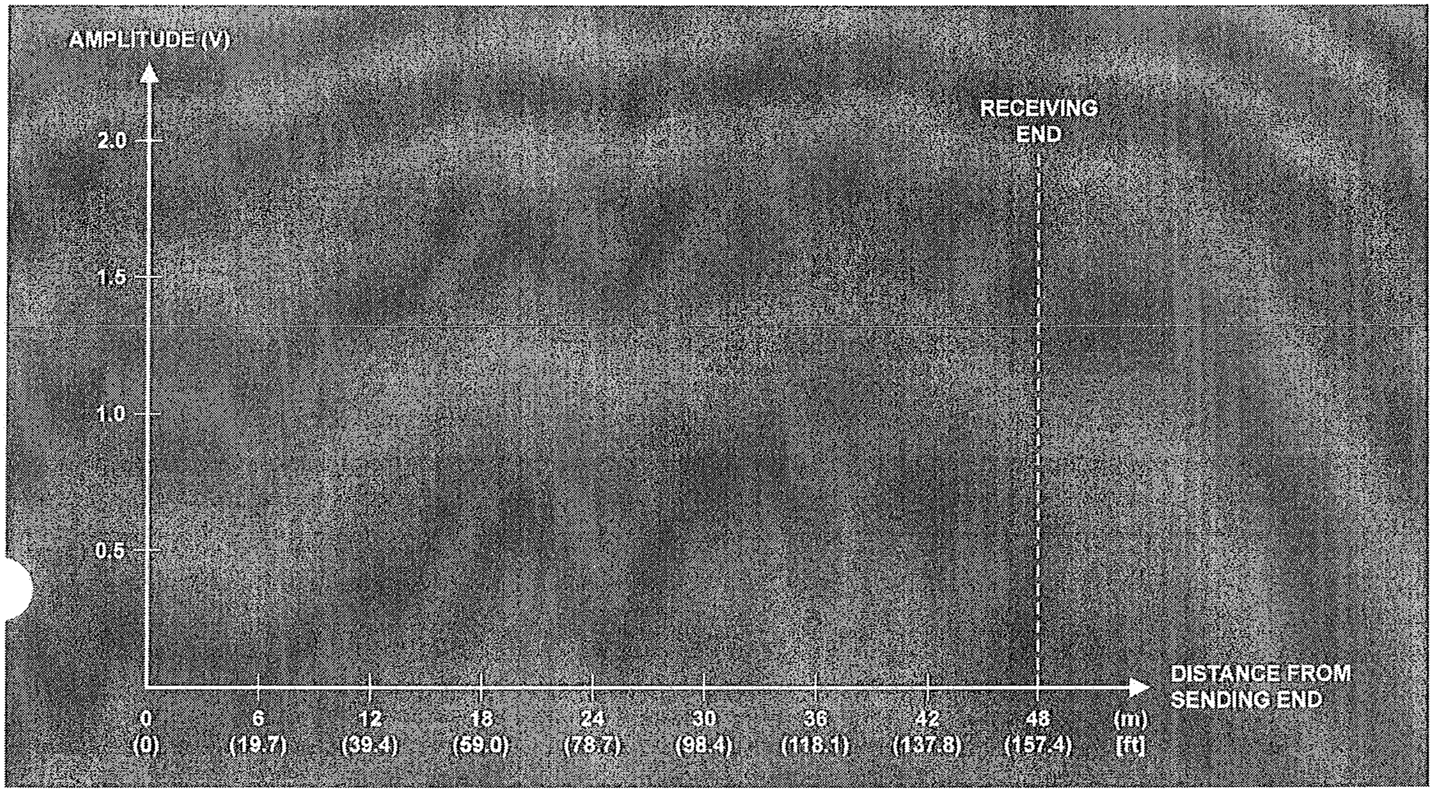
The voltage and current used in the FACET Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch "live" wires with your bare hands or with tools.
5. Be careful not to short circuit the electrical components of the Step Generator and Signal Generator with tools or with the BNC connectors of the cables upon connection or disconnection of these cables.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your FACET course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.

APPENDIX B – THE VOLTAGE REFLECTION DIAGRAM



APPENDIX C – GRAPH FOR PLOTTING THE STANDING WAVES ON THE TRAINER TRANSMISSION LINES



APPENDIX D – THE SMITH CHART