

Agilent Technologies
Innovating the HP Way

Transmission-Line Fundamentals

Agilent Technologies

Innovating the HP Way

Agilent Technologies™ is a trademark of
Agilent Technologies, Inc.

Microsoft®, MS-DOS®, and Windows®
are registered trademarks of Microsoft Corporation.

IBM® and PC/AT® are registered trademarks of
International Business Machines Corporation.

Adobe Type Manager® is a registered
trademark of Adobe Systems Incorporated.

Agilent Technologies
Innovating the HP Way

Notice

The information contained in this document is subject to change without notice.

Agilent Technologies provides this material "AS IS" and makes no warranty of any kind, expressed or implied, including, but not limited to, the implied warranties of merchantability and fitness for a particular purpose. Agilent Technologies shall not be liable for errors contained herein or for incidental or consequential damages (including lost profits) in connection with the furnishing, performance, or use of this material whether based on warranty, contracts, or other legal theory.

Some states do not allow the exclusion of implied warranties or the limitation or exclusion of liability for incidental or consequential damages, so the above limitations may not apply to you. This warranty gives you specific legal rights, and you may also have other rights which vary from state to state.

Agilent Technologies assumes no responsibility for the use or reliability of its software on equipment that is not furnished by Agilent Technologies.

Agilent Technologies
395 Page Mill Road
Palo Alto, CA 94306

Purpose of this Course

This course is designed for those who have a basic knowledge of electronic theory and circuits and wish to learn about the electrical characteristics of transmission lines. When you have completed this course, you will have a basic knowledge of the technology, terminology, and measurement techniques of transmission lines.

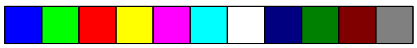
Conventions

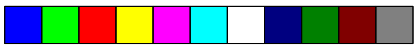
The following conventions are used throughout this manual:

- **Bold** is used to emphasize important information in the text or to highlight menu selections or text to be entered from your computer's keyboard.
- *Italics* are used for titles that refer to the course and its lessons, to indicate selections to be made, or for emphasis.
- **<Keystroke>** indicates a key or combination of keys to be pressed.

Table of Contents







Agilent Technologies
Innovating the HP Way

1

Transmission-Line Fundamentals Computer-Based Training

- **Course Objectives**
- **The Transmission-Line Fundamentals Program**
- **Hardware/Software Requirements**

Course Objectives

When you have completed this course, you will be able to:

- Recognize that transmission-line effects must be considered when dealing with high frequency signals or waveforms with fast transitions.
- Recognize that transmission lines present an impedance to AC signals that is not related to DC resistance.
- Explain how changes in impedance along a transmission line cause some or all of the signal energy to be reflected back along the line.
- Define reflection coefficient, standing-wave ratio, and return loss.
- Describe how these terms relate to changes of impedance along a transmission line.
- Relate significance of transmission-line effects to high-frequency measurements.

The Transmission-Line Fundamentals Program

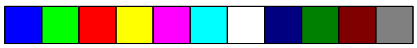
The program resides on two 3-1/2" high-density diskettes. Please see Chapter 2 for instructions on installation of the program on your hard disk.

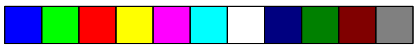
Hardware/Software Requirements

To use *Transmission-Line Fundamentals*, you will need a Vectra computer or an IBM PC/AT compatible computer equipped with the following:

- DOS 3.1 or higher
- Windows 3.0 or higher
- 4 MB of RAM
- A hard disk with 4.0 MB of available space
- One 1.44 MB diskette drive
- A Microsoft-compatible mouse
- VGA or higher resolution monitor. When using SVGA, the program will occupy only a portion of the screen.
- A processor running at 75 MHz is recommended for optimum performance. The program will run satifactorily on slower processors, but will take more time to complete.







Agilent Technologies
Innovating the HP Way

2

Getting Started

- **Setup and Installation**
- **Starting the Program**

2-1

Setup and Installation

Follow these steps to setup and install *Transmission-Line Fundamentals*.

1. Save the file TLF.exe to your computer.
2. Double-click on TLF.exe to unpack.
3. Choose the current file destination or change the folder name to another temporary directory. Note: these files will not be deleted during installation.
4. Click the unzip button.
5. Go to the destination folder you selected and open up the Set Up folder.
6. Then open up the Disk 1 folder.
7. Look for the setup.exe file and click on it to begin installation.
8. The set up and installation will start up.
9. Follow the step by step instructions for installation.

Starting the Program

Click on the Start button; go to Programs and look for TLF Fundamentals *and open your new program*.

You can go back and delete the setup files unpacked in the temporary folder.

Agilent Technologies
Innovating the HP Way

3

Troubleshooting

- **Installing**
- **Uninstalling**
- **During the Program**

Installing

Below are error messages which could appear while you install, deinstall, or use *Transmission-Line Fundamentals*, along with their causes and solutions.

The target location must be different from the source
Try another disk as the target.

The disk drive is an invalid disk
The disk can't hold the program.
Try a different disk drive.

There is not enough space
There is not enough room on the hard drive for the program. You will need to clear enough room for the program.

Unable to create specified path
You may have typed in the wrong path.
Retype the path.

Unable to copy, compress, or delete file
The file is missing or corrupted on the disk.
You may need a new copy if installing.
You may need to use Microsoft Windows Explorer if deinstalling.

Cannot start ISlauncher
Your virus detection program is interfering with the installation. Scan the disks for viruses first, then turn off the detection program and install normally. Reactivate your virus detection program after installation.

Uninstalling

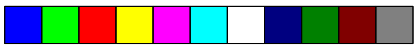
Unable to copy or decompress file?

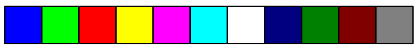
You may be uninstalling while the program is still running, or the file may already have been deleted.

During the Program

There is not enough memory...

You may not have enough RAM. Remember that you need at least 4 MB to be running extended memory drivers.



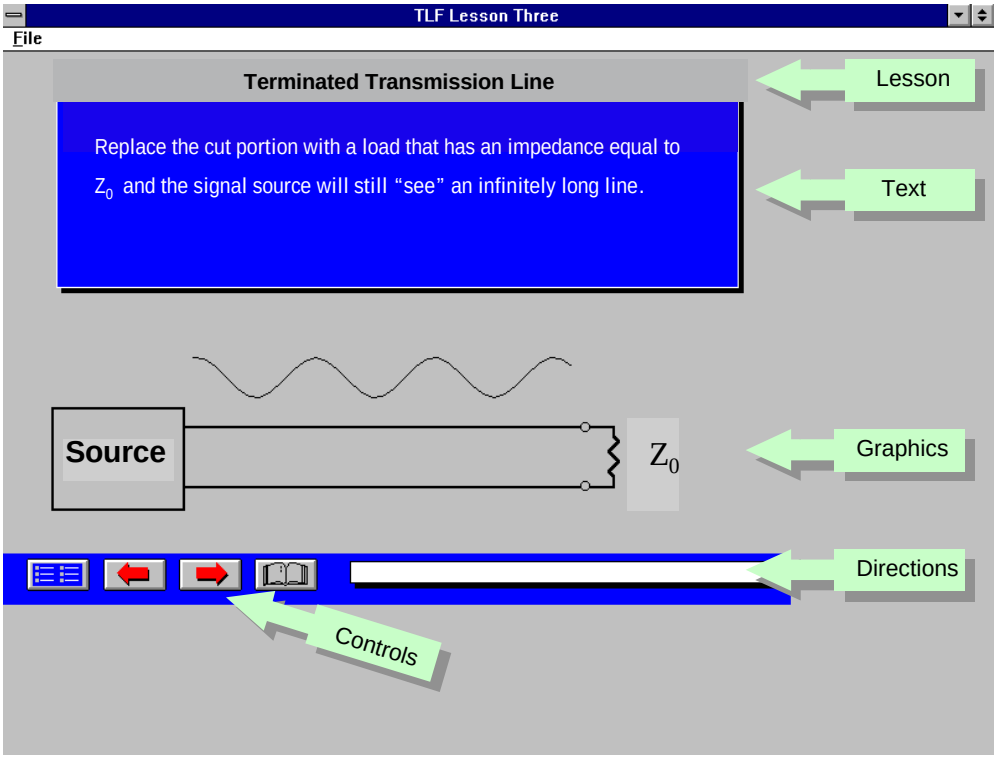

Agilent Technologies
Innovating the HP Way

4

Using the Program

- **Screen Layout**
- **Navigating**
- **Glossary**
- **Printing**
- **Exiting**

A typical screen is organized like this:



Text
Provides instruction, description, or questions.

Directions
Tells you where to click.

Controls
Provides navigation through the course.

Graphics
Illustrates the meaning of the text.

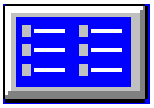
Lesson
Tells you which lesson you're currently working on.

Navigating

Control Buttons

These four controls are used to navigate through *Transmission-Line Fundamentals.* They are grouped in a row on the lower left part of the screens.

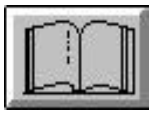
Control your course by pressing these buttons:



Returns you to the main menu.

Returns you to the previous screen.

Advances you to the next screen.



Takes you to the glossary.

Page Box

There is also a page box in the lower left corner which you can use to go to any page of the course. To access the page box, select **File** from the upper left corner and select **Page Numbers** from the menu. To use the page box, click on it, type the page number you want and press **<Enter>**.

Glossary

The glossary alphabetically lists and defines all the technical terms presented in this course. Each screen in the glossary covers listings under two letters of the alphabet (the first screen covers A-B, the second C-D, and so on) except the last, which covers W-Z.

A column of tabs which you can click to select any letter pair you want is provided on the right side of each glossary screen.

Scroll the glossary page up and down to run through all the listings for the letter pair selected.

To move to the listings for the next or previous letter pair, you can also click the page-ahead or page-back arrow at the bottom of the screen.

Clicking on the **Return** button will place you exactly where you were in the course before you entered the glossary.

See the Appendix for a complete listing of all terms in the Glossary.

Printing

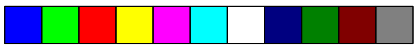
To print a screen, select **File** from the upper left corner and then select **Print Page**.

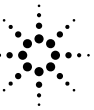
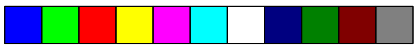
Exiting

You can exit the program from any screen by selecting the system menu box from the upper left corner and selecting **Close** from the menu.

You can also exit by using the **<ALT>** + **<F4>** combination.





Agilent Technologies
Innovating the HP Way

5

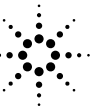
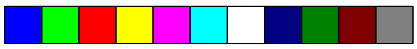
Course Contents

- **Lesson Topics**

Lesson Topics

The topic for each of the eleven lessons of the Transmission Line Fundamentals course is listed below:

Lesson	**1**	Why Transmission Lines?
Lesson	**2**	Transmission-Line Impedance
Lesson	**3**	Terminated Transmission Lines
Lesson	**4**	Effect of Open and Short Circuits
Lesson	**5**	Generation of Standing Waves
Lesson	**6**	The Standing-Wave Ratio
Lesson	**7**	The Reflection Coefficient
Lesson	**8**	The Complex Reflection Coefficient
Lesson	**9**	Measuring Impedance
Lesson	**10**	Relating Terms
Lesson	**11**	Review Quiz

Agilent Technologies
Innovating the HP Way

6

Appendix

- **Glossary of Transmission-Line Terms**

Glossary of Transmission-Line Terms

Antenna
The part of a transmitting or receiving system designed to radiate electromagnetic waves. Antenna components must have a size comparable to the wavelengths to be radiated.

Admittance
The reciprocal of impedance.

AM
See Amplitude Modulation.

Amplitude Modulation
A modulation process in which the instantaneous amplitude of a sinewave carrier is caused to vary from the carrier amplitude by an amount proportional to the instantaneous amplitude of the modulating wave.

Backplane
A printed circuit board that contains connectors and interconnect traces for communications between system components.

C
See Coupling Factor.

c_0 Speed of Light in Vacuum
2.99×10^8 m/sec.

Characteristic Impedance (Zo)
A parameter having the dimensions of impedance (volt per ampere = Ohm) that characterizes a mode of propagation. For a transverse electromagnetic (TEM) mode, the ratio of voltage to current at any cross section of a transmission line.

Glossary of Transmission-Line Terms

CMOS (Complementary Metal Oxide Semiconductor)
A silicon-based technology for making integrated circuits using field-effect transistors. Noted for low power comsumption and high immunity to noise; generally slower than TTL. CMOS circuits typically have 5 - 20 ns transition times and a logic threshold of 2.5 V.

Coaxial Cable
A two-conductor (center conductor, shield system), concentric, constant-impedance transmission line. CATV (cable TV) applications commonly use cable with 75 ohms characteristic impedance. Many electronic test systems use cable with 50 ohms characteristic impedance.

Complex Number
A number consisting of a real part (a) and an imaginary part (b) expressed in the form a + jb where $j^2 = -1$

Coupling Factor
A measure of how much signal appears at the auxiliary port of a directional coupler for a given signal level at the input port. Usually expressed as a ratio in dB. Typically coupling factors range from 6 dB for directional bridges to 20 dB for directional couplers.

dB
See Decibel.

Decibel
A standard unit for expressing the ratio between two parameters using logarithms to the base 10; ratio of two power levels in dB = 10 log (P1/P2).

Glossary of Transmission-Line Terms

Dielectric, Dielectric Constant
That property which determines the electrostatic energy stored per unit volume per unit potential gradient. Dielectric properties are often expressed as a numerical value related to the dielectric properties of vacuum.

Diode Detector
A device for sensing the presence of electromagnetic fields. Uses a diode to rectify the signal and a low-pass filter to reject the high frequency components to yield a dc voltage proportional to the high frequency signal.

Directional Coupler or Directional Bridge
A passive device used to divide and combine RF signals. A directional coupler is a three-port device which has the ability to sense a waveform applied to the input port by coupling some of that energy to an auxiliary port. Waveforms traveling in the opposite direction, i.e., applied to the output port, are not sensed at the auxiliary port. A directional coupler has the ability to sense energy traveling in one direction along a transmission line; used to separate incident voltage from reflected voltage on a transmission line when performing network measurements.
See Coupling Factor.

Discontinuities (in tranmission lines)
See Uniform Transmission Line.

Distributed (Inductance, Capacitance, or Resistance)
Inductive, capacitive or resistive characteristics which are distributed over a physical distance that is comparable to a wavelength.

Glossary of Transmission-Line Terms

Dual-Directional Coupler
A directional coupler with two auxiliary ports to measure incident and reflected voltages at the same time.

DUT
Device under test.

ECL (Emitter-Coupled Logic)
A silicon-based technology for making integrated circuits using bipolar transistors. ECL is a non-saturated logic design used for high speed switching applications. Faster than Schottky TTL technologies but has greater power consumption and heat dissipation. ECL circuits typically have 0.5 - 3 ns transition times and a logic threshold of - 1.3 V.

Electrical Length
For a traveling wave of a given frequency, a distance in a transmission or guiding medium expressed in wavelengths of the wave in the medium; sometimes expressed in degrees or radians.

Figure of Merit
A measure or means of performance comparison for components or systems.

GaAs (Gallium Arsenide)
A semiconductor technology for making integrated circuits using field effect or bipolar transistors. Gallium Arsenide has high majority carrier (electron) mobility which gives it very high speed switching abilities. Faster than silicon-based technologies. GaAs circuits typically have 100 - 200 ps transition times.

Glossary of Transmission-Line Terms

Impedance, AC Impedance
A measure of the complex resistive and reactive attributes of a component in an alternating-current circuit; a value relating any two of the three quantities, power, complex voltage, and complex current at a specified transverse plan in transmission lines.

Impedance Mismatch
A condition in which the impedance of a load does not match the impedance of the source to which it is connected; impedance mismatches cause reflections and standing waves in transmission lines.

Incident Voltage Vi
See Incident Wave.

Incident Wave
A wave that impinges on a discontinuity or a medium of different properties.

Input Impedance
The impedance as seen at the input terminals of a device.

Line Stretcher
A section of waveguide or transmission line having adjustable physical length; used as a phase adjusting device.

Lossless Transmission Line
A transmission line in which there is no absorptive loss; resistance is assumed to be zero.

Glossary of Transmission-Line Terms

Low-Pass Filter
An electronic device that transmits one group of frequencies including direct current (zero frequency) while rejecting higher frequencies.

Matching Impedance
A termination matched with regard to the impedance in a prescribed way. A circuit is said to be perfectly matched for maximum power transfer and no reflections when the load is the complex conjugate of the source.

Microstrip
A class of planar transmission lines consisting of one or more thin conducting strips parallel to a single, extended conducting ground plane. In common form, the strips are affixed to an insulating substrate attached to the ground plane.

Microwave
Generally refers to the super high frequency portion of the radio spectrum: 3 GHz to 30 GHz.

Mixer
A device used for mixing, or frequency conversion. Mixing is the process of combining an input signal with an injected frequency and putting them through a non-linear device which generates sum and difference frequencies. The desired converted frequency can be selected by filtering. Also called frequency multiplication.

Glossary of Transmission-Line Terms

Network Analyzer
An instrument that measures the two-port transmission and one-port reflection characteristics of a multiport network, usually over a range of swept frequencies. Vector network analyzers make magnitude and phase measurements while scalar network analyzers measure magnitude only.

The network analyzer typically has a RF signal port, a reference channel (R), and two measurement channels (A and B). The RF signal port provides a range of sweep-controlled frequencies which is applied to a DUT via a system of bridges and couplers and then measured using channels A and B. From these measurements transmission and reflection characteristics are calculated. The reference channel (R) is used for ratio measurements.

Nominal Value
A value in name only, rather than in fact; a value not measured but assumed.

Parasitic Reactances
Reactance due to unavoidable and unwanted inductance and capacitance within a system.

Peak Envelope Voltage
The maximum value attained by the standing wave “envelope” formed by an incident and reflected wave.

Pulse Transition Time, Pulse Rise Time
The interval between the instants at which the instantaneous value first reaches 10% and 90% of the peak pulse value.

Glossary of Transmission-Line Terms

Printed-Circuit Board (PCB)
A board for mounting components on which most connections are made by printed circuitry.

Reactance
The imaginary part of impedance; characterized by the reaction of energy storing circuit elements like inductors and capacitors to a varying voltage.

Radio Frequency
A frequency useful for radio transmission roughly between 10 kHz and 100 GHz.

Real Number
A member of the set of all positive and negative numbers, including integers, zero, mixed, fractional, rational, and irrational numbers.

Reflected Voltage, Vr
See Reflected Wave.

Reflected Wave
A wave returned from a reflecting discontinuity in a direction opposite to the incident wave.

Reflection Coefficient
At a given frequency and a given point, the ratio of some quantity associated with the reflected wave to the corresponding quantity in the incident wave. Most commonly in transmisssion lines, reflection coefficient = Vr/Vi where Vr is reflected wave voltage and Vi is incident wave voltage. The Greek letters gamma (Γ) is commonly used for reflection coefficient, a vector quantity; the Greek letter rho (ρ) is used for reflection coefficient magnitude.

Glossary of Transmission-Line Terms

RF
See Radio Frequency.

RF Carrier
An electrical signal that is modified in frequency, amplitude, and/or phase in order to transmit an information signal from one point to another.

Resistance, DC Resistance
The real part of impedance; determined from the ratio of voltage applied to current flowing in a body neglecting capacitive and inductive effects.

RMS Amplitude
Root-mean-square value of the amplitude of a periodic function. The square root of the sum of the squares of sampled values taken over the period of the waveform.

Scalar Network Analyzer
See Network Analyzer.

Slotted-Line, Slotted Waveguide
A section of a waveguide or shielded transmission line the shield of which is slotted to permit the use of a carriage and traveling probe for examination of standing waves.

Source Impedance
The impedance as seen at the output terminals of a source or signal generator.

Speed of Light

See c_0.

Glossary of Transmission-Line Terms

Standing Wave
A wave in which the ratio of the instantaneous value at one point compared to that at any other point does not vary with time. Standing waves are most frequently produced by reflection. The sum of incident and reflected waves will produce a standing wave if they are periodic.

Standing Wave Ratio
The ratio of the maximum amplitude of a standing wave to its minimum amplitude. The standing wave ratio in a uniform transmission line is $(1 + \rho) / (1 - \rho)$ where ρ is the reflection coefficient.

Stub or Quarter-Wave Stub
A portion of shorted waveguide attached to, and used for mounting a waveguide. If the stub is made one quarter wavelength long, transmission-line effects make it look like an open circuit and therefore an insulator to signals traveling along the waveguide.

Susceptance
The imaginary part of admittance.

Swept-Frequency
The use of sweep generator output to control frequency for the purpose of measurement over a range of frequencies.

SWR
See Standing Wave Ratio.

TEM
See Transverse Electromagnetic.

Glossary of Transmission-Line Terms

Termination or Terminating Impedance
The closing of the circuit by the connection of some device. Termination in itself does not imply any special condition such as the elimination of reflection.

Transmission Line
A system of material boundaries or structures for guiding electromagnetic waves, in the TEM (transverse electromagnetic) mode. Commonly a two-wire, twisted pair or coaxial system of conductors.

Transmission-Line Effects
Those waveform effects that are observed when the signal wavelength applied to a system is comparable with its size. In such a system voltages will vary across the system due to the sinusoidal nature of the signal. Transmission-line theory must be used to analyze these systems.

Transverse Electromagnetic (TEM)
An electromagnetic wave in which both the electric and magnetic field vectors are everywhere perpendicular to the direction of propagation.

TTL (Transistor-Transistor Logic)
A silicon-based technology for making integrated circuits using bipolar transistors. Schottky TTL is a non-saturated logic used for high speed applications. TTL circuits typically have 1 to 10 ns transition times and a logic threshold of 1.5V.

Glossary of Transmission-Line Terms

Twin Lead or Twin Wire
A cable composed of two small insulated conductors laid parallel, having a common covering. Common application is for TV antenna connections with characteristic impedance of 300 ohms.

Uniform Transmission Line
A transmission line which does not change geometry along the path of propagation; has no discontinuites.

Unterminated
A circuit without a termination; an open circuit.

Vector Network Analyzer
See Network Analyzer.

Wavelength (λ)
The distance between two points in a periodic wave that have the same phase. For a given electromagnetic frequency f, $\lambda = c/f$, where c is the speed of light in the transmitting medium.

Z_0
See Characteristic Impedance.

Z_L
Load Impedance. See Terminating Impedance.

Z_S
See Source Impedance.