components will always maintain this phase relationship no matter what values the components are set to.

Note how the V(C) and the V(L) curves are exactly equal in magnitude and opposite in phase. Their sum is always zero. That is the definition of resonance. That is why, under these component values, V(in) is exactly equal to V(R).

Change the value of R. The voltage V(R) changes in response. Why doesn't V(L) or V(C) change? Because the input is constant current. Therefore, a change in the value of the resistor doesn't change the current. Therefore the voltage across the other components doesn't change. Reset the value of R back to unity.

Add V(in) as a selection for viewing. Change the value for C. Note several things. The voltage V(C) changes. Therefore V(in) changes, since V(in) is the sum of V(R), V(C) and V(L). The phase relationship changes, since we are no longer at resonance. The V(in) curve shifts in phase relative to I(in). Why doesn't V(R) or V(L) change? Because we are still dealing with constant current in, and since their component values are not changing, the voltage across them doesn't either.

If the phase relationship is changing, why don't the curves shift relative to each other or to the vertical axis? Because we are dealing with constant current in. Therefore, V(R) is always in phase with I(in) (which is constant) and the other two voltages are always 90 degrees shifted in phase from V(R). Reset all component values back to unity.

SECOND STEP

Clear the check boxes for V(R), V(L), and V(C) and select the boxes for V(in) and I(in). If all component values are set exactly to unity, you probably see only one curve, not two. Why? Because when the component values are set to unity, the voltage and the current have the same magnitude. And since the system is at resonance, they have the same phase relationship. Therefore, they superimpose exactly on top of each other.

Now change the value for R. Note how the input voltage changes in proportion to R. Remember that the input current is constant, so less voltage is required for smaller resistance. Note how the phase relationship does not change simply because R is changing. Reset R to unity.

Decrease the value for C a little. Note that the voltage curve shifts to the right and the phase angle display shows a negative number. Why? Because voltage lags current when the circuit is capacitive. Note that the voltage peak occurs later than (lags) the current peak. Decrease the value for the inductor. The voltage curve continues to shift. Move the inductor and capacitor sliders all the way to their minimum positions, and select the x10 button to change the display scale. Note how the voltage curve lags the current curve by almost 90 degrees (the text box probably says something close to –84 degrees). This can be seen by comparing the position along the horizontal (time) axis of the peak of the voltage curve and the zero-crossing of the current curve.

Change the L and C settings to their other extreme. Note that the phase shift changes from almost –90 degrees (lag) to almost +90 degrees (lead).

THIRD STEP

Reset the component values back to unity and set the input condition to constant voltage. You may only see one curve, since with unity values (resonance) the V(in) and I(in) curves will be equal in magnitude and in phase. Note that the V(in) and I(in) curves have changed color. The white (constant) curve now indicates the voltage in.

Change the value for R. Note that input current changes inversely with R (since we now have constant voltage in). The phase relationship doesn't change because the LC circuit is still in resonance.

Change the value for C. Note that the phase relationship changes, and as C decreases current begins to lead voltage (and correspondingly, voltage lags current). Reset all component values back to unity.

FOURTH STEP

Deselect V(in) and I(in) for viewing, and select the other three voltages. Change the value for R. Note that V(R) does not change, but V(C) and V(L) both do. Why? This is a good question. First, with unity component values, V(C) and V(L) are at resonance, so their voltages are equal and opposite and cancel. So V(in) equals V(R). And since V(in) is now constant, so must V(R) be. But as R changes,

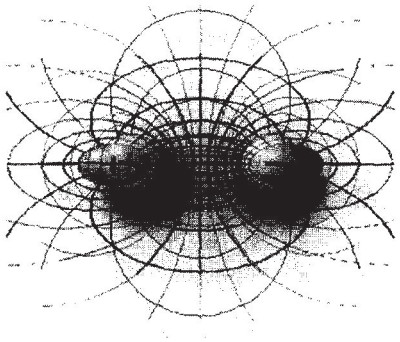
INTEL-1010
U.S. Patent 7,151,430

I(in) must change. As I(in) changes so do V(C) and V(L) change in response, but they change together, so that they are always equal and opposite and cancel.

Reset R to unity and begin to reduce the value for C. As C gets smaller, the voltage across it, V(C), increases. Since the total voltage is constant, the voltage across V(R) and V(L) must both decrease. That means Z must be increasing so I(in) is decreasing. Watch the values for Z and the phase angle in the text boxes.

The curves shift to the left, but they are all shifting exactly in the same phase. Remember, the phase relationship between V(C), V(L), and V(R) never changes.

This simulation allows you to visualize what is meant by phase shift and to see what it is that is shifting with respect to what else. Experiment with other combinations of component values and input conditions and then try to understand (and explain) what happens.



E COMPLEX ALGEBRA

The use of complex math and imaginary numbers is routine in electronic analysis. This appendix includes some Web links, hints about complex number resources available on PCs, a note on Euler's Formula and how it suggests the relationship between exponential functions and electronic sine waves, and a pretty good article summarizing the topic reprinted from Microsoft's Encarta.

WEB SITES

If you do a search for "imaginary numbers" on the Web you will get a great many hits. Some reasonable places to start are:

http://www.math.toronto.edu/mathnet/answers/imaginary.html ("Do Imaginary Numbers Really Exist?")

http://ca.yahoo.com/Science/Mathematics/Numerical_Analysis/Numbers/Complex_and_Imaginary_Numbers

http://forum.swarthmore.edu/dr.math/ (Note: This site has good links for many math questions, including Logs and complex math.)

http://mathworld.wolfram.com/topics/ComplexNumbers.html

http://www.sciencenewsbooks.org/scibook/imtalstorof1.html (Note: An interesting book on imaginary numbers can be found here.)

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COMPUTER RESOURCES

Current spreadsheets have varying degrees of capabilities with complex numbers. In Microsoft Excel, for example, after you install the Analysis Pack (see your documentation) some of the available functions include those shown in Table E-1.

Table E-1 Some Complex Functions Available in Microsoft Excel

	A	B	C
1		Some Excel Complex Algebra Functions	
2			
3	+COMPLEX(50,-100)	50-100i	Expresses a complex number
4	+COMPLEX(25,200)	25+200i	Expresses a complex number
5	+IMREAL(B3)	50	Real part of B3
6	+IMAGINARY(B3)	-100	Imaginary part of B3
7	+IMABS(B3)	111.8033989	This is |Z| = Sqrt(R^2 + X^2)
8	+IMARGUMENT(B3)	-1.10715	Angle, theta, in radians
9	+DEGREES(B8)	-63.43494882	Angle, theta, in degrees
10	+IMSUM(B3+B4)	75+100i	Sum of B3 + B4
11	+IMPRODUCT(B3,B4)	21250+7500i	Product of B3 * B4
12	+IMDIV(B3,B4)	-0.461538461538462-0.307692307692308i	Division of B3 / B4

Mathcad has an outstanding complex math capability. Figure E-1 shows the Mathcad program I used to compare the effects of ESR on two sets of bypass capacitor assumptions. Each set assumes 200 each .01 uF capacitors with 10 nH lead inductance and 100 each 50 uF capacitors with 20 nH inductance. The two curves represent assumptions of .1 Ω and .0001 Ω ESR, respectively. In a more general sense, this is simply an analysis of two parallel RLC circuits.

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$C1 := .01 \cdot 10^{-6}$

$R1 := .0001$

$L1 := 10 \cdot 10^{-9}$

Array of 200 $\quad X1(f) := \frac{1}{200} \cdot \left(\frac{1}{2i \cdot \pi \cdot f \cdot C1} + R1 + 2i \cdot \pi \cdot f \cdot L1 \right)$

$C2 := 50 \cdot 10^{-6}$

$R2 := .0001$

$L2 := 20 \cdot 10^{-9}$

Array of 100 $\quad X2(f) := \frac{1}{20} \cdot \left(\frac{1}{2i \cdot \pi \cdot f \cdot C2} + R2 + 2i \cdot \pi \cdot f \cdot L2 \right)$

$C3 := .01 \cdot 10^{-6}$

$R3 := .1$

$L3 := 10 \cdot 10^{-9}$

Array of 200 $\quad X3(f) := \frac{1}{200} \cdot \left(\frac{1}{2i \cdot \pi \cdot f \cdot C3} + R3 + 2i \cdot \pi \cdot f \cdot L3 \right)$

$C4 := 50 \cdot 10^{-6}$

$R4 := .1$

$L4 := 20 \cdot 10^{-9}$

Array of 100 $\quad X4(f) := \frac{1}{20} \cdot \left(\frac{1}{2i \cdot \pi \cdot f \cdot C4} + R4 + 2i \cdot \pi \cdot f \cdot L4 \right)$

$fstart := 10^5 \quad fend := 10^9 \quad N := 5000 \quad n := 0, 1 .. N \quad f_n := \left[fstart \cdot \left(\frac{fend}{fstart} \right) \right]^{\frac{n}{N}}$

Figure continued next page.

Impedance of first part $Z1_n := |X1(f_n)|$

Impedance of second part $Z2_n := |X2(f_n)|$

Both in parallel

$$Z0001_n := \left| \frac{X1(f_n) \cdot X2(f_n)}{X1(f_n) + X2(f_n)} \right|$$

$$Z1_n := \left| \frac{X3(f_n) \cdot X4(f_n)}{X3(f_n) + X4(f_n)} \right|$$

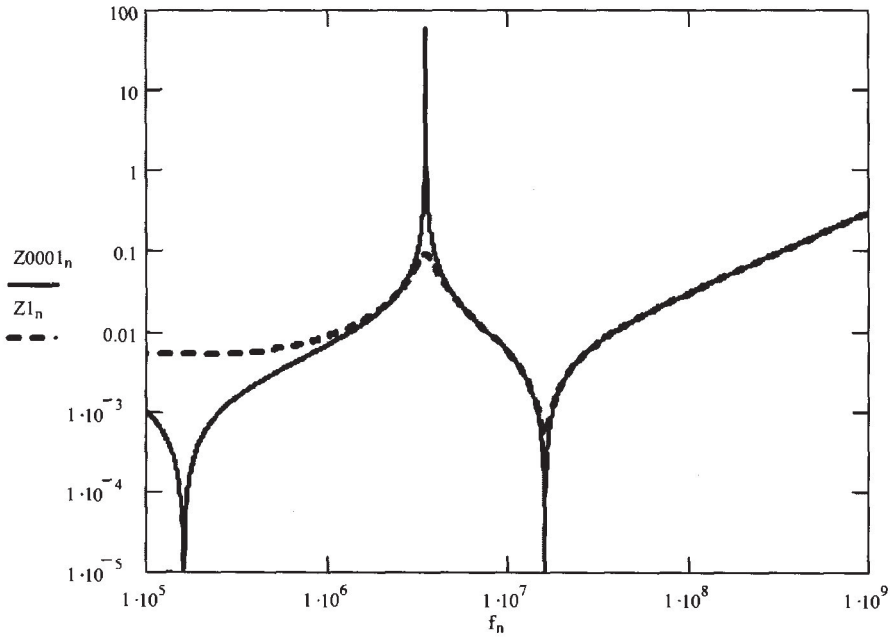


Figure E-1 Mathcad program used to evaluate parallel RLC circuits.

EULER'S FORMULA

A man named Leonhard Euler discovered a mathematical identity related to complex numbers way back in 1748. Think about the resources he had available to him when he did this. His identity is:

$$e^{jx} = \cos(x) + j\sin(x)$$

(In this relationship, x is measured in radians.) Now do two things. Substitute ωt for x and recognize that sin(x) is the same as $\cos(x - 90°)$. Then we have:

$$e^{j\omega t} = \cos(\omega t) + j\cos(\omega t - 90°)$$

This looks awfully close to some of the formulas we worked with for impedance and time constants. On the left side we have an exponential, and on the right side we have a real number and an imaginary number shifted 90 degrees in phase. The real relationships that tied these together are too complex for this book, but this gives a hint about how that relationship is going to look.

Here is another interesting thing about Euler's Formula. Suppose you substitute π for x in the first formula. Then, recognize that $\cos(\pi) = -1$ and $\sin(\pi) = 0$. Therefore:

$$e^{j\pi} = -1 \text{ , or}$$
$$e^{j\pi} - 1 = 0$$

This second form connects the five most common constants in mathematics: e, π, j, 0, and 1.

One more interesting result of this occurs if you substitute $\pi/2$ for x in the top equation, and then recognize that $\cos(\pi/2) = 0$ and $\sin(\pi/2) = 1$:

$$e^{j\pi/2} = j$$

Now raise both sides of this relationship to the power of j (and note that $j^2 = -1$).

$$e^{-\pi/2} = j^j$$

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Using a simple calculator, you can evaluate $e^{-\pi/2}$ and show that

$$j^j = .2078795763.....$$

That is, raising an imaginary number to an imaginary power can lead to a real-number answer.

COMPLEX NUMBERS (REPRINTED BY PERMISSION FROM MICROSOFT ENCARTA 2000)

I Introduction

Complex Number, in mathematics, the sum of a real number and an imaginary number. An imaginary number is a multiple of i, where i is the square root of –1. Complex numbers can be expressed in the form a + bi, where a and b are real numbers. They have the algebraic structure of a field in mathematics. In engineering and physics, complex numbers are used extensively to describe electric circuits and electromagnetic waves. The number i appears explicitly in the Schrödinger wave equation, which is fundamental to the quantum theory of the atom. Complex analysis, which combines complex numbers with ideas from calculus, has been widely applied to subjects as different as the theory of numbers and the design of airplane wings.

II History

Historically, complex numbers arose in the search for solutions to equations such as $x^2 = -1$. Because there is no real number x for which the square is –1, early mathematicians believed this equation had no solution. However, by the middle of the 16th century, Italian mathematician Gerolamo Cardano and his contemporaries

were experimenting with solutions to equations that involved the square roots of negative numbers. Cardano suggested that the real number 40 could be expressed as

$$\left(5+\sqrt{-15}\right)\left(5-\sqrt{-15}\right)$$

Swiss mathematician Leonhard Euler introduced the modern symbol i for $\sqrt{-1}$ in 1777 and expressed the famous relationship $e^{\pi i} = -1$ which connects four of the fundamental numbers of mathematics. For his doctoral dissertation in 1799, German mathematician Carl Friedrich Gauss proved the fundamental theorem of algebra, which states that every polynomial with complex coefficients has a complex root. The study of complex functions was continued by French mathematician Augustin Louis Cauchy, who in 1825 generalized the real definite integral of calculus to functions of a complex variable.

III Properties

For a complex number a + bi, a is called the real part and b is called the imaginary part. Thus, the complex number –2 + 3i has the real part –2 and the imaginary part 3. Addition of complex numbers is performed by adding the real and imaginary parts separately. To add 1 + 4i and 2 – 2i, for example, add the real parts 1 and 2 and then the imaginary parts 4 and -2 to obtain the complex number 3 + 2i. The general rule for addition is

$$(a + bi) + (c + di) = (a + c) + (b + d)i$$

Multiplication of complex numbers is based on the premise that ii = -1 and the assumption that multiplication distributes over addition. This gives the rule

$$(a + bi)(c + di) = (ac – bd) + (ad + bc)i$$

For example,

$$(1 + 4i)(2 – 2i) = 10 + 6i$$

If z = a + bi is any complex number, then, by definition, the complex conjugate of z is

$$\overline{z} = a - bi$$

and the absolute value, or modulus, of z is

$$|z| = \sqrt{a^2 + b^2}$$

For example, the complex conjugate of 1 + 4i is 1 – 4i, and the modulus of 1 + 4i is

$$\sqrt{1^2 + 4^2} = \sqrt{17}$$

A basic relationship connecting absolute value and complex conjugate is

$$z\bar{z} = |z|^2$$

IV The Complex Plane

In the same way that real numbers can be thought of as points on a line, complex numbers can be thought of as points in a plane. The number a + bi is identified with the point in the plane with x coordinate a and y coordinate b. The points 1 + 4i and 2 – 2i are plotted in Figure E-1 and correspond to the points (1,4) and (2, –2). In 1806 Swiss bookkeeper Jean Robert Argand was one of the first people to express complex numbers geometrically as points in the plane. For this reason, Figure E-1 is sometimes referred to as an Argand diagram. If a complex number in the plane is thought of as a vector joining the origin to that point, then addition of complex numbers corresponds to standard vector addition. Figure E-2 shows the complex number 3 + 2i obtained by adding the vectors 1 + 4i and 2 – 2i.

Since points in the plane can be written in terms of the polar coordinates r and Θ,every complex number z can be written in the form

$$Z = r\,[\cos(\Theta) + i\sin(\Theta)]$$

Here, r is the modulus, or distance to the origin, and Θ is the argument of z, or the angle that z makes with the x axis. If

$$z = r[\cos(\Theta) + i\sin(\Theta)] \text{ and}$$
$$w = s[\cos(\Phi) + i\sin(\Phi)]$$

are two complex numbers in polar form, then their product in polar form is given by

$$zw = rs[\cos(\Theta + \Phi) + i\sin(\Theta + \Phi)]$$

This has a simple geometric interpretation that is illustrated in Figure E-3.

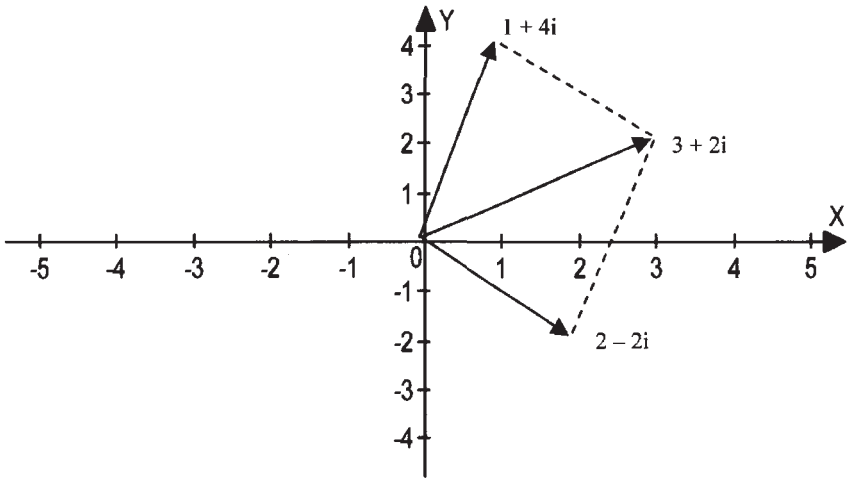


Figure E-2 This graph illustrates the addition of two complex numbers by using vectors in the complex plane with cartesian coordinates. The parallelogram shows that the sum of 1 + 4i and 2 – 2i is 3 + 2i.

V Solutions to Polynomials

There are many polynomial equations that have no real solutions, such as

$$x^2 + 1 = 0$$

However, if x is allowed to be complex, the equation has the solutions $x = \pm i$, where i and –i are roots of the polynomial $x^2 + 1$. The equation

$$x^2 - 2x + 2 = 0$$

has the solutions $x = 1 \pm i$. In his fundamental theory of algebra, Gauss showed that every nontrivial (having at least one nonzero root) polynomial with complex coefficients must have at least one complex root. From this it follows that every complex polynomial of degree n must have exactly n roots, although some roots may be the same. Consequently, every complex polynomial of degree n can be written as a product of exactly n linear, or first-degree, factors.

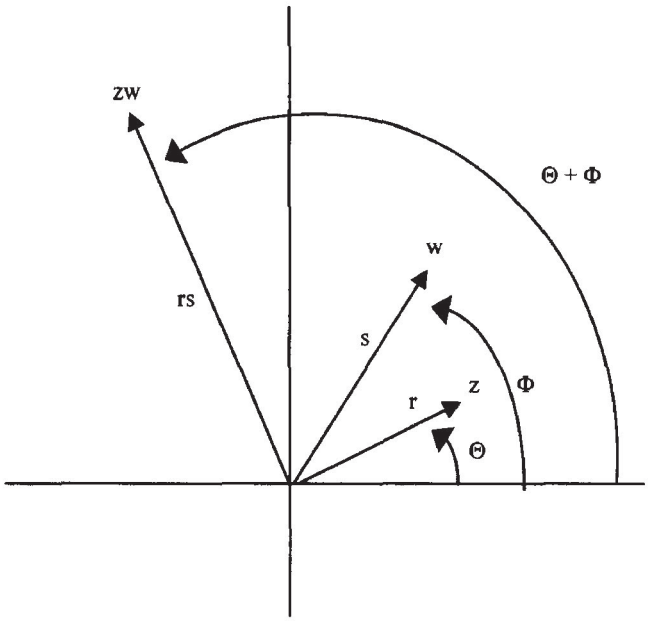
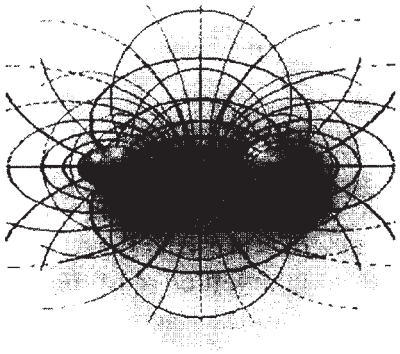


Figure E-3 This graph illustrates the multiplication of two complex numbers by using vectors in the complex plane with polar coordinates. The product of vectors *z* and *w* is a vector whose length is the product of the lengths of *z* and *w*, and whose angle with the x axis is the sum of the angles that *z* and *w* make with the x axis.

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F TRANSMISSION LINE SIMULATOR

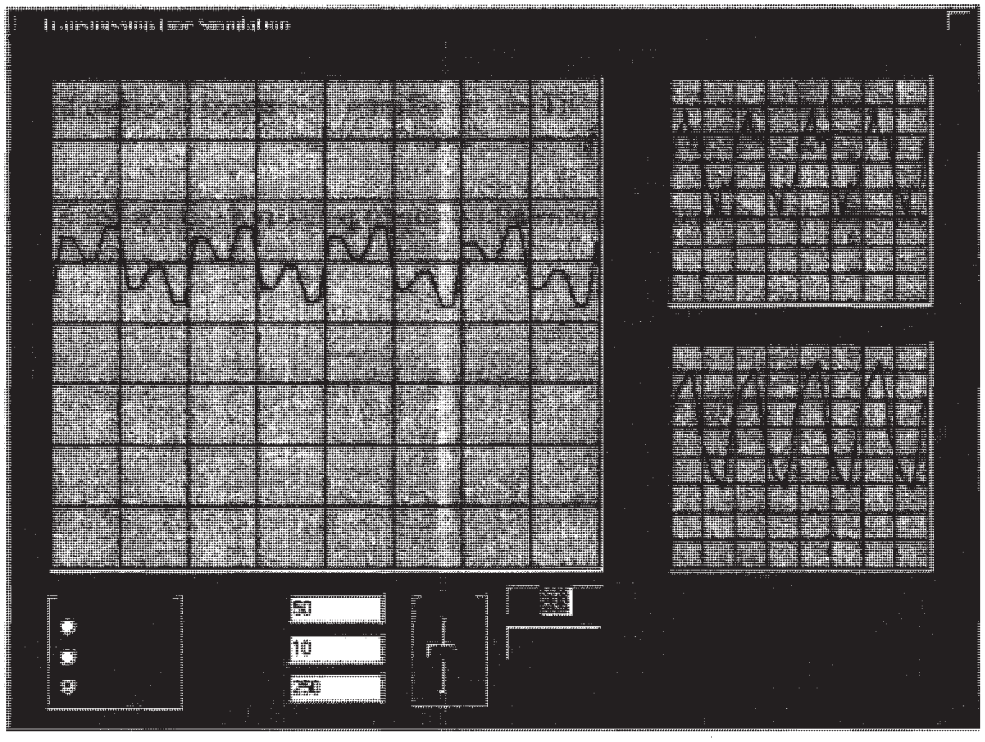


Figure F-1 Transmission Line Simulator

This simulator can be downloaded from
http://www.ultracad.com/prenticehall/tlinesim.zip.

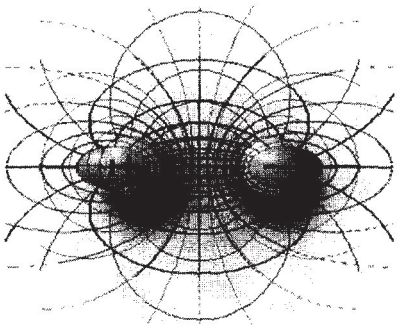
Unzip the file to obtain tlinesim.exe and execute the file. The program shown in Figure F-1 will start.

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The main screen represents a transmission line. The pattern represents the signal at every point along the line in real time. The left edge of the screen at the upper right represents the instantaneous signal level at the very beginning of the trace, and the left edge of the screen at the lower right represents the same thing for the far end of the trace. In this way, you can visualize what is happening at every point along the line.

The Input waveform selection enables you to select a single step-function change in voltage, a single pulse, or a repetitive square wave (much like a clock signal) as the driving signal. The three text boxes allow you to specify the characteristic impedance of the transmission line, and the resistive loading at each end. Having set these, the right arrow then starts the selected waveform down the trace. The waveform will reflect back and forth for at least 5 cycles, illustrating what happens to the waveform under various termination conditions. The speed at which the waveform travels is controlled by the speed selector slider.

The other two selection buttons allow you to pause or reset the simulation.



G ECHO ILLUSTRATION

A clear message (signal) will be distorted if there are any reflections from the end of the transmission line. One solution to the reflection problem is to slow down the message (slow down the rise time of the signal). UltraCAD has placed three audio files on its Web site that illustrate these points. The first, testwave1.wav, is a simple phrase. The second, testwave2.wav, is the same phrase with considerable (admittedly forced) echoes (reflections) added. The third, testwave3.wav, is the same expression with the same echoes, but the phrase is spoken more slowly.

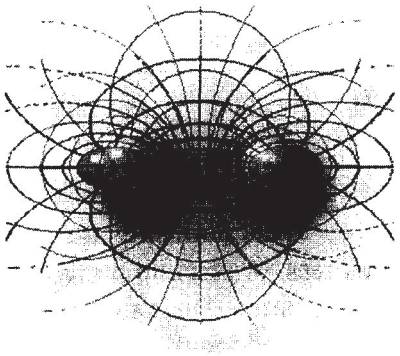
The three files illustrate how reflections can obscure a message, and how slowing down the message can help improve the receiver's ability to understand it. The three files can be found at:

- *http://www.ultracad.com/prenticehall/testwave1.wav* (76k)
- *http://www.ultracad.com/prenticehall/testwave2.wav* (76k)
- *http://www.ultracad.com/prenticehall/testwave3.wav* (376k)

Your browser may play the file directly. Alternatively you might get better results if you go to *http://www.ultracad.com/prenticehall,* right-click each file individually, and download it to your computer. Then you will be able to play the file locally. Of course you will not be able to play the file if you do not have an audio card and speakers.

This illustration is admittedly exaggerated. It is not intended to accurately reflect what happens on a transmission line. Its purpose is to suggest, by analogy, what happens when transmission lines are not terminated properly and reflections are allowed to exist on a line.

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H UltraCAD FREEWARE CALCULATORS

UltraCAD Design, Inc. has developed several freeware calculators for people to use. They are all located on the UltraCAD Web site at *www.ultracad.com/calcs*.

This appendix describes three of them that are useful for signal integrity purposes. As a general warning, be sure to read the help file associated with each calculator before using it.

IMPEDANCE (ULTRACLC.EXE)

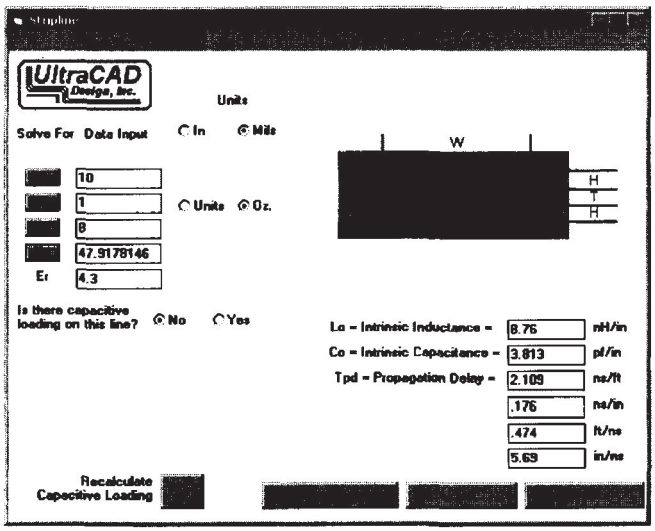


Figure H-1 A typical stripline screen from UltraCAD's impedance calculator.

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This tool, shown in Figure H-1, can be used to determine the trace width, thickness, or stackup dimensions required to hit an impedance target, or it calculates the trace impedance given the other parameters. It gives helpful results for microstrip, embedded microstrip, stripline, and asymmetric stripline configurations. The calculations are based on the standard equations found in the industry and summarized at the end of Chapter 10.

Note: This calculator is not designed to be used for differential impedance calculations.

CROSSTALK (ULTRA_CT.EXE)

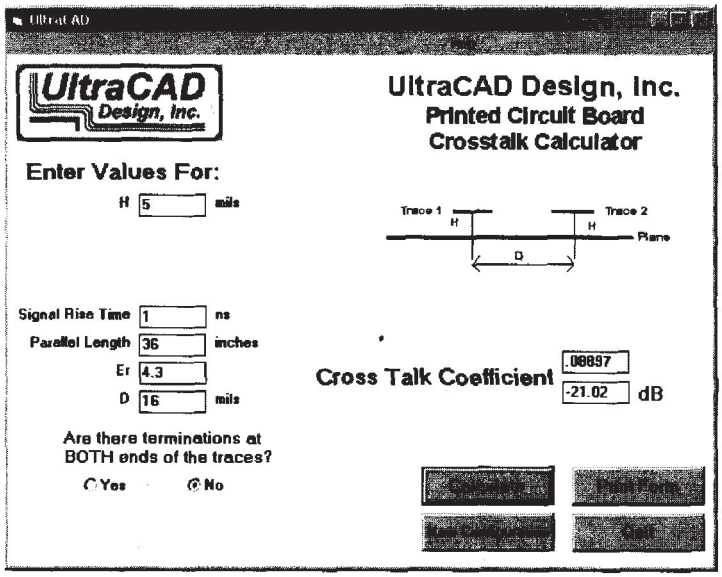


Figure H-2 A typical screen from UltraCAD's crosstalk calculator.

UltraCAD's crosstalk calculator, shown in Figure H-2, is useful for making estimates of the crosstalk coefficient between adjacent traces. Since there are many factors that can affect crosstalk, the calculator is not intended to give precise results. Rather it gives an approximate, worst-case indication. People should look at existing boards with this calculator and calibrate the calculator to previous designs.

BYPASS CAP AND ESR (UCADESR3.EXE)

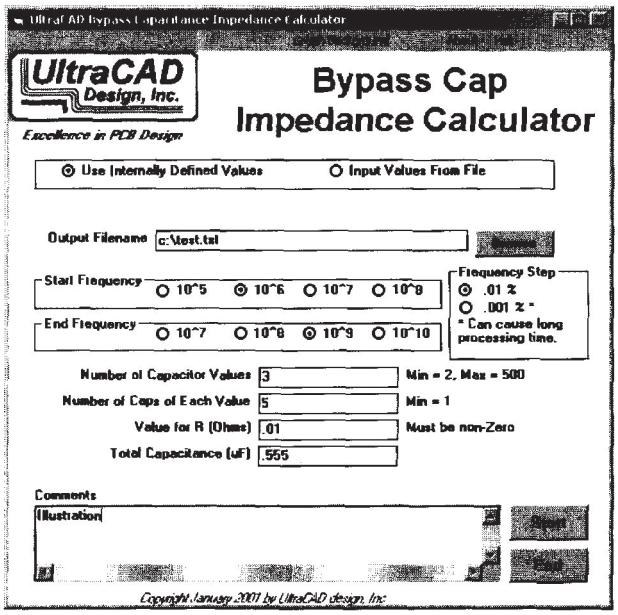


Figure H-3 One of the screens from UltraCAD's Bypass Cap Impedance Calculator.

The equations for a system of parallel capacitors (each with lead inductance and ESR) get very complicated very quickly. The manual calculation of results becomes impractical when the number of parallel capacitors reaches three or four. Unfortunately there are very few, if any, practical alternatives for making these calculations.

UltraCAD designed this calculator (see Figure H-3) for its own internal use for making these types of calculations. It can determine the resonant frequencies and plot an impedance curve for a system of up to 500 different capacitor values with an effectively unlimited number of capacitors of each value. A typical graphical output is shown in Figure H-4. Output data is also written to a text file. The useful frequency range of analysis is from 100 kHz to 10 GHz.

The calculator operates in two modes. The first is a demonstration mode in which the calculator defines the capacitance and inductance values over a particular range, based on some general user inputs. The second mode accepts virtually any user-specified values through an easily programmed input file.

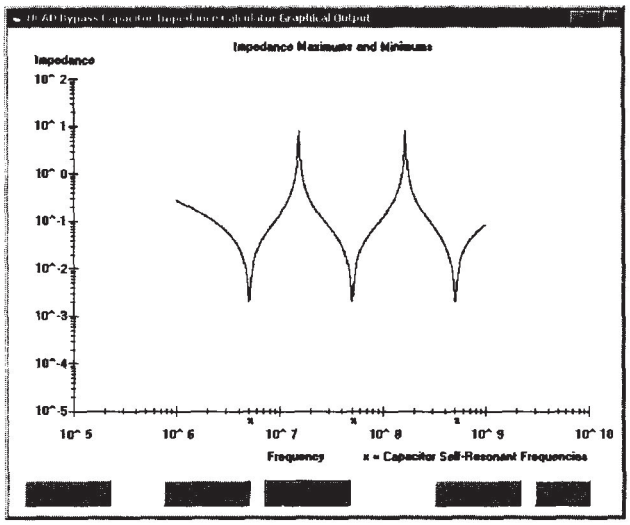
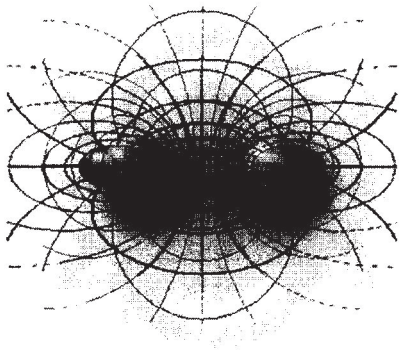


Figure H-4 Representative output from UltraCAD's bypass capacitance calculator.

The freeware version of this calculator accepts up to three capacitance values. A nominal license is necessary to extend the capability of the calculator beyond that limitation.



I TDRs and VNAs

It is not uncommon now to read an article or see a presentation with references to a time domain reflector (TDR) analysis or to see a graph of an analysis based on a TDR response. Less commonly we are beginning to see references to similar analyses with vector network analyzers (VNAs). Many designers have never had the opportunity to learn what these tools do or how they work. This appendix gives an overview of the operating principles behind the tools so you can at least understand what it is they are able to show.

Basic Concepts

In one sense, the operating principles behind TDRs and VNAs are almost identical. They have very similar block diagrams, analyze the same circuits, and give equivalent results. Both are used to analyze impedance-controlled traces or networks. Figure I-1 illustrates the block diagram that applies to each.

Each has a signal-generating circuit we can model as a Thevenin equivalent circuit (see Chapter 5). This is shown in the left section of Figure I-1. The series (output) resistor is shown as 50 Ω, which is typical, but in some instruments the output impedance can be varied by the user. Each has a signal analysis circuit at the output of the tool to analyze the signal and its return from the device under test. Provision must be made for some sort of output, but this can take many different forms. The output might be a built-in display, it might be an output to a plotter, or it might be a text output to a screen or a file. In some cases (see Figure I-2) it might be an output to a separate computer.

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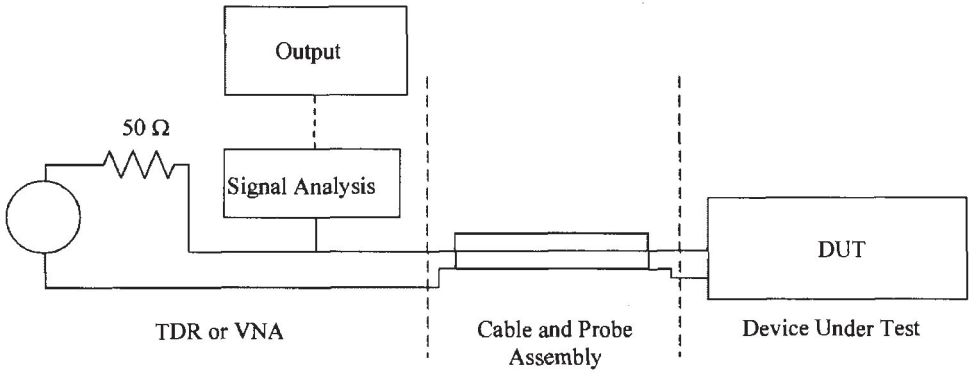


Figure I-1 Block diagram of a TDR or VNA test setup.

The device under test (DUT) is shown as the right section in the figure. This can be an actual circuit board or it can be a specially designed or processed test board. It can also be a real-world network of some type. For example, TDRs can be used to determine where a fault is along a telephone line between the central office and your home.

Each product must be connected to the DUT by a cable and probe assembly, shown as the middle section. This would normally be an impedance-controlled cable that would match the source impedance of the tool. If the TDR or VNA is used to analyze the impedance characteristics of a DUT, it is clear that the cable and probe assembly should match the impedance of the testing tool, so as not to introduce any erroneous indications into the analysis. Attaching the cable and probe assembly to the DUT in such a way as to introduce no additional impedance discontinuities can be *the* most difficult part of any TDR or VNA analysis.

Now consider what happens when the tool (TDR or VNA) sends a signal through the cable to the DUT. Let's assume the cable and probe assembly is 2 ns long and the trace under test is 3 ns long. The signal analysis circuit looks at the signal at the output of the tool. At first it sees only the output of the tool. It takes 2 ns for this output to travel to the front of the DUT. If there is any kind of reflection from the front of the DUT (e.g., the probe connection is not exactly 50 Ω) there will be a reflection from that point back to the tool. This reflection will arrive 2 ns later at the signal analysis circuit. Any additional impedance discontinuities will also cause reflections that will travel back to the signal analysis circuit. By measuring the signal level and its time delay, and comparing that to the source signal, the signal analysis circuit has all the information it needs to characterize the DUT.

TDR vs. VNA

TDRs and VNAs have one very significant difference between them. The TDR transmits a step-function change in signal to the DUT. For simplicity, let's think of that signal being a *very* fast transition from a logical zero to a logical one, or from 0.0 volts to 1.0 volt. Rise times in the picoseconds are not uncommon. This signal travels down the DUT and returns. By analyzing the signal level and the time it took for the signal to travel over its distance, any *specific, individual point* along the trace can be characterized. Because the TDR looks at the response as a function of time, it is referred to as a *time domain* device, hence the name. It looks at reflections as a function of time.



Figure I-2 Polar Instruments CITS500s TDR measuring system using a standard PC for data analysis, processing, and display (courtesy Polar Instruments).

By contrast, a VNA sends a longer (sine-wave, AC) signal down the trace at a specific frequency. The pulse width of this AC signal is long enough for the reflections from the DUT to stabilize, but it is still a very short period of time in real

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terms. The signal analysis circuit then measures the stabilized response, calculates the impedance of the DUT, and calculates the phase shift of the returned signal. Then the VNA shifts to another frequency and does this analysis all over again. After a period of time, the VNA has "swept" over a range of frequencies and characterized the DUT at each one of them. The output of the test is a plot of the impedance and phase shift as a function of frequency. Since the VNA looks at the response of the DUT as a function of frequency, it is referred to as a *frequency domain* device.

Thus, a TDR is a time domain tool that looks at the impedance characteristics of a trace at each individual point along the trace. A VNA is a frequency domain device that looks at the average impedance and phase shift of an entire trace at each individual frequency across a range of frequencies.

PRINCIPLES OF OPERATION: TDR

Figure I-3 is a TDR response taken directly from a study done in the early1990s.[1] It illustrates a trace exactly 15 inches long with three equally spaced vias along it. The trace passes through each via to another signal layer on the test board. All traces are designed to be 50-Ω traces. There is a high-frequency 50-Ω SMA connector at the front of the trace.

As is typical of TDR analyses, the graph does not show the portion of the signal travel along the cable and probe assembly. Thus, it starts at 20 ns after the pulse from the TDR. At about 21.4 ns there is a sharp, momentary drop in the signal level. This is the point at which the signal travels through the connector, which (from this figure) is obviously not exactly 50 Ω. Then the signal level rises above the reference, indicating that the actual impedance of the trace is higher than the targeted 50 Ω.

The vias are spaced at intervals of 3.75 inches. Each via shows up as a momentary drop in signal level, meaning that each one looks somewhat capacitive to the circuit. There is a 50-Ω terminating resistor at the end of the trace, beyond which the graphical output signal is relatively flat.

[1]Brooks, Douglas, "The Effects of VIA on PCB Traces," *Printed Circuit Design*, August 1996, available at *www.ultracad.com*.

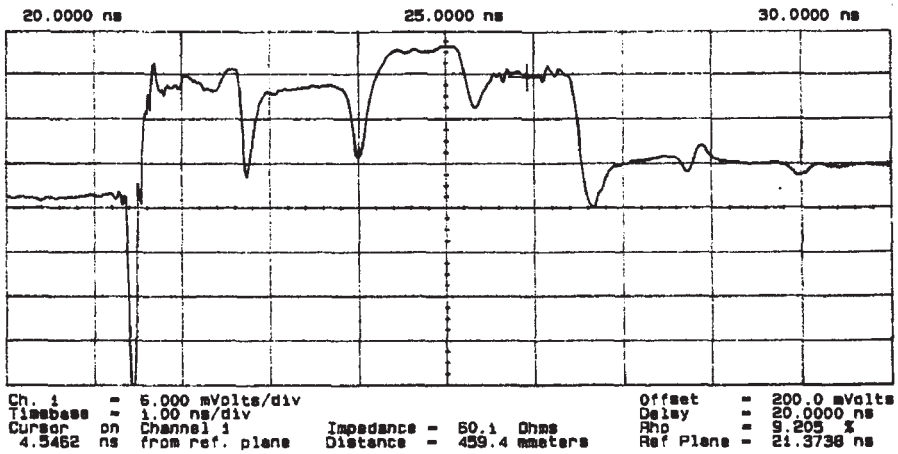


Figure I-3 TDR output showing a 15-inch trace with three equally spaced vias.

Note that the time period along the chart from the signal drop at the connector to the signal stabilization at the terminating resistor is almost exactly 5 ns. This represents the round trip time for the signal to travel down the 15-inch trace and back again. That means the one-way trip is 2.5 ns, which is almost exactly 6 inches/ns, a comforting result.

At each impedance discontinuity there is a reflection. If we call the signal the *incident* wave, then there will be a portion of that wave that is reflected backward and a portion that is transmitted forward. If our TDR is designed to have a Zo of 50 Ωs, and the impedance at the discontinuity is Ztest, then the relationships shown in Equations I-1 and I-2 hold:

$$\frac{V_{reflected}}{V_{incident}} = \rho = \frac{Z_{test} - 50\Omega}{Z_{test} + 50\Omega} \qquad [I\text{-}1]$$

so

$$Z_{test} = \frac{1+\rho}{1-\rho}(50)\ \Omega \qquad [I\text{-}2]$$

Thus, the signal analysis circuit can calculate the specific impedance, Ztest, at each individual point along the trace. The waveform pictured in Figure I-3 is just such a plot.

You might pick up on one real potential problem, though. Consider the reflection at, for example, the second via. There will be a reflected waveform from that via flowing back toward the TDR. But this reflection will flow past the first via, from which there will also be a reflection, and also past the connector, from which there will be an additional reflection. Each of these reflections will have their own incident, reflected, and transmitted components. How, then, do we separate out all these secondary reflections from the primary ones we are interested in? The straightforward answer is that it isn't easy.

The other answer is that it is done through software. It is common in the industry that such software is provided by third-party vendors rather than the TDR hardware manufacturers. Thus a well-equipped analytical test bench will commonly have one or more TDRs from hardware suppliers and also some analytical software from other suppliers.

PRINCIPLES OF OPERATION: VNA

When we send a steady state frequency along the DUT, we also get a transmitted and reflected wave. But since we are dealing with average conditions (instead of instantaneous ones) we use different terms. The terms are called *S parameters*.[2] (Think of S as meaning "scatter," as in the DUT starts *scattering* the waveforms.) In this context, we use the parameters S11 and S12. S11 represents the part of the signal that is going into terminal 1 (the front end of the transmission line under test) and reflected back from the same terminal. S12 represents that part of the waveform that is going on from terminal 1 toward terminal 2 (the other end of the transmission line under test). The analysis is very similar to the TDR case, but now we refer to Ztest as the *average* impedance of the DUT, not the instantaneous impedance at a particular point along the DUT. Equations I-1 and I-2 now become:

[2]For an excellent discussion of S parameters, see Bogatin, Eric, "Get Your S (Parameters) Together," *Printed Circuit Design*, February 2003.

$$\frac{V_{reflected}}{V_{incident}} = S11 = \frac{Z_{test} - 50\Omega}{Z_{test} + 50\Omega} \quad [I\text{-}3]$$

$$Z_{test} = \frac{1+S11}{1-S11}(50)\ \Omega \quad [I\text{-}4]$$

The S parameter is a complex function that has a magnitude and a phase. For a perfect transmission line, with perfect termination, S11's magnitude and phase would be zero (because there is no reflection). For a uniform 50-Ω transmission line, open at the far end, the magnitude of S11 would be 1.0 (100% reflection). But the phase of S11 would be more complicated.

To visualize what happens from a phase standpoint, assume we send a 1.0-GHz signal down the open line. Assume also that the propagation time is exactly 6 in./ns. The wavelength of the signal would be

$$\frac{1}{(1.0)10^9 \frac{\text{cycles}}{\text{sec}}}\left(\frac{6}{10^{-9}}\right)\frac{\text{in.}}{\text{sec}}$$

$$\left(10^{-9}\frac{\text{sec}}{\text{cycle}}\right)\left(\frac{6}{10^{-9}}\frac{\text{in.}}{\text{sec}}\right) = 6 \text{ in./cycle}$$

Suppose the line were exactly 3 inches long. The round trip down the line and back would be 6 inches. So, what would the phase relationship be between the incident waveform and the reflected waveform? The answer is they would be exactly in phase. The reflection would return exactly one cycle (360 degrees) after it started down the line. We could say that the reflected wave was lagging the incident wave by 360 degrees, or that the incident wave was leading the reflected wave by 360 degrees. But for all practical purposes, that is the same thing as saying that they are actually in phase.

Now, assume we increase the frequency to 1.25 GHz. When the reflected wave returns to the front of the DUT, the incident wave will have progressed through 360 + 90 = 450 degrees. The reflected wave is now lagging the incident wave by an additional 90 degrees. As we increase the frequency slightly, the reflected wave lags further behind. At an incident frequency of 1.5 GHz, the reflected wave will be lagging by an additional 180 degrees. At 1.75 GHz, it will be lagging

by an additional 270 degrees. At 2.0 GHz, it will be lagging by another 360 degrees again.

Now here is a (perhaps) philosophical question for you: At 1.75 GHz, is the reflected wave lagging (minus sign) the incident wave by 270 degrees, or is it leading (plus sign) it by 90 degrees? At 1.5 GHz, is the reflected wave lagging (minus sign) the incident wave by 180 degrees or is it leading (plus sign) it by 180 degrees? In each case, both answers are correct. We normally define the phase relationship by a convention that says as we pass 180 degrees the phase shift changes from a lead to a lag, or vice versa. Thus, in this example, the phase relationship of this experiment with frequency is graphed as shown in Figure I-4. This is one place in electronics (passing through 180-degrees phase shift) where we allow an instantaneous (no rise or fall time) change between values.

By looking at both the average impedance of the DUT and the phase shift of the returned signal relative to the VNA signal as a function of the frequency of the VNA test signal, engineers can characterize the full nature of the transmission line under test.

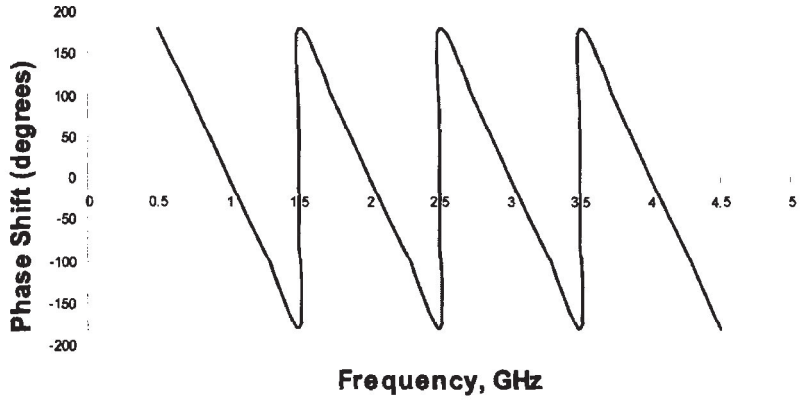
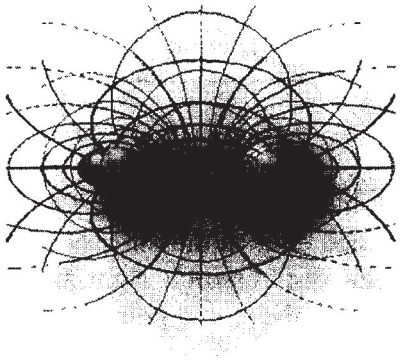


Figure I-4 VNA phase shift from the open end of a 3-inch line.



J RIGHT ANGLE CORNERS

The influence of 90-degree corners on neighboring circuits is one of the most controversial topics in PCB design. It ranks right beside the routing of bypass capacitor leads as a guaranteed argument starter.

The arguments against 90-degree corners fall into two categories: impedance control and EMI. I summarize each one of those here.

IMPEDANCE CONTROL

Unless very carefully constructed, a trace rounding a corner will necessarily be wider at the corner than it is in the middle of the trace. Since control over impedance requires a controlled geometry, and since a trace that changes width does not have a controlled geometry by definition, then necessarily there must be an impedance discontinuity (a change in impedance) at that point. The concern, then, is whether this change in discontinuity will cause a reflection down the trace.

Figure J-1 illustrates several geometric trace configurations, the maximum change in width that occurs as the trace rounds the corner, and the approximate impact on the calculated trace impedance. Since the trace gets wider as it goes around the corner, the capacitance between the trace and the plane increases and the impedance goes down. The exact impact on the impedance depends on the magnitude of the other variables. That's why the impact is shown as a range.

The idea of a true right-angle corner is a misnomer. Since traces are typically "drawn" with a laser plotter using a circular spot, the traces on our films really

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look like (b) in the figure. The traces have a sharp edge at the inner corner but a rounded edge at the outer corner. So, at most the impact on impedance, if we let our design systems route right-angle corners, is 10% or less. But that is at a single, sharp, well-defined point. The impact is less than that everywhere else. Remember the concept of critical length introduced in Chapter 10? For a trace width of 6 mils we are talking in the terahertz range before this distance approaches the critical length. So in reality there is no impedance impact at all for signals rounding corners.



	(a)	(b)	(c)
Max Width	1.414W	1.207W	1.04W
Approximate Impact on Zo	−15% to −18%	−7% to −10%	−1.5% to −2.0%

Figure J-1 The maximum trace width and impact on Zo is a function of trace geometry.

If that answer doesn't convince you, then think of the impedance discontinuity that we experience around vias. A via is a much worse geometrical perturbation and is so over a much longer distance than a corner. We intuitively know that vias generally don't present a serious discontinuity problem, so the impedance question related to 90-degree corners is really a nonissue.

EMI Radiation

A different argument against right-angle corners goes like this. There is electromagnetic energy surrounding a high-speed trace, by definition. The fields, and therefore that energy, become concentrated at the corners. The sharper the corner, the greater the concentration of energy. Therefore, right-angle corners lead to radiation problems at these points of concentration.

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The impedance argument can be argued theoretically. The radiation argument, on the other hand, does not lend itself to an easy theoretical analysis. The argument sounds good, but the proof is really in the empirical analysis.

UltraCAD participated in a study in which a test board was designed and fabricated with several different kinds of corners for test.[1] These corners ranged from smoothly curved arcs to radically diabolical 135-degree sharp bends (see Figure J-2). These traces were then tested for radiation in a controlled test. There were no significant differences in the radiation levels from any of the traces at frequencies up to about one GHz (the upper limit of the test).

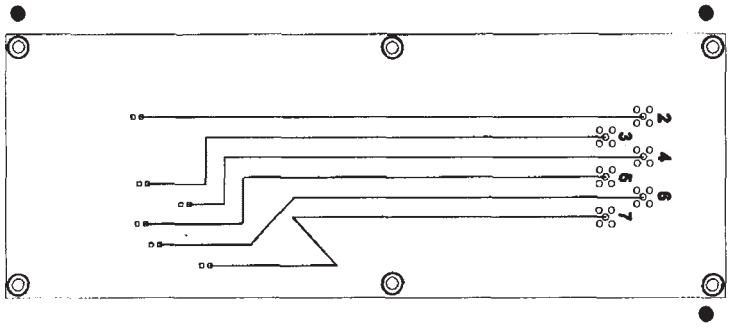
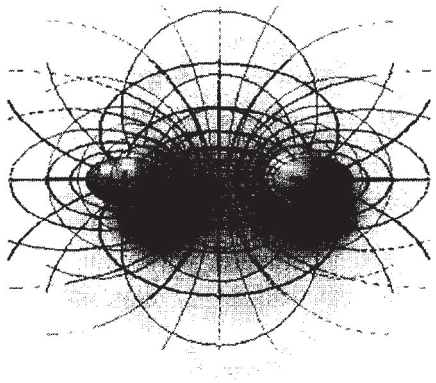


Figure J-2 Partial layout of an EMI test board.

CONCLUSION

On circuit boards, at least up into the gigahertz range, there is no particular performance reason to avoid 90-degree corners. We at UltraCAD avoid them anyway. We think mitered corners look better, but we cannot argue a performance reason for taking the time for the mitering process.

[1] "90 Degree Corners, The Final Turn," *Printed Circuit Design*, January 1998, copy available at *www.ultracad.com*.



GLOSSARY

*N*ote: Many of these entries are explained in nontechnical terms for ease of understanding. They are explained principally as they relate to PCB design issues. *sy* = symbol; *typ* = typical usage in our industry; *val* = value of a constant or formula relationship.

AC (alternating current) A current that repeatedly changes value or changes direction with time.

Admittance *sy* Y, *val* 1/Z, the inverse of impedance.

Anti-resonance *typ* Term used to describe the parallel resonance that can occur between two capacitors wired in parallel.

Atom A basic physical building block consisting of protons, neutrons, and electrons.

Backward crosstalk Coupled noise from an aggressor trace to a victim trace that travels in a direction opposite to that of the aggressor signal.

Bandwidth *typ* A range of frequencies that a circuit passes or handles with minimal distortion.

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Capacitive coupling A signal that couples from one circuit, wire, or trace to another circuit, wire, or trace caused by changing levels of electrical charge.

Capacitor, capacitance A device or condition that opposes the flow of current while causing a –90-degree voltage phase shift. Also a device that stores charge.

Capacitor, bypass *typ* A capacitor with the primary function of stabilizing a power supply voltage, especially for an adjacent device or circuit.

Charge A measure of electrical energy. Particles with like charge repel each other. Particles with opposite charge attract each other. The forces are proportional to the magnitude of the charge and inversely proportional to the square of the distance.

Charge, negative A negative unit of charge. Electrons have negative charge. Charge is often relative; that is, one point is negatively charged relative to another point, not necessarily in absolute terms.

Charge, positive A positive unit of charge. A proton has positive charge. Positive charge often results from a lack of electrons (negative charges). Charge is often relative; that is one point is positively charged relative to another point, but not necessarily in absolute terms.

Common log *sy* Log Logarithm taken to the base 10, (cf. *Natural log*).

Common mode current *typ* Refers to a return signal when the current flows where you do not expect it to flow.

Common mode signal *typ* Signals that are equal in magnitude and phase at the inputs of a device.

Complex number *typ* A number containing both a real and an imaginary part.

Conductance *sy* G, *val* = 1/R, the inverse of resistance.

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Constant current generator A source that generates, or supplies, a constant current regardless of load. This would imply a very high voltage if the load is very high impedance.

Constant voltage generator A source that generates, or supplies, a constant voltage regardless of load. This implies it can supply a very large amount of current if the load impedance is very low.

Coulomb An amount of charge equal to 6.25×10^{-18} electrons.

Critical length A trace length for which the propagation time equals one-half the signal rise time.

Crosstalk A signal induced in one wire or trace by current in another wire or trace.

Current *sy* i, Flow of electrons.

DC (direct current) A current that flows in one direction, usually without changing magnitude.

di/dt A change of current divided by a change in time for a very short time period. Often, dt represents the rise or fall time.

Dielectric *typ* The insulating material between trace layers.

Dielectric absorption A condition in which the molecules in the dielectric begin to absorb very high-frequency energy causing signal losses at the higher-frequency harmonics.

Dielectric constant A measure of an insulator's ability to store charge. It actually may not be a constant under certain conditions.

Dielectric constant, relative *sy* = ε_r, Dielectric constant of a material divided by the dielectric constant of a vacuum.

Differential impedance The impedance seen by a driver when a pair of traces are driven differentially.

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Differential mode *typ* Refers to a signal and its return when the current flows where you expect it to flow.

Differential signals *typ* A signal paired and routed in close relationship with its return, often for improved signal–noise ratio.

Differential traces A pair of traces routed in relationship to each other for conducting differential signals.

DUT Device under test.

e A constant = 2.718282....., the base of the natural logarithm.

Electromagnetic coupling A signal induced in another conductor as a result of electromagnetic radiation.

Electromagnetic radiation A current radiates both an electrical field and a magnetic field. Collective name for these fields.

Electron An atomic particle (circling around the nucleus) containing negative charge. There are as many electrons in an atom as there are protons.

EMC (electromagnetic compliance) Compliance to rules and regulations controlling EMI.

EMI (electromagnetic interference) Interference caused by electromagnetic radiation.

Equalization *typ* A technique for compensating for frequency-related losses along transmission lines.

Equivalent circuit A simplified circuit with outputs that are the same as those of a more complex circuit. Typically contains only a power source and an impedance.

ESR (equivalent series resistance) *typ* The real part of the impedance expression for a capacitor.

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Exponent The power a number is raised to. n is an exponent in the expression a^n.

Exponential *typ* Any function containing the constant e raised to a power.

Eye diagram Method for visualizing a large number of changing logic states at a point in a system under a large number of signal conditions.

Fall time Time required for a signal to fall from its highest value to its lowest value. Typically measured between the 90% and 10% points on the curve, but sometimes between the 80% and 20% points.

Farad A measure of capacitance.

Forward crosstalk Coupled noise from an aggressor trace to a victim trace that travels in the same direction as the aggressor signal.

Fourier analysis An analytical technique for separating a complex mathematical waveform into a function or summation of a number of simpler trigonometric waveforms.

Frequency, angular *sy* ω, *typ* A frequency measure based on radians. $\omega = 2\pi F$.

Frequency, definition *sy* F, *typ* The number of cycles a sine wave completes in one second.

Frequency domain Analyses performed as a function of frequency. When graphed, frequency would typically be on the horizontal axis, (cf. *time domain*).

Generator Device that converts mechanical motion to electrical energy. Can be the same device as a motor.

Giga 1,000,000,000 or 10^9.

Guard band A grounded trace typically placed between two signal traces for the purpose of controlling crosstalk.

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Harmonic *typ* Frequencies that are multiples of a fundamental frequency.

Henry A measure of inductance.

Imaginary operator *sy* j, *val* the square root of –1. Since there is no number which, when multiplied by itself, can be negative, it is called imaginary.

Imaginary part *typ* Any expression for voltage, current, or impedance that is multiplied or divided by j and is shifted ± 90 degrees in phase from the real part of the same expression.

Impedance *sy* Z, *val* R + jX, Opposition to the flow of current, typically with both resistive and reactive components but may contain only either one.

Impedance, characteristic *sy* Zo, *typ* The input impedance of a transmission line.

Impedance, common mode The impedance seen by a driver when a pair of traces is driven with a common signal.

Impedance, differential The impedance seen by a driver when a pair of traces is driven differentially.

Impedance, single-ended *sy* Zo or Z11, The characteristic impedance of an individual trace, even if it is part of a differential pair.

Impedance, transmission line *sy* Zo, *typ* The input impedance of a transmission line.

Inductive coupling A signal that couples from one circuit, wire, or trace to another circuit, wire, or trace caused by a changing magnetic field.

Inductor, inductance A device or condition that opposes the flow of current while causing a +90-degree voltage phase shift.

j Constant, the square root of −1. The symbol i is used in every other discipline, but is not used in electronics to avoid confusion with the symbol for current.

Kilo 1,000, or 10^3.

Logarithm A numeric operation. If a base B is raised to the a power, then the log, to the base B, of that operation is a. $Log_b(b^a) = a$. See also *common* or *natural log*.

Loop area An area defined by the signal path and its return path, relevant for EMI considerations.

Mega 1,000,000, or 10^6.

Micro .000001, or 10^{-6}.

Microstrip A trace configuration where there is a reference plane on only one side of a signal trace.

Milli .001, or 10^{-3}.

Motor A device that converts electrical energy to mechanical motion. Can be the same device as a generator.

Nano 10^{-9}.

Natural log *sy* Ln, Logarithm taken to the base e.

Neutron An atomic particle (part of the nucleus) containing no charge.

Ohm *sy* Ω, A measure of resistance.

Ohm's Law Relationship between voltage, current, and resistance. *typ* E = I x R.

Period *sy* τ, *val* 1/F, The time required for one complete waveform cycle. The inverse of the cyclical frequency.

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Phase Relationship of the angular position on a sinusoidal waveform compared to a reference, such as another waveform.

Phase shift *typ* The difference in the phase between a voltage and a current waveform, or a difference caused by some other factor, such as impedance.

Pi *sy* π, A constant = 3.14159.....

Pico 10^{-12}.

Propagation speed The speed with which a signal propagates along a trace. Often expressed in units of distance per unit time. The inverse of propagation time.

Propagation time The time required for a signal to move (propagate) along a trace.

Proton An atomic particle (part of the nucleus) containing positive charge. There are as many protons in an atom as there are electrons.

R *typ* Resistance or the real part of a complex number.

Radian The angle formed by a length along the circumference of a circle equal to the radius. There are 2π radians in 360 degrees.

Reactance *sy* X, Resistance to a flow of current with a 90-degree phase shift.

Real part Any numeric expression for voltage, current, or impedance that is not multiplied by j and does not have a phase shift.

Reflection coefficient *sy* ρ, *val* (Zo – RL)/(Zo + RL), its value ranges from +1 to –1. It determines the magnitude of the reflection at the end of a transmission line.

Relative dielectric constant *sy* ε_r, Dielectric constant of a material divided by the dielectric constant of a vacuum.

Resistance *sy* R, Resistance to the flow of current without causing a phase shift.

Resistor A device that opposes the flow of current without causing a phase shift.

Resonance A condition in which the reactance term goes to zero. *typ* Where the impedance function peaks or minimizes.

Resonant frequency The frequency where the reactance term goes to zero.

Right-hand rule A rule that helps determine the relationship between the direction of current flow and its accompanying magnetic field.

Rise time Time required for a signal to rise from its lowest value to its highest value. Typically measured between the 10% and 90% points on the curve but sometimes between the 20% and 80% points.

RMS Root Mean Square. For an AC waveform it is the equivalent DC value that would generate the same power.

Signal-to-noise ratio The ratio of a circuit signal to the electrical noise in the circuit. In general, higher ratios are better.

Skin effect Tendency for the current density to be greater at the edge of a wire or trace instead of being evenly distributed over the entire cross-section. Effect increases with frequency.

Step function *typ* Suggests an instantaneous change from one voltage level to another or one logic state to another. Since instantaneous changes are not possible, step function implies a very rapid rise or fall time.

Stripline A circuit board configuration in which a signal trace is placed between two reference planes.

Stub *typ* A short trace extending from a main trace to a component pin.

Susceptance *sy* B, *val* 1/X, the inverse of reactance.

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TDR Time domain reflectometer; an instrument for measuring impedance.

Termination One or more components used in conjunction with a transmission line to control signal reflections.

Time constant A measure calculated as 1/RC or L/R. Any RC or RL circuit typically exhibits very predictable behavior when looked at in terms of time constants.

Time domain Analyses performed as a function of time. When graphed, time would typically be on the horizontal axis, (cf. *frequency domain*).

Transmission line *typ* A tightly geometrically controlled trace structure, typically with respect to a reference plane or other return path.

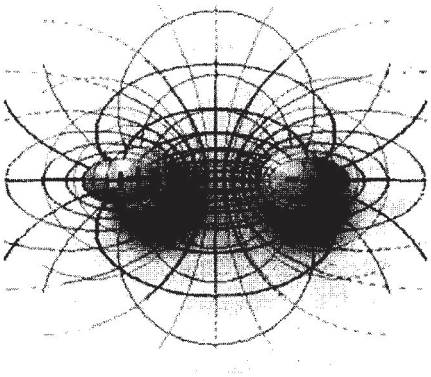
Tuned trace A trace trimmed to a precise length to achieve a timing objective.

VNA Vector network analyzer; an instrument for measuring impedance and circuit characteristics.

Voltage An electrical force caused by the difference in charge between two points.

Wavelength *sy* λ, The distance a signal travels in one complete cycle, (cf. *propagation time*).

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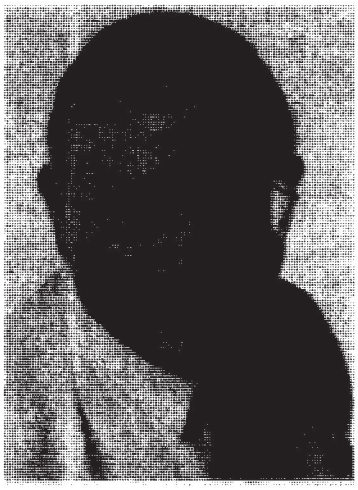
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