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*Training for Signal Integrity and Interconnect Design*

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Printed Circuit Design Magazine, Jan, 2000, p. 18

## What is Characteristic Impedance?

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### ***Introduction***

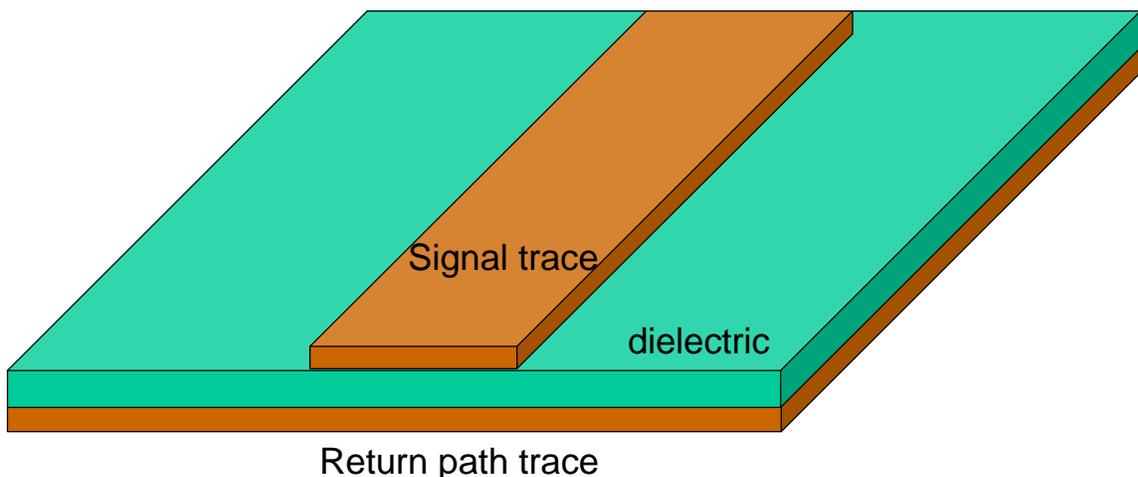
Perhaps the most important and most common electrical issue that keeps coming up in high speed design is controlled impedance boards and the characteristic impedance of the traces. Yet, it is also one of the most un-intuitive and confusing topics for non electrical engineers. And, in my experience teaching over 2000 engineers, it's confusing to many electrical engineers as well. In this brief note, we will walk through a simple and intuitive explanation of characteristic impedance, the most fundamental quality of a transmission line.

### ***What's a transmission line***

Let's start with what's a transmission line. All it takes to make a transmission line is two conductors that have length. One conductor acts as the signal path and the other is the return path. (Forget the word "ground" and always think "return path"). In a multilayer board, EVERY trace is part of a transmission line, using the adjacent reference plane as the second trace or return path. What makes a trace a "good" transmission line is that its characteristic impedance is constant everywhere down its length. What makes a board a "controlled impedance" board is that the characteristic impedance of all the traces meets a target spec value, typically between 25 Ohms and 70 Ohms. But what's this quality, characteristic impedance?

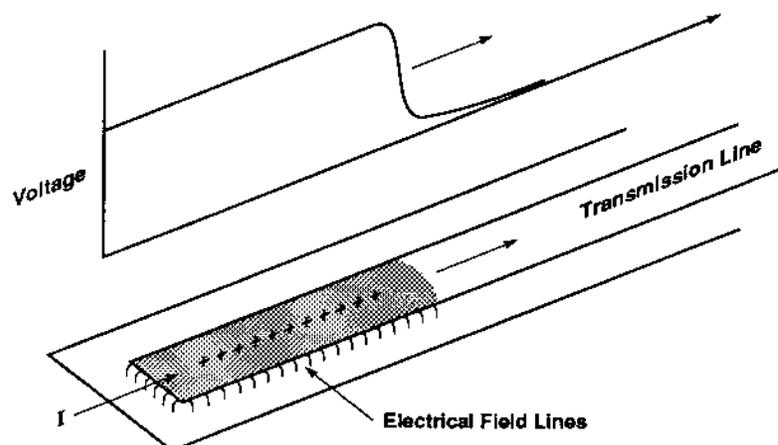
## ***Be the Signal***

The easiest way to think about characteristic impedance is to look at what a signal sees when it travels down a line. First, let's consider a transmission line that just happens to look like a microstrip and has the same cross section as we move down the line. An example of a microstrip is shown in Figure 1.



***Figure 1. Cross section of a typical microstrip transmission line.***

Suppose we launch a step voltage wave of 1 volt into the line. For example, we connect to the front end of the line, between the signal path and the return path, a 1 volt battery. The instant we make the connection, this voltage wave signal begins to move down the line at the speed of light in the dielectric medium, typically about 6 inches/nsec. (Why it moves so fast and is not the speed of the electrons, which is closer to 1 cm/sec, might be the topic of a future article). The "signal", of course, is really the voltage difference between the signal line and the return path, measured between any point along the signal line and the adjacent point on the return path. The voltage edge moving down the line is illustrated in Figure 2.



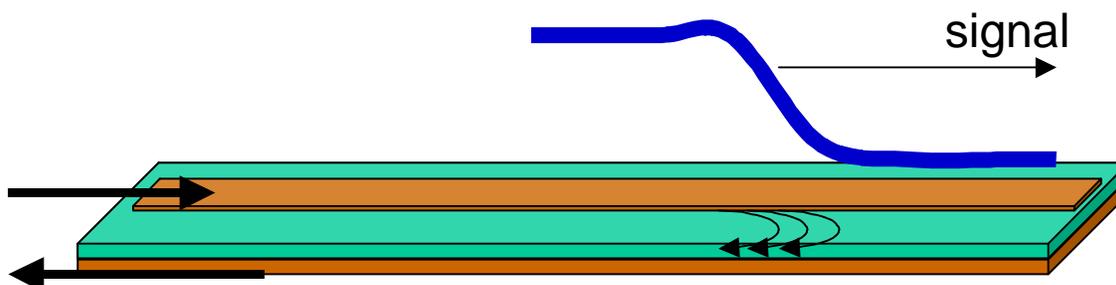
**Figure 2. Signal moving down transmission line, frozen in time. Courtesy of ICE**

In a Zen sort of way, “be the signal”, and travel down this transmission line at 6 inches/nsec. What do you see? In the first 10 psec, you have “walked” about 0.06 inches down the line. Let’s freeze time and look at the line. Behind you, you have left a wake of a constant voltage of 1 volt between the signal line and an adjacent point on the return path. This means there is some excess “+” charge on the trace behind you and some excess “-” charge on the return path behind you. It’s this excess charge difference that sustains the 1 volt signal between these two conductors that make up a capacitor.

Ahead of you, the line doesn’t know you are coming and the voltage between the signal line and the return path is still zero. In another 10 psec, with your next step, you will transform the voltage in the 0.06 inch section under your foot from 0 volts to 1 volt. To do this, you must add some “+” charge to the signal line and add some “-” charge to the return path line. For each 0.06 inch step you take, you are adding more “+” charge to the signal line and more “-” charge to the return path. Every 10 psec, another section of the transmission line gets charged up and the signal propagates down the line. But where does this charge come from?

Answer: it comes from the source- the battery we attached to the front of the transmission line to launch the initial signal. As we, the signal, march down the transmission line, we are charging up successive sections of the line as we go, leaving behind a 1 volt different between the signal and return path lines. Every 10psec, we take a step and draw another small charge,  $\delta Q$ , from the battery. This constant amount of charge,  $\delta Q$ , flowing out of the battery, in constant time interval,  $\delta t$ , is a constant current. There is + current flowing into the signal line and at the same time, - current flowing into the return path.

The “-“ current flowing into the return path is really the same as “+” current flowing out of the return path. And, right at the wave front of the signal, the (AC) current flows through the capacitance between the top line to the bottom line, closing the loop. This is illustrated in Figure 3.



**Figure 3. Current paths in a transmission line as the signal propagates. Note that the current returns to the source where ever the signal voltage is changing.**

### ***Impedance of the Line***

From the battery’s perspective, it sees that as soon as you connected its leads to the front of the transmission line, there is a constant draw of current, for its constant applied voltage. If you were to ask it, what sort of circuit element behaves this way- has a constant current draw for constant applied voltage, of course, it would say a resistor.

To the battery, *while the signal is moving down the transmission line*, (emphasis added) charging up successive 0.06 inch sections every 10 psec, drawing a constant current from the source, the transmission line looks like a resistor and has a constant value of resistance, which we call the “surge” impedance of the line.

Likewise, for you as the signal, walking down the line, with each step you take, you are constantly probing the electrical environment of the line and asking “what is the impedance of my next step?” As you put your foot down on the line, you are electrically asking, what is the current required to charge up this footstep to 1v, in the 10 psec I have until my next step? This is the instantaneous impedance you are probing for.

As we saw with the battery, if you move down the line at a steady pace, and the line has the same cross section, then taking each step requires the same amount of charge in 10 psec, for the same signal voltage. With every step you take, you

will draw the same current from your foot (and the battery), at the same voltage, and you too will see the same instantaneous impedance as you walk down the line.

If the line has the same signal velocity down its length and it has the same capacitance per length down its length then with every step you, the signal, take you will see the same instantaneous impedance as you move down the line. Because this impedance is constant along the line, we give it the special name that says it is characteristic for this particular transmission line. We call it the “characteristic impedance” of the line. **Characteristic impedance is the instantaneous impedance a signal sees as it moves down the line.** If, as the signal moves down the line, it sees the same characteristic impedance with every step, we can label the line as a controlled impedance line.

### ***What’s so Important about the Characteristic Impedance of a Transmission Line?***

The instantaneous impedance, or characteristic impedance, is an important quality for a signal. If the impedance of the next step is the same as the last step, life will be wonderful and you will continue on as you were. If the next step is different than the last and the impedance changes, you will reflect a little energy back and what continues gets a little distorted.

For optimal signal quality, the goal in interconnect design is to keep the impedance the signal sees as constant as possible. This means primarily, keep the characteristic impedance of the line constant. Hence the growing importance in manufacturing controlled impedance boards. All the other tricks like minimize stub lengths, terminate the ends, daisy chain rather than branch, are all designed to keep the instantaneous impedance the signal sees constant.

### ***Calculating Characteristic Impedance***

From this simple model we can derive a value for the characteristic impedance, which is the instantaneous impedance the signal sees as it walks down the line. The impedance seen in each step,  $Z$ , is just the basic definition of impedance:

$$Z = V/I$$

The voltage is the voltage of the signal launched into the line,  $V$ , and the current,  $I$ , is the charge that flows out of your foot,  $\delta Q$ , in the time for each step,  $\delta t$ :

$$I = \delta Q/\delta t$$

The charge that flows out of your foot (coming ultimately from the battery), is the charge needed to charge up the capacitance,  $\delta C$  of one footprint, to the voltage of the signal,  $V$ :

$$\delta Q = \delta C V$$

We can relate the capacitance of one footprint to the capacitance per length,  $C_L$ , of the transmission line and the speed of the signal,  $v$ , down the line. We need to remember that the length of a footprint is our speed,  $v$ , times the time to take each step,  $\delta t$ .

$$\delta C = C_L v \delta t$$

Combining all the pieces, we can write the instantaneous impedance as:

$$Z = V/I = V/(\delta Q/\delta t) = V/(\delta C V/\delta t) = V/(C_L v \delta t V/\delta t) = 1/(C_L v)$$

We see that the instantaneous impedance is related to the capacitance per length of the transmission line and the speed of the signal. This is also the definition of the characteristic impedance of the line. To distinguish the term characteristic impedance from the actual impedance,  $Z$ , we add a small zero to it. We have just derived the characteristic impedance of a transmission line as:

$$Z_0 = 1/(C_L v)$$

If the capacitance per length of a line and the speed of a signal are constant down its length the line will have a constant characteristic impedance, and would be called a controlled impedance line.

This simple expression allows us to tie our intuition about capacitance to our newfound intuition for characteristic impedance. It says that if you increase the capacitance per length of a line, as for example, making the signal line wider, you will decrease the characteristic impedance of the line.

### ***A Final Teaser or Two***

OK, I can hear the question being asked all the way out here in Kansas. "But when the battery gets connected to the transmission line, if it sees an impedance of 50 Ohms, for example, how come when I connect my Ohm-meter to a 3 foot section of RG58 cable, I measure infinite impedance?"

The answer is that the impedance looking into the front of any transmission line is time dependent. If you measure the impedance of the cable in a time short compared to the round trip time of flight of the cable, you will measure the "surge

impedance”, or the characteristic impedance of the cable. But, if you wait long enough for some reflected energy to come back and get picked up, you will see the impedance change- typically the impedance will bounce around until it reaches a steady value of infinite if the end is open or zero if the end is shorted.

For your 3 foot cable, you have to complete the measurement of the impedance in less than 3 nsec. This is what a TDR (Time Domain Reflectometer) does. It can measure the dynamic impedance of a transmission line. If it takes you 1 second to do the impedance measurement of your 3 foot cable, the signal has bounced back and forth millions of times and you get a different result from the surge impedance- an open.

I can still hear the shouts of “what about the inductance of the transmission line? Doesn’t it affect the characteristic impedance of the line?”

If you found this article of interest, you might want to check out some of the courses on signal integrity and interconnect design offered by Bogatin Enterprises. Visit our web site at [www.BogatinEnterprises.com](http://www.BogatinEnterprises.com).

### **Resources:**

1. visit [www.BogatinEnterprises.com](http://www.BogatinEnterprises.com): my web site has reviews and links to 20 recommended Signal Integrity textbooks, trade journals, conferences and web sites. Many articles and publications on signal integrity and interconnect design are also available for download.
2. visit [www.ChipCenter.com/signalintegrity](http://www.ChipCenter.com/signalintegrity): this web site has a number of useful on line tools for impedance calculation and signal integrity simulation.
3. Check out Digital Systems Engineering, by W.J. Dally and J.W. Poulton, 1998 by Cambridge University Press, for more information on transmission lines, circuit performance and system design. An excellent intermediate level textbook.
4. The IPC ([www.ipc.org](http://www.ipc.org)) has two very useful documents for transmission line design and analysis; IPC-2141: Controlled Impedance Circuit Boards and High Speed Logic Design, and IPC-D-317A: Design Guidelines for Electronic Packaging Utilizing High-Speed Techniques.

## *Bio*

Eric Bogatin received his BS in Physics from MIT and his Masters and Ph.D., in Physics from the University of Arizona in Tucson. For the past 19 years, he has been actively involved in the field of signal integrity and interconnect design, working at companies such as AT&T Bell Labs, Raychem Corp, Sun Microsystems, and Ansoft Corp.

Currently, Eric is an independent consultant with Bogatin Enterprises, specializing in training classes for signal integrity and interconnect design. Bogatin Enterprises is devoted to accelerating engineers up the learning curve by providing an entire continuing education curriculum of signal integrity and interconnect design classes. Eric has trained over 2,000 engineers and lectures worldwide on signal integrity topics.

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