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Transmission Lines: From Barbed Wire to High-Speed Interconnect

by Barry Olney

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Long before Facebook and Twitter, there was a more primitive type of social network. Hailing from the Old West, it allowed distant communities to meet remotely to share music, spread news and to just gossip. The non-proprietary, ad hoc network was an unwitting model of democracy and free speech. Unfortunately however, it collapsed—overwhelmed by commercial pressure. The long-forgotten social revolution, and extremely basic technology, was built on barbed wire fences.

Barbed wire fences appeared in the United States in the 1860s and their success, in the control of cattle, swept across the North. However, the South, fearing that the product may harm their cattle, was hesitant to buy the fad at first but ultimately succumbed. Ironically, the barbed wire fence is associated with the cowboy, but unfortunately, it also sounded their end.

As with all communications systems, getting connected, particularly in remote areas, is always a challenge. In the early 1900s, the Bell Telephone company was focusing all efforts on connecting urban areas and like the telephone companies of today, had little interest in connecting remote communities, due to the cost of the infrastructure.

However, an enterprising rancher figured that the West was already sprawled with wire—barbed wire—and discovered that if you hooked two Sears or Monkey Ward telephone sets to a barbed wire fence, he could talk between the telephones as easily as between two city telephones connected via an operator's switchboard. A rural telephone system that had no operators, no bills—and no long-distance charges—was born.

But that lack of broader connectivity eventually doomed the ad hoc network. The commercial phone system's ubiquity, and especially their coveted connection to distant cities, eventually dominated. By the 1920s, the barbed wire telephones and the networks they helped spawn had disappeared.

By comparison, today's long-distance digital communications operate over various types of media including coax and twisted pair cables. And multilayer PCBs also transfer data via microstrip or stripline transmission lines. Surprisingly, all of these different types of media can be modeled using the same equations. The Telegrapher's Equations accurately model



Figure 1: Barbed wire fence (courtesy of fenceworkshop.com).

TRANSMISSION LINES *continues*

Figure 2: Broadcom Fast Ethernet 100Base-T4 over barbed wire (courtesy Broadcom).

the propagation of signals along the media providing the following:

1. A well-defined uniform path that exists for the flow of both signal and return current.
2. Conductors that are closely spaced by comparison to the wavelength of the signals.
3. Conductors that have a long length, compared to the space between the conductors.

In 1995 at the Interop Expo, Broadcom engineers demonstrated their T4 Ethernet chipset operating over the worst possible cable—barbed wire. During the show, 100Mbps of data was successfully transferred through rusty barbed wire. Figure 2 shows the setup. Wideband Corporation later effectively demonstrated 1Gbps over barbed wire with their transceiver. Providing the impedance and delay are constant along the length, the dielectric loss is low and the crosstalk is low (due to the large space between the pairs), the performance is not impaired. I wonder if razor wire would make it perform faster, as it is more cutting-edge.

You may wonder how this actually works, since it is obvious that two uninsulated twisted wires would touch. The trick is that they used rusty barbed wire; the ferric-oxide coating acts as an insulator and the twisted pair looks like

100 ohms of impedance. So, if you try this at home, don't use new wire.

Telegrapher's equations are a pair of linear differential equations that describe the voltage and current present on a transmission line relative to distance and time. Oliver Heaviside developed the transmission line model in the 1880s. Remarkably, the theory still applies to transmission lines, of all frequencies, including high-frequency transmission lines, as seen in the multilayer PCB. The telegrapher's equations have many derivatives and the math employed is beyond the scope of this column, not to mention beyond the ability of the author.

Contrary to common belief, the transmission line does not carry the signal itself but rather guides electromagnetic energy from one point to another. It is the movement of the electromagnetic field or energy, not voltage or current that transfers the signal. The voltage and current exist in the conductor, but only as a consequence of the field being present as it moves past.

The ICD Stackup Planner^[5], in Figure 3, illustrates the three most common transmission line structures of a multilayer PCB. For embedded microstrip (solder mask coated microstrip), the electromagnetic field propagates partially in the dielectric material (Isola 370HR), the solder mask and the air. Whereas, in both stripline structures, the electromagnetic field propagates in the dielectric material sandwiched between the planes. The traces simply guide the signals

Layer No.	Via	Description	Layer Name	Material Type	Dielectric Constant	Dielectric Thickness	Copper Thickness	Trace Clearance	Trace Width	Current (Amps)	Characteristic Impedance (Zo)	Edge Coupled Differential (Zdiff)	Broadside Coupled Differential (Zdbs)
		Soldermask		Liquid Photoimageable	3.8	0.5							
1	8	Signal	Top	Conductive			1.4	15	5	0.37	49.97	97.35	Embedded Microstrip
		Prepreg		370HR : 1080 ; Rc= 66% (5GHz)	3.72	2.9							
2		Plane	GND	Conductive			0.7						
		Core		370HR : 1-1652 ; Rc=51% (5GHz)	4.0	5.3							Symmetric Stripline
3		Signal	Inner 3	Conductive			0.7	12	4	0.19	49.75	98.29	
		Prepreg		370HR : 1652 ; Rc= 48% (5GHz)	4.09	5.3							
4		Plane	VDD	Conductive			0.7						
		Prepreg		370HR : 2116 ; Rc= 56% (5GHz)	3.92	4.8							
5		Signal	Inner 6	Conductive			0.7	12	4	0.19	51.22	100.76	Dual Asymmetric Stripline
		Core		370HR : 1-2113 ; Rc=46% (5GHz)	4.1	3							
6		Signal	Inner 7	Conductive			0.7	12	4	0.19	48.83	96.25	
		Prepreg		370HR : 3313 ; Rc= 59% (5GHz)	3.86	4.1							
7		Plane	GND	Conductive			0.7						

Figure 3: Embedded microstrip, symmetric and dual asymmetric stripline configurations.

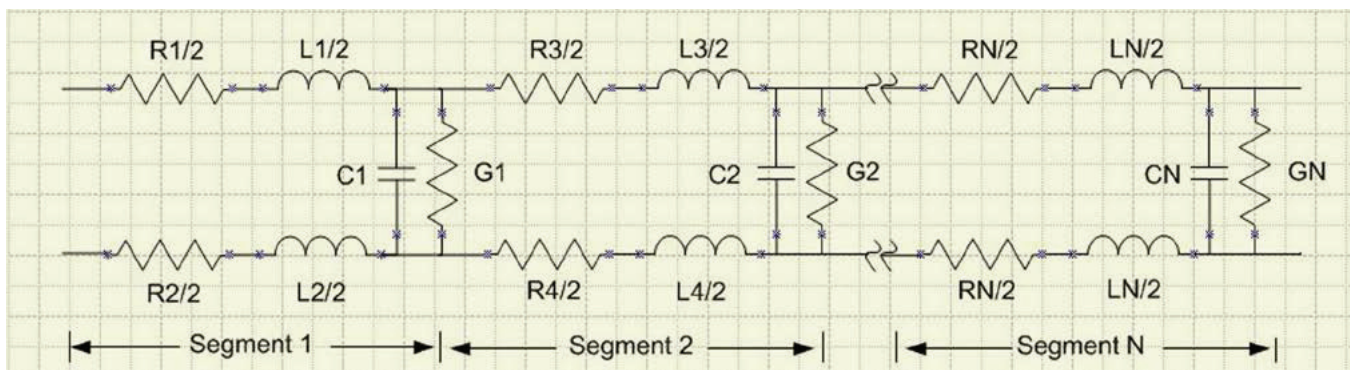


Figure 4: Transmission line represented by a series of R-L-C-G elements.

wave as the electromagnetic energy propagates in the dielectric material.

So the dielectric material determines the velocity (v) of propagation of the electromagnetic energy:

$$v = \frac{c}{\sqrt{Er}} \quad \text{Equation 1}$$

Remember that c is the speed of light (in free space) and Er is the dielectric constant of the material (FR-4 is ~4.0). By contrast, the Er of air is 1. Therefore, the velocity of propagation in FR-4 is about half the speed of light, or 6 inches per ns. The important concept is that it is the electromagnetic energy that propagates down the transmission line—not electron flow. Electrons flow at about 0.4 inches per second, a snail’s pace in comparison.

A transmission line can be represented by an infinite number of segments, incorporating series resistive (R) and inductive (L) elements with shunt capacitive (C) and conductive (G) elements, as in Figure 4. And because of the restricted velocity of propagation in the media, the signal does not know what the termination is at the end of the line. It can only see the impedance of the line. The impedance of the line can be represented by:

$$Zo = \sqrt{\frac{R + jwL}{G + jwC}} \quad \text{Equation 2}$$

$$w = 2\pi f$$

If we assume that the transmission line is lossless—which occurs at frequencies below a few hundred MHz—then the R (conductor loss)

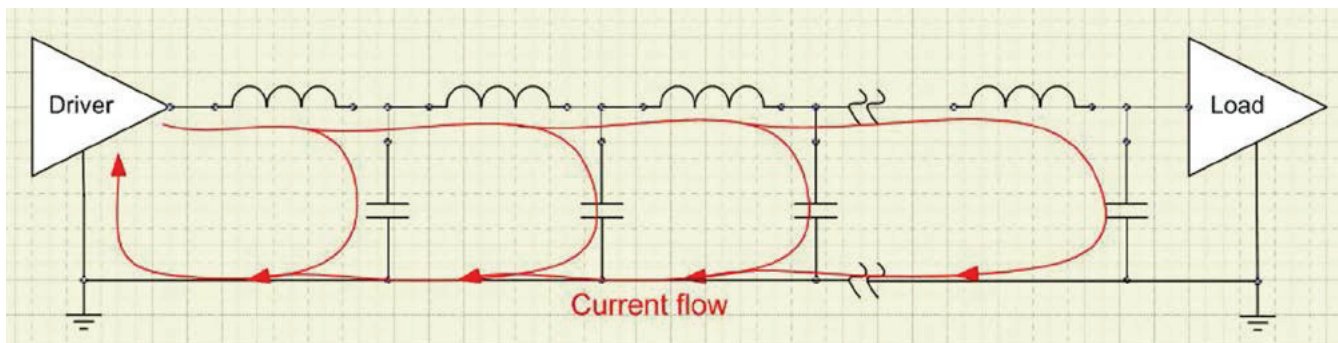
TRANSMISSION LINES *continues*

Figure 5: Model of a lossless transmission line indicating current flow.

and G (dielectric loss) terms can be assumed to be zero simplifying the equation to:

$$Z_0 = \sqrt{\frac{L}{C}} \quad \text{Equation 3}$$

The characteristic impedance (Z_0), of an ideal transmission line, remains constant at all frequencies. It has no imaginary part and is not frequency dependant. As the electromagnetic energy propagates down a transmission line, current is induced into the conductors as illustrated in Figure 5. The current flows along the conductors, charging the first section's parasitic capacitance and then flows back, on the return conductor (reference plane), to the source. The current exists only on the rising edge of the propagating wave and thus charges each section's capacitance as it moves down the line with the return current, from each section, flowing back to the source. Then as the pulse passes, the falling edge discharges each section's capacitance in turn. By the time the signal wave reaches the load, it has established multiple paths of return current along the PCB planes.

Current always flows in a loop. But it does not flow along the transmission line to the end (load) and then return to the source as one would expect with DC. But instead, the signal charges each section in turn as the rising edge propagates along the transmission line on the dielectric material.

Although a lossless model is a good representation of a typical low-frequency transmission line, at high frequencies, the conductor and dielectric losses need to be considered. For this reason, the closed-form equations shown here are approximations only and a 2D field solver, such as that integrated into the ICD Stackup Planner is required to accurately model the impedance of a multilayer PCB transmission line.

Points to Remember

- In the early 1900s, barbed wire fences were used as an ad hoc, rural telephone system that had no operators, no bills, and no long-distance charges.
- Telegrapher's equations still accurately model the propagation of signals along transmission lines.
- In 1995, Broadcom demonstrated its 100Base-T4 Ethernet chipset operating over barbed wire.
- Wideband Corporation later successfully demonstrated 1Gbps over barbed wire.
- A transmission line is a series of conductors that guide electromagnetic energy from one point to another. It is the movement of an electromagnetic field or energy—not voltage or current.
- The three common transmission line structures of a multilayer PCB are: embedded microstrip, symmetric, and dual asymmetric stripline configurations.
- The velocity of propagation in FR-4 is about half the speed of light, or 6 inches per ns.

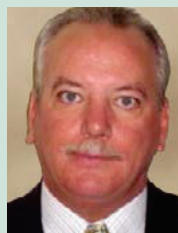
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- It is the electromagnetic energy that propagates down the transmission line—not electron flow.

- As the electromagnetic energy propagates along a transmission line, current is induced into the conductors. This current flows along the conductors, charging the first section's parasitic capacitance and then flows back on the return conductor (reference plane) to the source.

- Current always flows in a loop. But it does not flow along the transmission line to the load and then return to the source. The propagating signal charges up each section, in turn, as the rising edge propagates along the transmission line.

- Closed-form equations are approximations only and a 2D field solver is required to accurately model impedance of multilayer PCB traces. **PCBDESIGN**



Barry Olney is managing director of In-Circuit Design Pty Ltd (ICD), Australia. This PCB design service bureau specializes in board-level simulation, and has developed the ICD Stackup Planner and ICD PDN Planner software. To read past columns, or to contact Olney, [click here](#).

References

1. Henry Ott, Electromagnetic Compatibility Engineering
2. Howard Johnson, High-speed Signal Propagation
3. Bob Holmes, Bush Telegraph and New Scientist Magazine
4. Telegrapher's equations, Wikipedia
5. The ICD Stackup Planner and PDN Planner can be downloaded from www.icd.com.au

video interview**PCB Design From a Turkish Perspective**

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Halil Ibrahim Yaslak probably traveled a lot farther than most Designers Forum attendees. Halil is a PCB designer with the Turkish company Aselsan; you may remember that Halil won a Mentor Technology Leadership Award in the milaero category in 2012. He and Editor Kelly Dack discuss his company's cutting-edge work and the different challenges faced by designers worldwide.



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