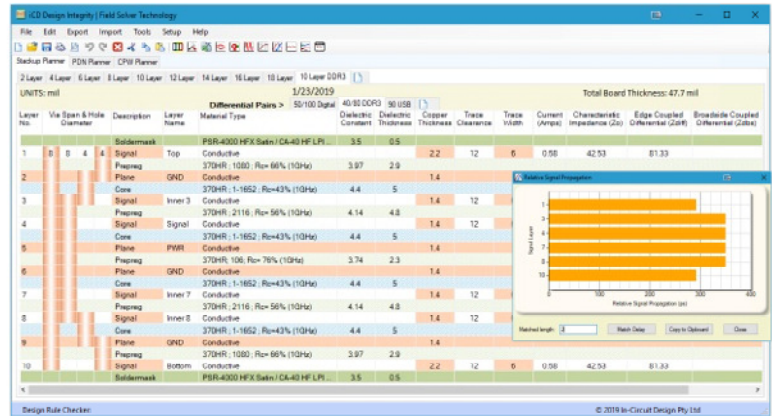


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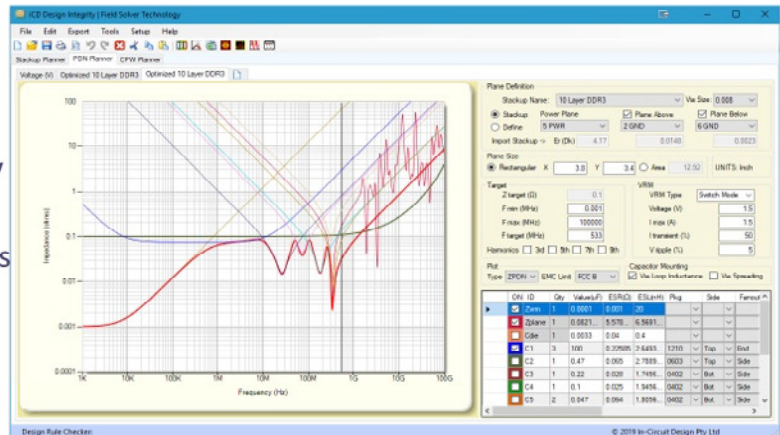
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 Integration of stackup plane data  
 Definition of voltage regulator, bypass/  
 decaps and mounting loop inductance  
 PDN EMI Plot with FCC and CISPR Limits  
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 Capacitor S-Parameter model import

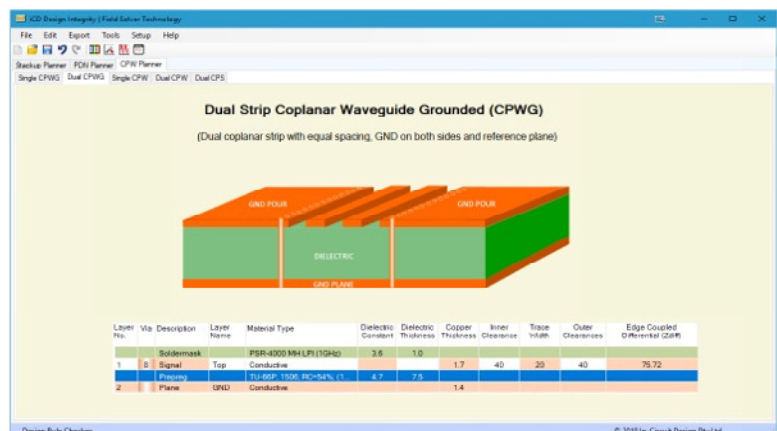
Analyze multiple power supplies to maintain low impedance over entire frequency range dramatically improving product performance



## iCD CPW Planner

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 Model single and dual (differential)  
 CPWs plus a dual Coplanar Strip (CPS)  
 Characteristic impedance and  
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 Optional Dielectric Materials Library

Model microstrip Coplanar Waveguides to reduce radiation loss, of high-speed serial links, significantly improving product performance



# The Big Bang: Lumped Element to Distributed System

## Beyond Design

by Barry Olney, IN-CIRCUIT DESIGN PTY LTD / AUSTRALIA

The simplistic approach to analyzing electronic circuits is to use the lumped element model. This methodology assumes that the attributes of the circuit—resistance, capacitance, and inductance—are concentrated into idealized electrical components connected by a network of perfectly conducting wires. However, in reality, that is not the case.

As the frequency and rise time increase, these elements become distributed continuously through the substrate along the entire length of the trace. The copper trace and the adjacent dielectric materials become a transmission line, the skin effect forces current into the outer regions of the conductor, and frequency-dependent losses impact on the quality of the signal. The PCB trace now behaves as a distributed system with parasitic inductance and capacitance characterized by delay

and scattered reflections. The behavior we are now concerned about occurs in the frequency domain. In this month's column, I will discuss the difference between the lumped element model and the distributed system (Figure 1).

In my previous column, "The Frequency Domain," we saw that impedance is defined in both the time and frequency domains. In the time domain, the impedance of a resistor (R) can be represented by a relationship between voltage and current (Ohm's Law). Similarly, an ideal capacitor (C) has a relationship between the stored charge and the voltage across its plates. And the behavior of an ideal inductor (L) is defined by how fast the current traveling through it changes in the time domain.

We group these three elements (RLC) in a category called lumped circuit elements, in the sense that their properties can be lumped into



Figure 1: (a) Lumped element; (b) distributed system.

a single point. This is quite different from the properties of an ideal transmission line, which also consists of these three elements, but they are distributed continuously through the dielectric materials along its length. The distributed model is used when the wavelength becomes comparable to the physical dimensions of the circuit, making the lumped model inaccurate. This typically occurs at high frequencies, where the wavelength is very short. However, it can also occur on very long, low-frequency transmission lines, such as high-voltage power lines. The three primary elements now include distributed capacitance, inductance, and conductance (G).

The lumped element model completely fails at one-quarter wavelength (a  $90^\circ$  phase change), with not only the value but the very nature of the component itself being unpredictable. Due to this wavelength dependency, the distributed system model is used mostly at higher frequencies.

It is important to realize that the terms lumped and distributed are not properties of the system itself. These properties are related to the size of the circuit, compared to the wavelength of the voltages and currents passing through it. So, a resistor is, or isn't, a lumped element (even though it is usually meant to be one), depending on the frequency of the applied signals.

Lumped systems are described by ordinary differential equations because, due to the small size of the system (compared to the wavelength), the spatial derivatives can be neglected and we only need to consider time

derivatives. On the other hand, for distributed systems, we need to take electromagnetic wave propagation into account to get spatial as well as time derivatives, which leads to partial differential equations in the frequency domain.

A transmission line can be represented by an infinite number of segments, incorporating series resistive and inductive elements with shunt capacitive and conductive elements, as in Figure 2. And because of the restricted velocity of propagation in the medium, the signal does not know what the termination is at the end of the line. It can only see the impedance of the line, which, by design, should be matched to the driver.

### What forms the electromagnetic field in the transmission line?

This is a question that even Google can't answer (until now). Here's how I see it: An electric field is produced when voltage is applied across an IC output driver. When a signal varies this voltage, there is a surge of current that produces a magnetic field. This electromagnetic energy then transmits the signal, at about half the speed of light—limited by the dielectric medium—down the length of the transmission line following the trace. The energy radiates into the surrounding dielectric material and couples into nearby structures, creating a distributed system of parasitic elements. The electromagnetic fields are not restricted to the multilayer substrate, and, if adequate care is not taken, may emit radiation causing electromagnetic interference.

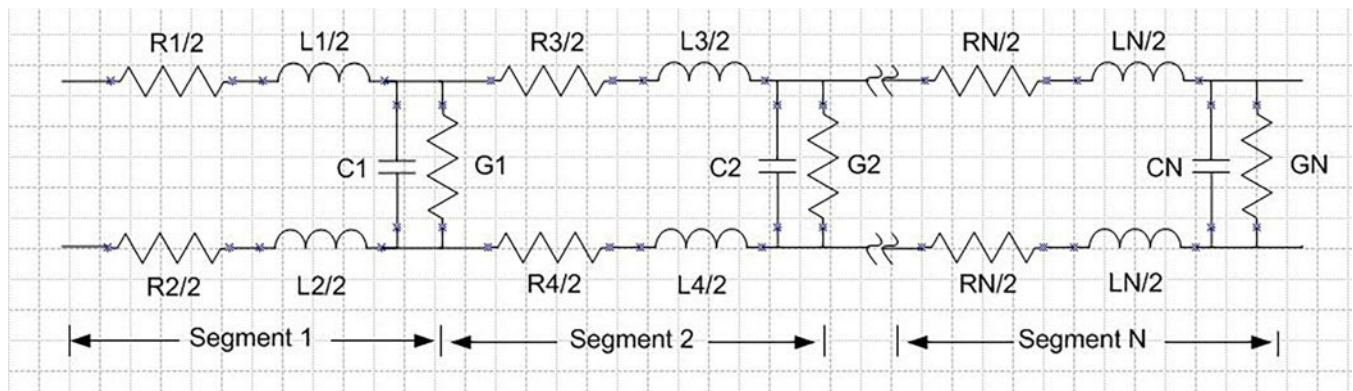


Figure 2: Transmission line represented by a series of R-L-C-G elements.

The distributed system model is more accurate but also more complex than the lumped element model. The selection of the model is dependent on the accuracy required in a specific application. There is no clear-cut demarcation in the frequency at which these models should be used, although the changeover is usually somewhere in the 100–500-MHz range. An often-quoted rule of thumb is that traces longer than one-tenth (0.1) wavelength will usually need to be analyzed as a distributed system, which is about where the two curves start to deviate noticeably in the example of Figure 3.

The technology employed and the physical scale of the design is also significant as miniaturized circuits can use the lumped model at a higher frequency. PCBs using plated through-hole technology are larger than equivalent designs using surface-mount technology. Hybrid integrated circuits are smaller than PCB technologies, and monolithic integrated circuits are smaller again. ICs can use lumped designs at higher frequencies than printed circuits, and this is done in some radio-frequency devices. This choice is particularly significant for handheld devices because lumped element designs generally result in a smaller product.

To illustrate the difference between the regimes of the analytical treatment of the transmission line, the two models are compared in a simulation for increasing lengths of transmission line (Figure 3). The analysis shows the behavior of the load voltage ( $V_L$ ) using lumped and distributed element calculations for a lossless transmission line. The frequency dependence is shown in the form of the trace length being a multiple of the wavelength.

Depending on the signal rise time, the distributed model for transmission lines starts deviating from the simplified lumped element model between a trace length of 0.01 and 0.1

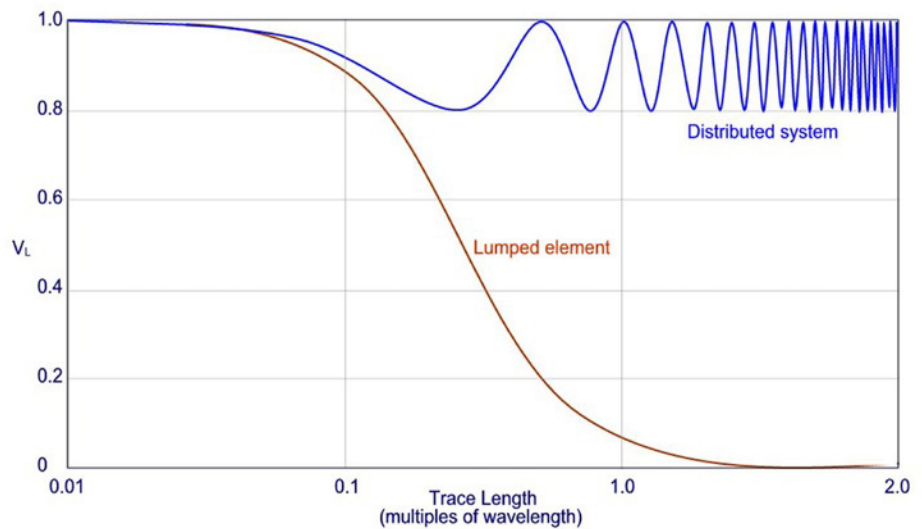


Figure 3: Lumped vs. distributed element analysis of a transmission line.

of the wavelength of the signal. This simulation uses a load impedance that is matched to the impedance of the transmission line, so the reflections are negligible.

Although a lossless distributed model is a good representation of a typical low-frequency transmission line, at high frequencies the conductor and dielectric losses also need to be considered.

### Key Points

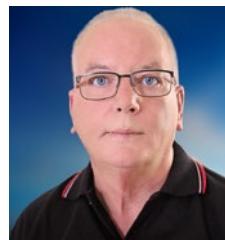
- The lumped element model assumes that the attributes of the circuit are concentrated into idealized electrical components connected by a network of perfectly conducting wires
- As the frequency and rise time increase, these elements become distributed continuously through the substrate along the entire length of the trace
- Electromagnetic energy radiates into the surrounding dielectric material and couples to nearby structures creating a distributed system of parasitic elements
- The distributed model is used, at high frequencies, when the wavelength becomes comparable to the physical dimensions of the circuit
- The lumped element model completely fails at one-quarter wavelength (a 90° phase change)

- The distributed system model is more accurate but also more complex than the lumped element model
- Traces longer than one-tenth wavelength will usually need to be analyzed as a distributed system
- The technology employed and the physical scale of the design is also significant as miniaturized circuits can use the lumped model at a higher frequency
- Lumped element designs generally result in a smaller product
- The distributed model for transmission lines starts deviating from the simplified lumped element model between a trace length of 0.01 and 0.1 of the wavelength of the signal

### Further Reading

- B. Olney, “Beyond Design: Controlled Impedance Design,” *The PCB Design Magazine*, May 2015.
- B. Olney, “Beyond Design: Transmission Lines—From Barbed Wire to High-speed Interconnects,” *The PCB Design Magazine*, May 2014.
- B. Olney, “Beyond Design: Effects of Surface Roughness on High-speed PCBs,” *The PCB Design Magazine*, February 2015.
- B. Olney, “Beyond Design: Common Symptoms of Common-mode Radiation,” *Design007 Magazine*, May 2018.
- Arthur Anderson, “Transmission Lines: From Lumped Element to Distributed Element Regimes,” *All About Circuits*, November 28, 2015.
- E. Bogatin, *Signal and Power Integrity: Simplified*, Prentice Hall, 2008.

*Editor’s note: All figures drawn by Barry Olney.*



**Barry Olney** is managing director of In-Circuit Design Pty Ltd. (iCD), Australia, a PCB design service bureau that specializes in board-level simulation. The company developed the iCD Design Integrity software incorporating the iCD

Stackup, PDN, and CPW Planner. The software can be downloaded [www.icd.com.au](http://www.icd.com.au). To read past columns or contact Olney, [click here](#).

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