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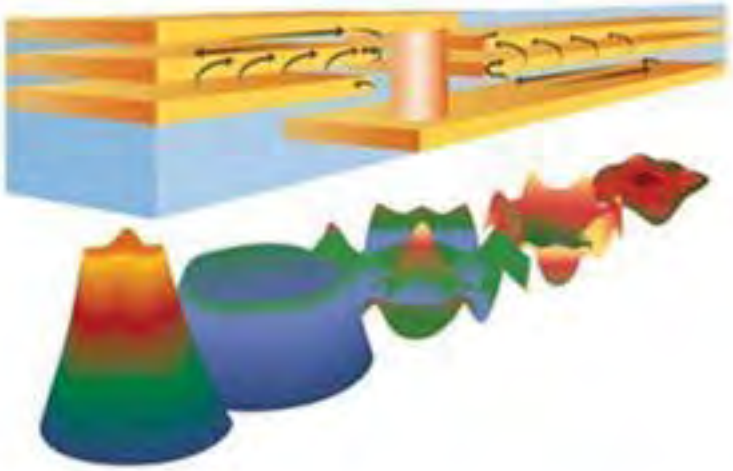
Signal and Power Integrity

SIMPLIFIED

Second Edition



Eric Bogatin

Prentice Hall Modern Semiconductor Design Series
Prentice Hall Signal Integrity Library

Signal and Power Integrity—

Simplified

Second Edition

Eric Bogatin

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The dedication of a book is called "The Dedication" because it requires dedication by the author to complete the work. As every author will tell you, writing is a solitary, alone process, the opposite of social activity. It's easy to become engulfed in the writing and researching and exclude more and more of the real world. Successful authors are either not married or married to an understanding, supportive spouse who sees his or her role as providing a nurturing environment in which creative juices can ferment.

Susan, my wife, patiently put up with my solitary writing, giving me the space to put in the dedication to finish the first and second editions. At the same time, she was also my anchor to the real world and forced me to keep a healthy balance between alone work and social life. The second edition is as much due to her efforts as from mine, and as I get to write the words, I am dedicating the second edition to her.

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PREFACE TO THE SECOND EDITION

Since the publication of the first edition of *Signal Integrity—Simplified*, the principles of signal integrity haven't changed. What has changed, though, is the prolific use of high-speed serial links and the critical role power integrity now plays in the success or failure of new product introductions.

In addition to fleshing out more details and examples in many of the chapters, especially on differential pairs and losses, two new chapters have been added to this second edition to provide a strong foundation to meet the needs of today's engineers and designers.

This first new chapter—Chapter 12—provides a thorough introduction to the use of S-parameters in signal integrity applications. If you deal with any high-speed serial links, you will encounter S-parameters. Because they are written in the foreign language of the frequency domain, they are intimidating to the high-speed digital designer. Chapter 12, like all the chapters in this book, provides a solid foundation in understanding this formalism and enables all engineers to harness the great power of S-parameters.

Chapter 13, the second new chapter, is on power integrity. These issues increasingly fall in the lap of the design engineer. With higher speed applications, interconnects in the power distribution path affect not just power delivery, but also signals' return paths and passing an EMC certification test.

We start at the beginning and illustrate the role of the power distribution interconnects and how design and technology selection can make or break the performance of the power distribution network. The essential principles of plane

impedance, spreading inductance, decoupling capacitors, and the loop inductance of capacitors are introduced. This valuable insight helps feed the intuition of engineers enabling them to apply the power of their creativity to synthesize new designs. Hand in hand with the creation of a design is the analysis of its performance so that cost-performance trade-offs can be explored and the PDN impedance profile can be sculpted to perfection.

If you are new to signal integrity, this second edition of *Signal and Power Integrity—Simplified* provides your starting place to build a strong foundation and empowers you to get your new signal integrity designs right the first time, every time.

Preface to the First Edition

"Everything should be made as simple as possible, but not simpler."

Albert Einstein

Printed circuit-board and IC-package design used to be a field that involved expertise in layout, CAD, logic design, heat transfer, mechanical engineering, and reliability analysis. With modern digital electronic systems pushing beyond the 1-GHz barrier, packaging and board designers must now balance signal integrity and electrical performance with these other concerns.

Everyone who touches the physical design of a product has the potential of affecting the performance. All designers should understand how what they do will affect signal integrity or, at the very least, be able to talk with engineers who are responsible for the signal integrity.

The old design methodology of building prototypes, hoping they work, and then testing them to find out is no longer cost effective when time to market is as important as cost and performance. If signal integrity is not taken into account from the beginning, there is little hope a design will work the first time.

In our new "high-speed" world, where the packaging and interconnect are no longer electrically transparent to the signals, a new methodology for designing a product right the first time is needed. This new methodology is based on predictability. The first step is to use established design guidelines based on engineering discipline. The second step is to evaluate the expected performance by "putting in the numbers." This is what distinguishes engineering from guesswork. It takes

advantage of four important tools: rules of thumb, analytic approximations, numerical simulation tools, and measurements. With an efficient design and simulation process, many of the trade-offs between the expected performance and the ultimate cost can be evaluated early in the design cycle, where the time, risk, and cost savings will have the biggest impact. The way to solve signal integrity problems is to first understand their origin and then apply all the tools in our toolbox to find and verify the optimum solution.

The design process is an intuitive one. The source of inspiration for a new way of solving a problem is that mysterious world of imagination and creativity. An idea is generated and the analytical powers of our technical training take over to massage the idea into a practical solution. Though computer simulations are absolutely necessary for final verification of a solution, they only rarely aid in our intuitive understanding. Rather, it is an understanding of the mechanisms, principles and definitions, and exposure to the possibilities, that contribute to the creation of a solution. Arriving at that initial guess and knowing the places to look for solutions require understanding and imagination.

This book emphasizes the intuitive approach. It offers a framework for understanding the electrical properties of interconnects and materials that apply across the entire hierarchy from on-chip, through the packages, circuit boards, connectors, and cables.

Those struggling with the confusing and sometimes contradictory statements made in the trade press will use this book as their starting place. Those experienced in electrical design will use this book as the place to finally understand what the equations mean.

In this book, terms are introduced starting at the ground floor. For example, the impedance of a transmission line is the most fundamental electrical property of an interconnect. It describes what a signal will see electrically and how it will interact with the interconnects. For those new to signal integrity, most of the problems arise from confusion over three terms: the *characteristic* impedance, *the* impedance, and the *instantaneous* impedance a signal sees. This distinction is even important for experienced engineers. This book introduces the reader to each of these terms and their meanings, without complex mathematics.

New topics are introduced at a basic level; most are not covered in other signal integrity books at this level. These include partial inductance (as distinct from loop inductance), the origin of ground bounce and EMI, impedance, transmission line discontinuities, differential impedance, and attenuation in lossy lines affecting

the collapse of the eye diagram. These topics have become critically important for the new high-speed serial links.

In addition to understanding the basic principles, leveraging commercially available tools is critical for the practicing engineer who wants to find the best answer in the shortest time. Tools for solving signal integrity problems fall in two categories: analysis and characterization. Analysis is what we usually refer to as a calculation. Characterization is what we usually refer to as a measurement. The various tools, guidelines on when they should be used, and examples of their value are presented throughout the book.

There are three types of analysis tools: rules of thumb, analytic approximations, and numerical simulation. Each has a different balance between accuracy and effort to use. Each has a right and a wrong place for its appropriate use. And each tool is important and should be in the toolbox of every engineer.

Rules of thumb, such as "the self inductance of a wire is about 25 nH/inch," are important when having a quick answer NOW! is more important than having an accurate answer later. With very few exceptions, every equation used in signal integrity is either a definition or an approximation. Approximations are great for exploring design space and balancing design and performance trade-offs. However, without knowing how accurate a particular approximation really is, would you want to risk a $10,000 board-fabrication run and four weeks of your schedule based on an approximation?

When accuracy is important, for example, when signing off on a design, numerical simulation is the right tool to use. In the last five years, a whole new generation of tools has become available. These new tools have the powerful combination of being both easy to use and accurate. They can predict the characteristic impedance, cross talk, and differential impedance of any cross-section transmission line and simulate how a signal might be affected by any type of termination scheme. You don't have to be a Ph.D. to use this new generation of tools so there is no reason every engineer can't take advantage of them.

The quality of the simulation is only as good as the quality of the electrical description of the components (i.e., the equivalent circuit models). Engineers are taught about circuit models of gates that perform all the information processing, but rarely are the circuit models of the interconnects reviewed. Fifteen years ago, when interconnects looked transparent to the signals, all interconnects were considered as ideal wires—no impedance and no delay. When these terms were added, they were lumped together as "parasitics."

Today, in a high-speed digital system with a clock frequency above about 100 MHz, it is the real wires—the wire bonds, the package leads, the pins, the circuit board traces, the connectors, and the cabling—that create signal-integrity problems and can prevent products from working correctly the first time. Understanding these "analog" effects, designing for them, specifying correct values for them, and including them in the system simulations before the design is committed to hardware, can enable moving a more robust product to market more quickly.

This book provides the tools to enable all engineers and managers involved in chip packaging and board, connector and interconnect design, to understand how these passive elements affect the electrical performance of a system and how they can be incorporated in system simulation. It illustrates how to perform engineering estimates of important electrical parameters and evaluate technology trade-offs. Examples are selected from a wide variety of common systems, including on-chip interconnects, wire bonds, flip chip attach, multilayer circuit boards, DIPs, PGAs, BGAs, QFPs, MCM connectors, and cables.

While most textbooks emphasize theoretical derivation and mathematical rigor, this book emphasizes intuitive understanding, practical tools, and engineering discipline. We use the principles of electrical engineering and physics and apply them to the world of packaging and interconnects to establish a framework of understanding and a methodology of solving problems. The tools of time- and frequency-domain measurement, two- and three-dimensional field solvers, transmission-line simulations, circuit simulators, and analytical approximations are introduced to build verified equivalent circuit models for packages and interconnects.

There are two important questions that all designers should ask of any model they use: How accurate is it? And what is the bandwidth of the model? The answers to these questions can come only from measurements. Measurements play the very important role of risk reduction.

The three generic measurement instruments, the impedance analyzer, the vector-network analyzer (VNA) and the time-domain reflectometer (TDR) are introduced and the interpretation of their data explained. Examples of measurements from real interconnects such as IC packages, printed circuit boards, cables, and connectors are included throughout this book to illustrate the principles and, by example, the value of characterization tools.

This book has been designed for use by people of all levels of expertise and training: engineers, project managers, sales and marketing managers, technology developers, and scientists. We start out with an overview of why designing the

interconnects for high-speed digital systems is difficult and what major technical hurdles must be overcome to reach high-frequency operation.

We apply the tools of electrical engineering and physics to the problems of signal integrity in digital signals through the entire range of interconnects. The concept of equivalent circuit models is introduced to facilitate the quantified prediction of performance. The rest of the book describes how the circuit models of interconnects affect the electrical performance of the system in terms of the four families of noise problems: reflections, cross talk, rail collapse in the power distribution network, and EMI.

This book originated from a series of short courses and semester-long courses the author gave to packaging, circuit-board, and design engineers. It is oriented to all people who need to balance electrical performance with all other packaging and interconnect concerns in their system designs. This book provides the foundation to understand how the physical design world of geometries and material properties affects electrical performance.

If you remember nothing else about signal integrity, you should remember the following important general principles. These are summarized here and described in more detail throughout this book.

Top Ten Signal Integrity Principles

1. The key to efficient high-speed product design is to take advantage of analysis tools that enable accurate performance prediction. Use measurements as a way of validating the design process, reducing risk, and increasing confidence in the design tools.
2. The only way to separate myth from reality is to put in the numbers using rules of thumb, approximations, numerical simulation tools, or measurements. This is the essential element of engineering discipline.
3. Each interconnect is a transmission line with a signal and a return path, regardless of its length, shape, or signal rise time. A signal sees an instantaneous impedance at each step along its way down an interconnect. Signal quality is dramatically improved if the instantaneous impedance is constant, as in a transmission line with a uniform cross section.
4. Forget the word *ground*. More problems are created than solved by using this term. Every signal has a return path. Think *return path* and you will train

your intuition to look for and treat the return path as carefully as you treat the signal path.

5. Current flows through a capacitor whenever the voltage changes. For fast edges, even the air gap between the edge of a circuit board and a dangling wire can have a low impedance through the fringe field capacitance.
6. Inductance is fundamentally related to the number of rings of magnetic-field lines completely surrounding a current. If the number of rings of field lines ever changes, for whatever reason, a voltage will be created across the conductor. This is the origin of some reflection noise, cross talk, switching noise, ground bounce, rail collapse, and some EMI.
7. Ground bounce is the voltage created on the ground return conductor due to changing currents through the total inductance of the return path. It is the primary cause of switching noise and EMI.
8. The bandwidth of a signal is the highest sine-wave frequency component that is significant, compared to an equivalent frequency square wave. The bandwidth of a model is the highest sine-wave frequency at which the model still accurately predicts the actual performance of the interconnect. Never use a model in an application where the signal bandwidth is higher than the model's bandwidth.
9. Never forget, with few exceptions, every formula used in signal integrity is either a definition or an approximation. If accuracy is important, do not use an approximation.
10. The problem caused by lossy transmission lines is the rise-time degradation. The losses increase with frequency due to skin depth and dielectric losses. If the losses were constant with frequency, the rise time would not change and lossy lines would be only a minor inconvenience.
11. The most expensive rule is the one that delays the product ship.