S-Parameters for Signal Integrity

Master the usage of s-parameters in signal integrity applications and gain full understanding of your simulation and measurement environment with this rigorous and practical guide. Solve specific signal integrity problems, including calculation of the s-parameters of a network, linear simulation of circuits, de-embedding, and virtual probing, all with expert guidance. Learn about the interconnectedness of s-parameters, frequency responses, filters, and waveforms. This invaluable resource for signal integrity engineers is supplemented with the open-source software *SignalIntegrity*, a Python package for scripting solutions to signal integrity problems.

Peter J. Pupalaikis is an electrical engineer and inventor who works for Teledyne LeCroy. He is an IEEE Fellow.

"The most modern and up-to-date book on linear network theory with applications. Deep and comprehensive theory is coupled with detailed applications, making this book a must-have not only for signal integrity professionals, but for any microwave engineer."

Andrea Ferrero, Keysight

"This book provides unique and consistent description of s-parameters' use for analysis of linear networks, and signal measurement and processing in one volume, supplemented and illustrated with free open-source signal integrity software. The book can be used for learning the subject of emerging microwave signal integrity or as a comprehensive and indispensable reference for every microwave and signal integrity engineer and scientist."

Yuriy Shlepnev, Simberian Inc.

"This is an outstanding and refreshing book for the novice and advanced engineer alike. Written by a well-known expert in the field, it provides a rather unique access to the difficult topic of signal integrity, through a systematic learning-by-doing approach. Software which is freely accessible through an open-source Python library, *SignalIntegrity,* allows the user to easily program the numerous examples that accompany the theory. The material ranges from simple to complex problems, using the s-parameter concept for high-speed signal integrity as a unifying theme. The book is appropriate for self-study and as a reference for teaching, and empowers the reader with a very unusual and stimulating blend of competences."

Peter Wittwer, University of Geneva

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This book is dedicated to my father, my favorite engineer, whose passing separated my life into the two parts that are with him and without him…

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Preface

THIS BOOK is the culmination of about ten years of writing that began while I was developing software for signal integrity analysis in oscilloscopes, which my company, Teledyne LeCroy, ended up branding as *Eye Doctor*. During the development of this software, I found many recurring patterns in the solutions of s-parameter systems that allowed me to do a lot of things with a slight change of the recipe. And in the development of the SPARQ and the WavePulser, two time-domain reflectometry instruments used to measure s-parameters, I learned a lot about s-parameters and calibrations.

Why s-parameters and signal integrity? Around the turn of the millennium, the field of signal integrity changed dramatically. I'm not even sure the field had an actual name at that time. As a check, I looked at two books written by a foremost authority on signal integrity and one of my favorite authors, Howard Johnson. His first book [1] published in 1993 has no index entry for signal integrity, while his second book [2], published in 2003, has extensive entries. As signal integrity became more about signal propagation (in the title of Dr. Johnson's second book), the field tended increasingly towards electromagnetic properties and today heavily overlaps with the field of microwaves and radio frequency (RF); with this has come an increasing use of scattering parameters, or s-parameters, and the vector network analyzer (VNA), which is the primary instrument for measuring them.

The fields of s-parameters and microwaves and RF are primarily about the frequency domain, while the business of signal integrity is the time domain. Despite the wide use of frequency-domain electromagnetic analysis, it's in the end mostly about whether a bit that is transmitted as a one or zero gets to the receiver and is interpreted properly.

S-parameters can be a confusing topic in many ways, including how they are measured, what they represent, how they connect to circuit theory, how they are manipulated either to integrate or remove them from a measurement, and especially how they interact with waveforms in the time domain. This book is mostly about these things.

My feeling is that it is always good to understand better what is going on, even if one is one is relying on software simulation tools or measurement instruments. Both of these require their own level of understanding and expertise. Any experienced engineer has been burned by the simulator or measurement instrument, either by doing something incorrectly, or because of the limitations of these tools, which is why we constantly try to correlate the two.

My expertise is mostly in measurement instruments, which are in themselves often quite intricate and expensive, and have an industry of their own. Software and simulation, meanwhile, have grown into a giant industry, and the advances in the technology, especially electromagnetic field solvers, have greatly increased the ability of signal integrity engineers. In some ways, however, they have weakened our minds, especially when overly relied on, and certainly have emptied our wallets. My original goal in the writing of this book was to teach methods that can be employed to solve relatively simple problems. These simple problems include aggregating systems of s-parameter blocks, de-embedding s-parameter blocks, performing linear simulations, and performing time-domain de-embedding and embedding of waveforms measured in systems. Expensive software is often used to perform even these common and not too difficult tasks. But, while writing out the math and explanations of all this, I was struck by a disappointing thought: No one is actually going to use this. I found that even these relatively simple solutions involved huge amounts of math with giant equations. That's when the idea for the *SignalIntegrity* software was born.

The *SignalIntegrity* software is an open-source library that allows you to do everything taught in this book, and it's free. I used this software to test what I had written, and, eventually, a lot of the book became about both the math used to generate the software and the software itself. Finally, somewhat close to the end of this project, I decided to wrap this up in a graphical user interface application which makes it much easier to solve these problems.

I'm a big fan of open-source software, and my desire is to collaborate with others in extending this software and to continue to advance its capability.

To summarize, this book is about:

1. S-parameters – it unifies the analysis of circuits and networks using s-parameters and methods conducive to s-parameters.
2. Four specific signal integrity problems and their solutions, these being the calculation of the s-parameters of a network, the linear simulation of circuits, de-embedding, and virtual probing.
3. A set of software tools called *SignalIntegrity*, a Python package that contains a library of modules used for scripting solutions to various problems in signal integrity; it also contains a graphical user interface (GUI) based application for schematic entry and solution.
4. The interconnectedness of s-parameters, frequency responses, filters, and waveforms, whose underlying theory enables one to deal with many signal integrity problems, especially where the time domain meets the frequency domain.

It is probably equally about these four things.

A colleague of mine who saw my original draft said to me, "This is not a signal integrity book." I was shocked by this. But I think what he meant is, "It's not the standard signal integrity book." It contains none of the things normally found, like board stack-ups, vias, electromagnetic theory, physics, or anything like that. Mostly it is about abstractions and mathematical manipulations of s-parameters and waveforms. It is also about how s-parameters connect with circuit theory.

And despite not being the typical signal integrity book, as another colleague told me, "It's your book." I hope you like it and that you learn something useful.

I would like to take this opportunity to thank and acknowledge several people. I'll start with people who did actual work on this.

First, and foremost, I'd like to thank Tom Reslewic, former CEO of Teledyne LeCroy. The contents of this book are intertwined so much with my company's work and intellectual property that it never could have been published without Tom going to bat for me. Despite the fact that Tom is foremost a businessman and I am foremost an innovator, we've shared

a relationship of trust through the years. I cannot understate the value of having a friend, colleague, and, now that I think of it, leader like Tom supporting my efforts.

Next, I'd like to thank my friend and colleague Dr. Kaviyesh Doshi. There was a time at LeCroy when I was *the* mathematics expert. That time ended with his arrival at the company, and we have worked so closely over the years that much of his knowledge was imparted to me. This book would be much less interesting without the things that he taught me, namely in the area of linear algebra, and Kavi contributed significantly to many of the algorithms and solutions presented in this text. Kavi read and checked the math presented here, but, as the saying goes, all errors are my own.

Finally, I'd like to thank my boss for many years, Dave Graef, former CTO of Teledyne LeCroy. Dave negotiated the contract with Cambridge University Press. For some reason, this was a long and drawn out process that I thought would never end. He promised me that the contract would be signed before he retired and he kept his word; it was his last act as CTO prior to leaving the company.

Several people were generous with their time and attention in looking over the first manuscript. Their generosity is a testament to the kinds of people I find myself surrounded with in this field.

Dr. Istvan Novak, a colleague and friend, gave me lots of helpful advice and, most importantly, encouragement to finish this truly enormous task.

My college professor who I've now known for over thirty years, Dr. Peter Wittwer, also gave lots of encouragement and advice on the organization of this book. The multi-port s-parameter calculation came from collaboration with him originally.

During my writing, I reached out to Dr. Gilbert Strang, who is the world's top authority on linear algebra. I asked him some philosophical questions about writing and teaching in an e-mail; he responded in five minutes and, after sending him a chapter that he immediately read and reviewed (and corrected), he allayed my fear of presenting all this math. And his last e-mail comment was "...and back to writing my [his own] book." Thanks a lot Dr. Strang.

Dr. Yuriy Shlepnev provided important feedback on certain areas such as normalization and local port referencing; feedback that I mostly followed. And, despite critical comments, he also gave a lot of encouragement.

Dr. Eric Bogatin, himself a prolific author, supplied the "It's your book" encouragement.

I'd like to thank Julie Lancashire, executive editor at Cambridge University Press, for providing the opportunity to offer this book through such a prestigious publisher, and especially Irene Pizzie, who proofread this book and corrected my numerous grammatical errors.

I'm grateful to everyone involved.

Abbreviations

AC alternating current
ADC analog-to-digital converter
AMS American Mathematical Society
API application programming interface
BERT bit error rate tester
CZT chirp z-transform
DC direct current
DFT discrete Fourier transform
DSO digital storage oscilloscope
DSP digital signal processing
DUT device under test
ESD electrostatic discharge
ESR effective series resistance
FET field-effect transistor
FFE feed-forward equalizer
FIR finite impulse response
GPL general public license
GUI graphical user interface
IDFT inverse discrete Fourier transform
ISI inter-symbol interference
KCL Kirchhoff's current law
KVL Kirchhoff's voltage law
LMSE least mean-squared error
NRZ non-return-to-zero
PAM pulse amplitude modulation
PCB printed circuit board
PRBS pseudo-random bit sequence
PyPI Python Packaging Index
RF radio frequency
RLGC resistance, inductance, conductance, capacitance
rms root mean squared
SNR signal-to-noise ratio
SOLT short-open-load-thru
SOLR short-open-load-reciprocal
SVD singular value decomposition
TDR time-domain reflectometer
UI unit interval
UML universal modeling language
VNA vector network analyzer