X-Parameters

This is the definitive guide to X-parameters, written by the original inventors and developers of this powerful new paradigm for nonlinear RF and microwave components and systems.

Learn how to use X-parameters to overcome intricate problems in nonlinear RF and microwave engineering, as the general theory behind X-parameters is carefully and intuitively introduced, and then simplified down to specific, practical cases, providing you with useful approximations that will greatly reduce the complexity of measuring, modeling, and designing for nonlinear regimes of operation.

Containing real-world case studies, definitions of standard symbols and notation, detailed derivations within the appendices, and exercises with solutions, this is the definitive stand-alone reference for researchers, engineers, scientists, and students looking to remain on the cutting edge of RF and microwave engineering.

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The Cambridge RF and Microwave Engineering Series

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Characterization, Modeling, and Design of Nonlinear RF and Microwave Components

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For Marilyn, with thanks for her patience, support, and, most of all, her love.
David

In memory of Petrus Verspecht.
Jan

To Jessica, Jonathan, and Elise, my inspiration.
Jason

To Domnica, for the patience shown in the many evenings and weekends that I have spent away from her.
Mihai

"Just as the S-parameters revolutionized linear microwave circuit engineering nearly 60 years ago, the relatively new development of the X-parameters and the mixer-based VNA provides a truly scientific approach to nonlinear RF and microwave circuit design. This book, written by experts, contains a wealth of information about the characterization and modeling of nonlinear components as well as their applications to various types of designs. I can only wish that such capability and textbook had been available when I was a design engineer."

Les Besser
Founder of Compact Software and Besser Associates

"S-parameters revolutionized linear RF and Microwave design in the 1970s and X-parameters are doing the same for non-linear design today. Starting with the familiar foundation of S-parameters, the text guides the reader through the additional non-linear terminology needed to provide a clear and practical view of X-parameters. Many practical examples show how to apply them in real world designs and answers are provided to some of the more subtle concepts of cross-frequency phase and memory effects. In a world where wireless is proliferating, this book will be an invaluable reference for any RF designer to reduce design turns and improve their first-pass designs."

Mark Pierpont
Agilent Technologies

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Preface

The need for a rigorous, yet practical, framework for characterization, modeling, and design of nonlinear electronic components at high frequencies has never been more urgent. The communications revolution is inexorably forcing active devices into more and more strongly nonlinear regimes of operation. This is a consequence of the relentless drive for more efficiency in order to save power, extend battery life, and minimize cooling. The price for efficiency is nonlinearity. Dealing with nonlinearity means that new measurement instrumentation and new modeling and design methodologies are required that go far beyond linear S-parameters. Fortunately, there is an overarching, interoperable paradigm combining all these pieces of the nonlinear puzzle together, seamlessly. The new paradigm is called X-parameters,[1] and that is what this book is about.

The book is intended as a comprehensive introduction to X-parameters. It is aimed at a diverse audience with a wide range of backgrounds. This is quite a challenging undertaking! We are targeting professional microwave engineers, device modeling engineers and scientists, RF and microwave circuit designers, electronic and communications engineers, CAE professionals developing simulator algorithms, and microwave and RF professionals developing new high-speed instrumentation for a wide range of nonlinear characterization applications. The inherent interdisciplinary nature of X-parameters is the prime reason we seek to appeal to this broad audience. The practical solutions based on X-parameters deployed by industry over the past several years depend on contributions in all of these areas.

With this diverse audience in mind, we have chosen a particular sequence with which to introduce the subject. We start with a concise summary of the well-known time-invariant linear theory, namely S-parameters. We choose this context, familiar to many readers, to introduce more advanced concepts that will be needed for the remainder of the book. Chapter 2 introduces X-parameters, based on multi-tone nonlinear spectral maps defined on a harmonic grid, and goes into significant detail about the application and implications of the constraint of time invariance. Chapter 3 simplifies the general discussion to simple practical cases, based on the application of spectral linearization, a useful approximation that reduces complexity, enabling practical applications. Several examples are presented demonstrating the power, utility, and relative simplicity of these

[1] "X-parameters" is a trademark of Agilent Technologies, Inc.

simplest X-parameters. The origins of "conjugate" terms in the spectral linearization are discussed. Chapter 4 is devoted to how X-parameters are measured, and also to how they are computed (generated) from within a circuit simulator. The functional block diagram of the main instrument (the nonlinear vector network analyzer – NVNA) is discussed, and the application of measurements using a pulse generator phase reference to obtain the key X-parameter quantities is reviewed. Chapter 5 extends the treatment of X-parameters to multiple large signals and multiple ports, as is necessary in the treatment of many mixers, the treatment of intermodulation with phase, and the large-signal response of power amplifiers as nonlinear functions of both input power and reflections of electrical signals back into the device due to large mismatch, going beyond the first spectral linearization approximation of Chapter 3. Finally, Chapter 6 extends the treatment of X-parameters to dynamic "memory effects," important phenomena exhibited by practical modern high-speed devices in response to wide-band communication signals, for example. Several appendices are provided for detailed derivations, standard symbol and notational definitions, and further elaboration of some parts of the main text to help serve as a reference for workers in the field.

The book is appropriate as a text for an advanced undergraduate or graduate course in electrical engineering. In fact, we perceive an acute need to make X-parameters a standard part of the electrical engineering curriculum. The book may also be appropriate for applied mathematicians and scientists with an interest in rigorous and practical foundations for applications to a wide range of nonlinear systems well beyond electronics.

The background needed by readers of this book is not much more than first-year calculus, basic circuit theory, and simple Fourier analysis. Rudimentary knowledge of electronic power amplifiers and transistors, S-parameter fundamentals, differential equations, circuit design, and circuit simulation would certainly be helpful.

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The authors are profoundly grateful to our many dedicated and talented colleagues who collaborated with us to develop and deploy X-parameter technology, products, support, and services. We are grateful to our many customers, academic researchers, and practicing professionals for their thoughtful feedback, stimulating discussions, and creative applications of this technology. We thank Agilent management for their vital support. Finally, we thank the staff at Cambridge University Press for their commitment to this project, their cheerful professionalism, and their patience.